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Session: HS7.4 – Future hydroclimatic scenarios in a changing world

Stochastic Analysis of the Hydrological Cycle in the Mediterranean and its Recent Climatic Variations

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Climate Variability in the Mediterranean: Insights from ERA5 Reanalysis

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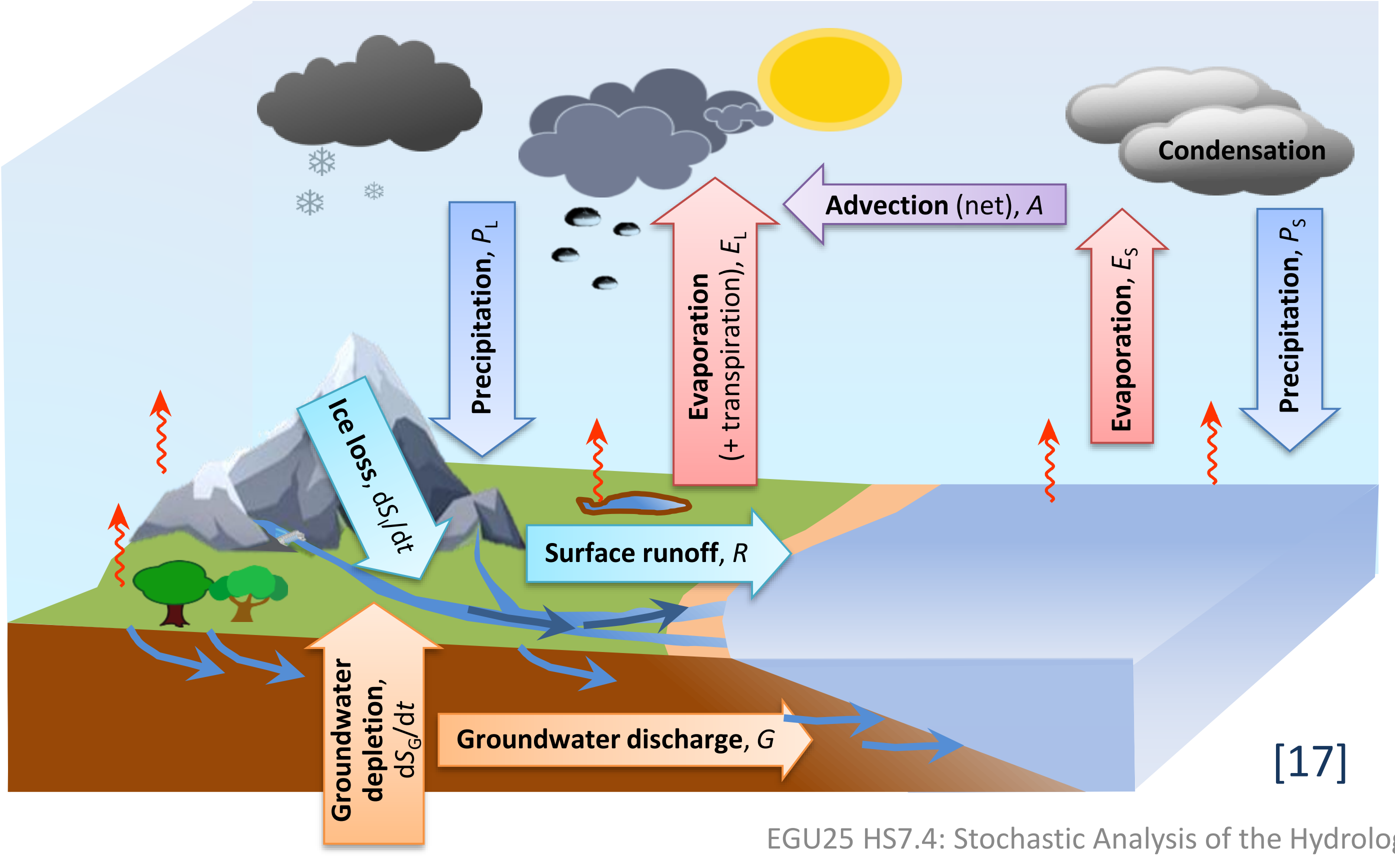


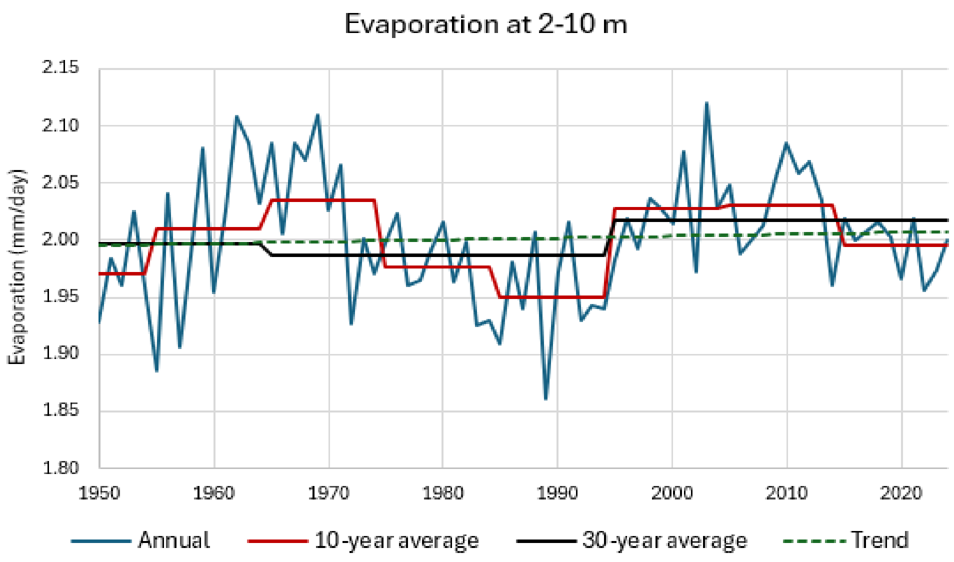
[17]

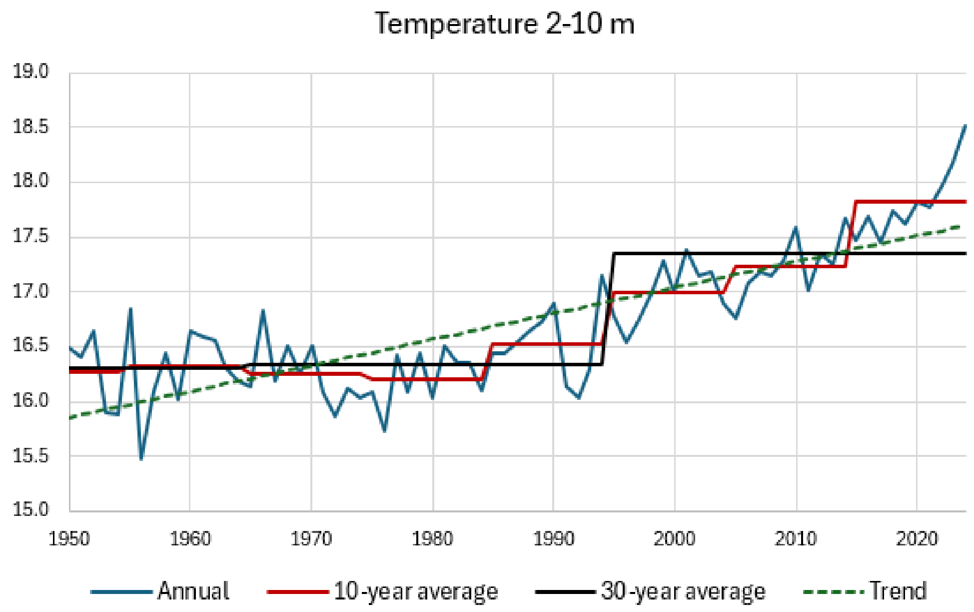
Having collected data from the **Climexp (KNMI) ERA5 Reanalysis dataset** [1] for multiple climate variables across different altitudes in the Mediterranean region, **for the period 1950-2024**, we investigate the long-term persistent (LTP) trends/slopes and the stochastic variability [2].

Climate variables included:

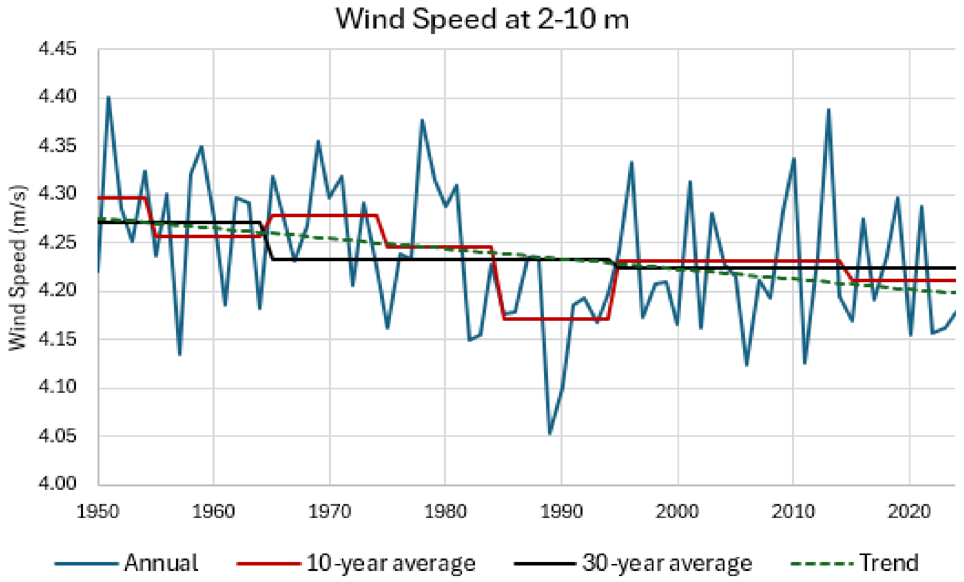
- Temperature [3]
- Precipitation [4]
- Evaporation and potential evaporation [5]
- Wind speed [6]
- Zonal and meridional wind
- Column water and relative humidity [7]
- Latent, sensible heat flux and specific humidity [7]

Evaporation Stability Despite Warming: The Role of Wind Speed





Slope	
Temperature	0.0236
Wind Speed	-0.0011
Evaporation	0.0002



Although temperature shows a clear positive trend, evaporation does not follow, suggesting it is not primarily temperature-driven (r=0.05).

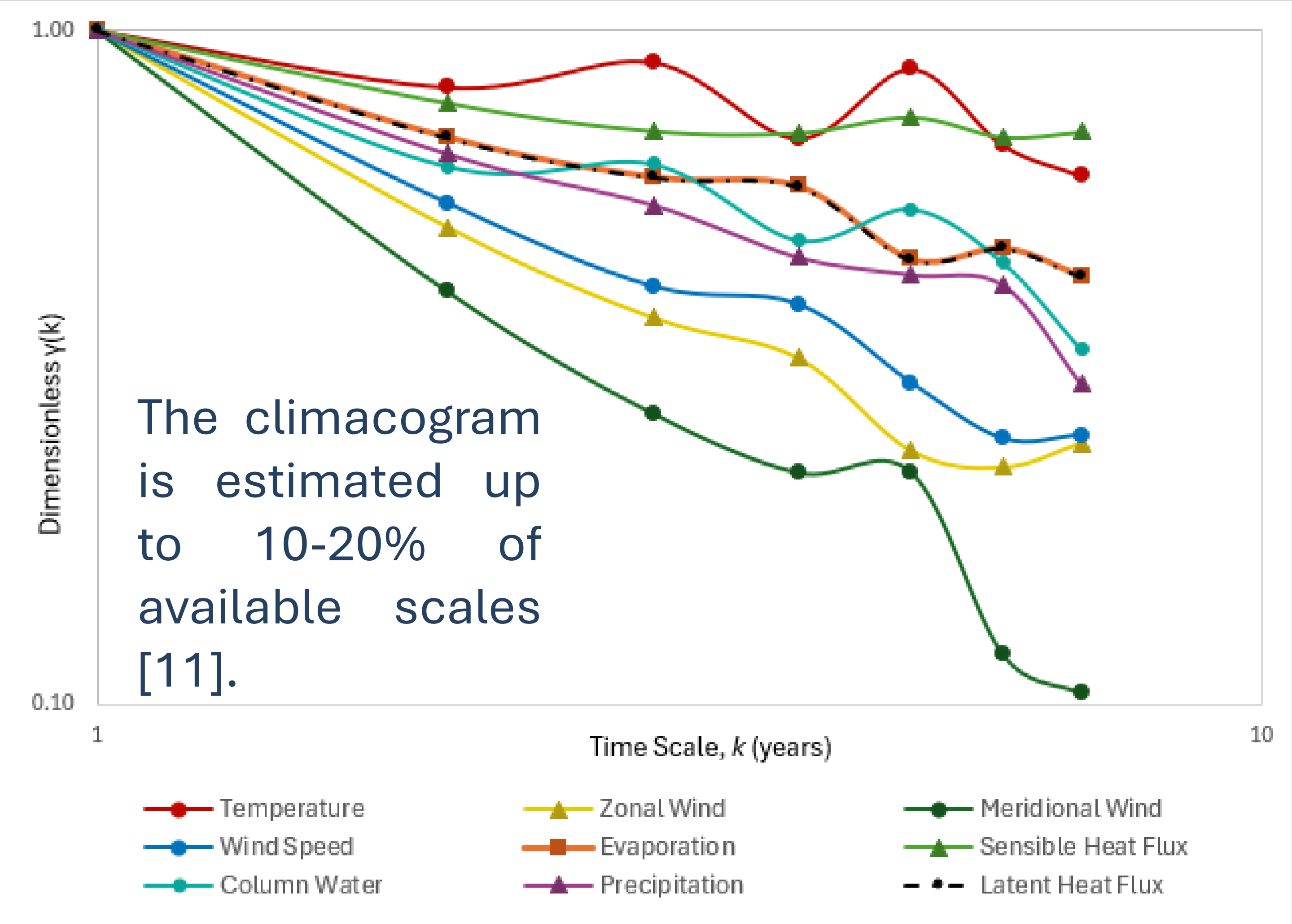
Instead, it correlates more with wind speed (r=0.44, [8]), which, like evaporation [9], remains nearly stable over time (slopes: -0.0011 and +0.0002, respectively).

Stochastic Investigation of Variability: Hurst-Kolmogorov process

To capture the **stochastic and persistent nature** of hydrological processes, we apply the **Hurst-Kolmogorov model** using observed climatic data. [10]

$$\gamma_k \coloneqq var[\underline{x}_j^{(k)}] = \gamma_1/k^{2-2H}$$

Hurst	Empirical	Theoritical (Corrected for Bias)
Temperature	0.90	0.96
Zonal Wind	0.62	0.65
Column Water	0.77	0.82
Meridional Wind	0.53	0.55
Wind Speed	0.64	0.68
Evaporation	0.79	0.85
Precipitation	0.73	0.78
Latent Heat Flux	0.79	0.85
Sensible Heat Flux	0.92	0.97



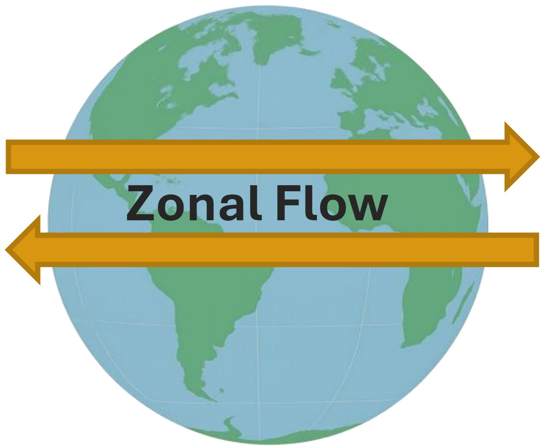
The climacogram is estimated up to 10-20% of available scales [11].

Zonal and Meridional Wind

Zonal Wind (Zonal Flow)

- Refers to air movement that follows a path **parallel to the equator and lines of latitude** – flowing either from west to east (westerly) or from east to west (easterly).
- This pattern of circulation tends to support **consistent temperatures along those latitudinal zones**. [15]

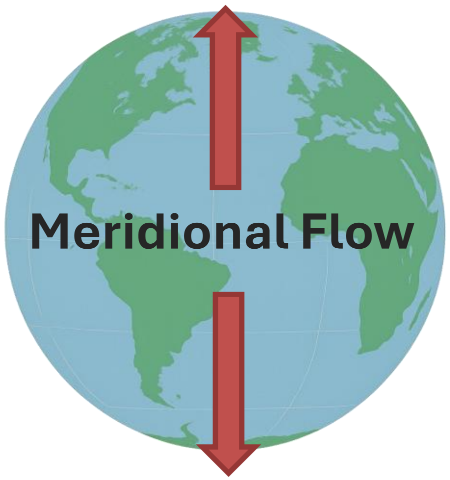
Zonal Wind



Meridional Wind (Meridional Flow)

- Indicates to air movement that **follows the lines of longitude** (meridians) – flowing either from north to south or from south to north.
- Responsible for: · **cold air outbreaks** from the poles moving south
  · **warm air surges** from the tropics moving north [15]

Meridional Wind



Total Column Water Vapour & Relative Humidity

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Total Column Water Vapour

- Refers to the total amount of **water vapour in a vertical column** of the atmosphere, from the surface to the top of the atmosphere.
- If fully condensed and precipitated, it would form a surface layer of water of equivalent thickness. [15]

Units of measurement:
mm or kg/m^2

Relative Humidity

- The **ratio of** the **current amount of water vapour** in the air **to** the **maximum amount** it could hold at that temperature.
- **Highly temperature-dependent**: warmer air can hold more water vapour. [15]

Expressed as
a percentage (%)

The available data provide **Total Column Water Vapour at the surface** and **Relative Humidity at** pressure levels of **850 hPa** (≈1.5 km altitude), **500 hPa** (≈5.6 km) and **200 hPa** (≈11.8 km).

Latent Heat Flux, Sensible Heat Flux, and Specific Humidity

Latent Heat Flux

- Involves **heat transfer** associated **with phase changes of water**, mainly ***evaporation*** and condensation.
- Specifically, latent heat flux is described by the following equation, where E′ represents evaporation.

$$\boldsymbol{\Lambda} = \boldsymbol{\lambda} \times \mathbf{E}'$$

where λ (kJ/kg) is calculated as $\lambda = 3139 - 2.336\, T_s$,with T_s the temperature in the surface of water in K.[16,18]

Sensible Heat Flux

- Refers to the **transfer of thermal energy** between the Earth's surface and the atmosphere due to temperature differences and occurs **without phase changes**. [15]

Specific Humidity

- Is equal to the **ratio of mass water vapor to the total mass of air**, regardless of whether the air is saturated – unlike relative humidity. [15]

Pressure to Altitude Conversion

- For altitudes **z ≤ 11,000 m**, the pressure is calculated using the following equation [12]:

$$p = 1013.25 \times [\,1\text{-}2.256\times10^{-5}\,z]^{5.256} \Leftrightarrow \; z = 44332\left[1-\left(\frac{p}{1013.25}\right)^{0.1925}\right]$$

while for **11,000 ≤ z ≤ 20,000 m**, pressure follows the expression below:

$$p = 226.27\ e^{-0.00015769(z\text{-}11000)} \Leftrightarrow \; z = 11000 + 6341.6\ln\left(\frac{226.27}{p}\right)$$

- **Units of measurement**: altitude (z): m, pressure (p): hPa

Based on the above equations, the pressure values were converted to the corresponding altitudes as shown below:

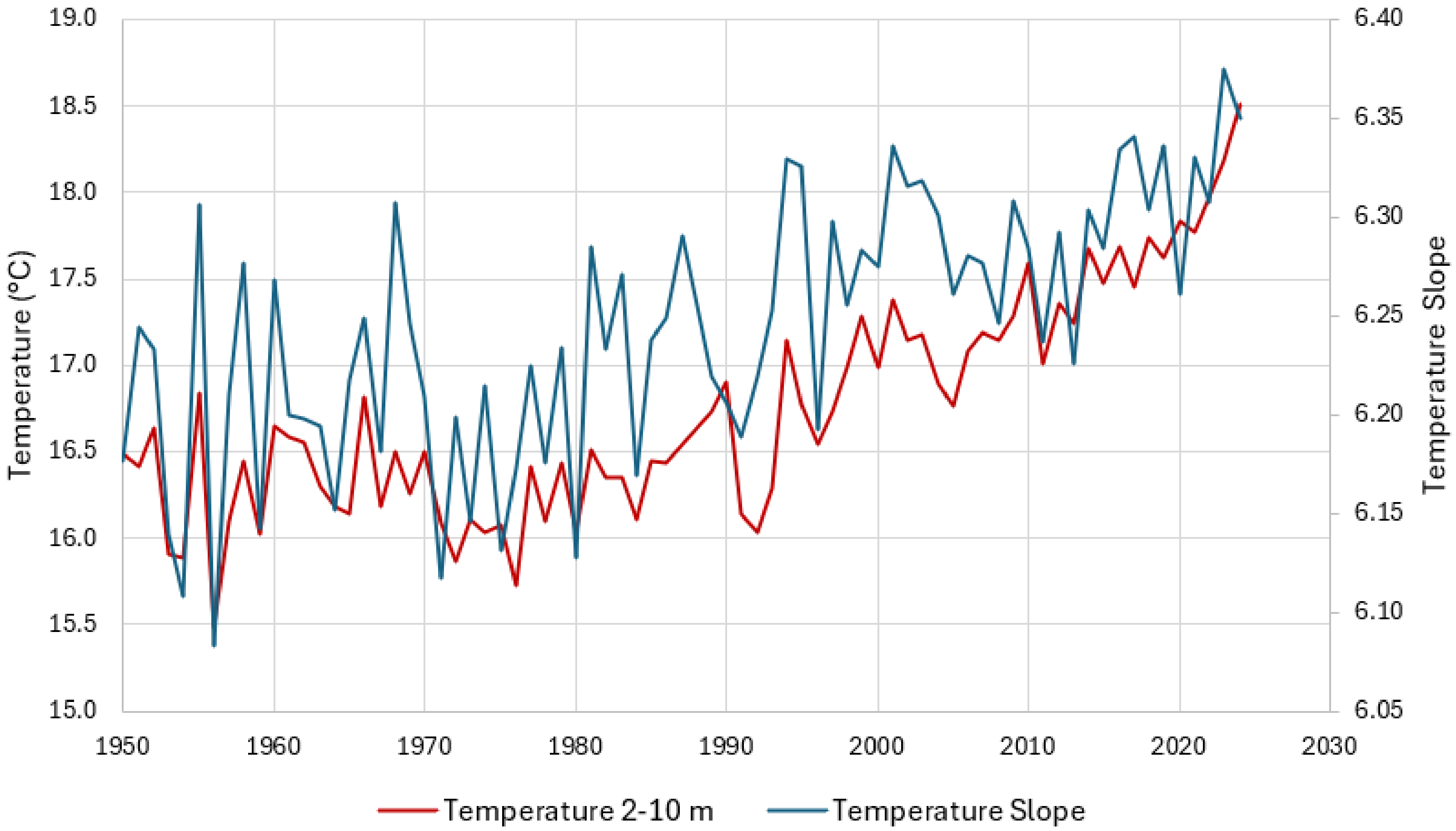
Pressure (hPa)	Altitude (km)
Surface - 1013.25	0
850	1.5
500	5.6
200	11.8

Slopes of Climate Variables Across Different Altitudes

Slope						
Variable	Unit/year	Altitude				
		Surface	2-10 m	1.5 km	5.6 km	11.8 km
Temperature	°C/year	-	0.023612	0.018929	0.016121	-0.000921
Zonal Wind	m/s/year	-	-0.001470	-0.004096	-0.009096	-0.011640
Column Water	$kg/m^2/year$	0.014411	-	-	-	-
Relative Humidity	%/year	-	-	-0.000436	-0.000074	0.000076
Meridional Wind	m/s/year	-	-0.011640	-0.001518	-0.004820	-0.010786
Wind speed	m/s/year	-	-0.001051	0.000010	0.000021	0.000021
Evaporation	mm/day/year	-	0.000165	-	-	-
Potential Evaporation	mm/day/year	-	-	0.002090	-	-
Precipitation	mm/day/year	0.000000	-	-	-	-
Latent Heat Flux	$W/m^2/year$	0.000000	-	-	-	-
Sensible Heat Flux	$W/m^2/year$	-	0.000000	-	-	-
Specific Humidity	kg/kg/year	-	-	0.000002	0.000001	0.000000

The table summarizes the **linear trends (slopes)** of key atmospheric variables across different altitudes; however, there is uncertainty in the estimation due to the nature of classical methods and the LTP [8,13].

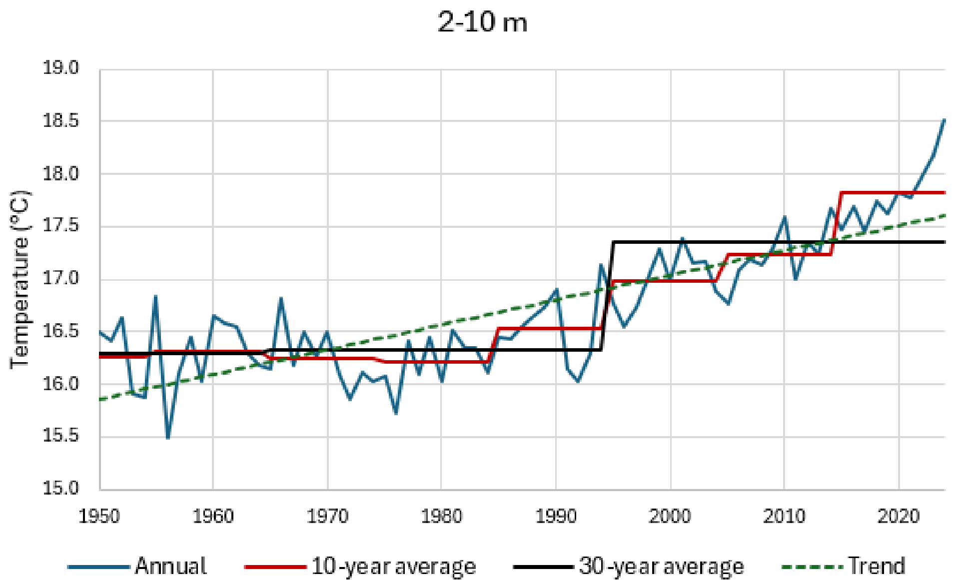
Increase in Temperature Slope

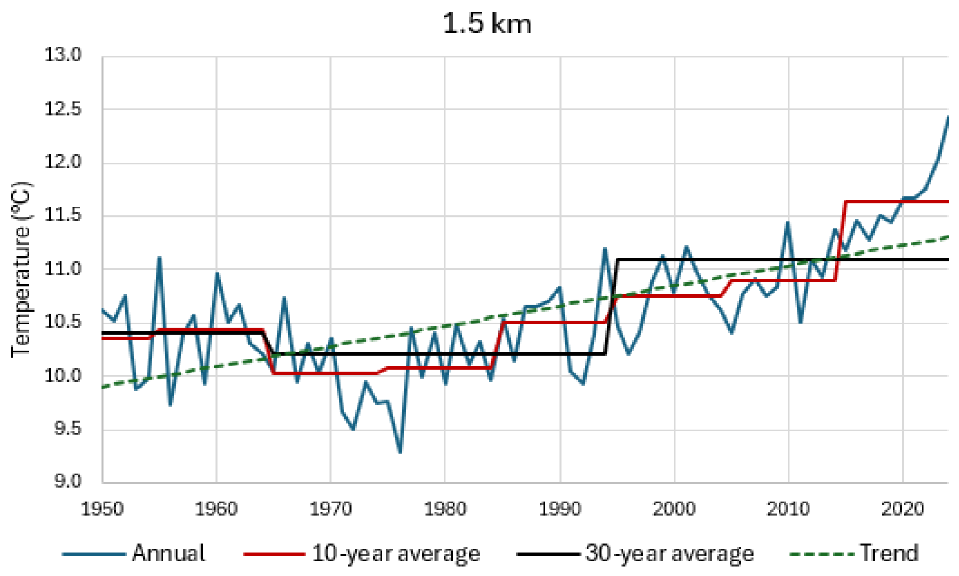


The temperature slope is increasing, exhibiting a positive trend.

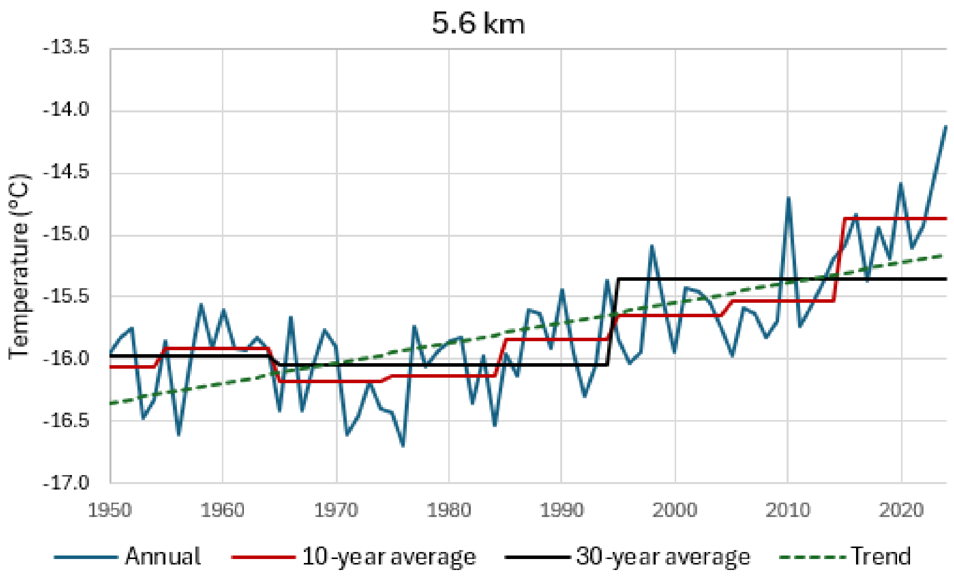
It is observed that it also follows the temperature at heights of 2-10 m, with slopes +0.0020 and +0.0236, respectively.

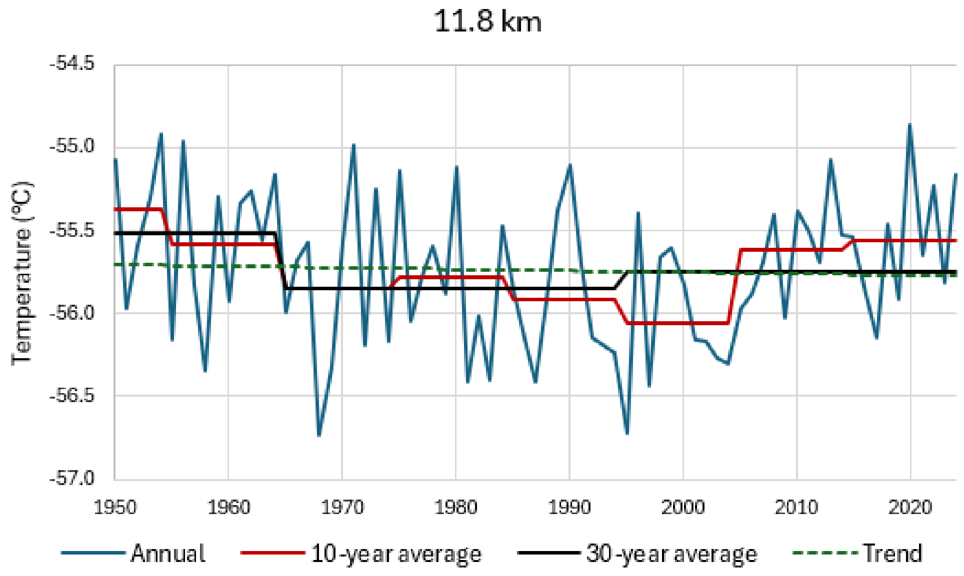
Temperature



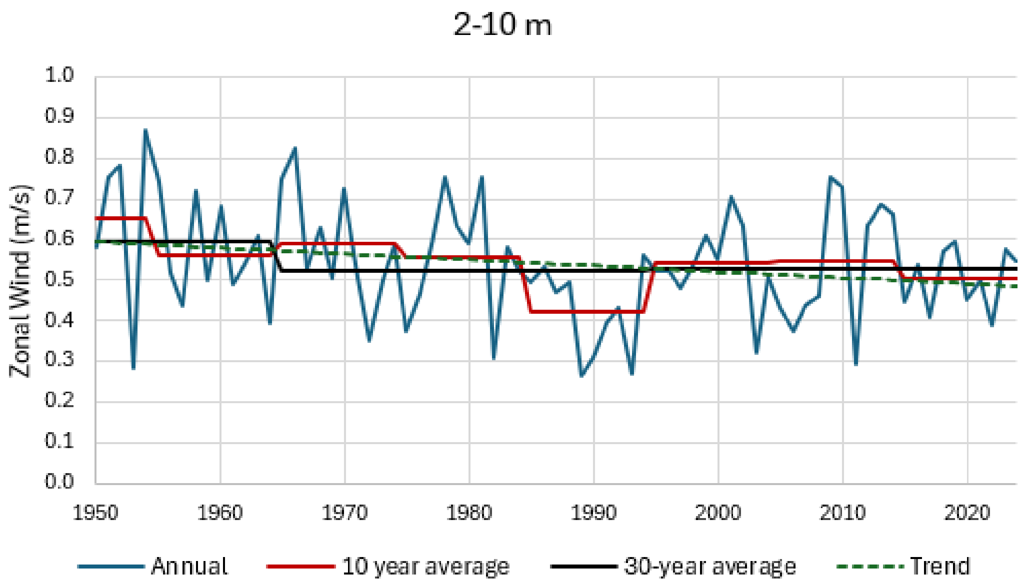


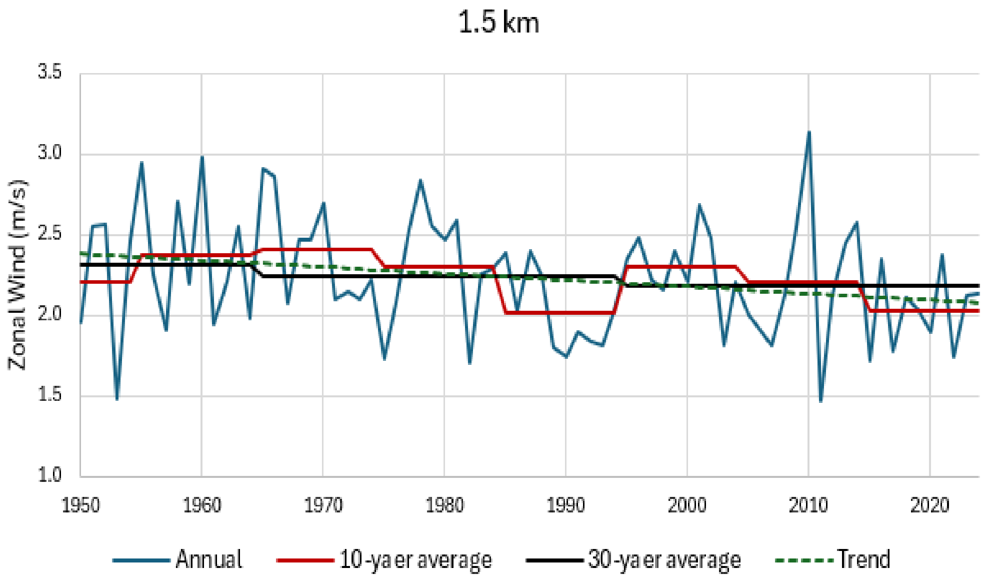
Slope	
2-10 m	0.023612
1.5 km	0.018929
5.6 km	0.016121
11.8 km	-0.000921



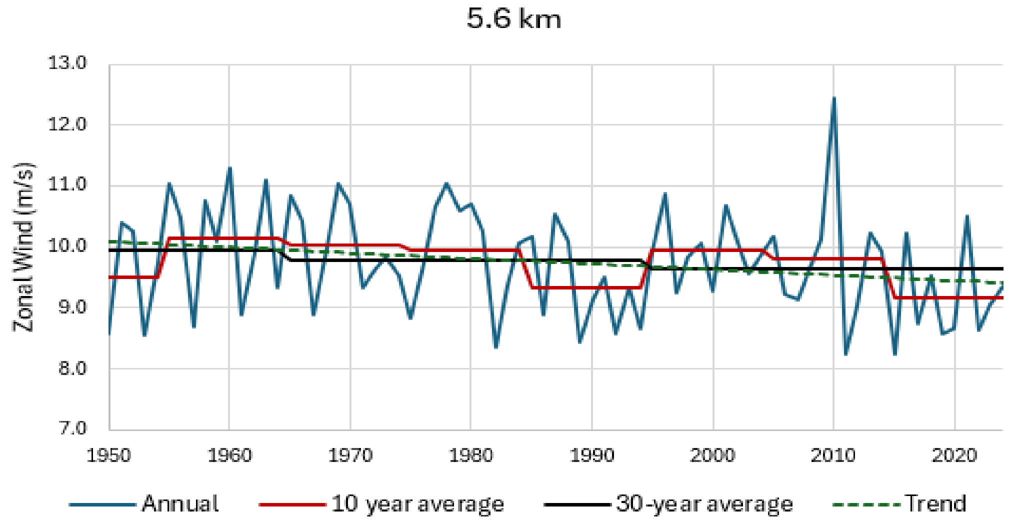


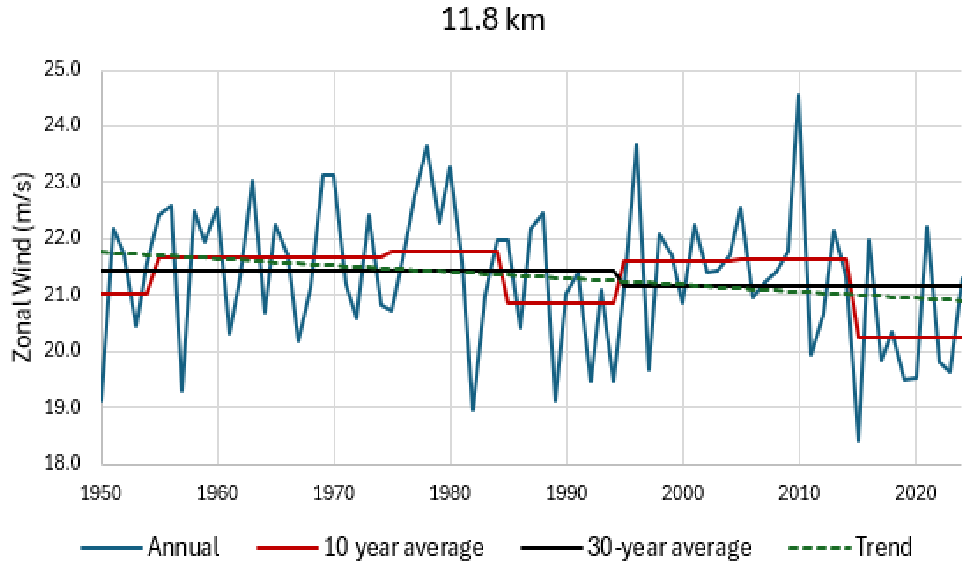
Zonal Wind



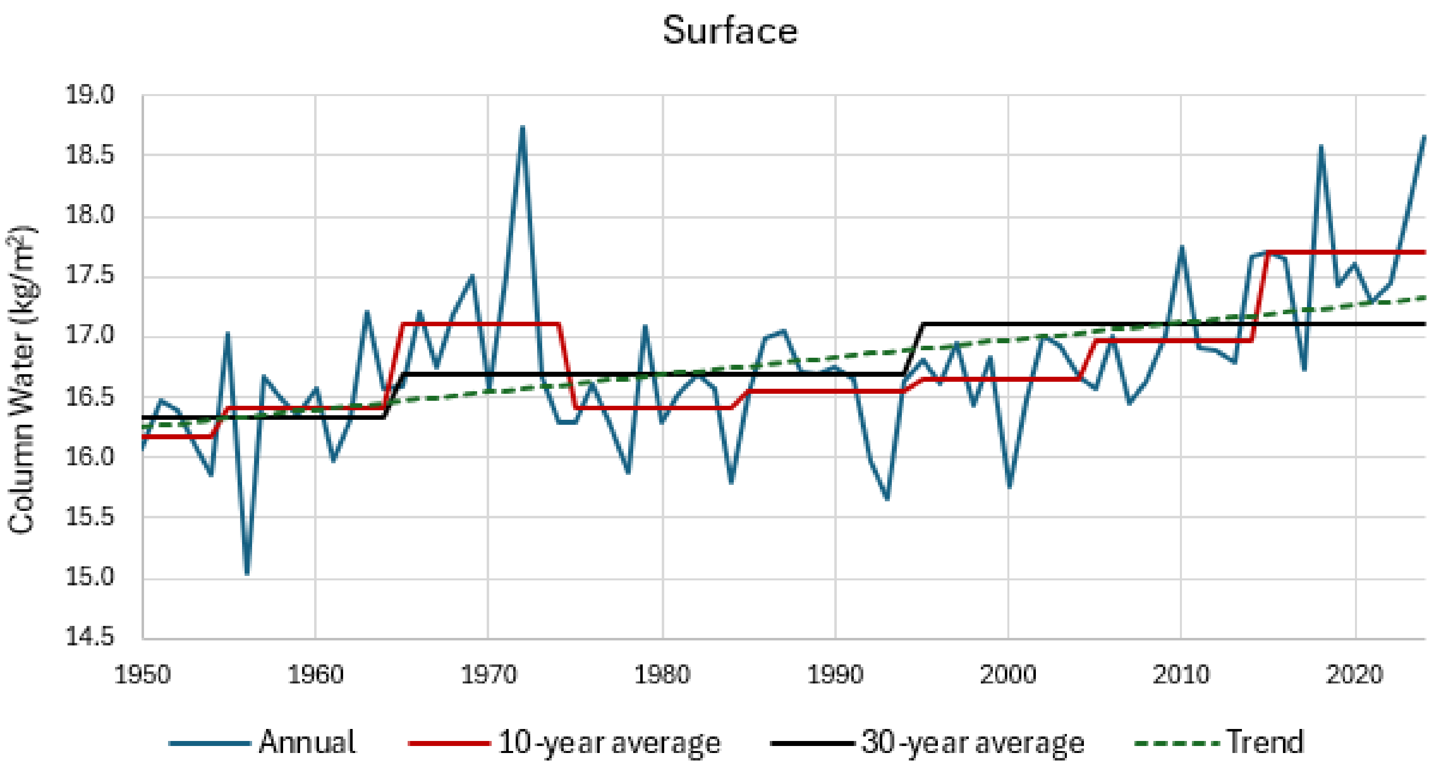


Slope	
2-10 m	-0.001470
1.5 km	-0.004096
5.6 km	-0.009096
11.8 km	-0.011640



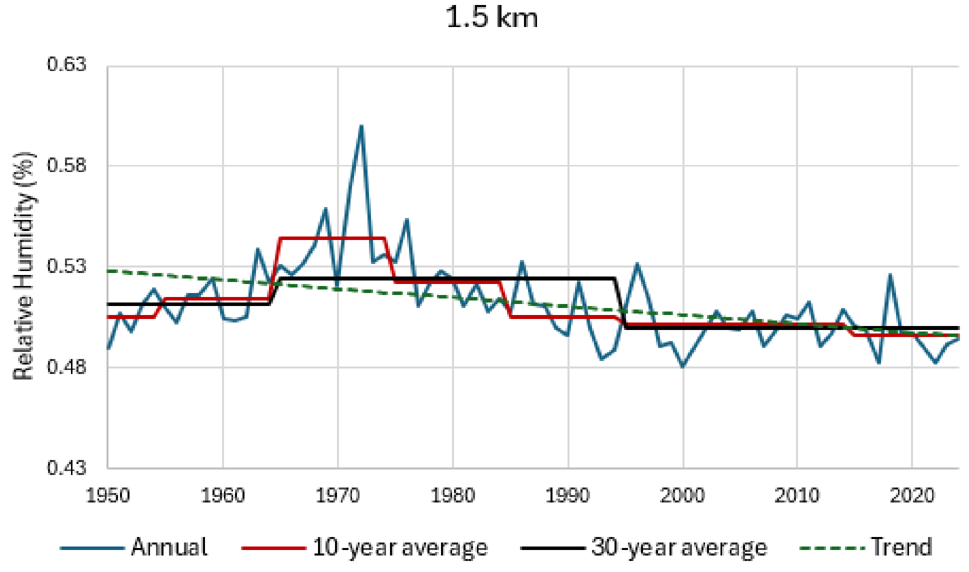


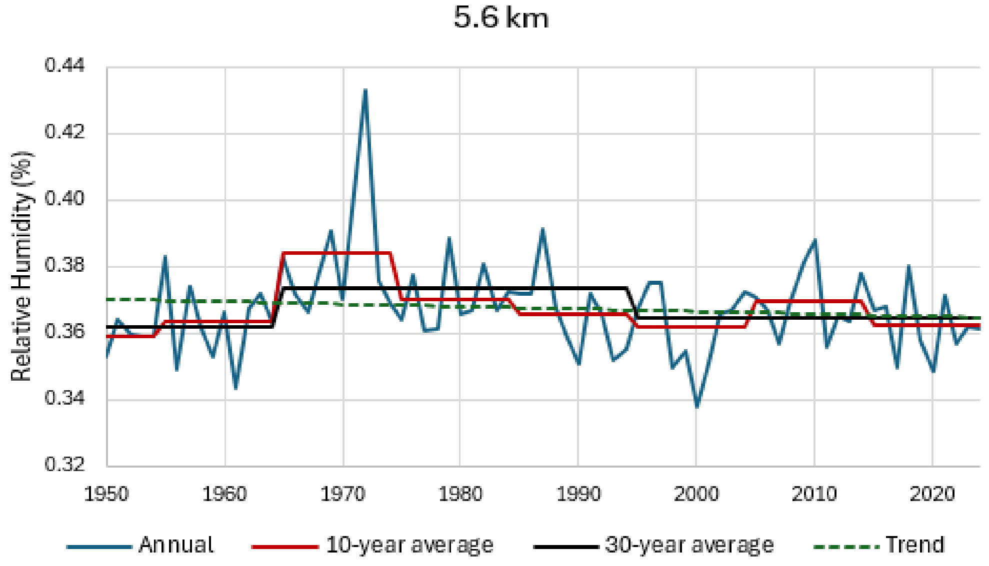
Column Water

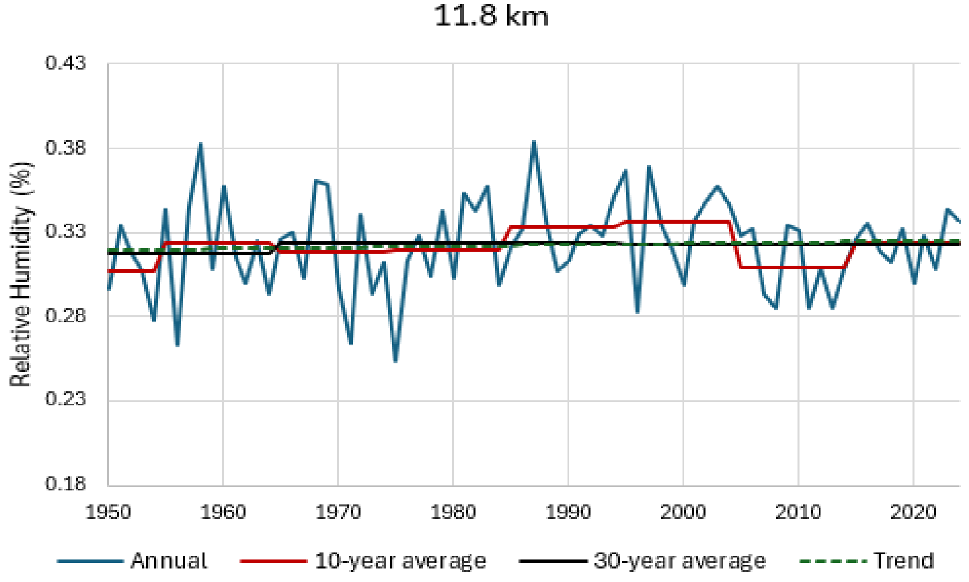


Slope	
Surface	0.014411

Relative Humidity

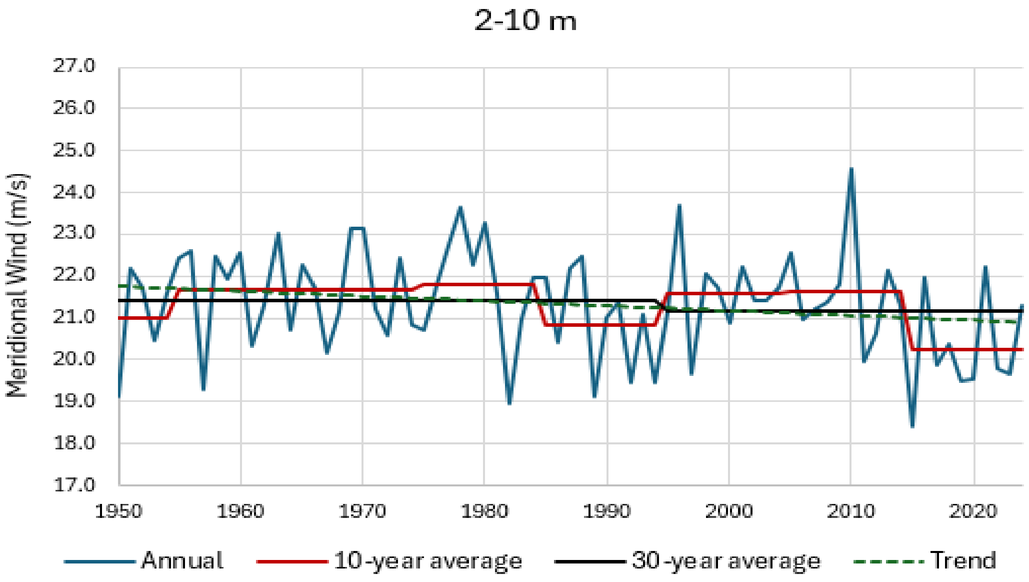


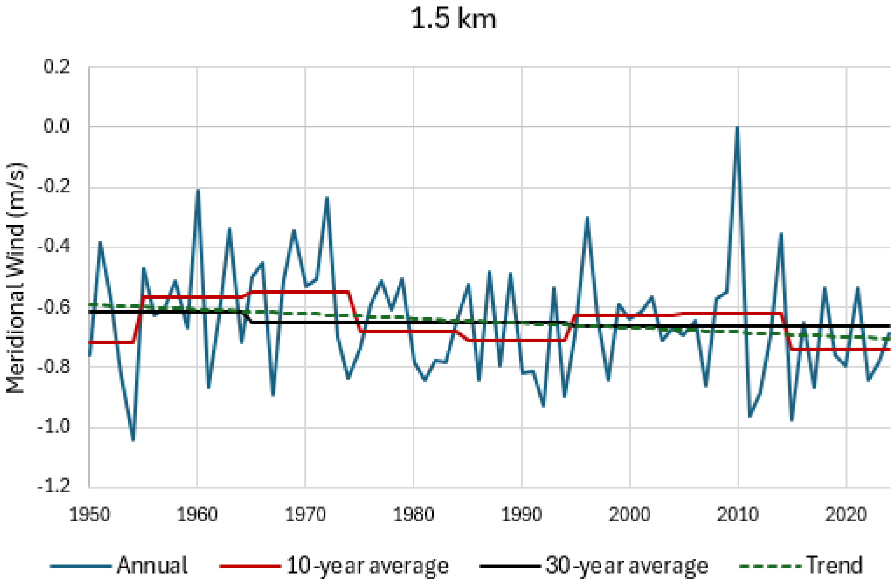




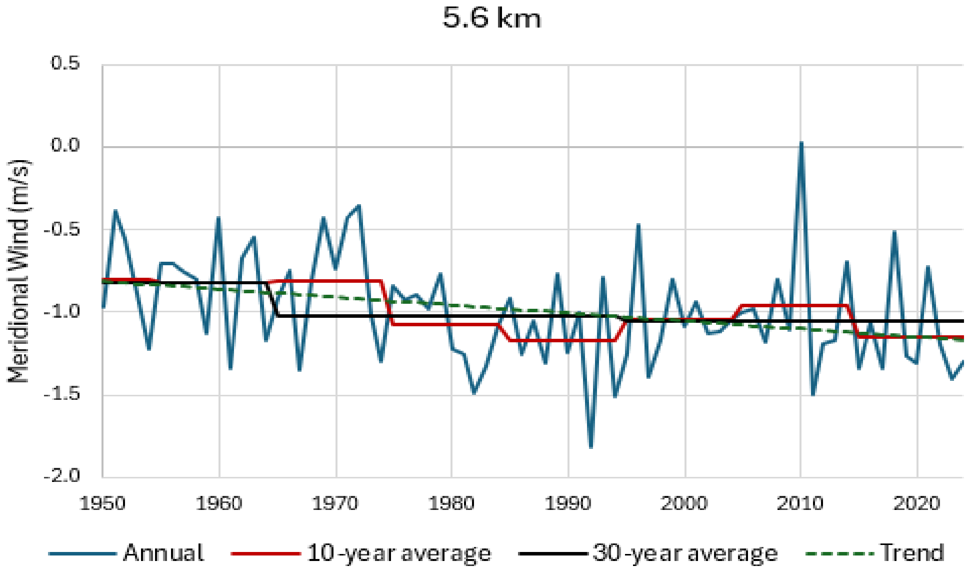
Slope	
1.5 km	-0.000436
5.6 km	-0.000074
11.8 km	0.000076

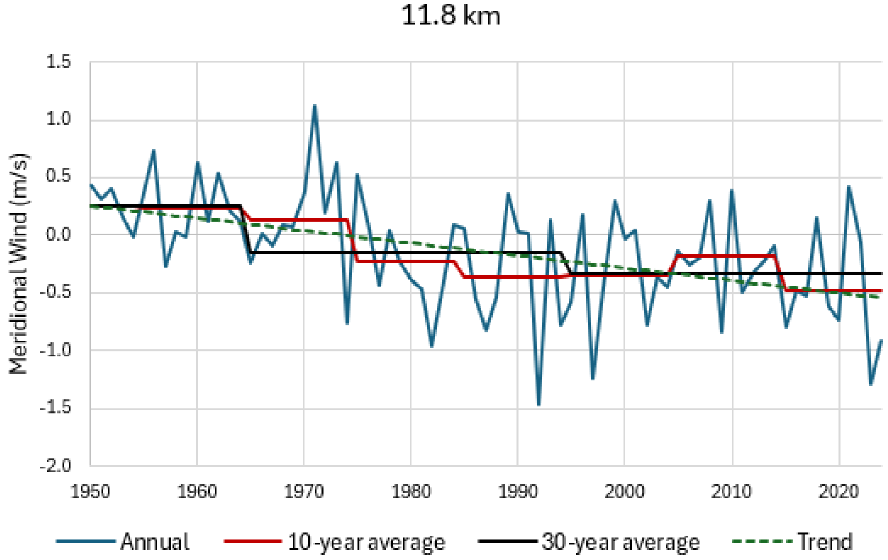
Meridional Wind



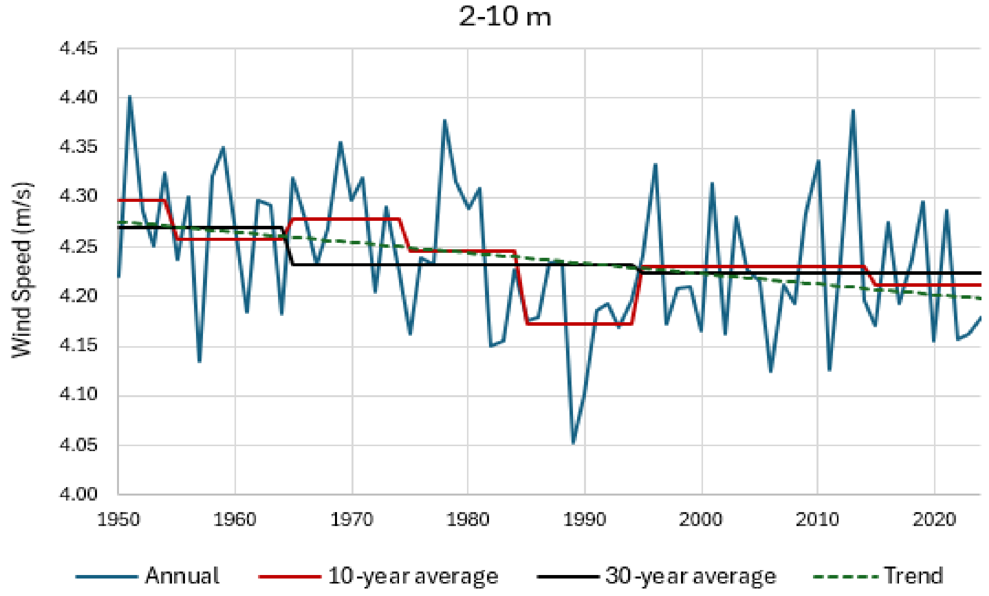


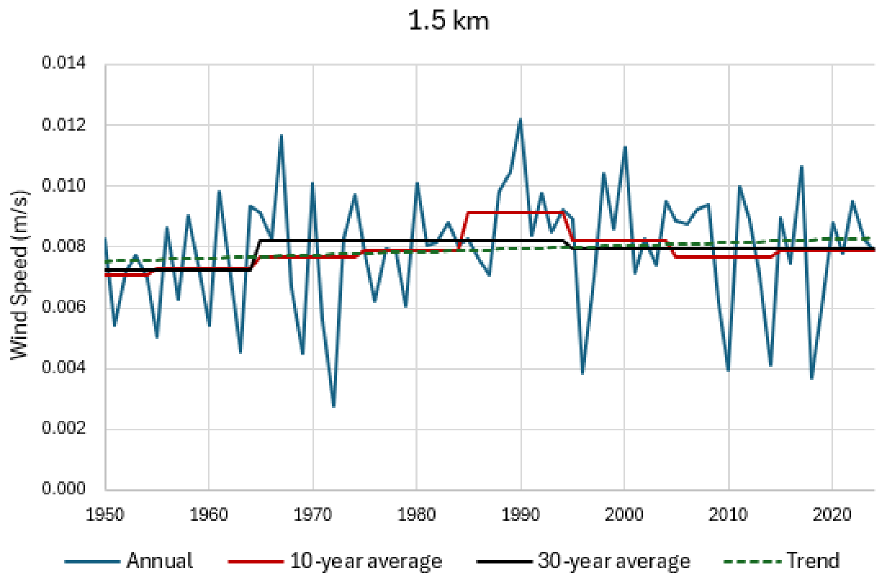
Slope	
2-10 m	-0.011640
1.5 km	-0.001518
5.6 km	-0.004820
11.8 km	-0.010786

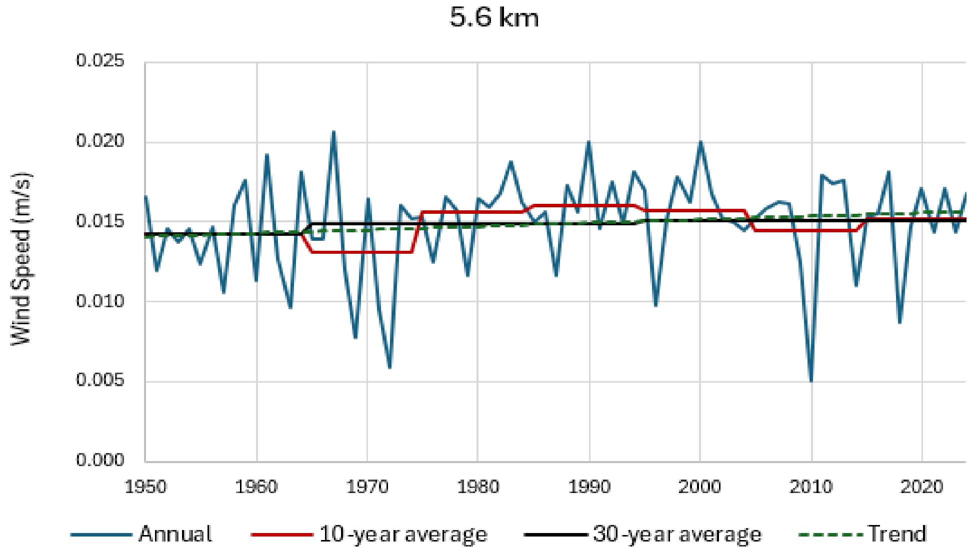


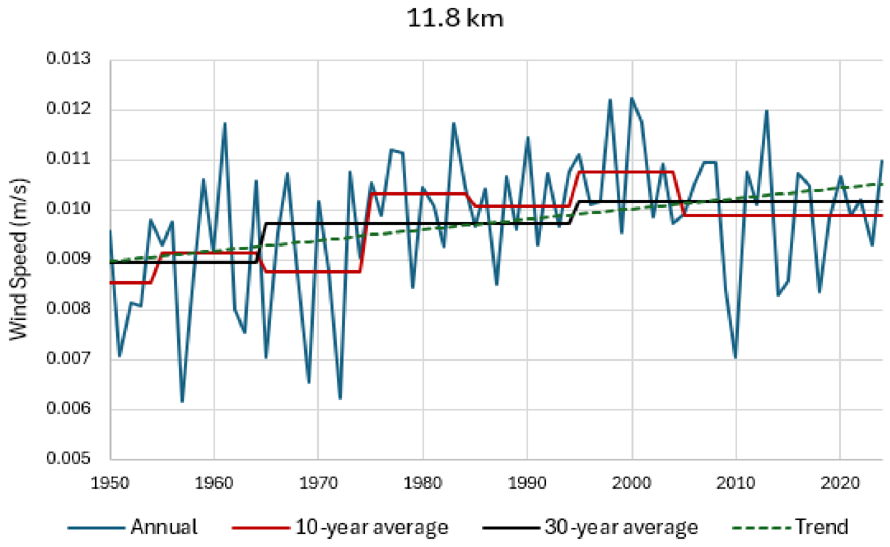


Wind Speed



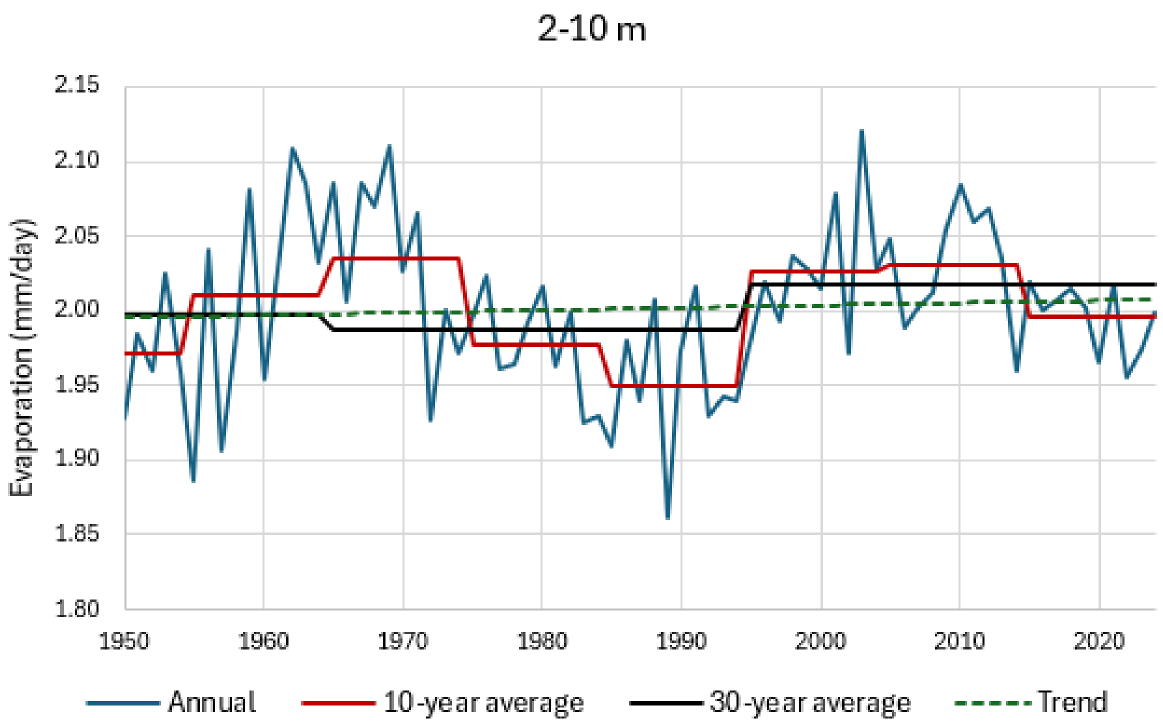


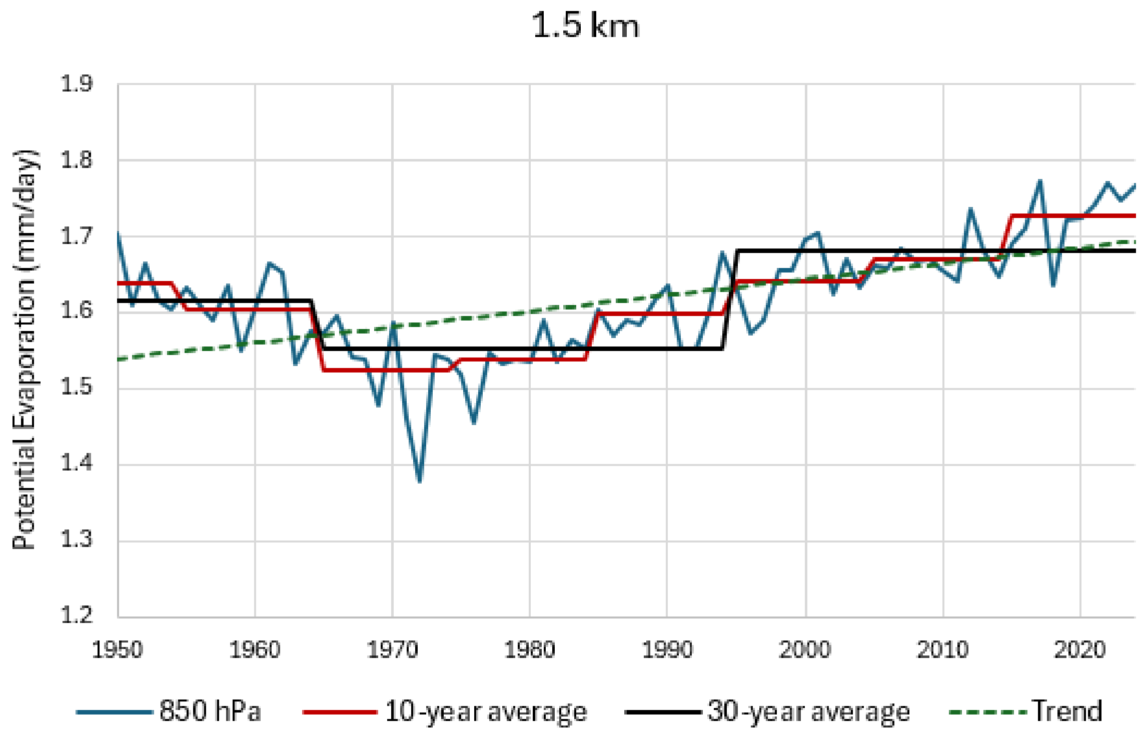




Slope	
2-10 m	-0.001051
1.5 km	0.000010
5.6 km	0.000021
11.8 km	0.000021

Evaporation and Potential Evaporation

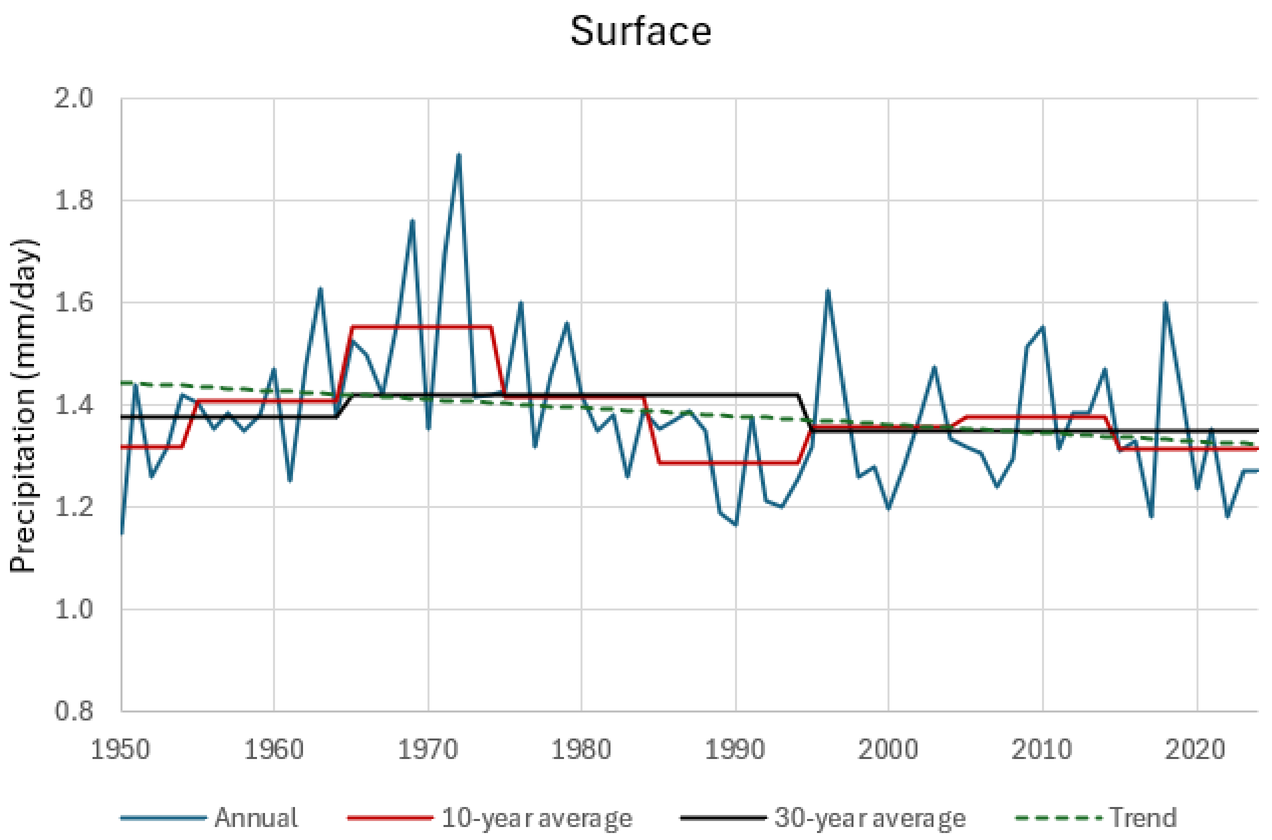




Slope	
2-10 m	0.000165

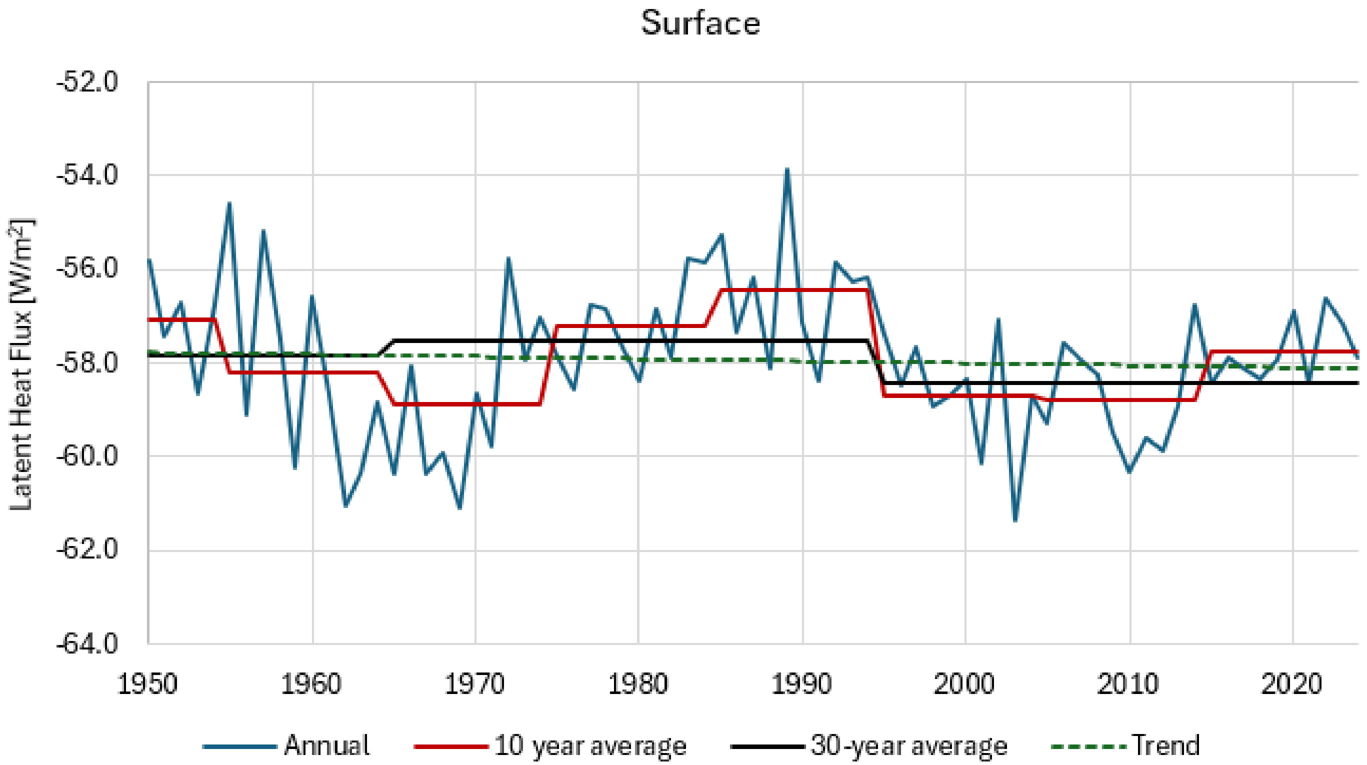
Slope	
1.5 km	0.002090

Precipitation



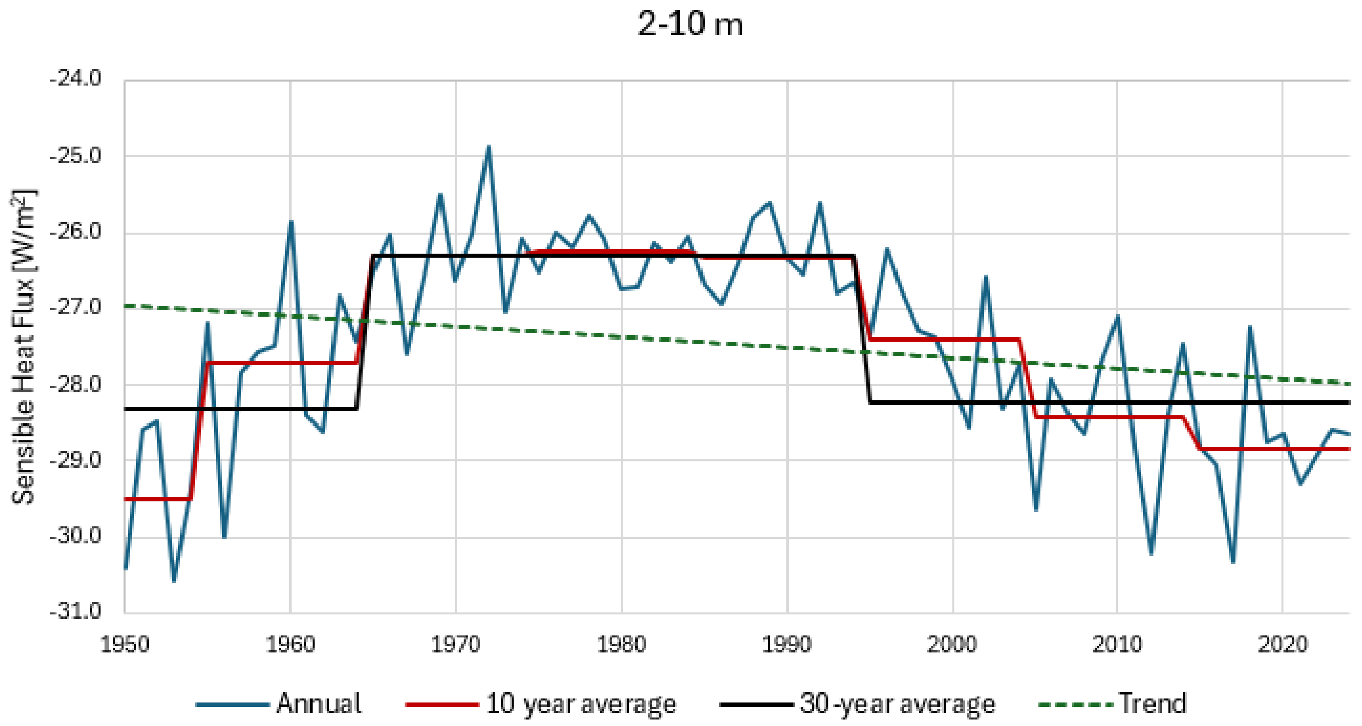
Slope	
Surface	-0.001644

Latent Heat Flux



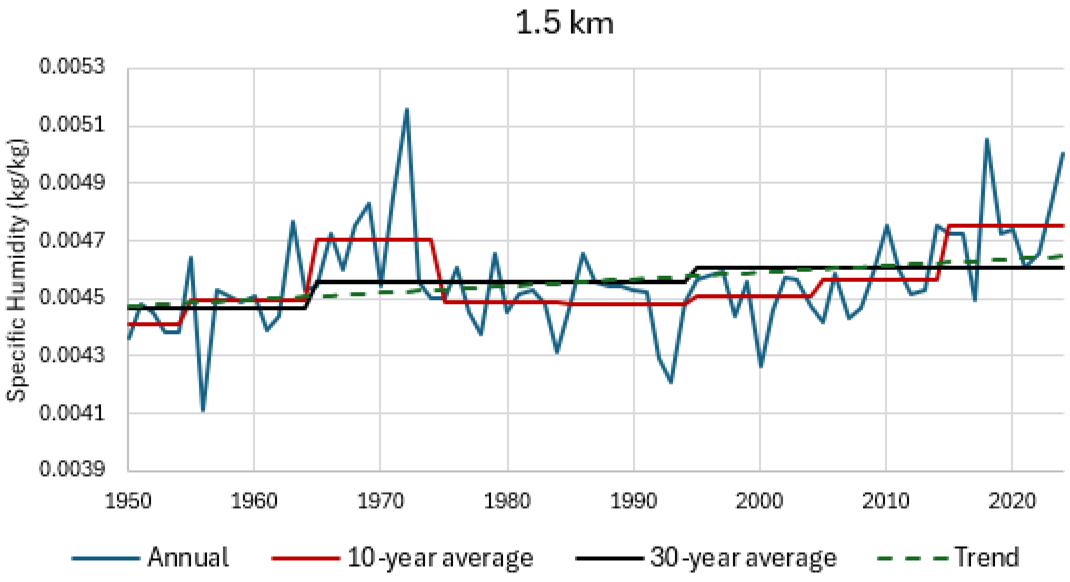
Slope	
Surface	-0.004645

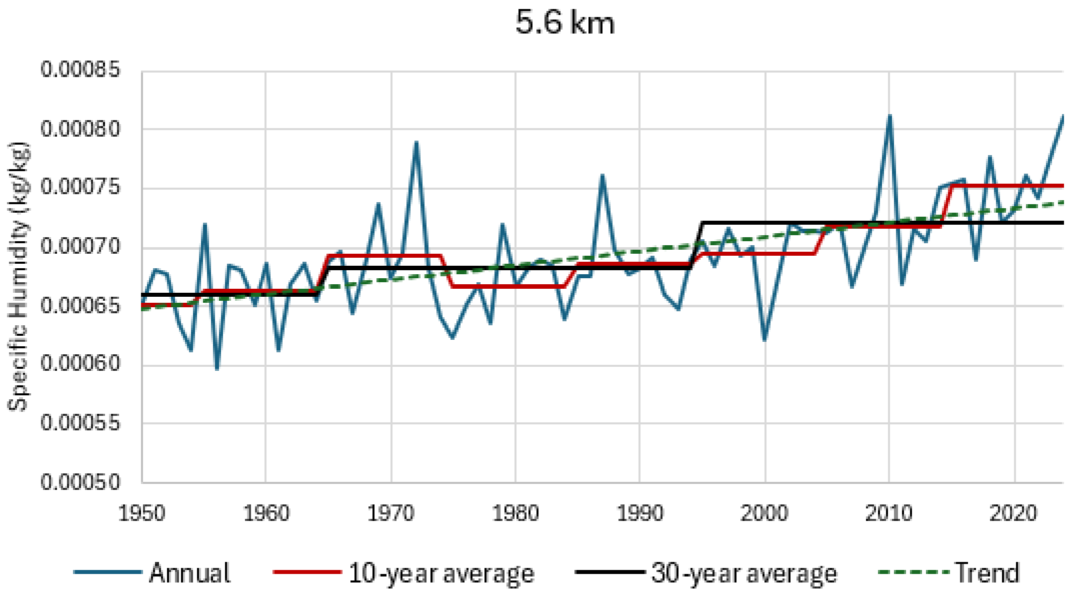
Sensible Heat Flux

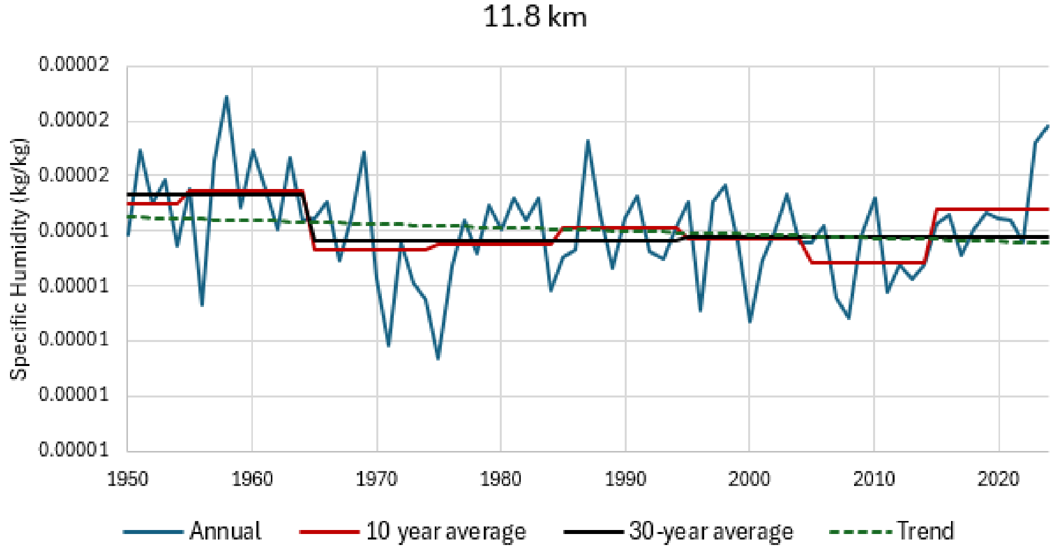


Slope	
2-10 m	-0.013819

Specific Humidity

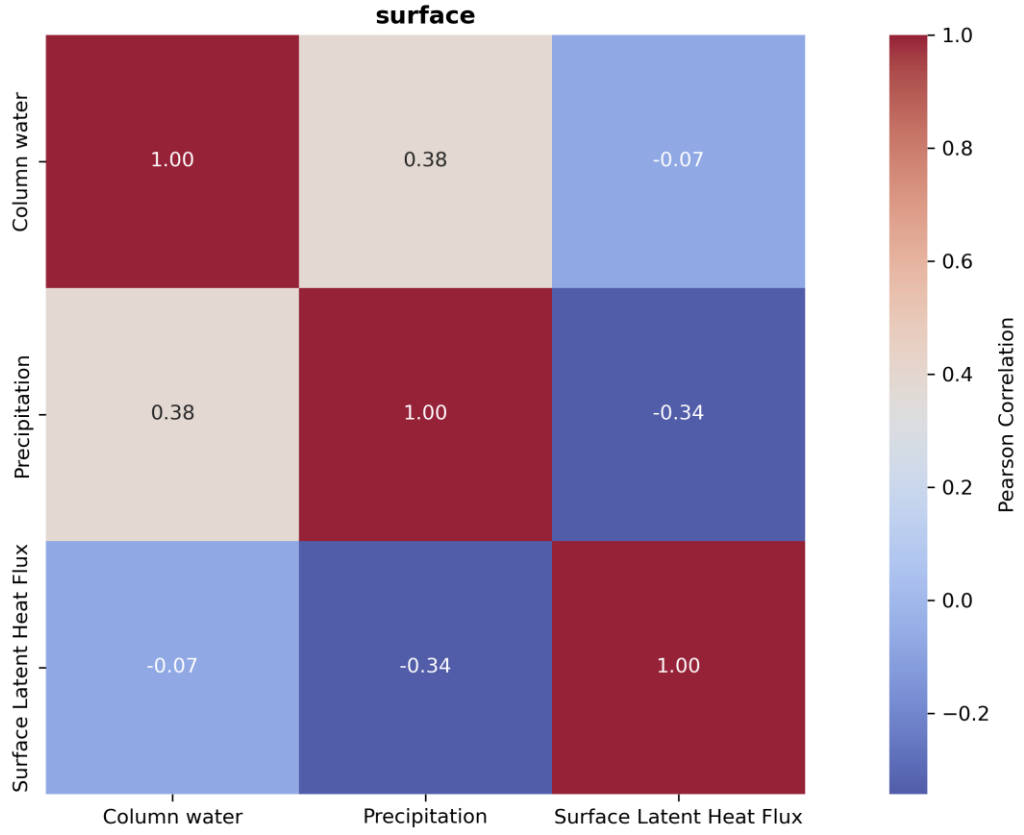


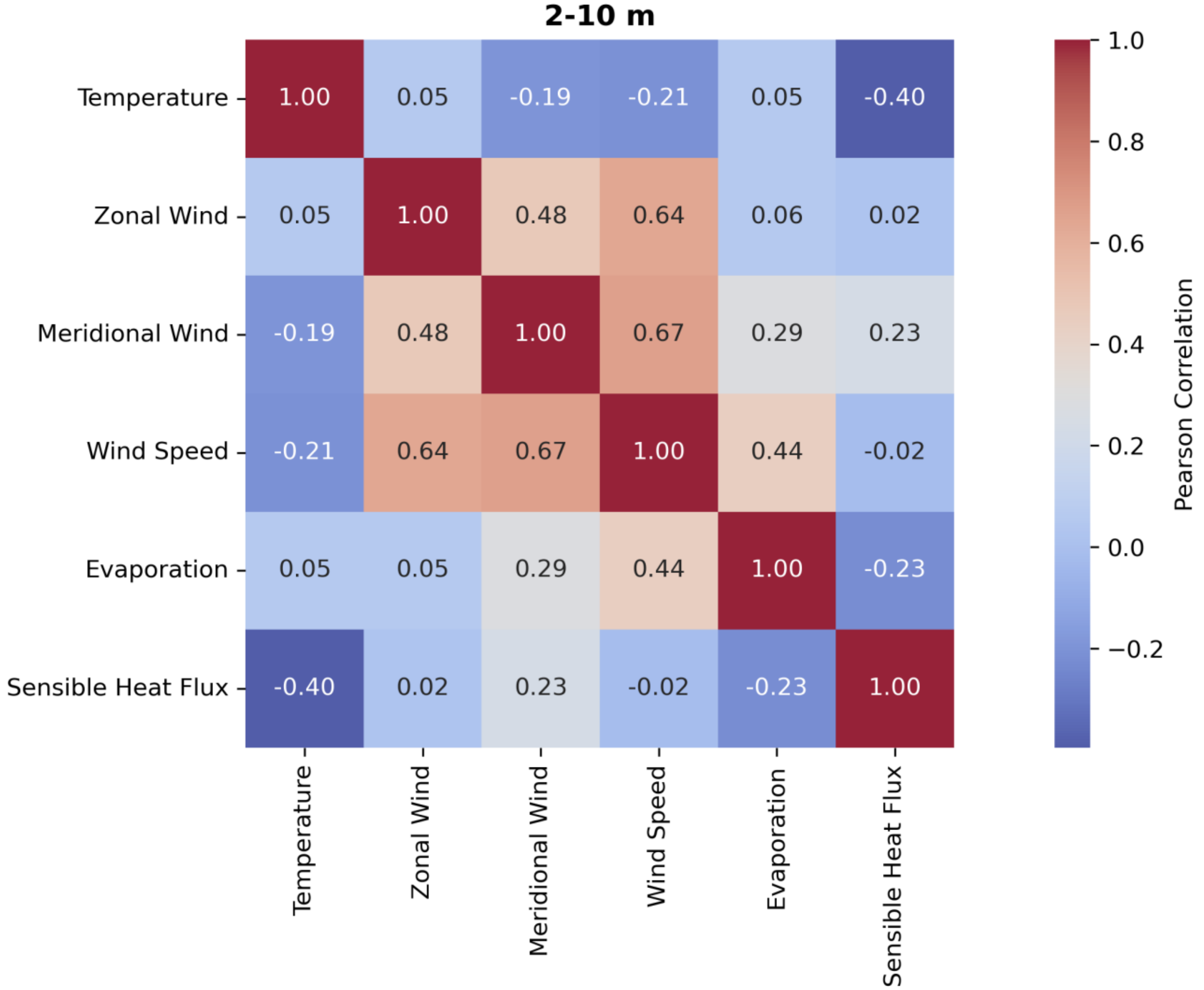




Slope	
1.5 km	0.000002
5.6 km	0.000001
11.8 km	0.000000

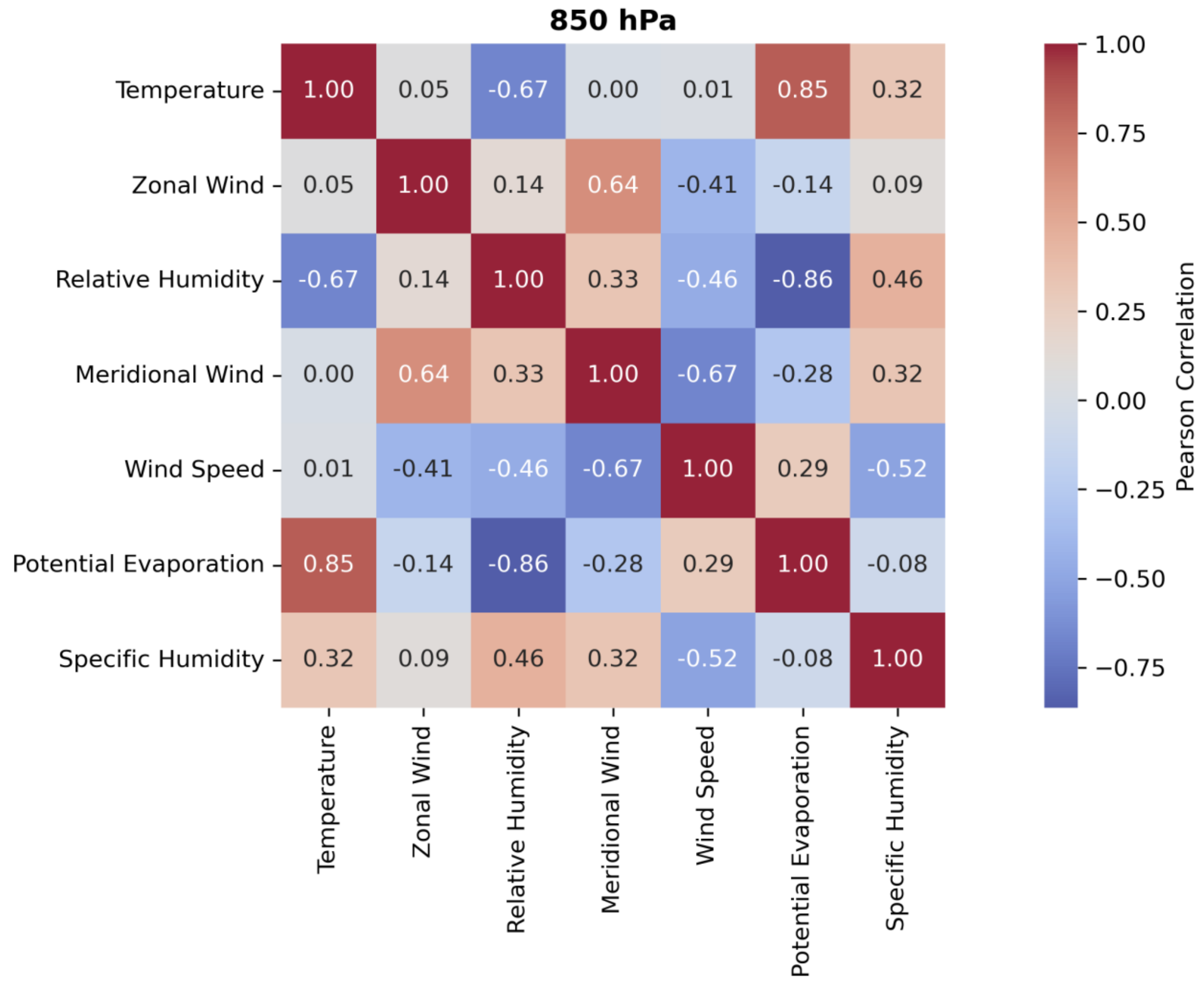
Pearson Correlations Between Variables at Different Altitudes (I)

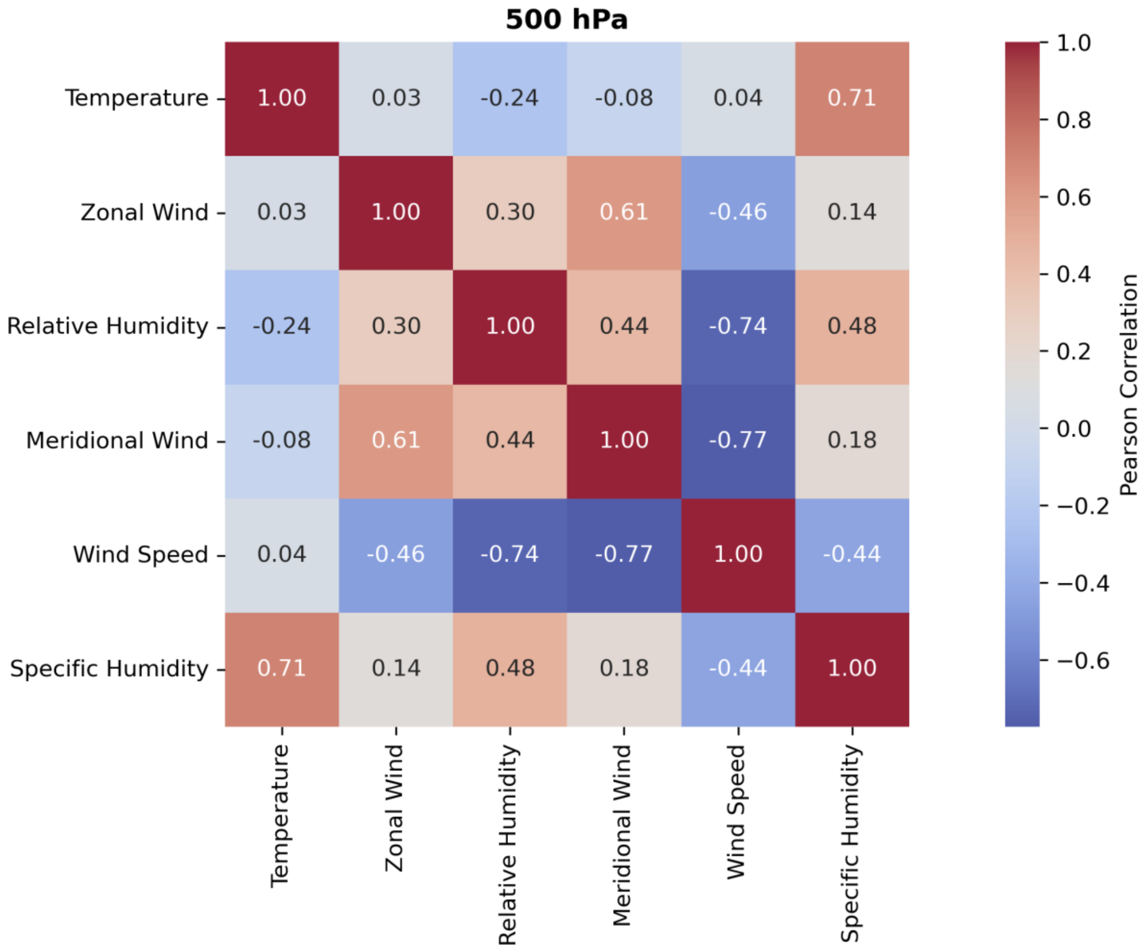




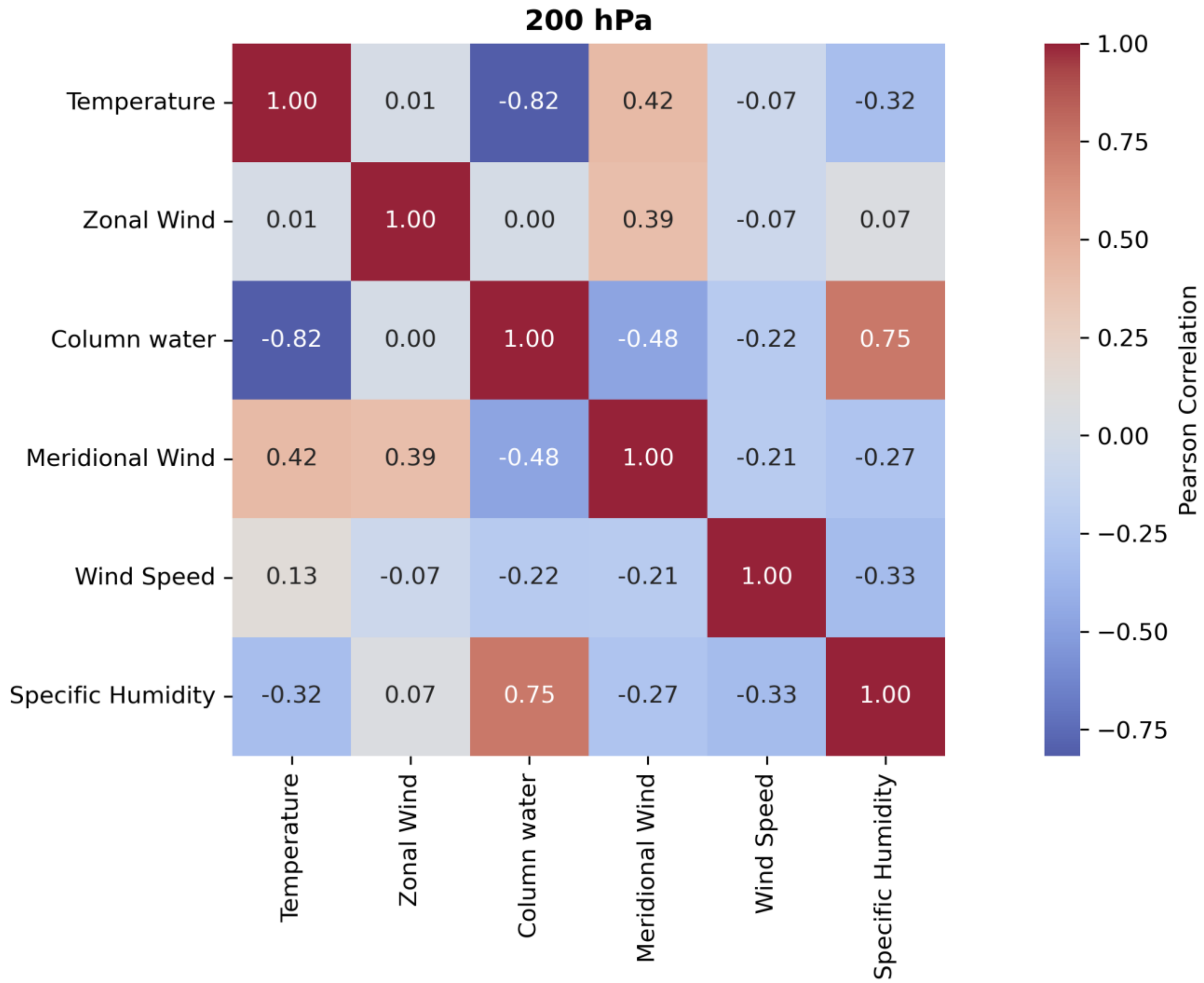
- **-1 ≤ r ≤ 1**
- Significant positive correlation: **r > 0.25**
- Significant negative correlation: **r < -0.25**

Pearson Correlations Between Variables at Different Altitudes (II)





Pearson Correlations Between Variables at Different Altitudes (III)



Conclusions

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- **Rising Temperature**: A clear and statistically significant positive trend in temperature is observed across all altitude levels in the Mediterranean region, with linear slopes indicating a persistent warming since 1950.

- **Evaporation Stability Despite Warming**: Despite the ongoing temperature increase, evaporation and potential evaporation remain nearly stable. The weak correlation with temperature ($r = 0.05$) suggests that temperature alone does not drive evaporation.

- **Wind Speed as a Key Driver:** Wind speed exhibits a stronger correlation with evaporation ($r = 0.44$). Wind speed itself remains relatively stable, with a slight negative trend.

- **Importance of Interconnected Climate Drivers:** The results highlight that evaporation is influenced by a combination of factors — especially wind speed — and not just temperature alone. Understanding these interdependencies is crucial for accurate climate analysis.

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