

Developing Climate Data for Egyptian Heritage Sites in the Theban Necropolis

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Abstract

To develop heritage site preservation strategies, site-specific climate data is required, especially when those sites are made from natural materials. This study focuses on Egyptian archaeological case study locations in the Theban Necropolis, a cliff above tomb KV42 and the interior of tomb TT95, to develop methodologies for improving climate analysis (1984 to 2024) that can be used to enhance localized climate data. Using a combination of National Oceanic and Atmospheric Administration (NOAA) weather station data, climatological techniques, and geographic information system (GIS)-based spatial interpolation, this research analyzes temperature and relative humidity variability for the majority of the populated area in Egypt. For comparison, a more detailed analysis is performed with local weather information at the two case study locations. By focusing on the relationship between regional climate trends and local climate measurements at archaeological sites, this project contributes to the broader efforts in climate-informed heritage preservation. A significant portion of this project addresses the challenges of relying on station data collected near or within archaeological sites, including data sparsity, instrument maintenance, and remote accessibility. The results indicate that much of Egypt is undergoing a warming and decreasing relative humidity trend, with average temperature increases ($0.35^{\circ}\text{C}/\text{decade}$) exceeding the global average ($0.20^{\circ}\text{C}/\text{decade}$). These climatic shifts can hasten rock degradation, potentially resulting in irreversible damage. The spatial interpolation maps developed in this research effectively capture these trends, as demonstrated by the similarity between the interpolated data and the observations at Luxor airport and KV42. The work done in this project can be adapted to other heritage sites globally, offering a source of supplemental data that can be used by researchers seeking to incorporate climate data into their preservation efforts.

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Table of Contents

Abstract	ii
Acknowledgments	iii
Table of Contents	iv
List of Tables	vii
List of Figures	viii
1 Introduction	1
1.1 Climatic Background and Environmental Context of Egypt	2
1.2 Previous Studies on Climate Impacts on Archaeological Field Sites	3
1.3 Statistical Downscaling and Spatial interpolation in Climate Research	4
1.4 Egypt’s Climate and Seasonal Characteristics	5
1.5 Overview of Case Study Sites (KV42, TT95)	6
1.6 Past Preservation Practices at Heritage Sites	11
1.7 Gaps in Current Knowledge	15
1.8 Research Questions	16
1.9 Study Goals and Objectives	17
2 Methodology for Climate Data Processing and Analytical Techniques	19
2.1 Data Sources	19
2.1.1 NOAA Weather Station Data	19
2.1.2 KV42 and TT95 In-Situ Data	19
2.1.3 Satellite imagery for Land-Use Changes	25
2.2 Data Processing	26
2.2.1 NOAA Temporal Coverage and Station Selection	26
2.2.2 Quality Control Procedure	27
2.3 Derived Variables	29
2.3.1 Relative Humidity Calculation	29

2.4	Statistical Analyses	30
2.4.1	Hourly, Daily, Monthly, and Seasonal Averages	30
2.4.2	Trend Calculation	31
2.4.3	Correlation, Relative Error, Min/Max Comparisons	31
2.5	Spatial Interpolation	33
2.5.1	ArcGIS Natural Neighbor Technique	33
3	Temperature and Relative Humidity Interpolated Spatial Maps	35
3.1	Temperature Climatology Interpolated Spatial Maps	35
3.1.1	Addition of Temperature Site Specific Data	35
3.2	Relative Humidity Climatology Interpolated Spatial Maps	41
3.2.1	Addition of Relative Humidity Site Specific Data	41
3.3	Temperature Trend Interpolated Spatial Maps	44
3.4	Relative Humidity Trend Interpolated Spatial Maps	44
3.5	Common and Divergent Findings from Spatial Interpolation	44
4	KV42 vs. Luxor Data Comparisons	51
4.1	Correlation and Relative Error	51
4.1.1	Temperature Correlation and Relative Error	52
4.1.2	Relative Humidity Correlation and Relative Error	52
4.2	Temperature and Relative Humidity Hourly Comparisons	56
4.2.1	Temperature Hourly Comparison	57
4.2.2	Relative Humidity Hourly Comparison	57
4.3	Temperature and Relative Humidity Trend Comparisons	60
4.3.1	Temperature Trend Comparison	60
4.3.2	Relative Humidity Trend Comparison	62
4.3.3	Max/Min Temperature and Relative Humidity Luxor Error Bars	62
4.4	Detailed Relative Humidity Comparisons	63
4.5	Summary of KV42 and Luxor Climate Comparisons	66
5	TT95 Interior Climate Variation Results	67

5.1	Air Temperature Relative Error and Correlation Analysis	68
5.2	Relative Humidity Relative Error and Correlation Analysis	68
5.3	Air Versus Rock Temperature Relative Error and Correlation Analysis	70
5.4	Summary of TT95 Interior Climate Findings	72
6	Discussion	73
6.1	Interpretation of Temperature and Relative Humidity Rate of Change Maps	73
6.2	Interpretation of Regional and Local Climate Differences	77
6.3	Reliability of Regional Data for Microclimate Assessments	83
7	Conclusions	87
7.1	Summary of Findings	87
7.2	Practical Recommendations for Site Preservation and Monitoring	88
7.3	Suggestions for Policymakers and Preservation Agencies	90
7.4	Limitations of this Research	91
7.4.1	Data Availability and Temporal Gaps	91
7.4.2	Spatial Interpolation Uncertainty	91
7.4.3	Sensor and Instrumentation Constraints	91
7.4.4	Limited Representation of Micro-climates	92
7.4.5	Limited Climate Variables	92
7.5	Continuation of the Research	92
	Bibliography	94
	Appendices	101
A	Other Excel Formulas	101
B	Additional Figures	102

List of Tables

1	DAQ 's environmental sensor, BME280 temperature and relative humidity sensor's specifications [32]	22
2	Geographical information for meteorological stations selected for analysis and KV42	29

List of Figures

1	Map of Egypt (from GoogleMyMaps). Blue marker indicates the location of tombs KV42 and TT95, near Luxor, Egypt, where our local climate data is collected	7
2	Map of Theban Necropolis (from [22]) which is home to the two case-study archaeological sites in this research: KV42 and TT95. KV42 is located in the Kings Valley and the Tomb TT95 is near Sheikh Abd el-Qurna.	8
3	Visual image of surrounding area at the entrance to KV42, illustrating the extent of the cliff above KV42 that is being monitored by sensors in the lateral fracture to measure crack movement, a weather station to monitor local climate variations including air temperature, humidity, solar radiation, wind speed and direction, and rock temperature, as well as a Infrared thermal (IRT) station that points towards the cliff face. Image Credit: Rodrigo Alcaino Olivares	9
4	Photos of the system on the cliff above KV42, showing (a) the overall position of the data acquisition system, solar panels, and sensors, as well as (b) a close up the Libelium data acquisition system installed in 2018. Image Credit: Bora Suda (February 2025)	10
5	Image of the TT95's entrance. The right most pillar is the pillar of interest used for monitoring. Image Credit: M. Kacicnik (University of Basel)	11
6	Image of the TT95's collapsed ceiling, assumed to be the reason why the tomb was abandoned. A constructed roof can be seen in the upper right corner. Image Credit: Bora Suda (November 2025)	12
7	(a) A wooden table at TT95 which holds several devices (including the Yield Point data loggers, which were generously donated by Yield Point), in the case of this research the important devices shown are the Raspberry Pi and the DAQ agriculture unit (Taken by Bora Suda in November 2025) (b) An image of the TT95 environmental monitoring system's instruments monitoring the pillar (Taken by Bora Suda in November 2025)	13
8	Map of Egyptian locations with accessible NOAA Hourly Weather Data. Made with Google-MyMaps. The 10 locations marked in green have a complete temporal range from 1984 to 2024 and are considered ideal for temporal analysis. The 3 locations marked in yellow have a nearly complete coverage, missing 5 years or fewer. The 2 locations marked in orange include most of the 1984 to 2024 period, with 6 to 9 missing years. The 39 locations marked in red contain only a small portion of the 1984 to 2024 record, with 10 or more years missing. The 17 locations marked in gray have little or no temporal data. Blue marker indicates the location of KV42 and TT95	20

9	Schematics of KV42 and TT95 data transfer. The top diagram is a visual diagram of the KV42 data transfer which transfer hourly weather data from the DAQ weather station to an online server (ThingSpeak) via cellular connection. The bottom diagram is a visual diagram of the TT95 data transfer, the data transfer from the environmental monitoring system is similar to the code used at KV42, however, data is routed from the DAQ to the Pi, which uses a SIM for internet connectivity and remote access. The Yield Point (measures the pillar movement) and the Arduino (measures temperature in a hole within the tomb) also sends data to the RaspberryPi, where the data is not used in this research study.	21
10	KV42 temperature, relative humidity and rock temperature data 2018 to 2024 annual sample size	23
11	KV42 temperature data 2018 to 2024 monthly sample size	24
12	KV42 relative humidity data 2018 to 2024 monthly sample size	24
13	KV42 wind speed and direction data sample numbers for 2018 to 2021	25
14	Number of NOAA weather stations within each temporal coverage quality category. Green markers represent stations with complete coverage (1984 to 2024), yellow represents stations with minor gaps (missing 5 or less years), orange represents stations with moderate gaps (missing 6 to 9 years), red represents stations with substantial missing data (10 or more years missing) and gray represents stations with minimal to no usable temporal coverage. . .	27
15	Map of Egyptian locations used for spatial analysis. Made with GoogleMyMaps. Blue marker indicates the location of KV42 and TT95	28
16	Average number of days per year (1984–2024) in which at least one hourly observation reached 100% relative humidity (temperature equals dew point temperature) at each of the 13 meteorological stations used for analysis.	30
17	Example of a Voronoi polygon around a query point used in the Natural Neighbour interpolation algorithm [46] The olive-coloured polygons are the polygons constructed around the inputted points (exclusive of the query point) [2]. The beige polygon is then constructed around the query point, marked with a red star [2].	34
18	Temperature climatology (°C) for Egypt during 1984 to 2024, derived from NOAA observations and spatially interpolated using the Natural Neighbour technique. Winter in Egypt spans from November to April, while summer extends from May to . The local case study locations are in Luxor which is indicated with a purple star	36
19	Temperature climatology (°C) for Egypt during 2018 to 2024, derived from NOAA observations and spatially interpolated using the Natural Neighbor technique. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star	37

20	Temperature climatology (°C) for Luxor’s surrounding area during 2018 to 2024, derived from NOAA data and interpolated using the Natural Neighbour method. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star	38
21	Temperature climatology (°C) for Luxor’s surrounding area, including KV42, during 2018–2024, derived from NOAA and KV42 data and interpolated using the Natural Neighbour method. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star	39
22	Time series comparison of actual versus estimated (extracted from the spatial interpolation without the KV42 data) temperature values at KV42 for 2018 to 2024	40
23	Relative error between actual versus estimated (extracted from the spatial interpolation without the KV42 data) temperature values at KV42 for 2018 to 2024	40
24	Relative humidity climatology (%) for Egypt during 1984 to 2024, derived from NOAA observations and spatially interpolated using the Natural Neighbour technique. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star	42
25	Relative humidity climatology (%) for Egypt during 2018 to 2024, derived from NOAA observations and spatially interpolated using the Natural Neighbour technique. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star	43
26	Relative humidity climatology (%) for Luxor’s surrounding area during 2018 to 2024, derived from NOAA data and interpolated using the Natural Neighbour method. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star	45
27	Relative humidity climatology (%) for Luxor’s surrounding area, including KV42, during 2018–2024, derived from NOAA and KV42 data and interpolated using the Natural Neighbour method. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star	46
28	Time series comparison of actual versus estimated (extracted from the spatial interpolation without the inclusion of the KV42 data) relative humidity values at KV42 for 2018 to 2024	47
29	Relative error between actual versus estimated estimated (extracted from the spatial interpolation without the inclusion of the KV42 data) relative humidity values at KV42 for 2018 to 2024	47

30	Rate of change in temperature ($^{\circ}\text{C}$ per decade) across Egypt for 1984–2024, derived from NOAA data and interpolated using the Natural Neighbour method. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star	48
31	Rate of change in relative humidity (% per decade) across Egypt for 1984–2024, derived from NOAA data and interpolated using the Natural Neighbour method. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star	49
32	Libelium weather station data from KV42, showing the monthly mean temperature from 2018 to 2024	51
33	Libelium weather station data from KV42, showing the monthly mean relative humidity from 2018 to 2024	52
34	Temperature time series for Winter 2020 from KV42 (Libelium weather station) and Luxor airport weather station	53
35	Temperature time series for Summer 2020 from KV42 (Libelium weather station) and Luxor airport weather station	53
36	KV42 (Libelium weather station) versus Luxor airport weather station April temperature data: correlation and average relative error, 2018–2024	54
37	KV42 (Libelium weather station) versus Luxor airport weather station May temperature data: correlation and average relative error, 2018–2024	54
38	Relative Humidity time series for Winter 2020 from KV42 (Libelium weather station) and Luxor airport weather station	55
39	Relative Humidity time series for Summer 2019 from KV42 (Libelium weather station) and Luxor airport weather station	55
40	KV42 (Libelium weather station) versus Luxor airport weather station April relative humidity data: correlation and average relative error, 2018–2024	56
41	KV42 (Libelium weather station) versus Luxor airport weather station May relative humidity data: correlation and average relative error, 2018–2024	57
42	KV42 (Libelium weather station) versus Luxor Airport weather station: differences of monthly temperature averages computed from hourly data for April and May, 2018 to 2024	58
43	KV42 (Libelium weather station) versus Luxor Airport weather station: April–May hourly average temperatures, 2018 to 2024	58
44	KV42 (Libelium weather station) versus Luxor Airport weather station: differences of monthly relative humidity averages computed from hourly data for April and May, 2018 to 2024 . . .	59

45	KV42 (Libelium weather station) versus Luxor Airport weather station: April–May hourly average relative humidity, 2018 to 2024	59
46	KV42 (Libelium weather station) and Luxor Airport weather station: April–May average temperatures compared with the global annual rate of temperature change [49]	61
47	KV42 (Libelium weather station) versus Luxor Airport weather station: hottest and coolest April–May daily values	61
48	KV42 (Libelium weather station) versus Luxor Airport weather station: April–May relative humidity averages.	62
49	KV42 (Libelium weather station) versus Luxor Airport weather station: most humid and least humid April–May daily values	63
50	“KV42 (Libelium weather station) versus Luxor Airport weather station: annual relative humidity relationship, 2018–2024	64
51	KV42 (Libelium weather station) versus Luxor Airport weather station: annual relative humidity relationship, 2019–2020	65
52	Winter and summer relative humidity relationships between Luxor airport and KV42	65
53	Number of hourly data samples for each year from 2022 to 2024 available from TT95’s interior environmental monitoring station	67
54	KV42 (Libelium weather station) versus TT95 (interior environmental monitoring station) annual temperature data correlation and average relative error, 2022–2024	69
55	Luxor airport weather station versus TT95 (interior environmental monitoring station) annual temperature data correlation and average relative error, 2022–2024	69
56	KV42 (Libelium weather station) versus TT95 (interior environmental monitoring station) annual relative humidity data correlation and average relative error, 2022–2024	70
57	Luxor airport weather station versus TT95 (interior environmental monitoring station) annual relative humidity data correlation and average relative error, 2022–2024	71
58	TT95’s annual air temperature versus rock temperature data correlation and average relative error from 2022–2024	71
59	Satellite view of Egypt from Google Earth Pro (Dec 2020) highlighting four areas that have undergone significant changes from December 1984 to December 2020 within the study area. The 4 indicated regions are further examined in more detail in the following figures	77
60	Satellite view of Egypt’s Northern Coast near Alexandria (Area 1), from Google Earth Pro. Left: Dec 1984 and Right: Dec 2020	78
61	Satellite view of Egypt, specifically near Farafra (Area 2), from Google Earth Pro. Left: Dec 1984 and Right: Dec 2020	78

62	Satellite view of Egypt, specifically near Dakhla (Area 3), from Google Earth Pro. Left: Dec 1984 and Right: Dec 2020	79
63	Satellite view of Egypt, specifically near Aswan (Area 4), from Google Earth Pro. Left: Dec 1984 and Right: Dec 2020	79
64	Total population in Egypt from 1984 to 2024. Data source: World Bank [53]	80
65	IRI Monthly Wind Climatology at 1000 mb. The white represents wind speed from 0 to 3 m/s and the light tan areas represent wind speed from greater than 3 m/s to 6 m/s. The arrows represent where the wind is coming from. Source: [66]	82
66	Elevation map of Egypt derived from the GTOPO30 digital elevation model (DEM) (Data is from [65])	83
67	Wind speed data at 100 meters height across Egypt for 2008 to 2017. Data source: Global Wind Atlas [67]	84
68	Wind speed data at 100 meters height for the Luxor region during 2008 to 2017 (Data source: Global Wind Atlas [67]) with elevation contours overlaid	85
A-1	Relationship between KV42's relative humidity and wind direction during 2019	102
A-2	Relationship between KV42's relative humidity and wind speed during 2020	103
A-3	Relationship between KV42's relative humidity and wind speed during 2019	103
A-4	Relationship between KV42's relative humidity and wind speed during 2020	104

1 Introduction

Climate change is both a prominent and increasingly urgent challenge to the preservation of archaeological sites across the world, especially in regions where structures made of certain natural materials can be more susceptible to environmental fluctuations. The country best known for their historical heritage, Egypt, with its extensive array of limestone, granite and sandstone monuments, tombs and temples, is also experiencing climatic shifts that continue to threaten the structural integrity of these irreplaceable cultural monuments. To provide numerical context, Egypt has 34 sites that are tentatively listed and 7 sites that are listed amongst the United Nations Educational, Scientific and Cultural Organization (UNESCO) Heritage sites [1]. To explain further, it is important to highlight that each site can include more than one temple or tomb. For instance, the Theban Necropolis is home to over seven named temples/complexes and over four hundred tombs [2] [3]. Climatic changes such as increasing temperatures, decreasing relative humidity and the intensification of seasonal extremes are accelerating the degradation of Egyptian archaeological sites [4]. In particular, these changes can complicate conservation and preservation strategies. However, despite the growing concern and awareness of the aforementioned threats, there currently remains a critical gap in the availability of site-specific climate data necessary for informed preservation strategies in Egypt.

This thesis explores methodologies for generating a localized climate dataset using regional observations and spatial interpolation techniques. The study focuses on two case study sites within the Theban Necropolis: KV42, a tomb located in the King's Valley where the cliff above is monitored and TT95, a tomb located in the Sheikh Abd el-Qurna where the pillar stability inside the tomb is monitored. In-situ weather stations have been installed to monitor temperature, relative humidity and other variables. These sites allow for the evaluation of the accuracy and usability of the interpolated climate maps derived from the usage of NOAA weather stations across Egypt. Through the integration of modern (1984 to 2024) climate data with geospatial tools such as ArcGIS, this research aims to assess whether regional climate data can reliably provide information on the microclimate conditions at archaeological sites in Egypt.

In terms of the broader reach of this work, this research hopes to provide information that can be used in climate-informed heritage preservation through the combination of climate science, environmental science and civil engineering. Previous studies have demonstrated the usage of methods such as statistical downscaling and spatial interpolation in regions with dense observational data coverage, but Egypt's sparse station coverage presents unique challenges. This study builds on pre-existing methodologies while incorporating an uncertainty analysis to evaluate the reliability of using interpolated regional data to supplement data-sparse localized environments. In addition, the research done in this study also explores the logistical and technical challenges associated with collecting weather data from remote archaeological sites such as issues with instrument maintenance, connectivity, and temporal accuracy.

This research contributes to the development of tools for which can be used for archaeological site monitoring, providing a framework which can be adapted to other regions facing similar data limitations. Through the usage of regional climate datasets, climate can be better understood to improve preservation at archaeological sites. This study aims to provide climate-based information for archaeologists, conservationists and

policymakers to promote actionable insights that support the long-term preservation of cultural landmarks in Egypt and could be applied across the world.

1.1 Climatic Background and Environmental Context of Egypt

Egypt's climate is characterized by arid and extra-arid conditions which pose challenges to the preservation of archaeological sites. Understanding these environmental factors is essential for assessing each specific site's vulnerability and to do so, Egypt's historical climate will provide insightful information.

A main threat associated with climate change is extreme weather events. Yet, during ancient times, Egypt underwent significant weather events due to natural changes in climate [5]. For example, every summer annually, the Nile would flood which was a vital process for agriculture in ancient Egypt [5]. However, archaeological evidence such as sediment deposits, show that during certain periods, the weather patterns were unusual, leading to variations in the timing and magnitude of the Nile's flooding which lead to droughts [5]. Periods of drought meant lower Nile water levels and arid conditions producing lower crop yields [5]. The agricultural period for that fiscal year would have lead to social issues amongst the community such as famine [5].

To further explain the direct link between weather and social relations within communities, taxation during ideal and poor weather periods, historical information is briefly examined. Ideal weather, which was moderate, allowed for the Nile Valley to thrive, leading to an increase in crop yields [6]. As a result, tax revenue would be increased during this time, since the amount of taxable agricultural production had increased and would attract outside communities who were willing to pay higher taxes, since the Nile Valley was more bountiful than surrounding areas [6]. In contrast, times in which the external area's agricultural output is more bountiful than the Nile Valley, due to extremely low or high flooding of the Nile, would lead to lower class populations either leaving the Nile Valley state or force taxation reduction [6]. During this time, the state would experience a consequent decrease in tax collection, which could lead to the destabilization of the state [6]. These taxes were used by the ruler for the construction of monuments such as pyramids or for festivals and luxury goods [6]. A decrease in such, may have lead to a decrease in the state's power, which may have caused the ruler to be dethroned [6].

One of the most prominent causes of natural climate change is volcanic eruptions. To explain further, around 405 to 30 BCE, large volcanic eruptions may have changed the annual African monsoon patterns leading to a reduction in Nile floods and consequently, agricultural production [5].

History has proven, that climate-related stress has caused deep-rooted issues for the residents [5]. So to survive during times in which the crops were not as bountiful, the ancient Egyptians learned to adapt such as relocation, grain reserves and changes in diet [5]. Additionally, ancient Egyptians built infrastructure in a response to the climate variability such as dams, basins and canals [7].

These historical climate events in ancient Egypt demonstrate how environmental stressors such as droughts and the Nile's water levels have influenced Egypt's environment and social dynamics for centuries. Even in the modern age, Egyptian residents heavily rely on the Nile, making up a total of 98% of the annual

renewable water resources [8]. However, increasing temperatures will lead to a decrease in water availability due to evaporative processes [8].

It is vital that proper climate analysis is done for local regions to devise efficient prevention and adaption methods. With this in mind, this study reinforces why localized climate data is essential for protecting heritage sites like KV42 and TT95, as well as understanding and preventing continued harm due to climate-related hazards.

1.2 Previous Studies on Climate Impacts on Archaeological Field Sites

Previous research has explored how climate change has affected archaeological sites, particularly those made entirely of natural materials. This subsection reviews global and regional studies to identify effective methodologies and the limitations associated with this type of study.

Mavrakou et al. (2025) used a detailed methodology to assess climate related hazards to open archaeological sites with the use of Olympia as a case study [9]. The methodological approach used in their research encompasses both climatic and non-climatic factors such as vegetation, land-use and geographical features [9]. With the use of downscaling procedures to General Circulation Models (GCMs), high-resolution regional climate assessments were derived [9]. The risk assessment methodology was based on the IPCC AR6 risk conceptual framework and was structured into five steps [9]. First, the site was characterized to identify its unique features and the interconnected systems that may be vulnerable to climate impacts [9]. Second, hazards due to climate such as heatwaves, droughts, floods and wildfires were identified based on both historical data and future projections [9]. Third, evaluation was done to determine the extent in which the site and its surroundings are vulnerable to these hazards [9]. Fourth, the vulnerability of the site was measured by assessing the sensitivity and adaptability of the site including factors like vegetation, slope and land cover [9]. Finally, the overall risk was determined by comparing climatic and non-climatic indicators against the country's averages, using ensemble climate model outputs to project future conditions [9]. The study found that under the RCP 8.5 scenario, Olympia is projected to experience an increase in mean air temperature, number of warm days and number of tropical nights [9]. These changes will lead to more frequent and intense heatwaves, ultimately increasing Olympia's vulnerability to extreme heat, droughts and risk of forest fire [9]. The study concluded that these climatic changes will lead to an increased deterioration of the Olympia archaeological site [9].

A study by Khater et al (2024) examined the effect of climate change on Egyptian heritage using the case study of the Kom El-Shouqafa catacombs in Alexandria, Egypt [1]. The study examines the location through the use of empirical data and analysis to gather insights on damage prevention strategies [1]. The study combined historical and descriptive methods [1]. The historical method identified the cultural significance of the site as well as its layout and background [1]. The descriptive methods involved on-site observations collected through field visits, these visits allow for the classification of deterioration, damage to the structure and environmental impact [1]. In addition, the study included collaboration with local community members, site crew, inspectors, allowing for an identification of the site's status based on different perspectives and a

more well-rounded approach [1]. The study also identified the climate change impacts on Egyptian archaeological sites such as scaling, material degradation, variation in salinity, cracking and possible collapse [1]. The results also presented that Egypt is a country that is particularly susceptible to exposure from climate change and therefore, requires an immediate focus on adaptation strategies [1]

While past studies have offered valuable frameworks to understanding the effect of climate change on archaeological sites, they often lack site-specific analysis for Egypt specifically. This gap highlights the importance of developing localized climate datasets for the use in heritage preservation.

1.3 Statistical Downscaling and Spatial interpolation in Climate Research

Statistical downscaling and spatial interpolation are important tools that have been used for estimating local climate conditions from regional climate data. These methods are most useful in areas like Egypt with sparse observational coverage.

The methodology used in this research reflects techniques used in statistical downscaling. Statistical downscaling is a process in which coarse resolution data is used to create localized climatic estimates [10]. The purpose of this research project is to test if regional Egyptian weather station data can be used to generate localized climate projections, particularly for sensitive areas such as archaeological sites. Statistical downscaling can be found in many different climatological studies in the field, for example, the research done by Crespi et al (2018) demonstrated the value of using high-resolution data to represent the precipitation patterns over small scale features [11]. Their study highlights how data dense areas provide more accurate estimates, where in contrast, data sparse areas provide a greater uncertainty [11]. Similar to Egypt, Norway also has an uneven spread of stations therefore, poor coverage areas such as high elevation areas may not have viable estimations [11]. However, the study by Crespi et al (2018) used over 1000 weather stations in Norway to interpolate their spatial map, yet, there are not as many available stations in Egypt [11]. As a result, it is important, to compare estimations with other datasets. Crespi et al (2018) compared their spatial interpolation with other models [11]. The analysis in this research differs as the focus is on Egyptian archaeological sites alongside comparisons between the regional spatial interpolation and in-situ weather station data at the case study sites.

As well, studies such as those done by Dibike et al (2008) focuses on the uncertainty associated with statistically downscaled climate data [12]. Their work emphasizes the importance of evaluating the reliability of downscaled data, especially for areas with complex terrain and varying land cover, conditions which are also prevalent in Egypt [12]. Dibike et al (2008) uses rigorous uncertainty analysis techniques to assess the performance of downscaled temperature and precipitation data in Northern Canada [12]. These methods revealed that although statistical downscaling can reproduce climatic patterns for local areas well, as mentioned above, the accuracy of these findings are highly dependent on the quality and amount of the observational data [12]. Therefore, the incorporation of an uncertainty analysis into this research is crucial for understanding the accuracy of the localized climate projections. In the instance of this research, the uncertainty analysis will be done to identify if the data of the closest weather station to the archaeological sites,

KV42 and TT95 can be used to supplement missing climate data.

Though the aforementioned techniques are useful, they must be tested in the context of Egypt's data sparse environment. This study validates these techniques through comparisons with archaeological site case studies to assess the reliability of applying statistical downscaling through spatial interpolation. While the general method used in this research follows the broad approaches found in literature, several adaptations were necessary due to the limitations of the available data. For instance, unlike studies conducted in data-dense regions, Egypt has a limited set of weather stations which required greater reliance on regional datasets and a more careful evaluation of how well these datasets represented local micro-climates at the archaeological sites. Additionally, the incomplete and occasionally inconsistent in-situ records at KV42 and TT95 introduced gaps that had to be addressed through supplementary uncertainty analysis using nearby NOAA weather station data.

1.4 Egypt's Climate and Seasonal Characteristics

A year in Egypt can be split into two distinct seasons, winter and summer. Winter spans from November to April and summer spans from May to October [13]. Studies such as those by Gabo et al (2019) and El-Geziry et al (2021) provide more insight into the definition of these seasonal patterns [13][14]. The characterization of these seasons are based on the average climatology of the entirety of Egypt. Winter is considered to be relatively milder with minimal rainfalls [13]. In contrast, summer is relatively warmer and less humid [13]. In addition, organizations such as the World Bank Climate Change Knowledge Portal and International Federation of Red Cross and Red Crescent (IFRR) also follow the aforementioned seasonal periods [15] [16]. These organizations specifically highlight the seasonal differences to understand the climatic changes over time. Near coastal regions, average temperatures can range from 14°C during the winter to 30°C in the summer [16]. However, inland desert areas such as Luxor and it's surrounding area can have temperatures change more rapidly during the summer [16]. For instance, temperatures can reach minimums of 7°C during the night to maximums of 43 °C during the day [16]. As mentioned above, winter is attributed to mild conditions since the diurnal temperature cycle does not fluctuate as rapidly relative to the summer [16]. For example, minimums can reach 0 °C during the night and increase to around 18 °C during the day. Locally, deserts in the northern Africa, such as in Egypt, have frequent windstorms (or the official term "khamsin") which can track both sand and dust across a large distance [16]. The frequency of these storms is the greatest from March to May [16]. These storms are extremely important when inspecting the local climate since the storms could increase the temperature in the area by 20 °C in only two hours [16]. These temperature increases could last for several days which can create outliers when calculating climatic parameters such as temperature and relative humidity [16].

On a more regional scale, the wind climatology along the Egyptian Mediterranean Coast is predominantly northwesterly trade winds [14]. These winds enhance the sea breeze from the Mediterranean and as a result are able to track over the Northern portion of Egypt without being blocked by mountain ranges [14]. Temperatures in Northern Egypt are usually more regulated due to these sea breezes [14].

Sea breezes are frequent along the Egyptian Mediterranean coast during the day, since the land warms faster than the water surface. Sea breezes occur due to a differential heating between the land and ocean [17]. As the land warms more quickly during the day, a low-pressure area forms over the land and a high-pressure area over the ocean [17]. During the night, a land breeze occurs where the reverse happens, the land cools faster than the ocean creating a high-pressure over the land and a low-pressure over the ocean [17]. The sea breezes bring moisture to coastal areas. The height of a sea and land breeze is dependent on attributes such as coastline, tides and topography [17].

In terms of wind climatology on a regional scale, Egypt is located within the Sahara desert which is the largest source of atmospheric mineral dust in the world [18]. Atmospheric dust can affect regional climate by scattering, absorbing and reflecting terrestrial and solar radiation [18]. The importance of regional dust transport is that it provides Egypt with spatial climate variation [18]. For example, although the weather stations in Kharga and Luxor are only 230 kilometres from each other, Kharga has a far greater annual mean frequency of dust emissions [18]. The variance in dust emissions is mainly due to the local environmental factors, since Kharga is for the most part more desert and Luxor is situated along the Nile river [18]. These local environmental factors play a large role in understanding how climate change effects various areas in Egypt.

The seasonal differences within Egypt highlights the need for continuous climate monitoring, especially for each season. With that in mind, applied preservation strategies must mitigate the damages associated with both seasons.

1.5 Overview of Case Study Sites (KV42, TT95)

Egypt is located on the northeastern edge of Africa where the map of Egypt can be seen in Figure 1. The geography of Egypt is split between North Africa and Southwest Asia, thus, the country is split into four distinct geographical regions [13]. These physical regions are the Sinai Peninsula, the Nile Valley, the Nile Delta, the eastern desert and the western desert [13]. Both case study sites, KV42 and TT95, are located within the western desert in the Theban Necropolis as seen in Figure 2 [19]. The Ancient Thebes is located 700 kilometers south of Cairo and on the banks of the Nile River [2]. The area consists of the Karnak and Luxor temples on the Nile's east bank and a large area of heritage sites on the west bank which consists of seven named temples/complexes [2]. Within the west bank, with a total approximate area of 10 kilometers squared lies the Theban Necropolis, a location studied for decades by archaeologists and the home of over a thousand discoveries of tombs and temples [2].

As seen in Figure 3, the KV42 weather station is located approximately 6 meters above the ground a rock pillar [20]. The rock pillar is above the KV42 entrance and is next to a ladder that tourists use to enter another tomb, KV34. Just to note, the infrared thermal station (IRT) station data is not used in this study [21].

Figures 4a and 4b provide a closer look at the weather station setup at KV42 which includes a solar panel, Libelium Data Acquisition Unit and anemometer. More information on this setup is covered in Section



Figure 1: Map of Egypt (from GoogleMyMaps). Blue marker indicates the location of tombs KV42 and TT95, near Luxor, Egypt, where our local climate data is collected

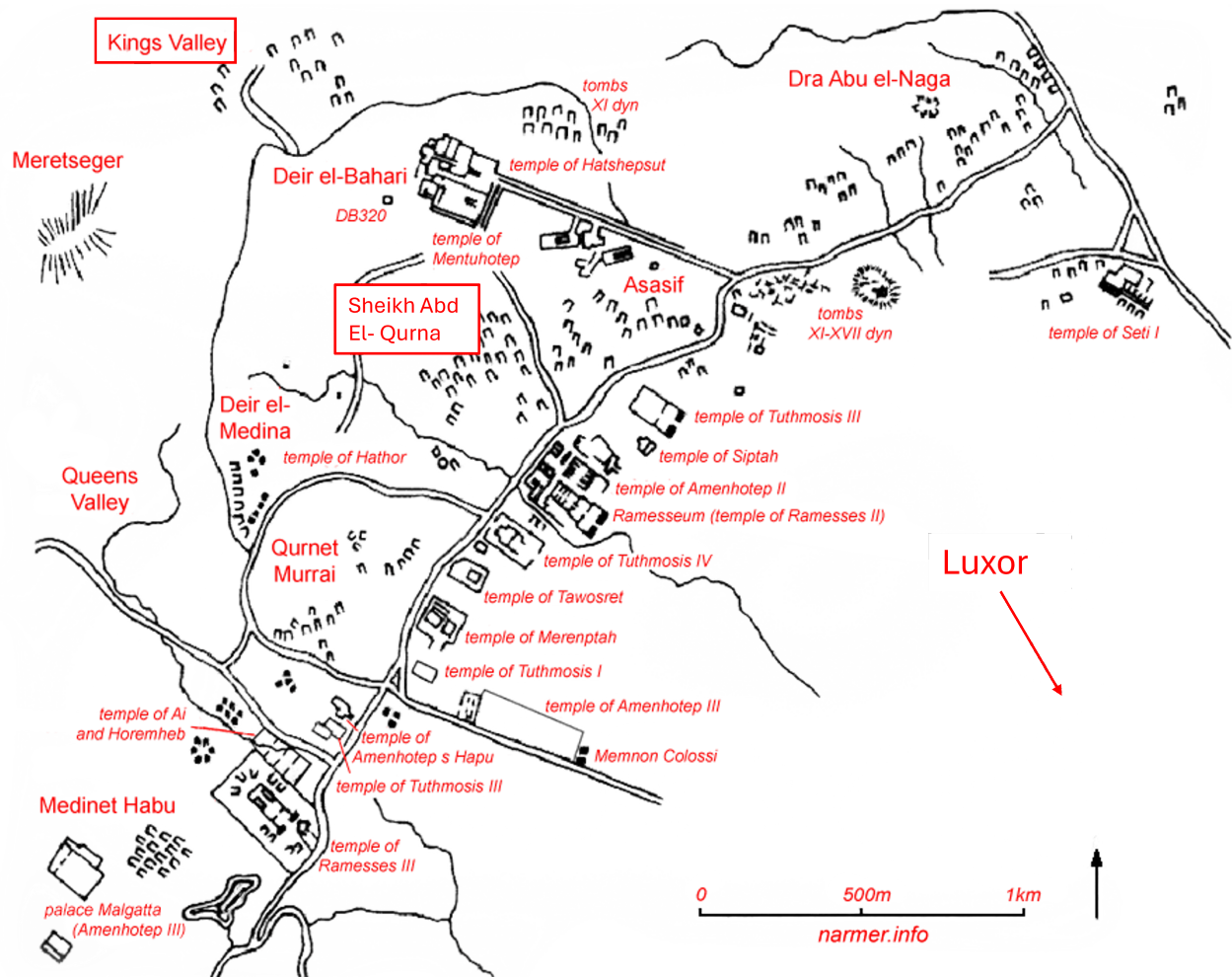


Figure 2: Map of Theban Necropolis (from [22]) which is home to the two case-study archaeological sites in this research: KV42 and TT95. KV42 is located in the Kings Valley and the Tomb TT95 is near Sheikh Abd el-Qurna.

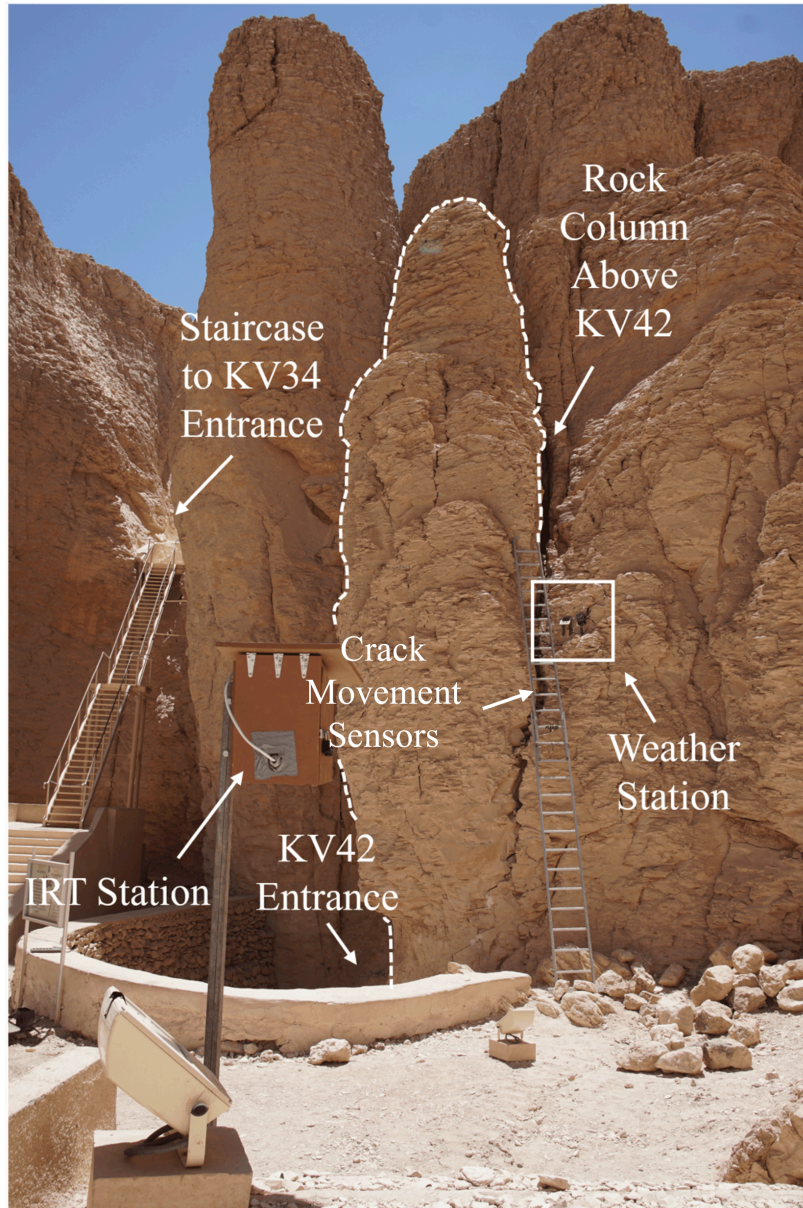
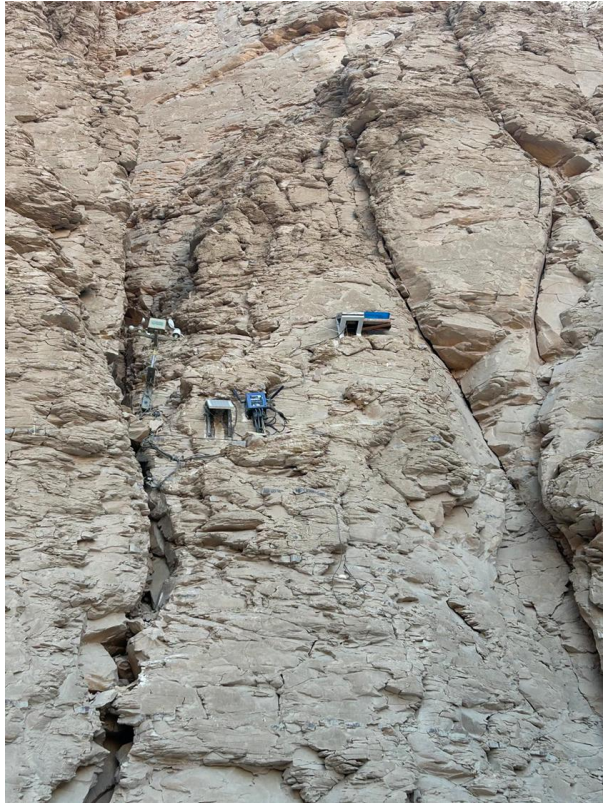


Figure 3: Visual image of surrounding area at the entrance to KV42, illustrating the extent of the cliff above KV42 that is being monitored by sensors in the lateral fracture to measure crack movement, a weather station to monitor local climate variations including air temperature, humidity, solar radiation, wind speed and direction, and rock temperature, as well as a Infrared thermal (IRT) station that points towards the cliff face. Image Credit: Rodrigo Alcaino Olivares



(a)



(b)

Figure 4: Photos of the system on the cliff above KV42, showing (a) the overall position of the data acquisition system, solar panels, and sensors, as well as (b) a close up the Libelium data acquisition system installed in 2018. Image Credit: Bora Suda (February 2025)

2.1.2.

Approximately 1.5 kilometres SSE of KV42 is where TT95 located. The tomb is located within the Sheikh Abd El-Qurna, which is home to hundreds of tombs excavated into the rock material [23]. The Sheikh Abd El-Qurna faces east, and the southern portion of the hillside is home to 5 tombs, amongst these tombs is TT95 [24].



Figure 5: Image of the TT95's entrance. The right most pillar is the pillar of interest used for monitoring. Image Credit: M. Kacicnik (University of Basel)

The underground site is made of different sections with varying construction stages, As seen in Figure 5, where the left side is at the final stages of construction with a fairly smoother surface and the right side is less constructed with a rough surface [24]. During the creation of TT95, it was abandoned when a part of the roof within the entrance hall and pillar collapsed leading to the tomb becoming exposed to the outdoor elements through a hole in the roof [24]. The collapsed ceiling is shown in Figure 6. The TT95 underground weather station is shown in Figure 7. The purpose of the station is to monitor the stability of the key pillar (as seen in Figure 7 on the far right) and the influence of interior climate on the movement of the cracks in the pillars.

1.6 Past Preservation Practices at Heritage Sites

Over time, the methods used to preserve heritage sites have varied. For instance, earlier approaches were often limited by the tools available, meanwhile more modern, technological techniques focus on improving the efficiency of the preservation. By comparing traditional and modern preservation techniques, it is clear that there has been a surge of advanced observations and scientific testing as time progresses.

The conservation of heritage sites can be broken down into stages, these stages are organized in such a way as to promote efficient application and development. The first stage, detection and excavation, is to identify and explore the study area, specifically identifying the different components such as tombs within a site [25]. Traditionally the detection and excavation stage would be conducted using field surveys which was



Figure 6: Image of the TT95's collapsed ceiling, assumed to be the reason why the tomb was abandoned. A constructed roof can be seen in the upper right corner. Image Credit: Bora Suda (November 2025)



(a)



(b)

Figure 7: (a) A wooden table at TT95 which holds several devices (including the Yield Point data loggers, which were generously donated by Yield Point), in the case of this research the important devices shown are the Raspberry Pi and the DAQ agriculture unit (Taken by Bora Suda in November 2025) (b) An image of the TT95 environmental monitoring system's instruments monitoring the pillar (Taken by Bora Suda in November 2025)

both time consuming and effort intensive [25]. Therefore, methods such as ground penetrating radar (GPR), satellite imagery and magnetometry are used to increase the efficiency of the detection and excavation stage [25]. The second step is documentation, acquiring the necessary records about the archaeological site to ensure that that future preservation plans will protect the site [25]. Unfortunately, most archaeological sites across the world may not have sufficient past documentation which is why it is vital to document every preservation application to prevent further damage. Detailed documentation can be recorded using modern techniques such as areal photogrammetry, terrestrial photogrammetry, and laser scanning [25]. In addition, it is ideal to create a database that includes past, current and future information about the site including the preservation work [25]. Diagnosis and monitoring is the third step, particularly this step involves damage assessment of the site [25]. In the past, the third step would be done using direct visual observation [25]. However, in current times, technology such as infrared thermography, ultrasonic testing and endoscopy allows for detailed damage assessment [25]. The more detailed the assessment, the more information that is gathered to develop a preservation strategy. It is imperative that there is a focus on the sites' weak points to ensure that the fourth step, intervention is applied correctly. The intervention step requires knowledge on the archaeological sites' historical, architectural, and engineering aspects [25]. The planned treatment and the involved materials should follow recommendations from international standards such as those by UNESCO [25]. The level of intervention can be categorized into maintenance, emergency rescue, regeneration and environmental protection [25]. Examples of modern-day intervention strategies includes, shelters, enclosures and use of glass and iron elements [25].

An example of preservation application in Egypt is the Great Pyramid of Khufu. The Great Pyramid of Khufu was built during the fourth dynasty of Egypt and had severe degradation at the pyramid's base due to human action [26]. The base degradation was specifically due to the removal of the exterior stones and the degradation of the upper portions are due to prolonged climate exposure [26]. At the time of observation in 2019, the stone matter was continuing to degrade and not closely monitored [26]. In addition at this time, there was no sustained preservation method applied to the pyramid [26]. The pyramid's limestone material continues to degrade due to weathering, pollution, pillaging and poor restoration attempts [26]. An important point explored in this study on the Great Pyramid of Khufu, by Gandah (2019), is how important it is to use effective preservation strategies, since destructive methods may cause accelerated damage [26]. The applied preservation method must take into consideration the original construction techniques so that the sites' historic integrity is not distorted [26]. As well, these restorations should be tested for stability, structural safety and visual coherence [26].

Methods such as the usage of calcium carbonate nano-particles to enhance the durability of ancient Egyptian calcareous stone monuments has been studied previously [27]. A research study by Aldoasri et al (2017) tested the effectiveness of calcium carbonate nano-particles in an acrylic copolymer base to improve the strength of limestone [26]. The method used to test the effectiveness of the compound was artificial aging, specifically to varying changes in temperature and relative humidity [26]. The purpose of the test was to mimic the effects of climate change such as variations in temperature and relative humidity, on limestone, then test if the treated samples protected the material or not [26]. The samples were placed into a temperature-controlled oven and then underwent 30 cycles of 18 hours of immersion into distilled water and

then 6 hours of being placed into a temperature-controlled oven [26]. The main results showed that for a 0.15 gram calcium carbonate nano-particle treatment on limestone there was no visual changes to the material, increased mechanical strength and reduced water absorption in comparison to the samples treated with pure polymer [26].

In general, past preservation practices show that although traditional, historic methods were able to protect the sites at the time, it is clear that modern techniques are required to preserve sites from the effects of climate change. Some past preservation cases had poor documentation, insufficient monitoring and damaging interventions. Therefore, it is imperative that approaches such as the usage of careful planning, the application of international standards and scientific testing will continue to improve preservation effects. By combining knowledge of past and modern technology, it is possible to better protect heritage sites whilst maintaining their history and culture.

1.7 Gaps in Current Knowledge

Although existing studies acknowledge the environmental challenges facing archaeological sites in Egypt, there is still a notable shortage of localized climate data at archaeological sites. This subsection outlines these gaps and explains their importance for ongoing preservation efforts.

An article by Cathy Daly (2013) provides better context on the current level of knowledge available on the field's understanding of climate change and archaeological site conservation [28]. Daly highlights that most studies either take a risk analysis or material specific approach, which do not take a detailed site specific approach [28]. More recently, the field has started to see more material specific research approaches that were also site specific, such as the research done by Alcaino-Olivares et al (2019) where he studied the properties of limestone at KV42 [20]. In addition, the article highlights how imperative it is to study surrounding landscapes since climate change can drive variations in agriculture, vegetation and land use which can threaten archaeological areas [28]. Typically, built heritage sites are given more attention since they are more visible, yet there is a gap in research done on how changes in climate can effect underground archaeology such as tombs [28].

In addition, the study by Khater et al (2024) expresses how even with an abundance of literature on the history of archaeological sites, there still remains a gap in the understanding of how climate change can affect environmental factors and subsequently, the efficiency of archaeological site preservation.

Another challenge associated with assessing climatic trends in Egypt is the limitations associated with accessing meteorological data in Egypt, which is used in studies such as Abdrabo et al. (2023), where the data is not publicly available. Therefore, it will be difficult to review and replicate the study to expand on or add to their analysis [29]. This limitation forces researchers to interpolate the datasets where data-sparse areas like southwest portion of Egypt are approximated. While these interpolations provide national coverage, the uncertainty associated with the interpolation is not presented and could risk overstating confidence in localized projections. Abdrabo et al (2023) nonetheless makes a valuable contribution by examining climate change associated hazards on cultural heritage in Egypt through a GIS-based methodology, showing that

archaeological sites are exposed to varied hazards including increased temperature ranges, higher humidity, flash floods and potential sea level rise [29]. Their findings revealed that approximately 25% of Egypt's heritage sites are susceptible to a combined mix of high to moderate temperature ranges and humid conditions by 2065 under the Representative Concentration Pathways (RCP) 8.5 scenario, underscoring the urgency for conservation strategies that take into consideration climate change risks alongside the anthropogenic and environmental factors [29].

Beyond the gaps presented in the above literature, additional limitations become apparent when examining the practical challenges of collecting and analyzing climate data at local archaeological sites. Many regions of Egypt, particularly in the southwest, have both a limited spatial and temporal meteorological station coverage, which can reduce the accuracy of local climatic variability findings. In addition, with limited regional weather stations, analysis of in-situ monitoring at archaeological sites is further complicated. Data from archaeological sites can be inconsistent due to issues such as sensor failures, battery limitations and connectivity problems, as seen in the KV42 dataset. In addition, certain environmental variables that are highly relevant to site preservation, such as wind speed, wind direction and rock moisture are often variables that are either missing or only partially recorded. These variables are necessary to fully understand the micro-climatic conditions across Egypt.

Across the field, there is a lack of integrated assessments that combine climatic data analysis with land-use changes, population growth and other related environmental factors, even though these variables significantly influence local site conditions. These variables are not typically monitored by a traditional weather station and therefore, are only more recently recorded at a very few locations. While the research done in this study does not attempt to resolve all of these gaps, they do shape the research direction and provide context to the objectives that are addressed. For instance, the challenges related to data sparsity, uncertainty in interpolation and the reliability of using regional climate datasets to approximate local micro-climates such as archaeological sites, form the basis of this study's analysis.

1.8 Research Questions

The gaps identified in the previous sections highlight the different challenges associated with validating climate based findings in data-sparse environments such as Egypt. These gaps make it unclear whether regional climate information can accurately represent the micro-climatic conditions that directly affect archaeological preservation. Understanding these limitations lead to a set of research questions aimed at evaluating how regional and local datasets are related to one another and whether they can be used together to support the conservation of Egyptian archaeological sites.

This study is driven by the need to understand how regional climate change interacts with localized micro-climatic conditions at Egyptian archaeological sites. Although long-term observational datasets provide important information at a broad scale, it is still uncertain how this information can be used to capture local features. This study strives to answer the following research questions:

1. How do local climatic changes differ from the regional trends across Egypt?

2. Can regional climate data be reliably used to represent local climate trends in data-sparse locations?
3. What is the magnitude and spatial distribution of these climatic changes on both a regional and local scale? Can they be effectively visualized using geospatial tools such as ArcGIS?
4. What are the challenges associated with validating interpolated climate data with in-situ observations at case study sites (e.g., KV42 and TT95)?

In conjunction, these questions form the framework necessary for investigating the effectiveness of using regional climate data to understand climatic trends at nearby archaeological sites. The research done in this study aims to develop approaches that offer a more nuanced understanding of both the magnitude and the implications of climate change for local heritage sites in Egypt.

1.9 Study Goals and Objectives

The primary goal of this research is to develop an effective methodology for improving archaeological site climate analysis, with a particular emphasis on enhancing site-specific preservation strategies. To achieve this goal, first an understanding of how key climate variables, in this case temperature and relative humidity, change over time, is required. The magnitude and rate of these climate changes directly influence the degree of environmental stress on archaeological materials. For instance, sites experiencing greater climatic variability are likely to face more significant preservation challenges and therefore, must be prioritized in conservation efforts.

Most heritage sites in Egypt are constructed from sandstone and limestone, even though these materials are resilient to the test of time they are still vulnerable to temperature and moisture fluctuations [30]. Therefore, high resolution and accurate climate information is essential for assessing deterioration risks and conservation strategies. These data necessities are addressed by this study by developing relationships between regional-scale climate data and localized site-specific conditions.

The precise objectives are to:

1. Evaluate regional temperature and relative humidity trends across Egypt using NOAA weather station data.
2. Produce spatial interpolation maps to visualize and compare how temperature and relative humidity has changed between 1984 to 2024 and 2018 to 2024.
3. Compare interpolated values with in-situ measurements from KV42 (located in the King's Valley - outdoor location) and TT95 (located in Sheikh Abd el Qurna - indoor location) to evaluate how well regional data represents local micro-climates at archaeological sites.
4. Identify the main the challenges associated with using in-situ climate measurements near archaeological sites, such as data sparsity, instrument reliability, and site accessibility.

This study accomplishes the above objectives by establishing a versatile methodology that utilizes regional climate datasets, local archaeological site data, spatial analysis and statistical analysis tools. The

framework developed in this research project has a broader applicability by developing tools to promote the incorporation of climate data into deterioration risk assessments and preservation strategies for heritage sites worldwide, especially for regions with limited climate records.

2 Methodology for Climate Data Processing and Analytical Techniques

2.1 Data Sources

This subsection outlines the main sources of climate data used in this study, which includes regional weather station data from the National Oceanic and the Atmospheric Administration (NOAA), local weather measurements from KV42 and TT95 and satellite imagery for land-use analysis. These data sources lay the foundation necessary for spatial and temporal climate analysis at both the regional and local scales.

2.1.1 NOAA Weather Station Data

To address the spatial and temporal variability of local climatic conditions in Egypt, hourly weather station (temperature, dew point temperature) data from the National Oceanic and the Atmospheric Administration (NOAA) Global integrated surface dataset was investigated [31]. The dataset included 71 locations within Egypt as presented in Figure 8. Each location had downloadable .csv files, where each .csv file included hourly temperature and dew point temperature data for each available year.

2.1.2 KV42 and TT95 In-Situ Data

The weather station at the first case study location KV42 and the environmental monitoring station at the second case study location TT95 provided hourly measurements of temperature, relative humidity and rock temperatures. This data was crucial for testing the reliability of regional climate spatial estimates.

Figure 9 visually represents the data collection process at both KV42 and TT95. The weather station, a Libelium Data Acquisition (DAQ) Unit was first installed in 2018 and it currently operates with the same sensors, which comprises of air temperature, rock surface temperature and relative humidity sensors. At KV42, within the DAQ is a SIM card which allows data transfer to an online server (ThingSpeak) via cellular connection. The code that initiates the data transfer only works if the machine is turned on. The DAQ is charged using a solar panel and the amount of data recorded is dependent on the system's battery level. The DAQ will transfer the recorded measurements in its SD card and upload it using a file transfer protocol where the file is in the form of a text file. Data is sent every 12 recordings and uploads only occur if the battery level is over 25%. Specifically if the battery is above 75% then data is recorded every 5 minutes and if the battery is above 25% then data is recorded every 10 minutes. The weather data is logged locally and is sent to the online server. The data is then accessible as a .csv file, where the rock temperature, air temperature and relative humidity measured data, alongside the time of recording is accessible. The environmental monitoring station at TT95 follows a very similar code, however, instead of the data being uploaded to the online server, the data is sent to a raspberry pi. The SIM card within the router of the raspberry pi allows for the pi to be connected to the internet and therefore, the data can be accessed remotely.

The environmental sensor that is able to detect temperature and relative humidity is a circuit plugged into the DAQ, the Bosch BME280 [32]. The temperature and humidity sensors measure the air samples'

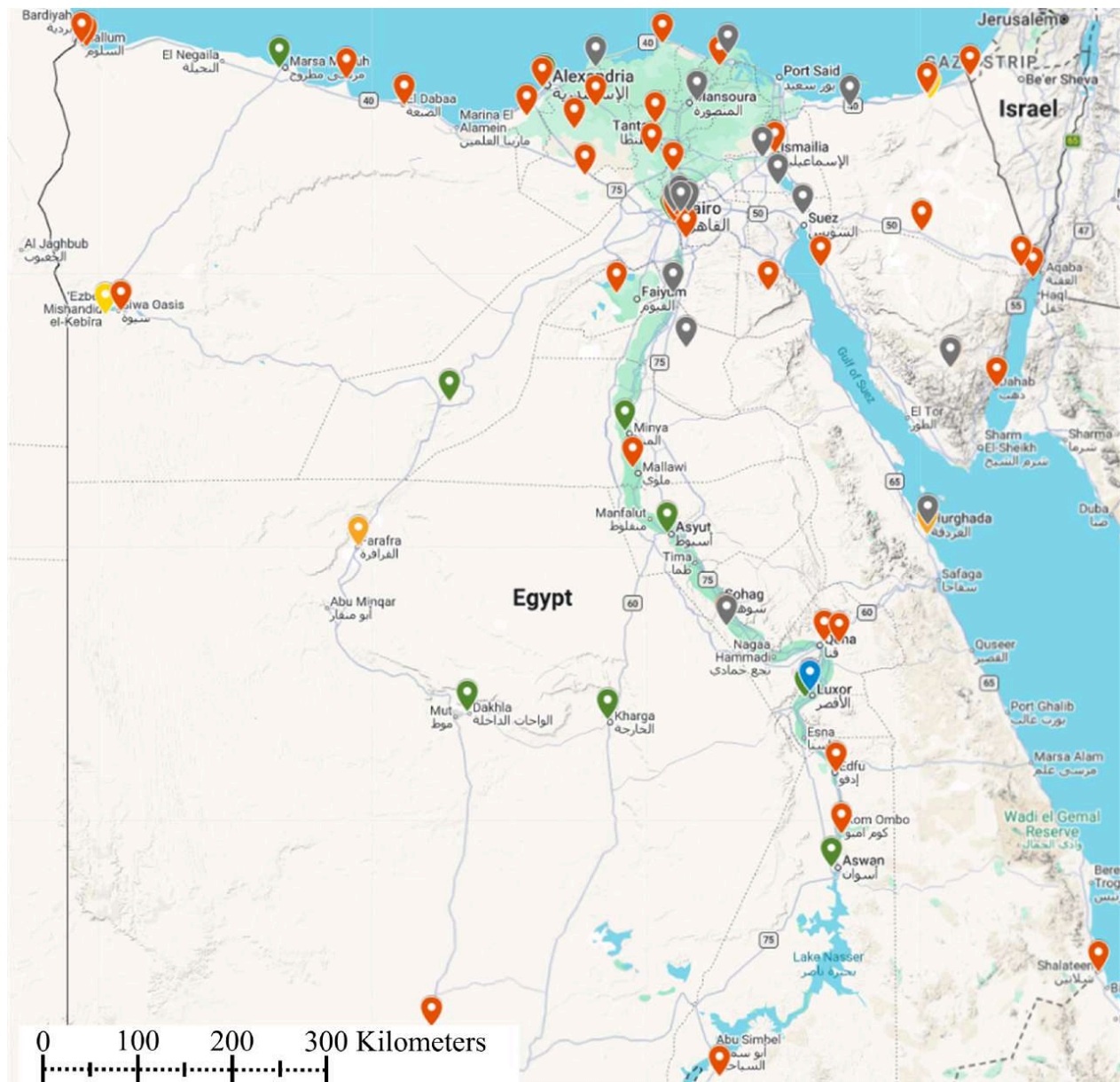


Figure 8: Map of Egyptian locations with accessible NOAA Hourly Weather Data. Made with GoogleMyMaps. The 10 locations marked in green have a complete temporal range from 1984 to 2024 and are considered ideal for temporal analysis. The 3 locations marked in yellow have a nearly complete coverage, missing 5 years or fewer. The 2 locations marked in orange include most of the 1984 to 2024 period, with 6 to 9 missing years. The 39 locations marked in red contain only a small portion of the 1984 to 2024 record, with 10 or more years missing. The 17 locations marked in gray have little or no temporal data. Blue marker indicates the location of KV42 and TT95

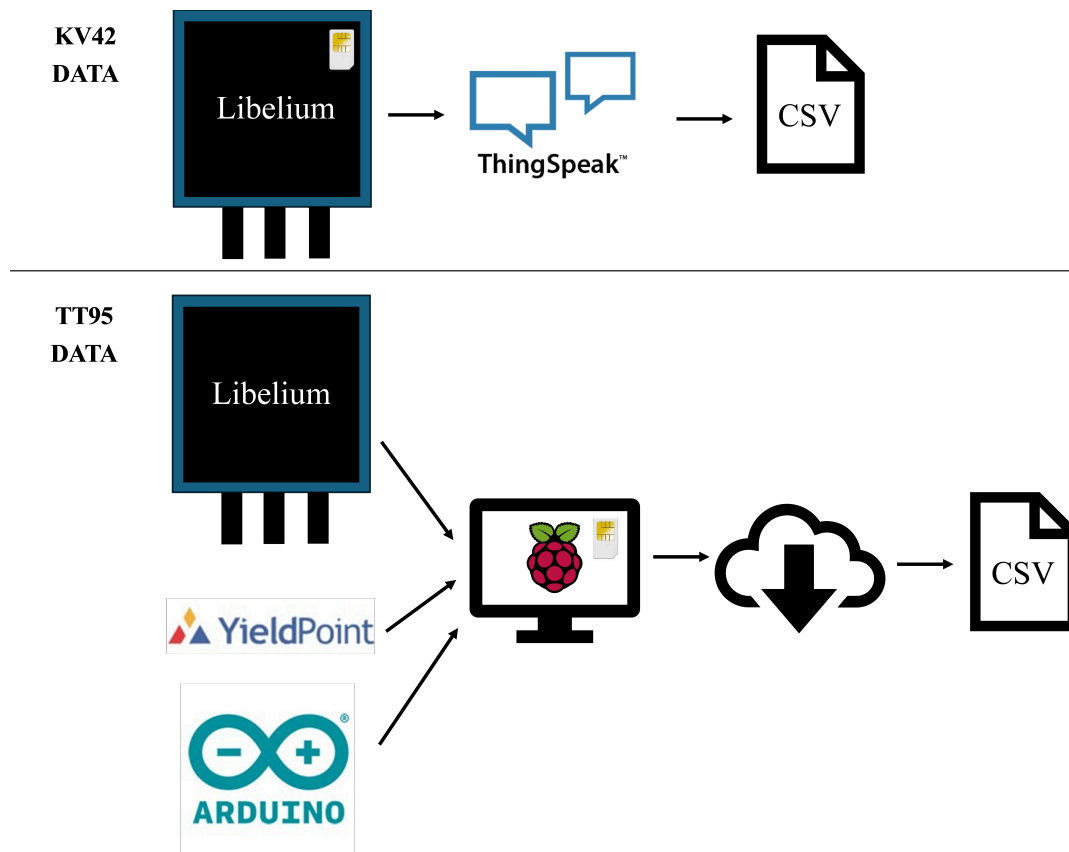


Figure 9: Schematics of KV42 and TT95 data transfer. The top diagram is a visual diagram of the KV42 data transfer which transfer hourly weather data from the DAQ weather station to an online server (ThingSpeak) via cellular connection. The bottom diagram is a visual diagram of the TT95 data transfer, the data transfer from the environmental monitoring system is similar to the code used at KV42, however, data is routed from the DAQ to the Pi, which uses a SIM for internet connectivity and remote access. The Yield Point (measures the pillar movement) and the Arduino (measures temperature in a hole within the tomb) also sends data to the RaspberryPi, where the data is not used in this research study.

capacitance or resistance [33]. Within the BME280 are two electrical conductors with a non-conductive film between the two conductors [33]. This setup creates an electrical field and when the field's voltage is changed due to moisture from the air collecting on the film then this change is converted into a digitalized measurement of the air's relative humidity [33]. The relative humidity measurement also takes into account the air temperature. Although, no official documentation explains explicitly the process at which temperature is measured by the BME280 it is assumed that a diode mechanism is used [34]. A diode is an electronic component with two terminals, which allows for current to flow in one direction whilst blocking current in the opposite direction [34]. When a diode is subject to a change in temperature, the diode's voltage drops based on the temperature change [34]. The change in voltage can then be extrapolated to measure the temperature at that time [34].

Sensor Type	Parameter	Value/Range
Temperature	Operational Range	-40 to +85°C
	Full Accuracy Range	0 to +65°C
	Accuracy	±1°C (within 0 to +65°C)
	Response Time	1.65s (63% response from +30 to +125°C)
Relative Humidity	Measurement Range	0 to 100%
	Accuracy	±3% (at 25°C. 20-80%)
	Operating Temperature	-40 to +85°C
	Response Time	1s (63% response to step change from 0 to 90% RH)

Table 1: DAQ 's environmental sensor, BME280 temperature and relative humidity sensor's specifications [32]

Due to the hot and arid climate in Egypt, it should be noted that temperatures may be more accurately represented than relative humidity values lower than 3% , in reference to the specifications listed in Table 1.

Annual temperature, relative humidity and rock temperature sample sizes are presented in Figure 10. This figure when analyzed show that all three variables have the same sample numbers for each year across all years, therefore clearly indicating that the sampling variability is due to a common issue amongst the temperature, relative humidity and rock temperature measurement processes. At the time of this study, a set calibration process had not been used and the sensors have not been previously calibrated. The reason for this is that the BME280 is the only temperature and relative humidity sensor at KV42's weather station. The analysis is therefore reliant on the manufacturer's specifications of the BME280 (Table 1).

It is clear that after 2020 there is a rapid decrease in the number of measurements collected. The presumed reason is connectivity issues. It is important to note that collecting data remotely from archaeological sites over 9,600 kilometers away presents logistical and technical difficulties. Therefore, traveling to Luxor to repair or replace the machine is both costly and doing so can be restricted. As well, it is difficult to find skilled workers to service the weather station on-site.

In July 2023, the DAQ at the KV42 site stopped sending data to the online server because the SIM card was inoperative. In February 2025, the SIM card was replaced and data from 2024 was now accessible. Another issue that caused data connectivity issues was the KV42 weather stations' batteries. Although, the

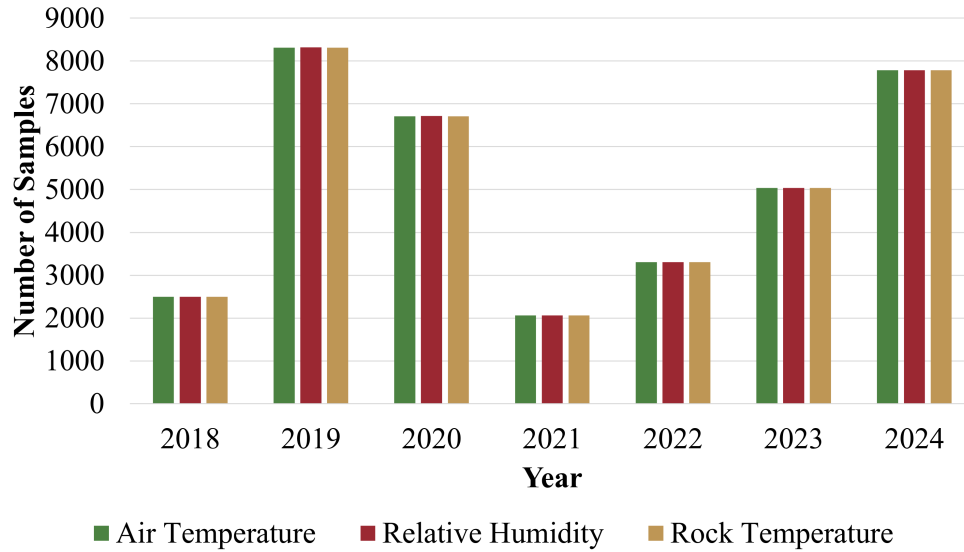


Figure 10: KV42 temperature, relative humidity and rock temperature data 2018 to 2024 annual sample size

main battery which powered the system, still held charge. The secondary battery which kept track of time malfunctioned and was unable to hold charge. As a result, when the main battery reached 0% the entire system lost track of time and resorted to the default time which is in the year 2000. As a consequence, the accuracy of the KV42 time of day is ± 5 days during the period of time from July 2023 until February 2025. Since February 2025, this issue has been corrected through update of the hardware. The reason for this significant uncertainty is due to the times of the missing day being varied and difficult to track. The correction process for the period in question involved the assumption that each machine reset occurred on the following day since the unit would then be charged by solar radiation. From there the resets are then counted and an educated guess is made on the amount of time missed. These obstacles define a few of the difficulties pertaining to collecting weather data at heritage sites, which means it is even more important that there is a way to compare the quality of the data. This research project explores this concept by comparing analysis between the sites and their nearest weather station to define a method that signifies if the usage of nearby stations is effective enough to check the soundness of the sites' weather data measurements. As well as a method to confirm if nearby station data can be used as supplemental data to predict the future climatic condition at these sites.

Figures 11 and 12 show that during the months, April and May, there is the most data available for 2018 to 2024 from the KV42 weather station, thus, most analysis of KV42 is done during this time period to maximize the accuracy and significance of correlation analysis.

Wind analysis at KV42 is ineligible due to the minimal amount of data. Wind data was collected from 2018 to 2021 with the use of a WS3000 cup anemometer to measure wind speed and a WS3000 wind vane to measure wind direction [20]. The lack of data can be attested to data connectivity issues and the inability to access the site during the time of COVID-19. As seen in Figure 13, there is minimal data for 2018 and 2021, the only years with significant data is 2019 and 2020. Therefore, with a short temporal range, changes

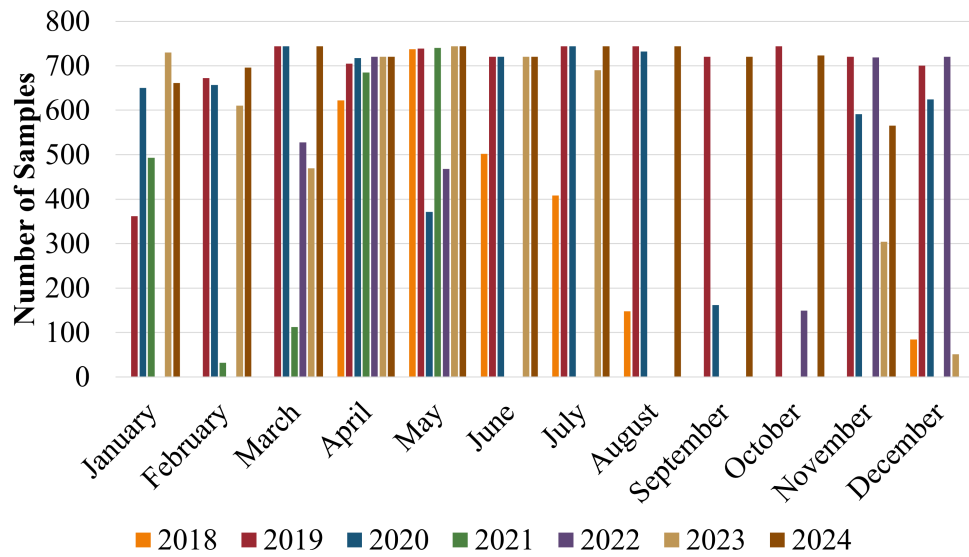


Figure 11: KV42 temperature data 2018 to 2024 monthly sample size

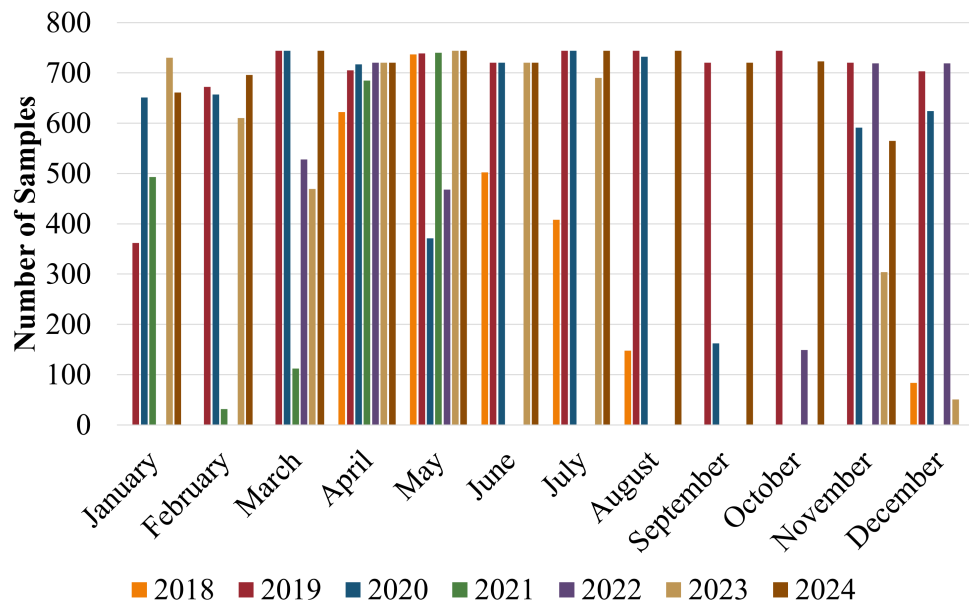


Figure 12: KV42 relative humidity data 2018 to 2024 monthly sample size

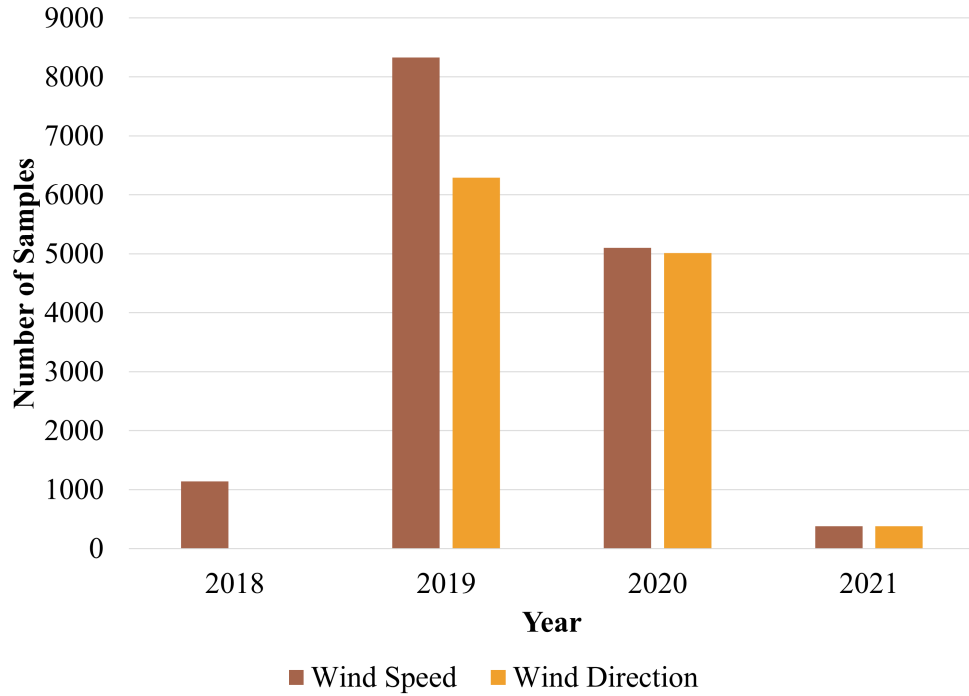


Figure 13: KV42 wind speed and direction data sample numbers for 2018 to 2021

in wind direction and speed cannot be analyzed.

Despite technical challenges that limited data collection, the in-situ measurements collected at KV42 provide valuable information on the micro-climatic conditions. These insights provide better information to benefit the efficiency of the applied preservation strategy.

Although, the process of data examination was the same for both KV42's and TT95's datasets, There is a limited scope of analysis on TT95's data simply due to the short duration of recording and collection challenges (which is later explored).

2.1.3 Satellite imagery for Land-Use Changes

Satellite imagery is a valuable tool for assessing land-use changes over time, allowing researchers to identify urbanization and agricultural development zones. These changes can influence local climatic conditions, making it essential to evaluate whether the observed climate trends are partially driven by land use shifts.

For this study, satellite imagery was sourced from Google Earth Pro, a free to use software which allows for the visualization of geospatial data such as satellite data [35]. In 2017, a time-lapse feature was added into Google Earth, which for the purpose of this research is helpful in analyzing land-use variations where the satellite imagery can be analyzed over a period of time (in this case 1984 to 2020, since Google Earth Pro's last accessible year is 2020) [36]. This update uses open data from the European Union's Copernicus program, Sentinel satellites and the NASA/US Geological Survey's Landsat program [36]. Land use is

described as an anthropogenic arrangement or activity over a particular land cover type, so that it can be used for a certain purpose such as urban and agricultural development [37]. Globally, from 1959 to 2019 around 19% of the net total anthropogenic carbon dioxide emissions was attributed to land use changes [37]. On a scale of tens of kilometres, changes in areas with vegetation such as deforestation can influence atmospheric circulations and cloud formation [37].

More specifically, areas such as Egypt, that are arid and hyper arid, have agriculture concentrated in rural communities [38]. These agriculture areas provide a cooling effect which can aid in mitigating surface temperature increases [38]. Yet, urban development has caused for these rural communities to decrease in size over time. Studies such as those by Mostafa et al (2023) has shown that for the El-Reyad District, Kafrelsheikh Governorate, Egypt in particular, there has been a decrease in agricultural lands of 3950.8 acres and an increase in urban areas of 6283.2 acres from 1988 to 2022 [38]. Over this period of time, the study area experienced increases in temperature from 32.4 °C to 33.6°C and is expected to reach 36 °C by 2036 [38]. In addition, the predictions from this study also showed that the agricultural land will decrease by 11.38%, in contrast, urban areas will increase by 4.6% [38].

Overall, satellite imagery is a useful way to track how land use has changed over time and how these changes may be affecting local climates. In Egypt, urban development has lead to increasing temperatures. Since the focus of this research is to aid preservation efforts in conserving archaeological sites like KV42 and TT95. Understanding climatic changes and its causes is vital, since knowing the causes allows for better damage prevention. By comparing satellite data from different periods of time (presented in Section 6.2), the areas with significant land use changes can be identified and then compared to the climate trend maps.

2.2 Data Processing

This subsection describes the produces used to clean and organize the NOAA regional weather data. The process includes the selection of stations and quality control. It should be noted that the DAQ data was organized.

2.2.1 NOAA Temporal Coverage and Station Selection

The number of available years for each NOAA station location provided insights on the available temporal range. The observed temporal range is then compared against the ‘ideal’ range (1984–2024), which is selected to provide a climate analysis that accurately captures modern climate change.

The different coloured markers are presented, as seen in Figure 8, are represented as the following. The 10 locations expressed by a green marker have a temporal range that includes 1984 to 2024 and thus, are seen as the ideal locations for temporal analysis. The 3 locations expressed by a yellow marker have a temporal range that includes nearly all of 1984 to 2024 (where 5 or less years are missing from the ideal temporal range). The 2 locations expressed by an orange marker have a temporal range that includes most of 1984 to 2024 (where 9 or less years are missing from the ideal temporal range). The 39 locations expressed by a

red marker have a temporal range that includes a small portion of 1984 to 2024 (where 10 or more years are missing from the ideal temporal range). The 17 locations expressed by a gray marker have little or no temporal data. It is clear from Figure 14 that a significant portion of the locations have a poor temporal range.

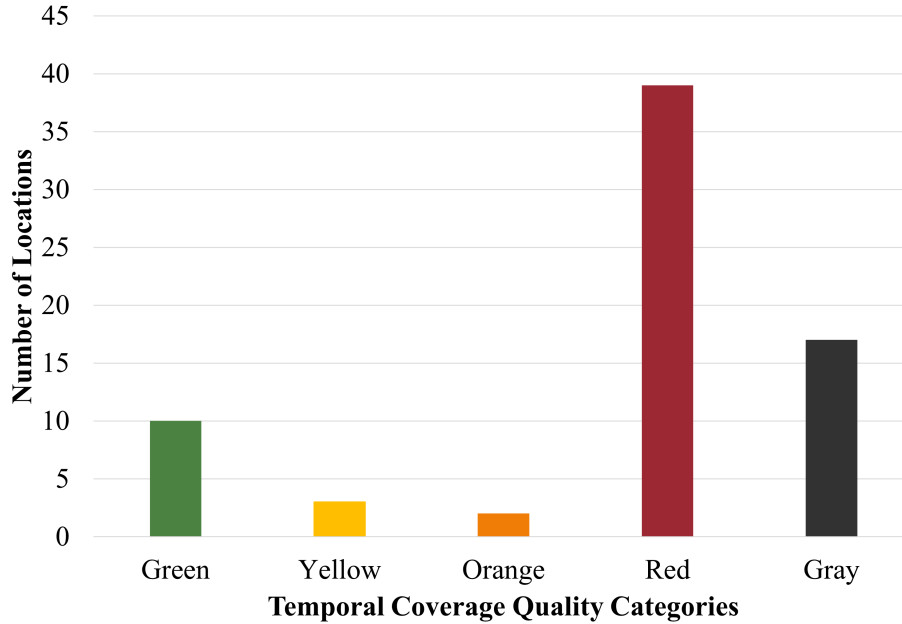


Figure 14: Number of NOAA weather stations within each temporal coverage quality category. Green markers represent stations with complete coverage (1984 to 2024), yellow represents stations with minor gaps (missing 5 or less years), orange represents stations with moderate gaps (missing 6 to 9 years), red represents stations with substantial missing data (10 or more years missing) and gray represents stations with minimal to no usable temporal coverage.

To ensure that only locations with satisfactory temporal ranges are used for spatial analysis, only locations represented by the green and yellow markers in Figure 8 are used as represented in Figure 15. The latitude, longitude and elevation of the 13 stations used in the analysis, as well as KV42, is presented in Table 2.

2.2.2 Quality Control Procedure

A substantial portion of this research process involved extensive data cleaning. The NOAA regional datasets required the removal of error values, correction of timestamp inconsistencies and missing periods. Each NOAA hourly observation included a corresponding quality control value provided by NOAA [39]. Observations with error values, which are represented as +9999,9 are removed from the analysis to maximize accuracy. Details of the process used to organize the regional data is expressed in Appendix A.

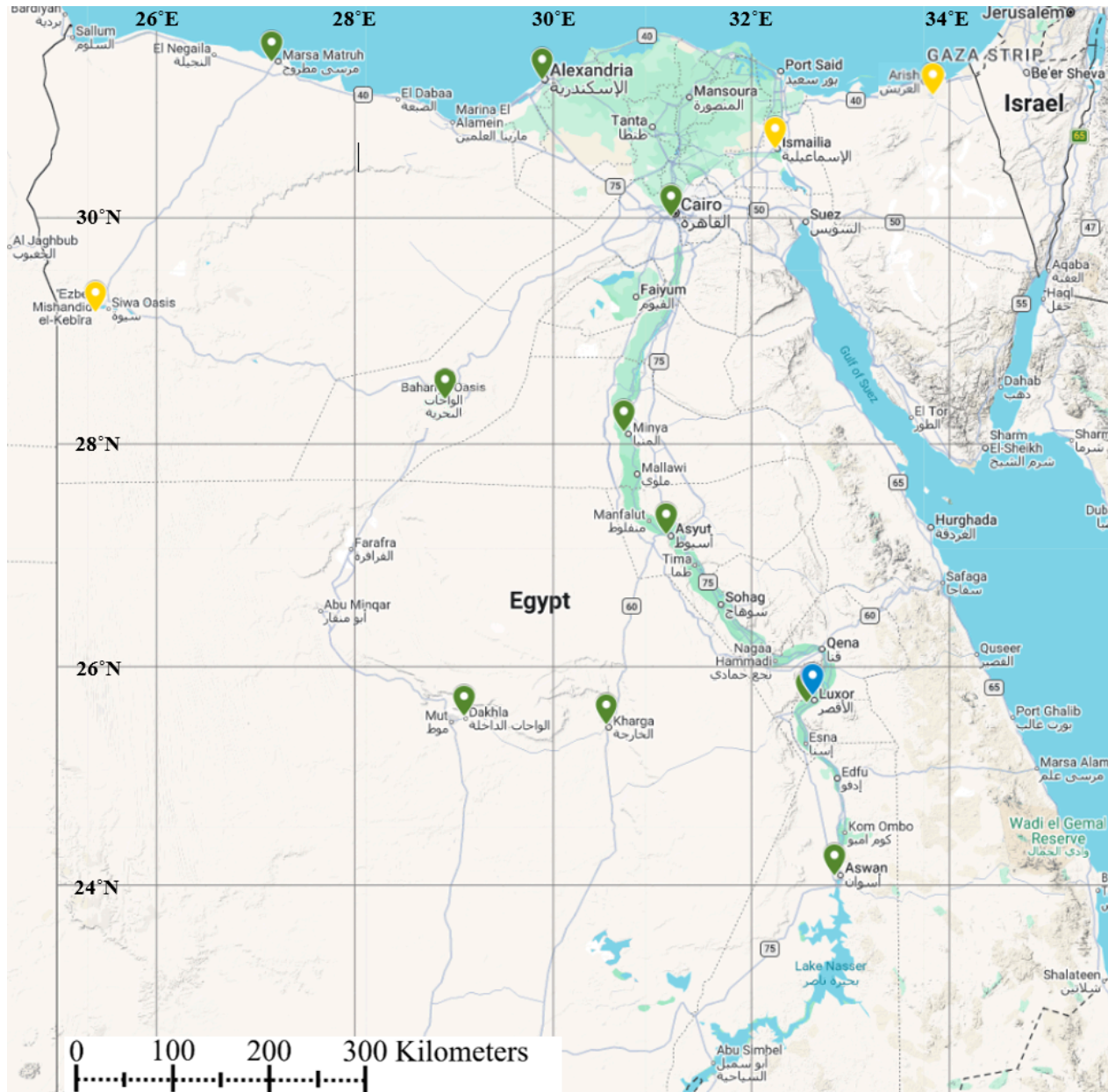


Figure 15: Map of Egyptian locations used for spatial analysis. Made with GoogleMyMaps. Blue marker indicates the location of KV42 and TT95

Station	Latitude	Longitude	Elevation (m)
Alexandria	31.1839	29.9489	-6
Aswan	23.9644	32.8200	196
Asyut	27.0465	31.0120	230
Baharia	28.3333	28.8667	132
Cairo	30.1219	31.4056	88
Kharga	25.4500	30.5333	87
Luxor	25.6710	32.7066	86
Mersa Matruh	31.3254	27.2217	26
Minya	28.0833	30.7333	43
Siwa	29.2000	25.4833	-16
Dakhla	25.5000	28.9667	110
El Arish	31.0733	33.8358	36
Ismailia	30.6000	32.2500	12
KV42	25.7381	32.6007	187

Table 2: Geographical information for meteorological stations selected for analysis and KV42

2.3 Derived Variables

2.3.1 Relative Humidity Calculation

Relative humidity is a measurement that expresses the ratio of the actual water vapour pressure to the saturation vapour pressure at a particular temperature. Since, saturation vapour pressure increases with temperature, relative humidity is strongly dependent on the temperature of the atmosphere. The variance of relative humidity over time is important for arid areas, since small fluctuations can cause structural changes within rock materials [40]. For a majority of the stations there is either minimal or no measured precipitation data within the NOAA global integrated surface dataset for Egypt. Thus, to grasp the aridness of the 13 locations used in analysis, Figure 16 is derived. Figure 16 presents the average number of days from 1984 to 2024 for each location, where in that day at least one hourly dew point temperature is equal to temperature, in other words when relative humidity is 100%. The minimal amount of 100% relative humidity measurements highlights just how rarely the atmosphere in these regions reaches saturation. This lack of moisture underscores the extreme aridity of Egypt as a whole and reinforces Egypt's hyper-arid environment.

Since there is no measured relative humidity data within the NOAA global integrated surface data set for Egypt, the following formula utilizes the NOAA temperature and dew point temperature data to calculate relative humidity (%) [41]:

$$RH = 100 \times [(e^{(17.625 \times T_D)/(243.04 + T_D)}) / e^{(17.625 \times T)/(243.04 + T)}] \quad (1)$$

Where (T_D) is the dew point temperature in units of °C.

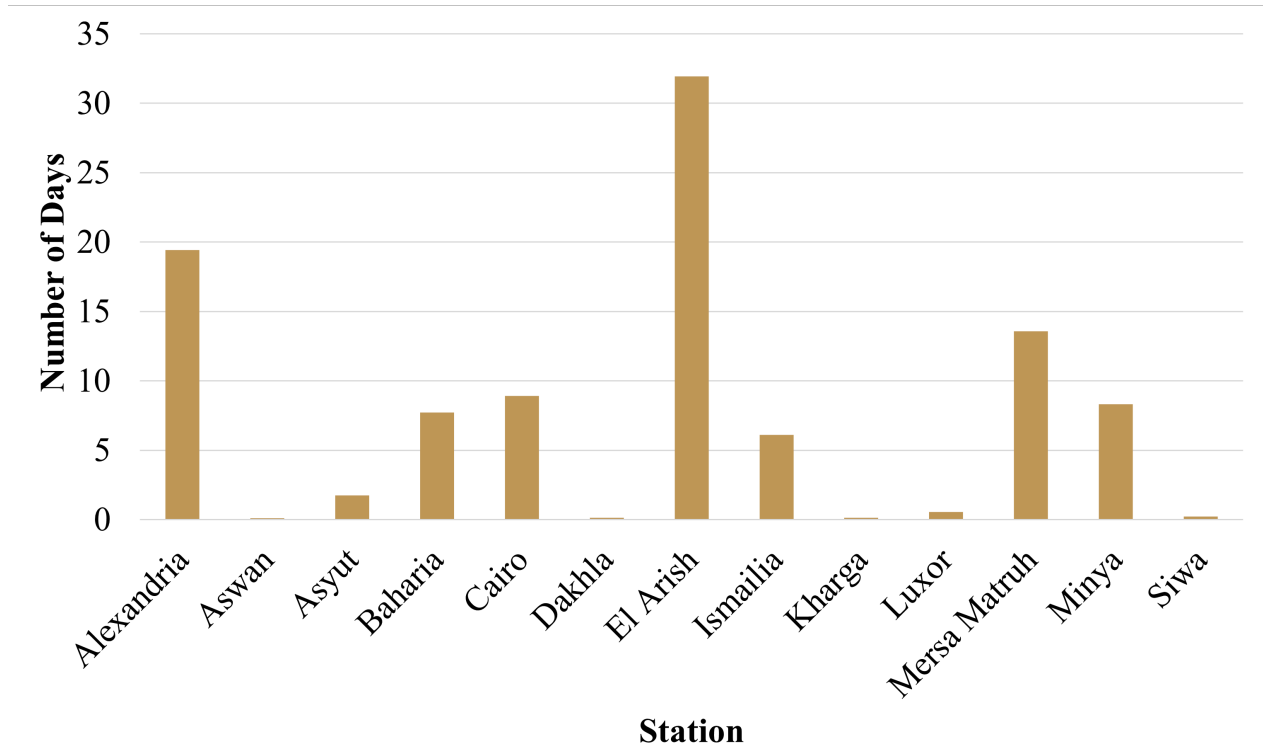


Figure 16: Average number of days per year (1984–2024) in which at least one hourly observation reached 100% relative humidity (temperature equals dew point temperature) at each of the 13 meteorological stations used for analysis.

(T) is the temperature in units of $^{\circ}\text{C}$.

Equation 1 is derived from the August-Roche-Magnus approximation [41]. Using equation 1, hourly temperature and dew point temperature values are then used to calculate hourly relative humidity for the NOAA data.

2.4 Statistical Analyses

Statistical techniques combined with Excel’s tools and functions were used to analyze climate data, as well as, compare data between KV42 and it’s nearest station, Luxor. These include averages (hourly, daily, monthly and seasonal), trend calculation, correlaton, relative error and minimum/maximum day value comparisons. The analysis done with the use of these methods will provide an understanding of how climate in changing in Egypt and how closely related KV42 and Luxor are to each other.

2.4.1 Hourly, Daily, Monthly, and Seasonal Averages

To calculate averages of the temperature and dew point temperature, the Excel function, Aggregate is used. The Aggregate function has the following format: *AGGREGATE(function num,options,dataset)* [42]. Where there is a total of 19 functions available within Aggregate, which is referred to as the function

num [42]. To calculate averages, the function num of 1 is used [42]. The different options available from 0 to 7, present options for how the function is calculated [42]. For the instance of this research, when "6" is applied the error values are ignored and when "7" is applied the error values and hidden cells are ignored [42].

However, to calculate the hourly average values from April to May for the years 2018 to 2024, the following Excel formula is used:

$$= AVERAGE(IF((HOUR(TimeData) = HourOfTheDay) \times (ISNUMBER(AllAvailableData)), AllAvailableData)) \quad (2)$$

The formula will only return a value if the time at that specific row is the same as a specified hour of the day (i.e., 0 is 12:00 AM) and the data is a valid number value. The formula will check each row for every hour of each day from April to May, and if both conditions are true, then the value is included into the hourly average calculation. Then all valid hourly values for the specified hour is used to calculate the average for that specific hour across all years (2018 to 2024). It is important to note for each year's data is stored in a separate column and each row represents a specific time for a specific day.

2.4.2 Trend Calculation

Then to calculate the trend, the function LINEST is used to calculate the linear line of best fit for a provided set of x and y data [43]. The LINEST function uses the least squares method to provide statistics on the best fit line for that particular set of data, such as the slope, slope's R^2 and uncertainty [43]. Where the least squares method is [43]:

$$m = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sum (x - \bar{x})^2}, \quad (3)$$

$$b = \bar{y} - m\bar{x} \quad (4)$$

In the above equations, $(\bar{x})$ and $(\bar{y})$ are the means of the samples.

2.4.3 Correlation, Relative Error, Min/Max Comparisons

To effectively compare the KV42 and Luxor weather station data, statistical tools such as correlation, relative error and max/min comparisons can be used.

For correlation, the CORREL function is used. The CORREL function can be used to acquire the coefficient of correlation between sets of data [44]. The calculation of the correlation coefficient is found using the following formula [44]:

$$Correl(X, Y) = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}}, \quad (5)$$

In the above equations, $(\bar{x})$ and $(\bar{y})$ are the means of the samples.

The correlation coefficient ranges from +1 to -1, which indicates a positive or negative correlation respectively [44]. A positive correlation between the two sets of data indicates that as data 1 increases data 2 also increases proportionally [44]. In contrast, a negative correlation indicates that as data 1 increases data 2 decreases proportionally [44]. Otherwise, a value of 0 or close to 0, indicates a weak or no correlation between both datasets [44].

To calculate relative error between the KV42 and Luxor weather station data, the following Excel formula is used:

$$= IF(OR(ISBLANK(KV42HRLYValue), ISBLANK(LuxorHRLYValue)), "", ABS((KV42HRLYValue - LuxorHRLYValue)/LuxorHRLYValue) \times 100) \quad (6)$$

The formula will only return a value if there is a value for both Luxor and KV42 at that time, otherwise a blank cell is displayed. The value returned is the difference between the KV42 and Luxor readings which is then divided by the Luxor value. To then convert the result as a percentage the value is multiplied by 100.

The above is calculated for the air temperature, rock temperature and relative humidity between KV42 and Luxor.

To calculate the minimum and maximum day value for each year during May and April, the following process is used. First, the average of each unique day is calculated using for year:

$$= IF(AND(COUNTIF(DAYRange, SpecificDay) > 0, ROW() = MIN(IF(DAYRange = SpecificDay, ROW(DAYRange), ""))), AVERAGEIF(DAYRange, SpecificDay, DataValue), "") \quad (7)$$

The formula will only return a value if the specified day exists in the dataset and the current day is the first time that the specific day appears. The formula ensures that the average is only calculated once per day for all hours. Then the resulting value is the average of all data entries on the same day for that year.

Then to calculate the minimum and maximum value based on the day values for each year, the Aggregate tool is used again where the function num is "4" for the resulting value to be maximum and "5" for minimum [42].

2.5 Spatial Interpolation

Spatial interpolation was done with the use of ArcGIS to create climate maps. The goal of this spatial interpolation was to interpolate regional data to capture trends at local archaeological sites. Therefore, the interpolated climate maps can be used to estimate climatic trends at Egyptian heritage sites with limited temporal data.

2.5.1 ArcGIS Natural Neighbor Technique

Within ArcGIS there are different types of interpolation techniques: IDW, Kriging, Natural Neighbour, Spline, Spline with Barriers, Topo to Raster and Trend [45]. The Inverse Distance Weighted (IDW) tool spatially interpolates by averaging the nearby points of inputted data where the closest points have a greater weight in the average than further points [45]. The Kriging tool uses advanced geostatistical methodologies to estimate a surface using inputted points [45]. The Natural Neighbor (also known as the Sibson or "area-stealing") interpolation tool finds the closest input data points to a specific query and applies proportional area weights to interpolate values [45]. The Spline interpolation tool uses a mathematical function to estimate values to minimize the curvature of the interpolated surface [45]. The result of this tool is a smooth surface that passes through the inputted points [45]. The Spline with Barriers tool is similar to the Spline but it includes discontinuities at both the provided barriers and the inputted data [45]. The Topo to Raster interpolation tool creates an interpolated surface that simulates natural drainage surface from the provided inputted data [45]. Finally, the trend interpolation tool uses a mathematical function, specifically a polynomial, to fit a smooth surface across the inputted data points [45]. The resulting surface changes gradually and has the ability to capture coarser patterns within the inputted data [45].

The Natural Neighbour tool has been determined to be the most appropriate to be used in this research since the tool interpolates the data whilst preserving the inputted data values. Unlike the other interpolation methods mentioned above, the generated fitted surface typically has the predicted value at a known point differ from the inputted, measured value. These tools were tested by comparing the preliminary results with each other and there were errors found between the fitted surface and actual boundary values. In regions with more stations, smoothing can be beneficial for reducing possible noise, but in Egypt's sparse network it risks distortion of inputted data. The Natural Neighbour tool is able to bypass this error by preserving the known values at their original locations by using the proportional area approach. The Natural Neighbour tool is regarded to using a "local" approach, in other words, the tool will only use a subset of samples that surrounds the query point [46]. The tool only interpolates the values within the range of the inputted values therefore, not interfering with the inputted values themselves [46]. As a result, the interpolated surface is smooth everywhere but where the input data is located [46]. Each inputted data value is regarded as an individual query point. For example ten inputted values will be regarded as query point 1, query point 2, and etc. The natural neighbours of these query points are the values associated with the neighbouring Voronoi (Thiessen polygons) [46]. Each Voronoi polygon that surrounds a single generated point will be calculated such that every point in that specific polygon is closer in distance to the single generated point than to the

other points [47]. As presented in Figure 17, the olive-coloured polygons are the polygons constructed around the inputted points (exclusive of the query point) [46]. Then, the beige polygon is then constructed around the query point, marked with a red star [46]. The proportional amount of overlap between the query point polygon and the rest of the polygons is then stored as weighting properties for averaging [46].

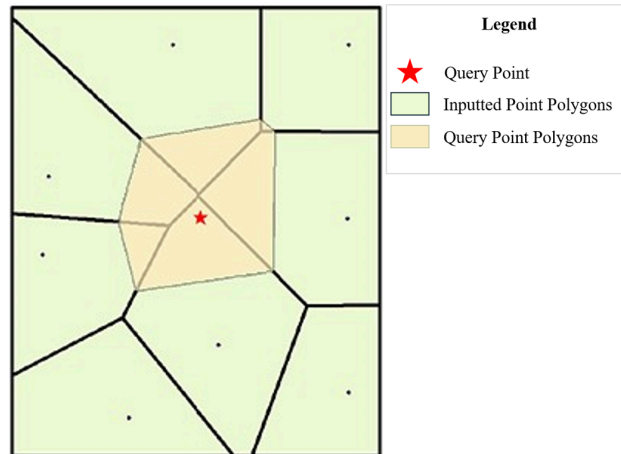


Figure 17: Example of a Voronoi polygon around a query point used in the Natural Neighbour interpolation algorithm [46] The olive-coloured polygons are the polygons constructed around the inputted points (exclusive of the query point) [2]. The beige polygon is then constructed around the query point, marked with a red star [2].

Within ArcGIS, the organized climate data is exported from Excel. The imported data is then transformed into point data using the "display XY data" tool where the x-field is the longitude and the y-field is the latitude using the coordinate system of GCS World Geodetic System (WGS) 1984. The point data can then be used for the Natural Neighbour interpolation as the input point features and the z value field (which is temperature and relative humidity values). As well, a symbology template is also imported into ArcGIS to ensure that all spatial maps for that particular analysis whether it be for climate or rate of change in climatic parameters for the temporal range of either 1984 to 2024 or 2018 to 2024. The values of the template uses the max and min values of that analysis so that no values are excluded. As well, it will help to better compare seasonal graphs with each other and provide a relative understanding. It should be noted that for rate of change in climatic parameters maps' point data, the statistical significance of the trend is calculated for each location. The formula for the statistical significance is simply the difference between the absolute value of the trend and the absolute value of the trend error. If this difference is negative then the trend at that point has poor statistical significance then the trend error is greater than the trend. In contrast if there is a positive difference then the trend at that point has decent statistical significance, where the trend is greater than its error. This binary system provides a perspective on not only the areas where the trend is insignificant, but of where it is. Therefore, providing insights into what information has more weight in the entirety of the analysis. To visually represent this, points with poor statistical significance are represented with a smaller point circle with a size of 3pt whilst points with decent statistical significance are represented with a larger point circle with a size of 7pt.

3 Temperature and Relative Humidity Interpolated Spatial Maps

Understanding the spatial variability of climate parameters such as temperature and relative humidity is essential for assessing regional risks and long-term environmental changes.

This chapter is organized into two main parts. First, the climatology maps are presented to establish a foundational understanding of how temperature and relative humidity has changed from one climatological period (1984 to 2024) to another (2018 to 2024). These two climatological periods are presented together because the purpose of this comparison is to evaluate how the long-term (1984 to 2024) period available with regional data contrasts with the short-term period (2018 to 2024) available with the in-situ data from KV42. In other words, using an overlapping of the shorter period allows for a direct comparison between the regional NOAA station-based climatology and the local archaeological site measurements. To better understand the changes in these climatic parameters over the years, the second part of this chapter examines long-term trends from 1984 to 2024 across Egypt.

3.1 Temperature Climatology Interpolated Spatial Maps

When comparing Figures 18 and 19, it is clear that there are some changes in the average regional temperatures between the two climatological periods. For example, during winter, there is warmer temperatures around the Ismailia region during the 2018 to 2024 period than the 1984 to 2024 period. A similar pattern is seen during the summer, across eastern regions such as El Arish, Ismailia, Luxor and Aswan.

3.1.1 Addition of Temperature Site Specific Data

The interpolated spatial maps presented in this section provide information on the climatology from 2018 to 2024 across Egypt. Although providing valuable information on a regional scheme, the resolution does not provide detailed information on specific municipalities such as Luxor. Therefore, a zoomed-in version of the spatial analysis is done around the Luxor area. To do so, the list of available NOAA stations data in Egypt is revisited and stations near Luxor with a sufficient temporal range from 2018 to 2024 is used to spatial interpolate with the above used methods around the Luxor area. These zoomed-in climatology spatial maps near Luxor are presented in Figures 20 and 26. To gather a better understanding of how the input of archaeological weather data can alter station based interpolation provides insight on how accurately station based interpolation can be used to understand the climate conditions at these archaeological sites, in this case KV42. These zoomed-in climatology spatial maps near Luxor including KV42 data is presented in Figures 21 and 27.

Through direct comparisons between Figures 20 and 21, it is clear that during Winter months the addition of KV42 does not make much difference to the original spatial analysis without the KV42 data. In contrast, during the summer, particularly during the first half of summer, as well between April and May, the original spatial maps underestimate the temperature at KV42, interpolating a lower temperature than the actual temperature.

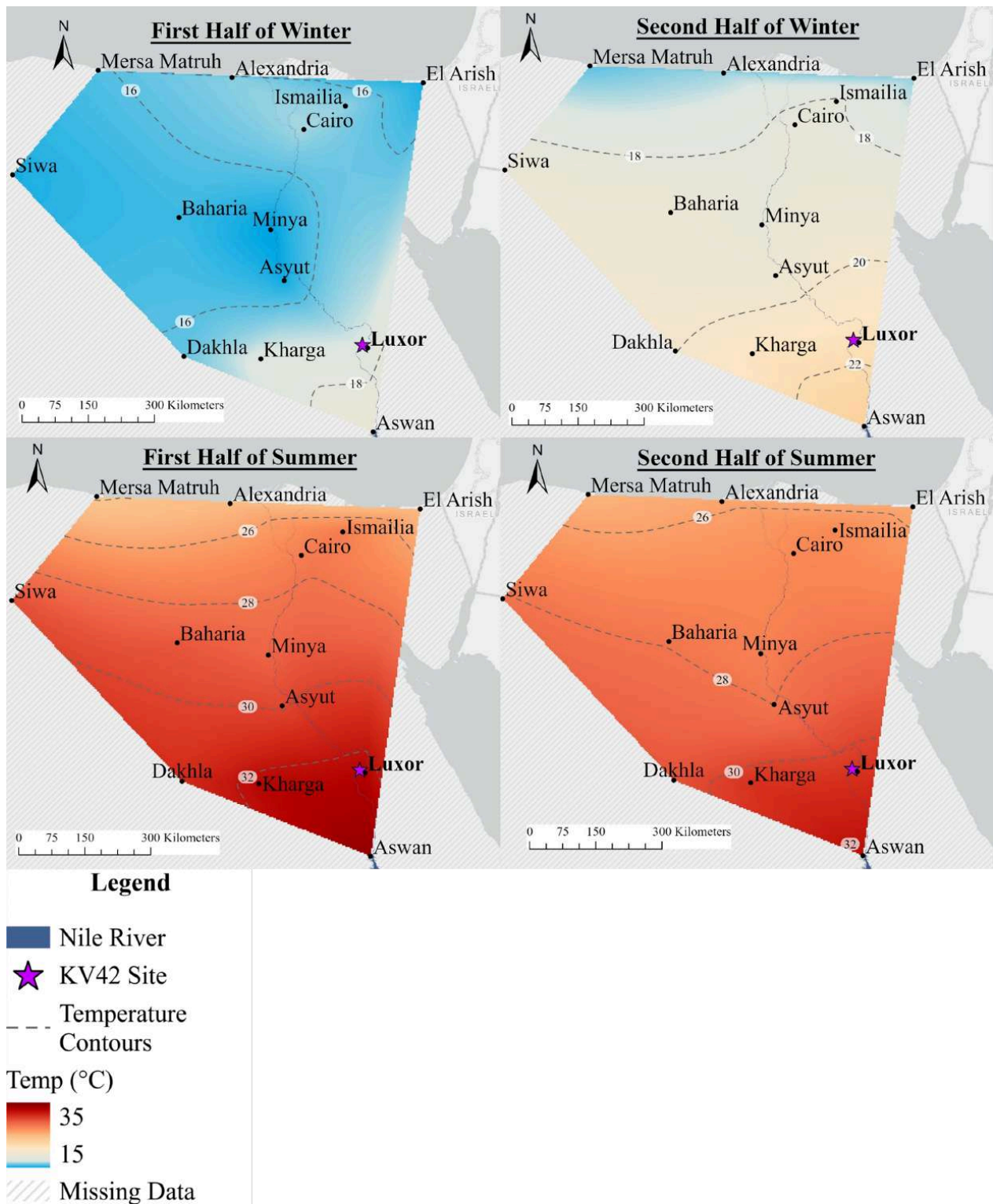


Figure 18: Temperature climatology (°C) for Egypt during 1984 to 2024, derived from NOAA observations and spatially interpolated using the Natural Neighbour technique. Winter in Egypt spans from November to April, while summer extends from May to . The local case study locations are in Luxor which is indicated with a purple star

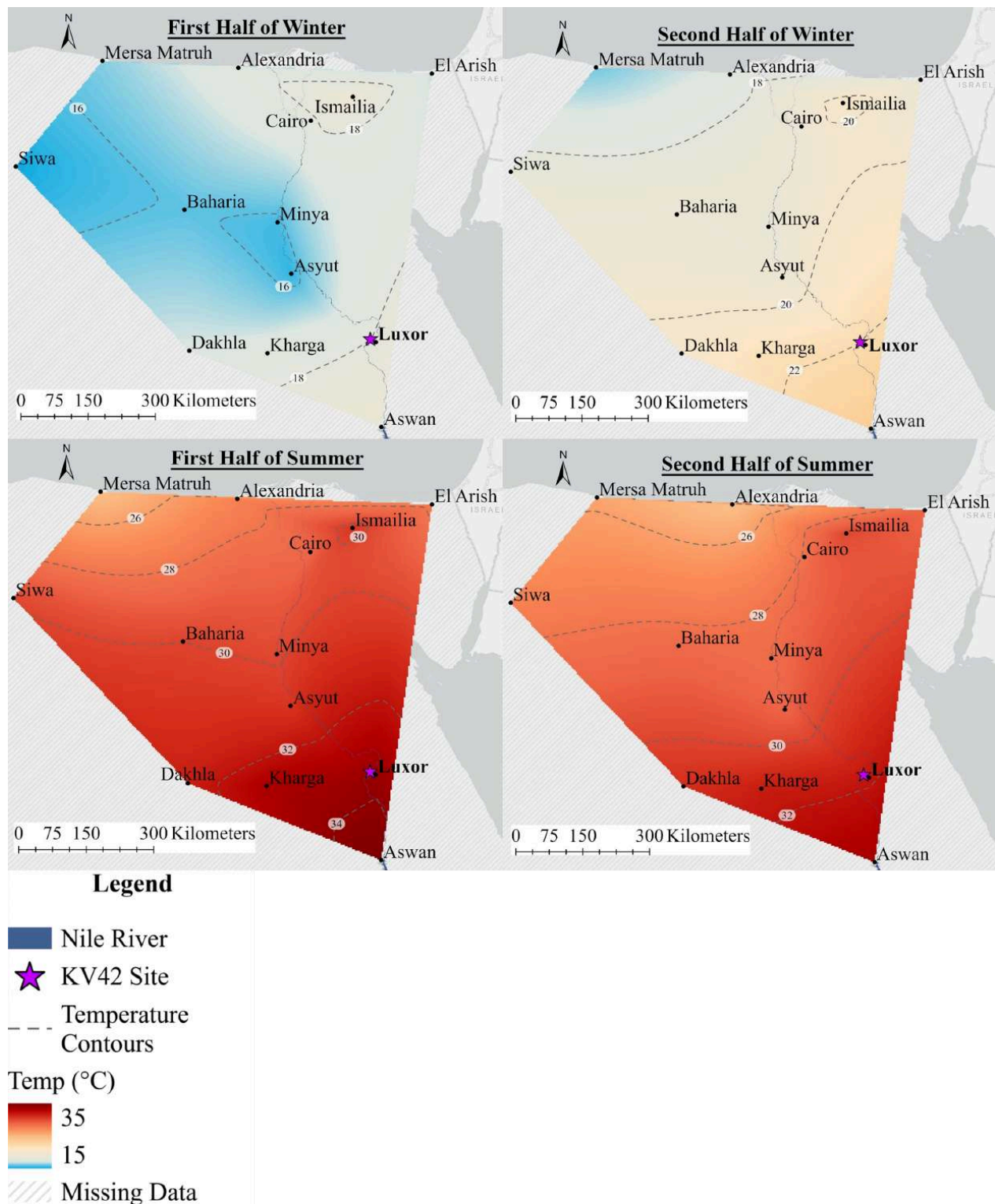


Figure 19: Temperature climatology (°C) for Egypt during 2018 to 2024, derived from NOAA observations and spatially interpolated using the Natural Neighbor technique. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star

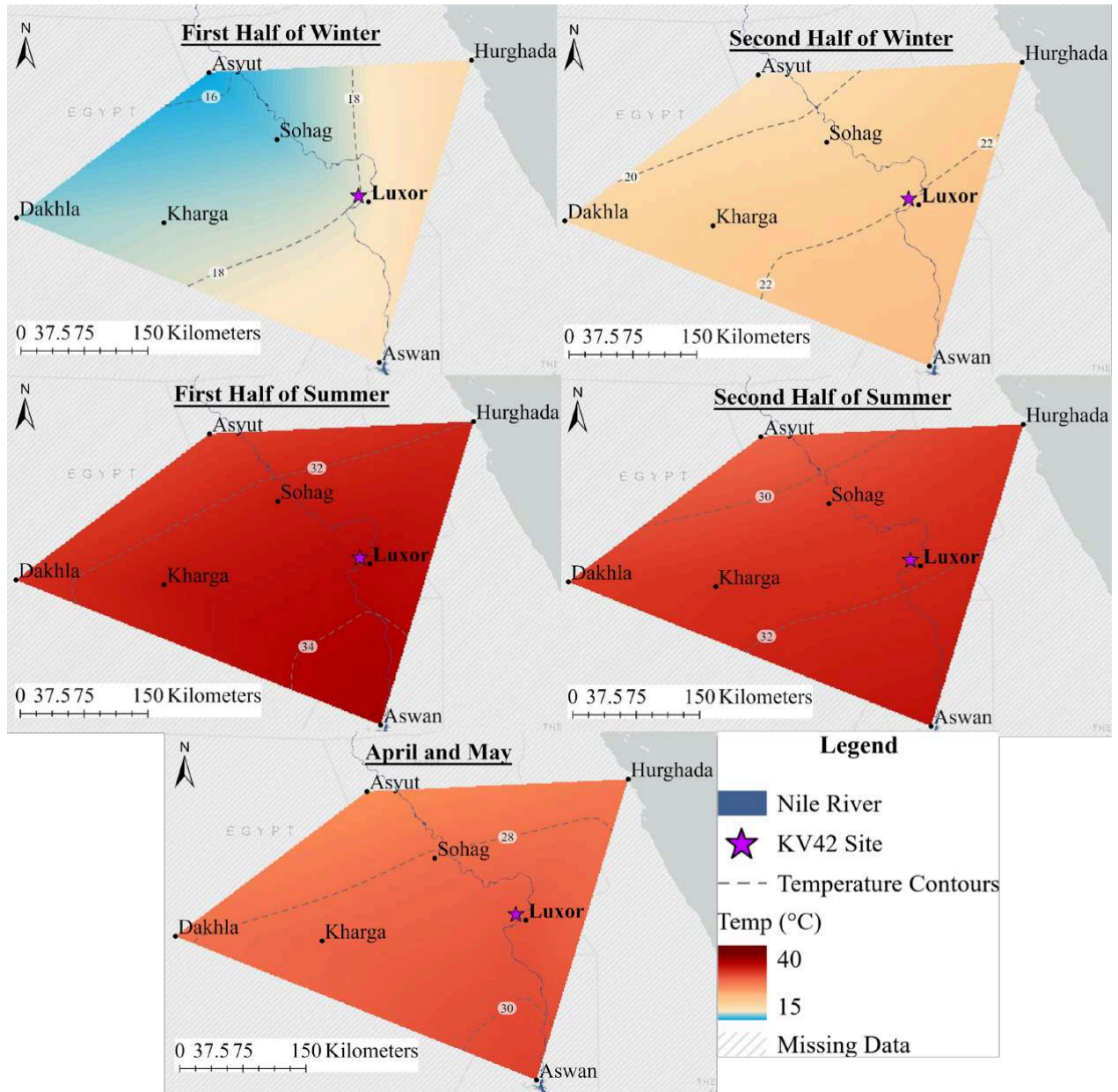


Figure 20: Temperature climatology (°C) for Luxor's surrounding area during 2018 to 2024, derived from NOAA data and interpolated using the Natural Neighbour method. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star

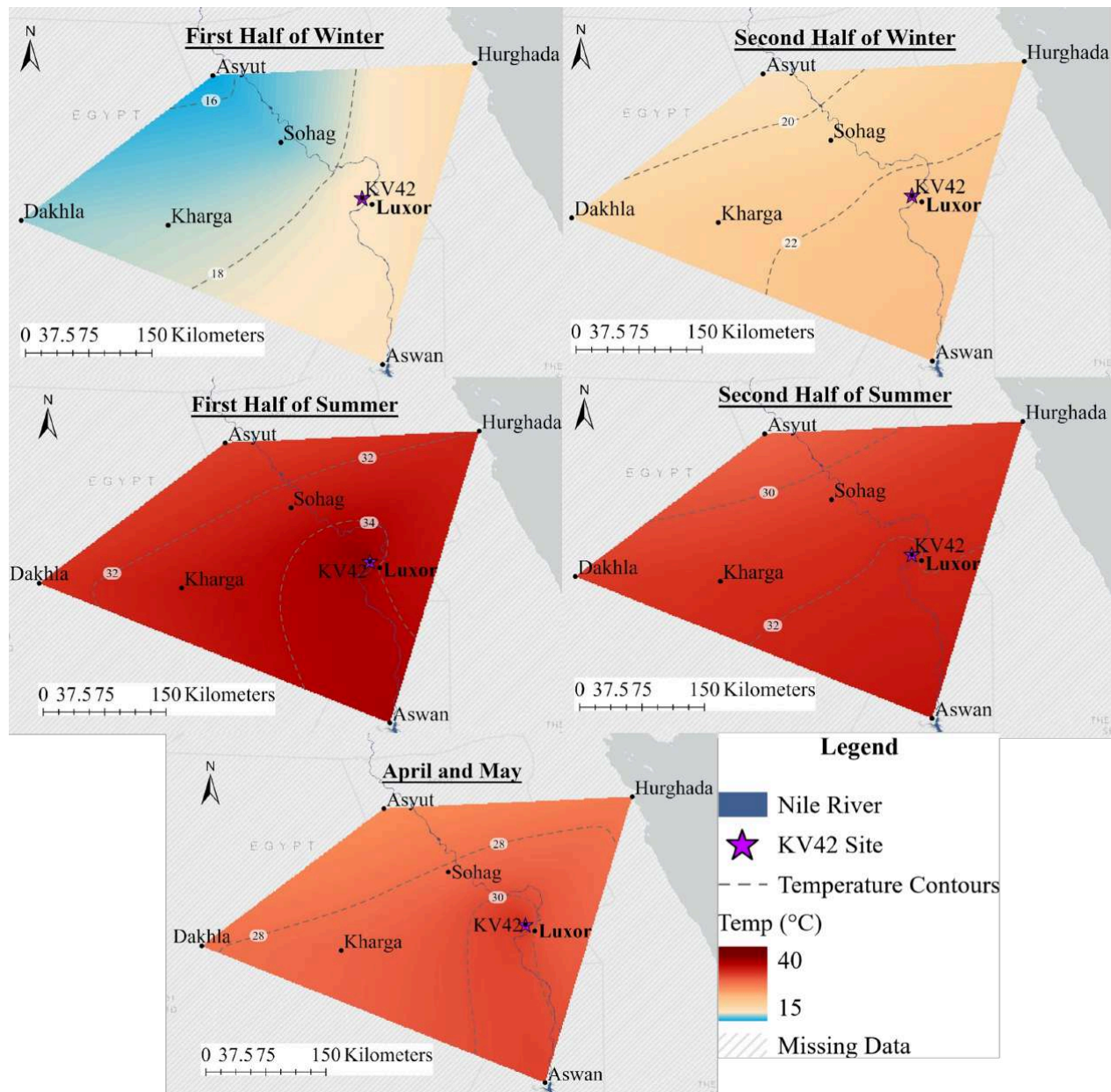


Figure 21: Temperature climatology (°C) for Luxor's surrounding area, including KV42, during 2018–2024, derived from NOAA and KV42 data and interpolated using the Natural Neighbour method. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star

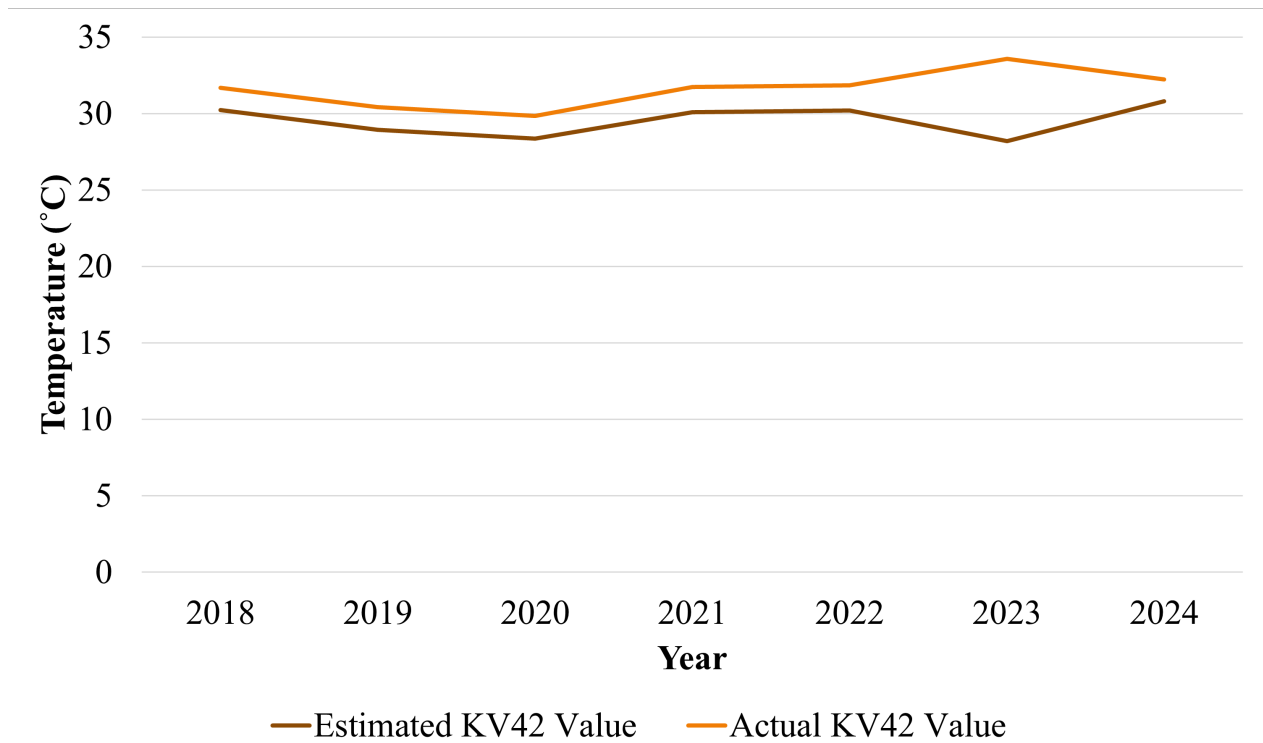


Figure 22: Time series comparison of actual versus estimated (extracted from the spatial interpolation without the KV42 data) temperature values at KV42 for 2018 to 2024

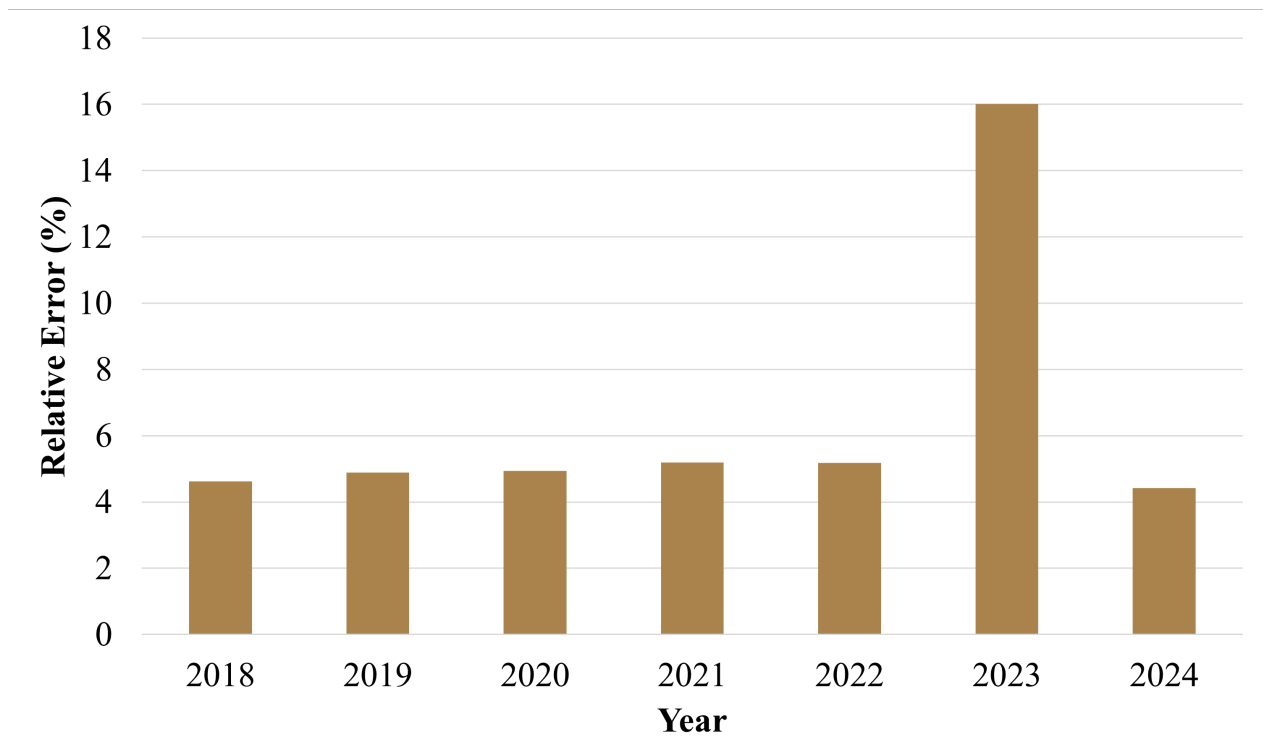


Figure 23: Relative error between actual versus estimated (extracted from the spatial interpolation without the KV42 data) temperature values at KV42 for 2018 to 2024

The quantification of the differences between the actual KV42 value and the estimation from the spatial interpolation was calculated. The estimated values were done using the spatial interpolation of Luxor's surrounding area using averages of the April to May period for the years 2018 to 2024. Then the value at KV42's location is extracted from the raster spatial interpolation without the inclusion of KV42's data to acquire the estimated value for each year. This extraction is done with the use of the Extract Values to Points tool in ArcGIS. The tool is able to extract the values of a cell at a specific point or points from a raster [48] April and May are the only months where KV42 has data for each year. The actual versus the estimated KV42 values are presented in a time series line plot as seen in Figure 22. Although the actual temperature values at KV42 are warmer than the estimated interpolated values, the values are quite close, deviating slightly in 2023. The correlation between the two sets of data is 0.163, indicating a weak positive relationship, a low correlation could be due to the deviation in 2023. To again quantify this further, relative error between the actual and estimated (extracted from the spatial interpolation without the inclusion of the KV42 data) KV42 values are calculated and presented in Figure 23. The relative error is minimal averaging around 6.5%, highlighting how close the estimated values are to the actual values. It should be noted that two locations were missing data during April and/or May for certain years. For example, Dakhla was missing April and May data for 2019, April data for 2020 and 2021. As well, Aswan was missing May data for 2023.

It is important to note that the interpolated maps cover only the portion of Egypt for where NOAA station data are available, the spatial interpolation could be potentially extended with the use of additional stations in neighbouring countries such as Israel, Saudi Arabia, Sudan and Libya. As well, the maps presented in this chapter provide estimates of surface-level air temperatures derived from the 13 available Egyptian weather station observations. Since, the interpolation method is simple and consists of minimal stations, caution should be taken when interpreting specific values.

3.2 Relative Humidity Climatology Interpolated Spatial Maps

When comparing Figures 24 and 25, it is clear that there are some changes in the average regional relative humidity values between the two climatological periods. For example, during winter and summer months, there is a lower relative humidity around the Ismailia and Cairo region, as well as the Southern Egypt region, during the 2018 to 2024 period than the 1984 to 2024 period. Increasing temperatures will lead to an increase in saturation vapour pressure, in other words, the warmer the atmosphere the more water vapour it is able to hold. Therefore, even if the actual water vapour pressure of the atmosphere stays constant, the increase in saturation vapour pressure would result in a lower relative humidity.

3.2.1 Addition of Relative Humidity Site Specific Data

However, in comparison to temperature, the relative humidity climatology maps provided a more significant change when adding KV42 to the spatial analysis. When comparing Figures 26 and 27 with each other, it is clear that across all seasons, the original spatial maps overestimates the relative humidity interpolated over KV42. The addition of KV42 to the spatial analysis provides context on how the initial spatial inter-

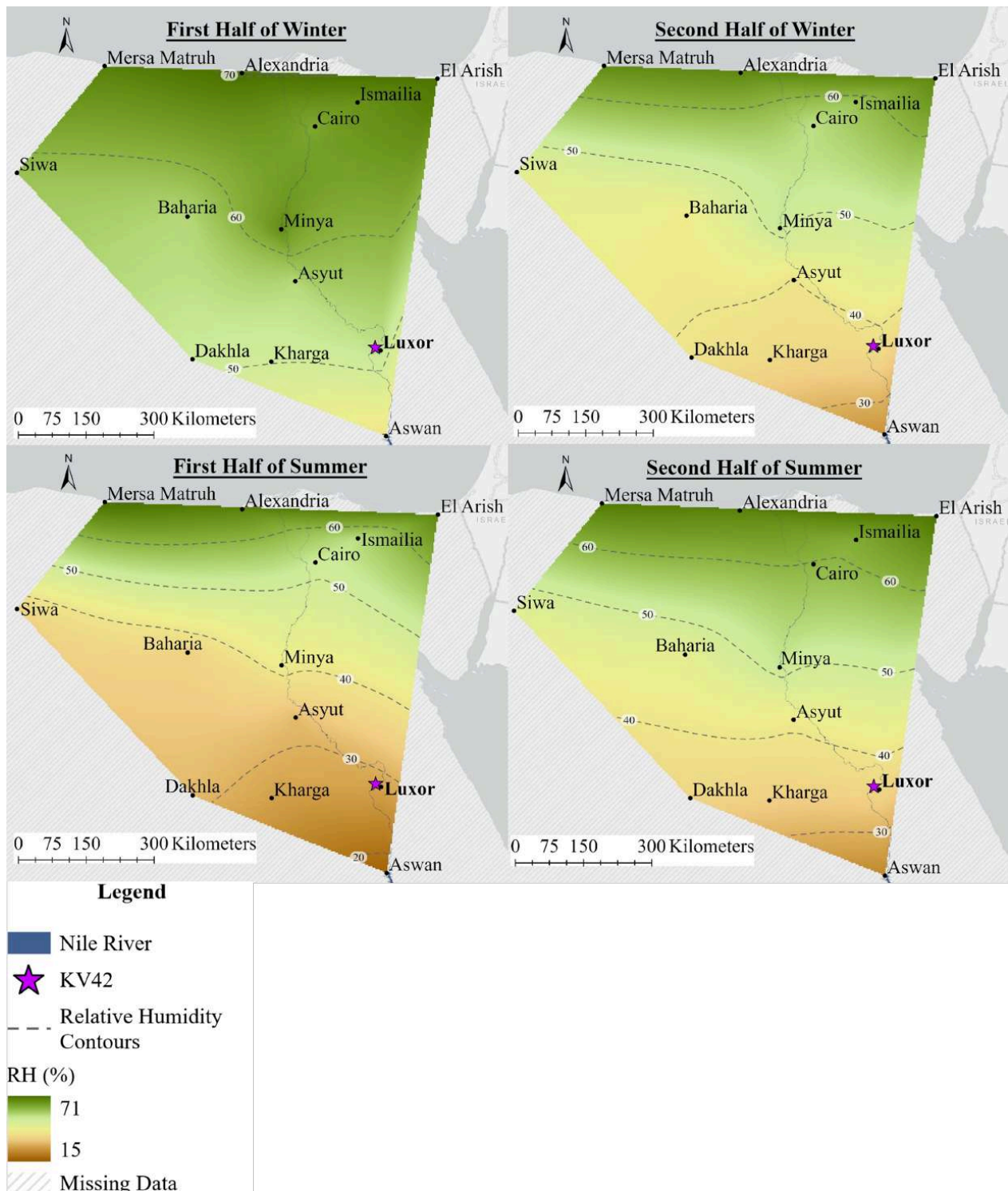


Figure 24: Relative humidity climatology (%) for Egypt during 1984 to 2024, derived from NOAA observations and spatially interpolated using the Natural Neighbour technique. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star

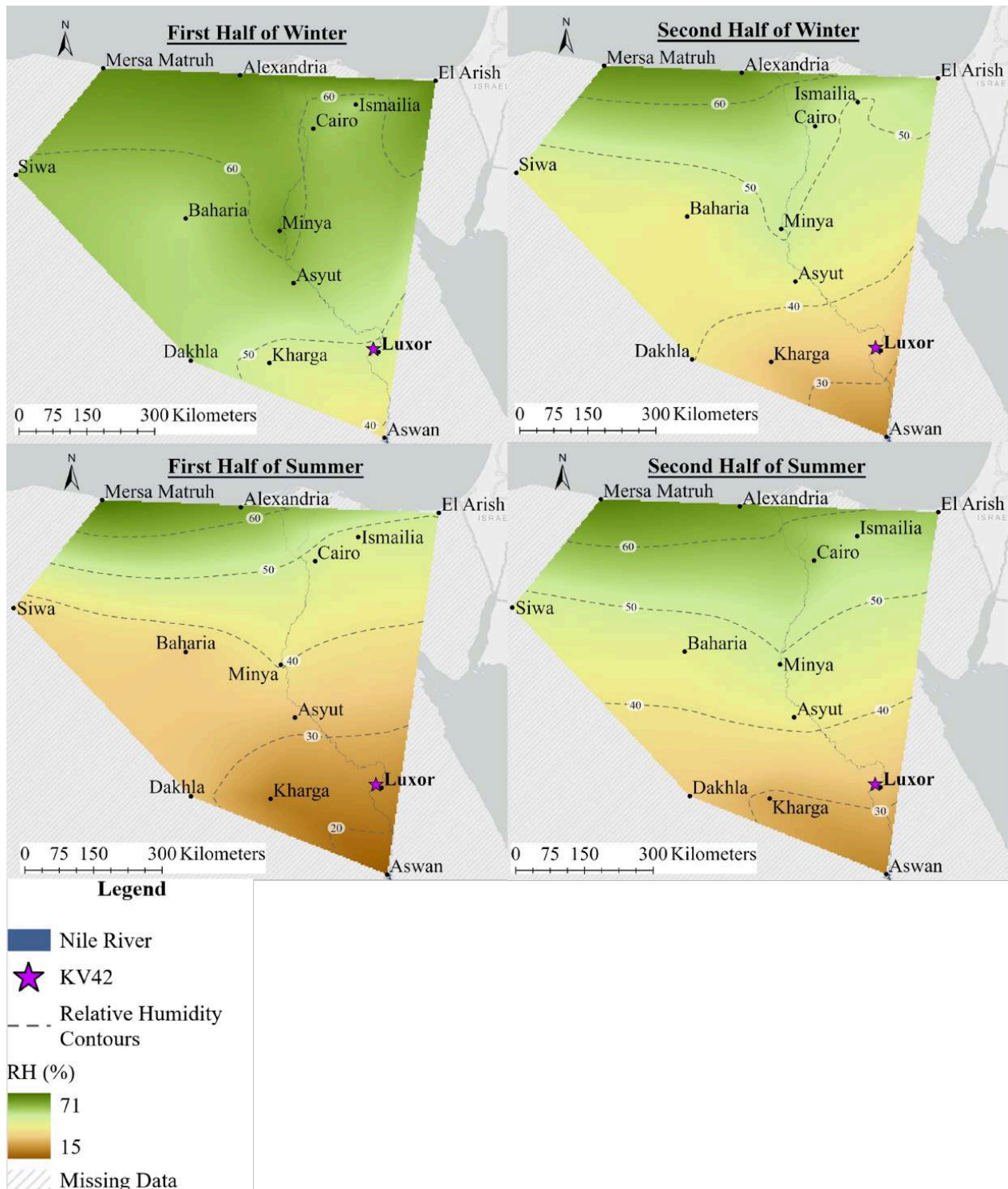


Figure 25: Relative humidity climatology (%) for Egypt during 2018 to 2024, derived from NOAA observations and spatially interpolated using the Natural Neighbour technique. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star

polation is unable to capture KV42's dryness especially during summer months, where the most significant change is during the first half of summer.

The actual versus estimated (extracted from the spatial interpolation without the inclusion of the KV42 data) KV42 relative humidity values are presented in Figure 28. The actual KV42 values are much less humid than the estimated values. The large difference is represented in Figure 29 with relative error values averaging 248.044%. However, the correlation between the two values are 0.757 indicating a moderate positive relationship between the two sets of data.

3.3 Temperature Trend Interpolated Spatial Maps

Figure 30 exhibits the change in temperature per decade across Egypt from 1984 to 2024. First, it should be noted that the greatest average change in temperature is observed during the second half of summer, where a majority of the area is undergoing a prominent increase in temperature. In contrast, the lowest average change in temperature is observed in the second half of winter, areas such as Siwa and Baharia have little to no changes during this time. It is clear that the areas with the greatest increase in temperature per decade is the northeast portion of Egypt. Overall, it is clear that no matter the season, the country is experiencing an increase in temperature over time with the most affected cities being Dakhla, Ismailia and El Arish. As well, during the summer months is when most areas undergo the greatest increase in temperature per decade.

3.4 Relative Humidity Trend Interpolated Spatial Maps

Figure 31 exhibits the change in relative humidity per decade across Egypt from 1984 to 2024. During the summer months, there is a greater magnitude of decreasing relative humidity over time across Egypt, especially during the second half of summer. Although there is mostly decreasing relative humidity across the region during winter months, areas such as Dakhla and Asyut experience increasing relative humidity over this period of time. In terms of magnitude of decreasing relative humidity, areas such as Ismailia and Cairo experience the greatest. However, it should be noted that Dakhla experiences relatively prominent increasing relative humidity in the first half of winter and then prominent decreasing relative humidity during the second half of summer. This shift in the wet season getting more humid and the dry season getting less humid will lead to more contrasts in the climate over time.

3.5 Common and Divergent Findings from Spatial Interpolation

The spatial interpolation results presented in this chapter highlight several climatic patterns that are consistent across Egypt, as well as important regional variations that have direct implications for heritage preservation. Across all climatology maps, a clear north-south gradient emerges, with cooler and more humid conditions along the Mediterranean coast and progressively warmer, less humid conditions towards the south. This pattern is reinforced by both long term (1984 to 2024) and short-term (2018 to 2024) climatology,

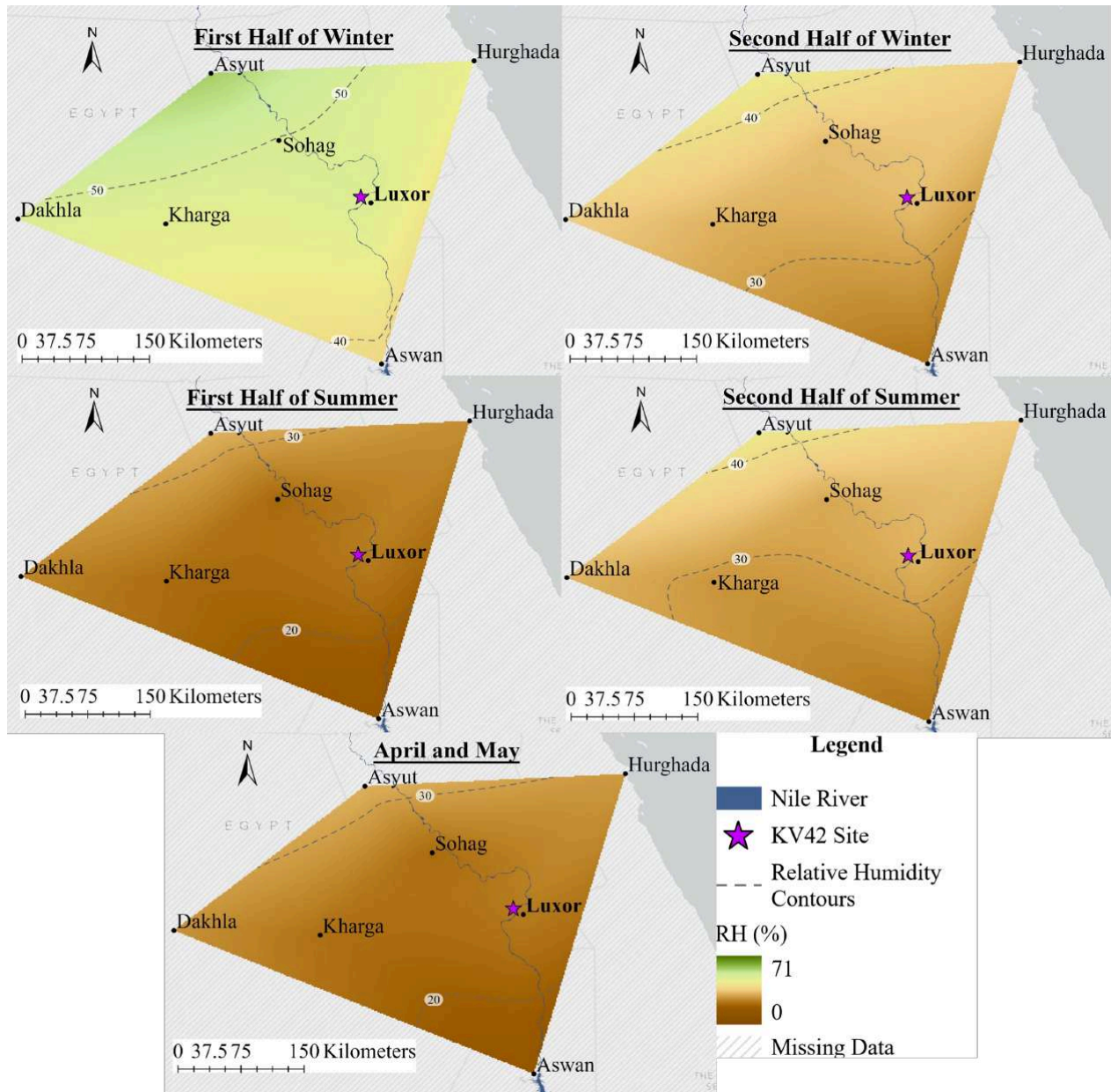


Figure 26: Relative humidity climatology (%) for Luxor's surrounding area during 2018 to 2024, derived from NOAA data and interpolated using the Natural Neighbour method. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star

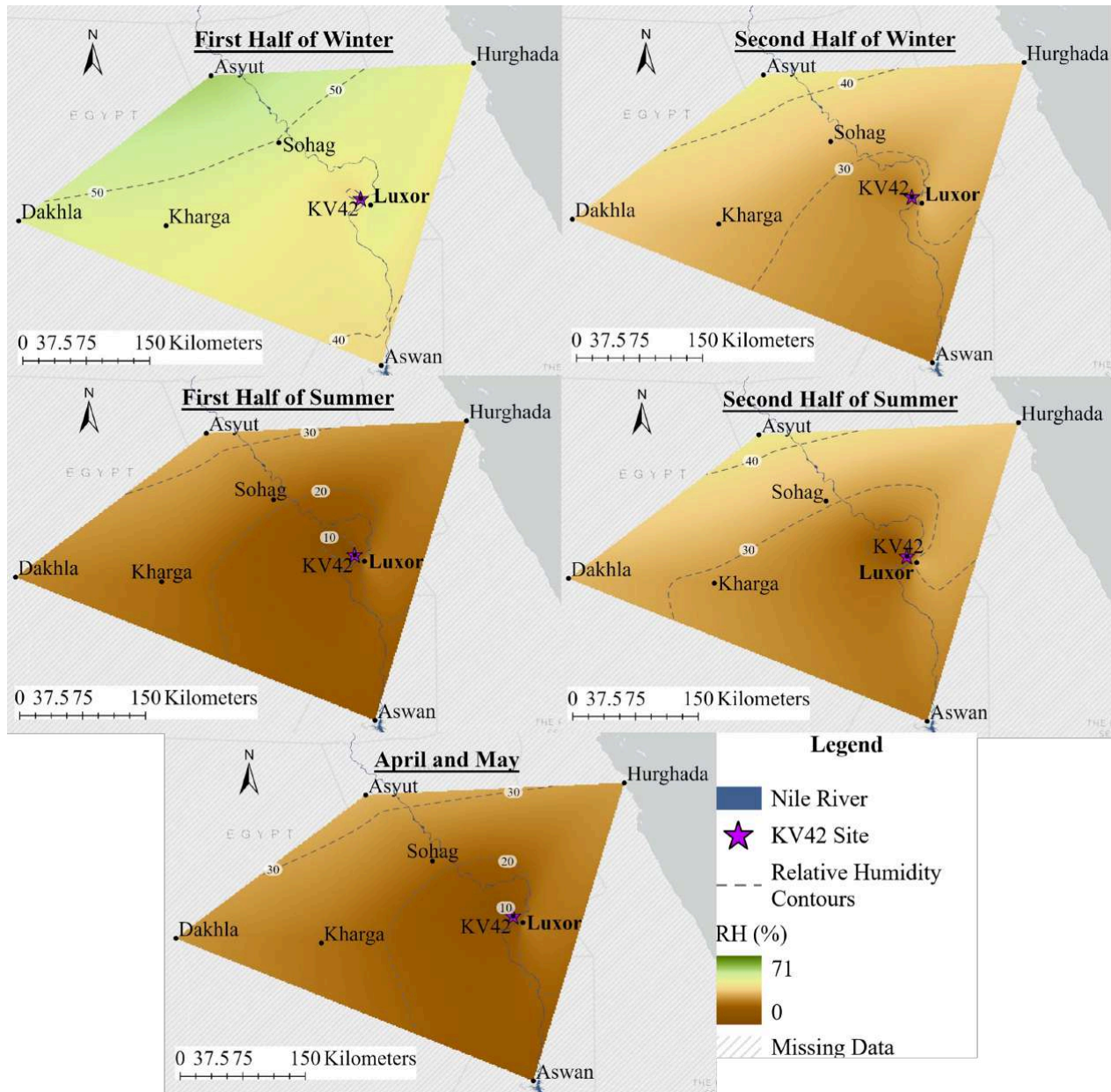


Figure 27: Relative humidity climatology (%) for Luxor's surrounding area, including KV42, during 2018–2024, derived from NOAA and KV42 data and interpolated using the Natural Neighbour method. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star

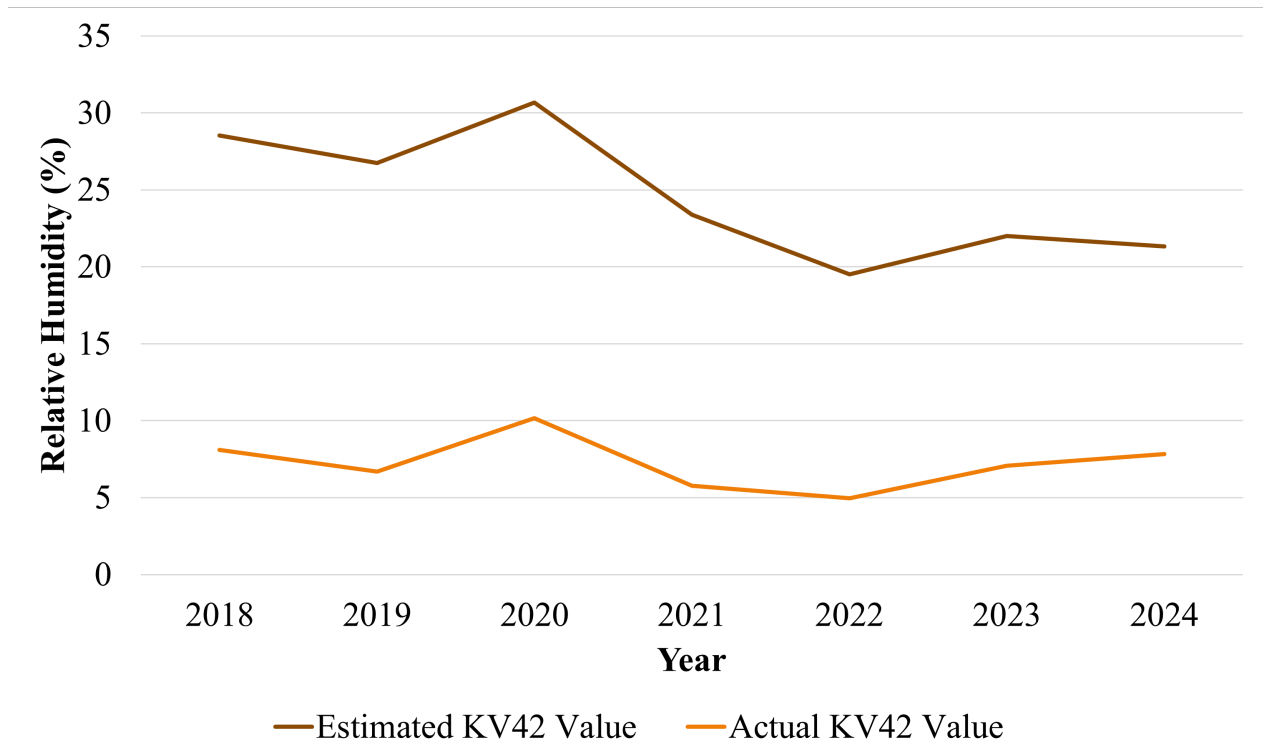


Figure 28: Time series comparison of actual versus estimated (extracted from the spatial interpolation without the inclusion of the KV42 data) relative humidity values at KV42 for 2018 to 2024

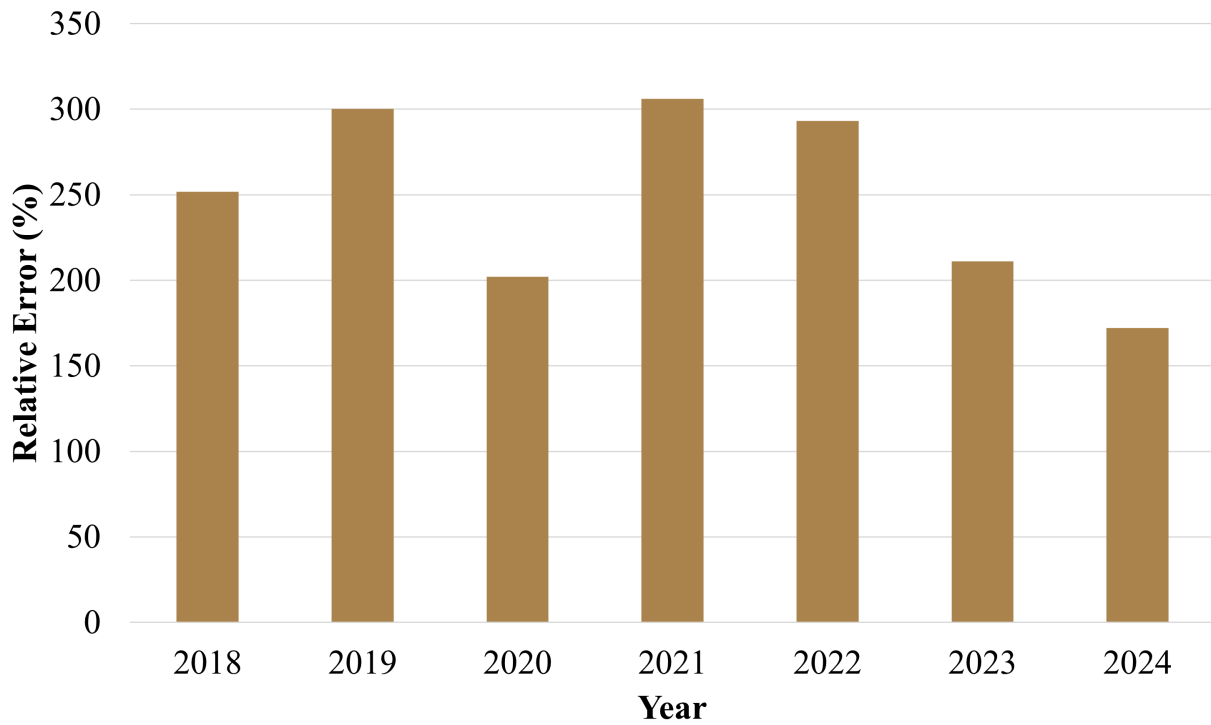


Figure 29: Relative error between actual versus estimated estimated (extracted from the spatial interpolation without the inclusion of the KV42 data) relative humidity values at KV42 for 2018 to 2024

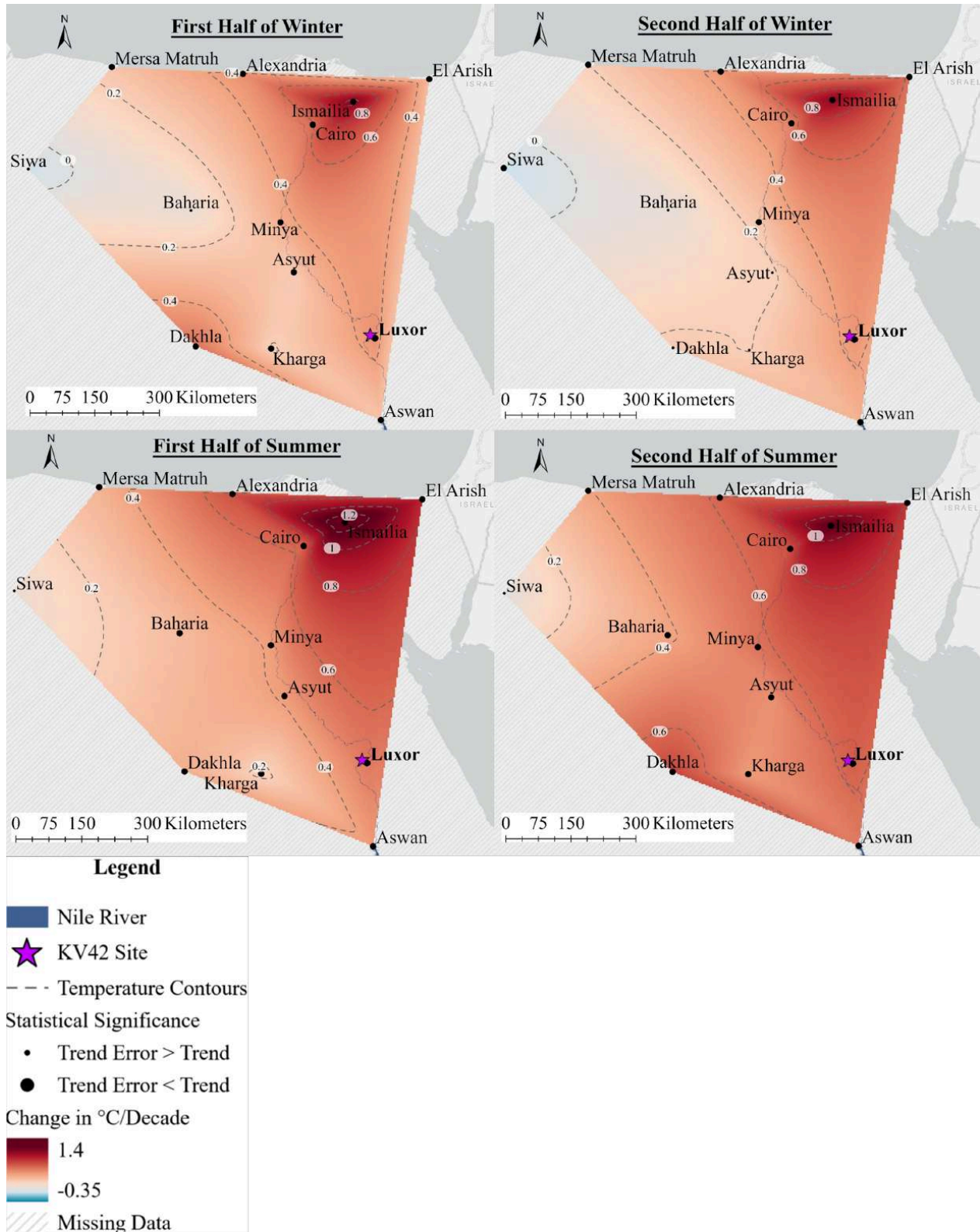


Figure 30: Rate of change in temperature (°C per decade) across Egypt for 1984–2024, derived from NOAA data and interpolated using the Natural Neighbour method. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star

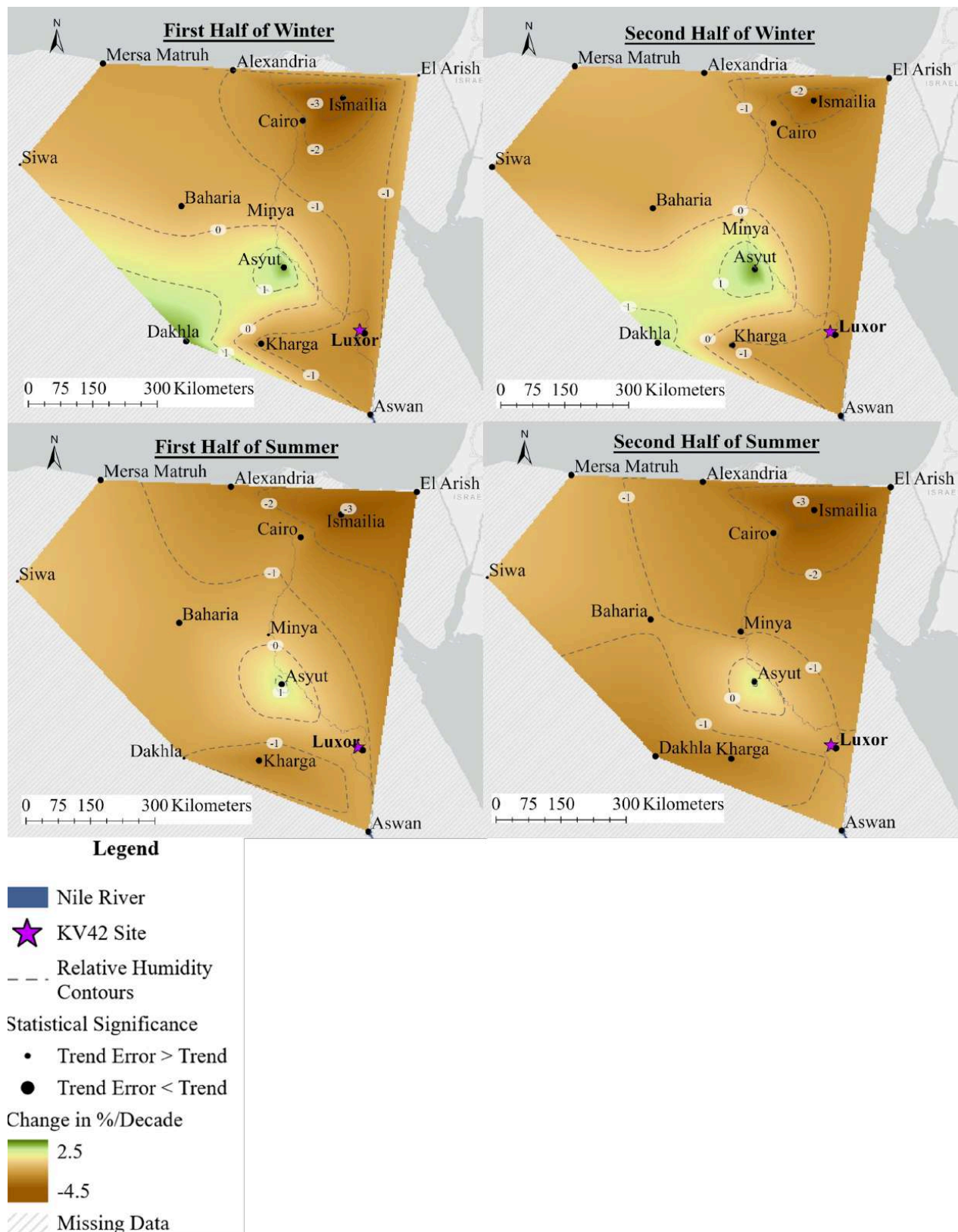


Figure 31: Rate of change in relative humidity (% per decade) across Egypt for 1984–2024, derived from NOAA data and interpolated using the Natural Neighbour method. Winter in Egypt spans from November to April, while summer extends from May to October. The local case study locations are in Luxor which is indicated with a purple star

demonstrating that although there are localized changes, the overall spatial structure of Egypt's climate remains consistent.

The interpolated temperature trend maps reveal a widespread warming pattern, with many regions experiencing temperature increases that exceed the global average. Interpolated relative humidity trend maps show a decreasing pattern, particularly in southern desert regions. These findings align with expectations for an arid environment undergoing warming and decreasing relative humidity but the spatial maps also provided insights into localized anomalies.

When KV42's data is incorporated into the interpolation, the localized influence of both topography and micro-climatic features becomes more apparent. The inclusion of site-specific measurements slightly modifies the surrounding interpolated fields, suggesting that regional datasets alone may not be able to fully capture micro-scale climate variability.

Overall, the spatial interpolation results establishes a clear climatic context for the case study sites, KV42 and TT95, since they are situated within one of the warmest and least humid regions of Egypt. The findings from this chapter provided context for the next, which evaluates how well regional data represents local conditions at KV42.

4 KV42 vs. Luxor Data Comparisons

To evaluate the accuracy of the interpolated climate spatial maps, this subsection compares the relationship between Luxor and KV42 to explore whether nearby regional weather stations are able to capture micro-climatic conditions.

When considering comparisons between Luxor and KV42 data from 2018 to 2024 such as relative differences and correlation, it should be important to note the amount of available data for KV42. To explain further, as seen in Figure 32, overall the monthly average temperature values are similar across years, however, there is a large gap of missing data from September to November. The reason for this gap in data during these specific months is currently unknown. Yet, this absence in data can make analysis of summer values difficult and therefore, deviations from the norm may be due to this lack of data. Similarly, as seen in Figure 33, the overall monthly average relative humidity values are similar across the years but again there is a large gap in data from September to November which will skew analysis.

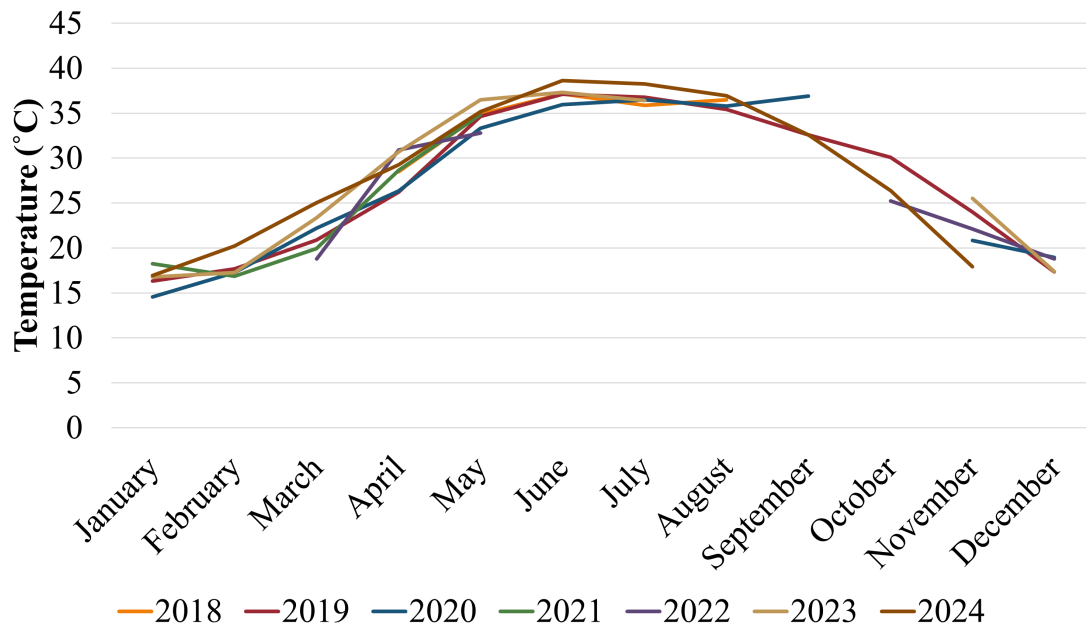


Figure 32: Libelium weather station data from KV42, showing the monthly mean temperature from 2018 to 2024

4.1 Correlation and Relative Error

To more closely examine the differences in weather patterns between KV42 and Luxor, particularly in their diurnal cycles, the two time series are plotted together (see Figures 34, 35, 38, 39) for each season, using the longest continuous data periods available without gaps. For further analysis, the correlation and average relative error between KV42 and Luxor is plotted in Figures 36, 40, 37 and 41.

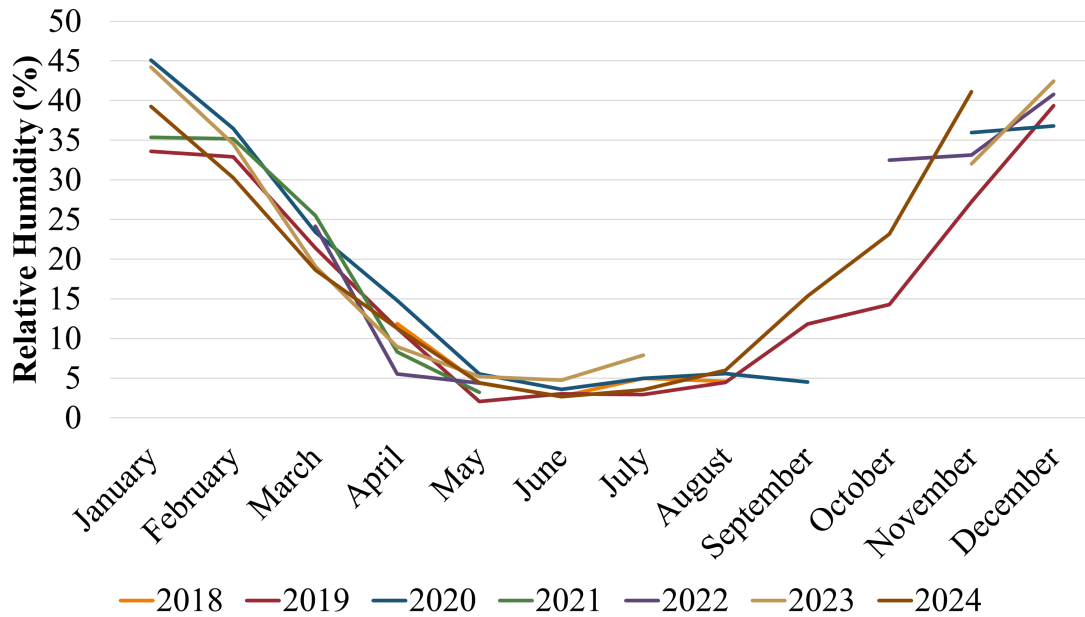


Figure 33: Libelium weather station data from KV42, showing the monthly mean relative humidity from 2018 to 2024

4.1.1 Temperature Correlation and Relative Error

In Figure 34, it is clear that typically during winter, Luxor has a greater diurnal temperature cycle but the two diurnal cycles do not vary significantly. It seems that minimum temperatures at Luxor are cooler than that at KV42. During summer, as seen in Figure 35, the temperatures appear to be typically closer to each in value in comparison to winter. The main reason for this appears to be that the minimum temperatures between the two sites do not vary as greatly. Overall for both seasons, the peaks and troughs between the two seasons resemble each other.

For temperatures during April, as seen in Figure 36, the correlation between the two sites decreases rapidly after 2021 going from a high positive correlation and a low average relative error to a low magnitude negative correlation and high average relative error. During May, presented in Figure 37, the correlation and relative error graph is very similar to that of April. The main differences between the two is that the peak relative error is slightly lower and the magnitude of the negative correlation is slightly higher.

4.1.2 Relative Humidity Correlation and Relative Error

In terms of relative humidity it is clearly evident that Luxor has a more humid climate than KV42 throughout the year. In Figure 38, Luxor's relative humidity during the winter fluctuates with a greater magnitude than KV42 but the diurnal trend in terms of peak and trough positioning are similar. In contrast, during the summer (Figure 39), the relative humidity difference between the two locations is significant since KV42 is below 10% relative humidity.

Similar to temperature, for relative humidity during April (Figure 40), the correlation between the two

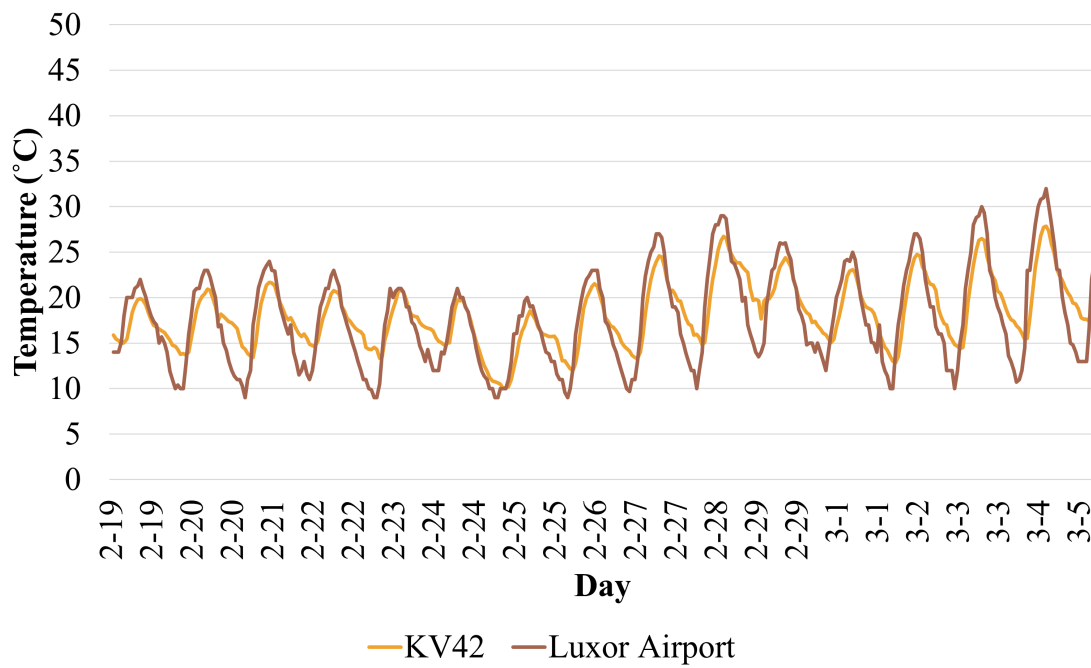


Figure 34: Temperature time series for Winter 2020 from KV42 (Libelium weather station) and Luxor airport weather station

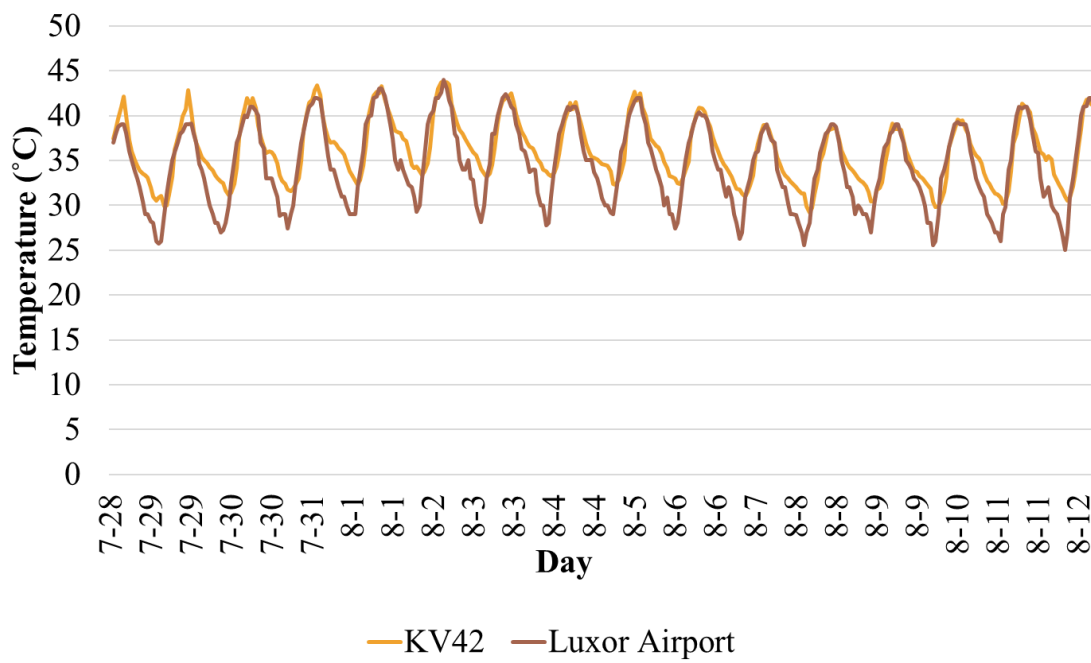


Figure 35: Temperature time series for Summer 2020 from KV42 (Libelium weather station) and Luxor airport weather station

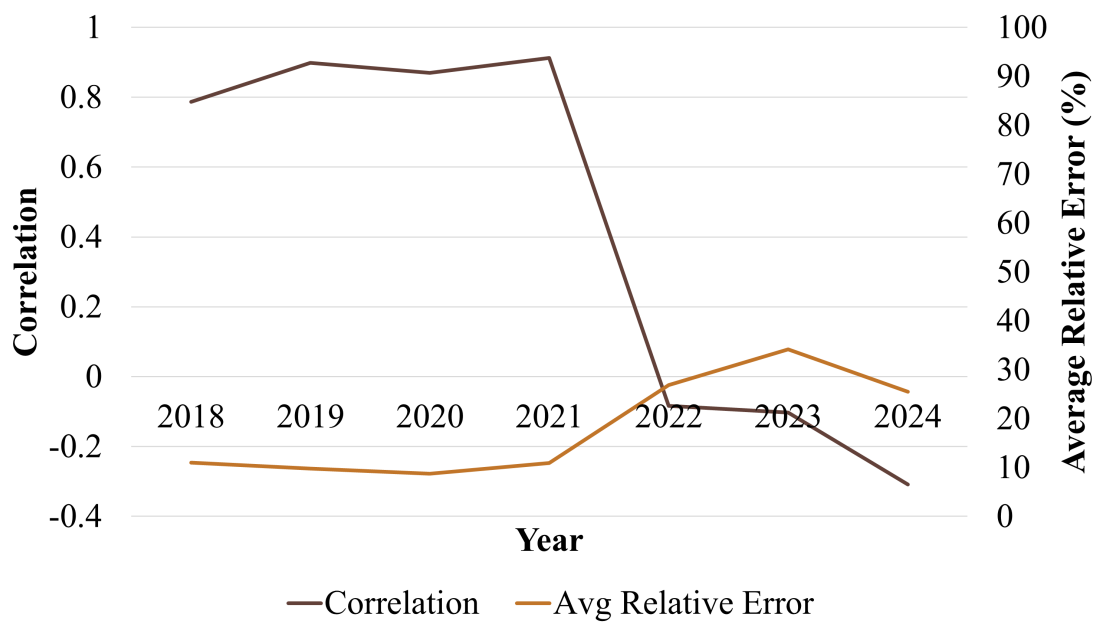


Figure 36: KV42 (Libelium weather station) versus Luxor airport weather station April temperature data: correlation and average relative error, 2018–2024

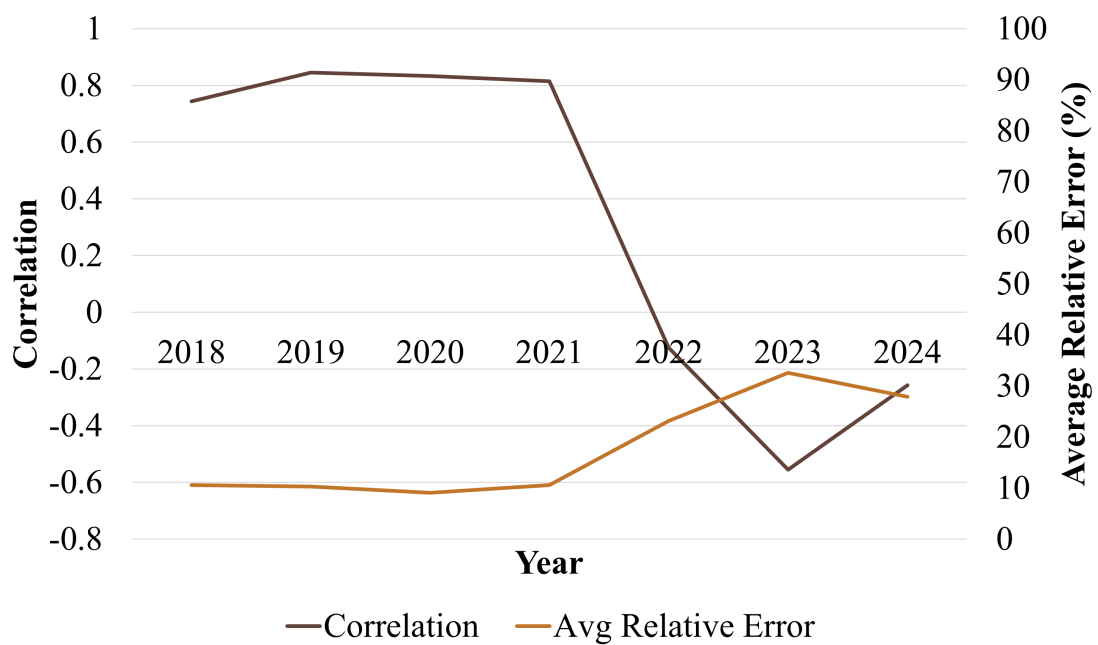


Figure 37: KV42 (Libelium weather station) versus Luxor airport weather station May temperature data: correlation and average relative error, 2018–2024

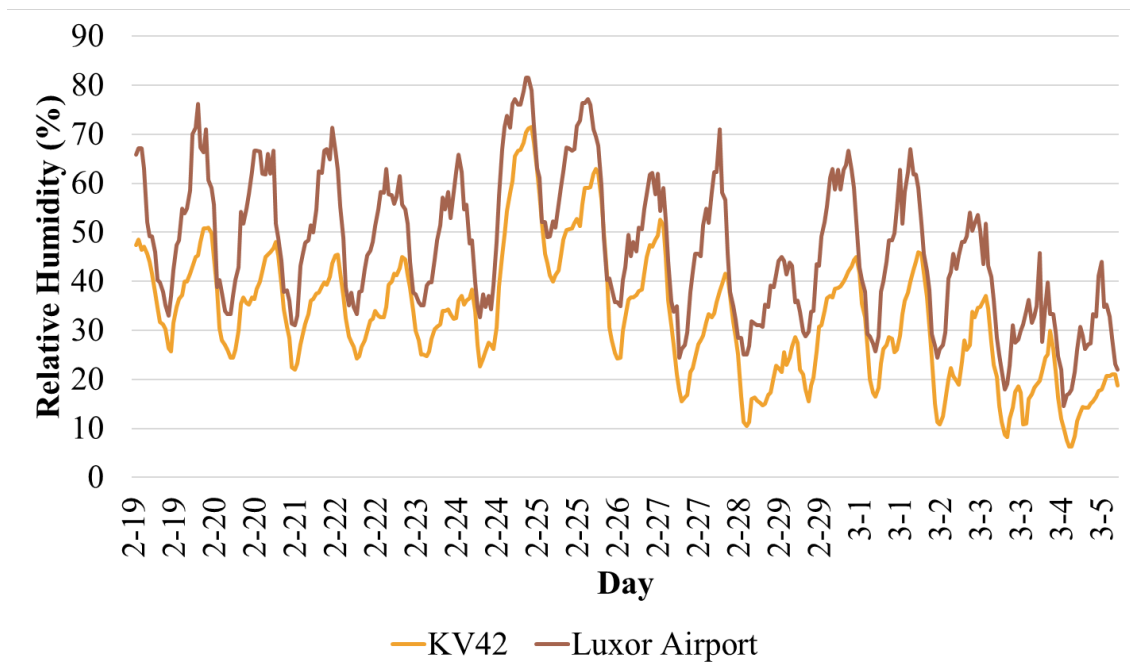


Figure 38: Relative Humidity time series for Winter 2020 from KV42 (Libelium weather station) and Luxor airport weather station

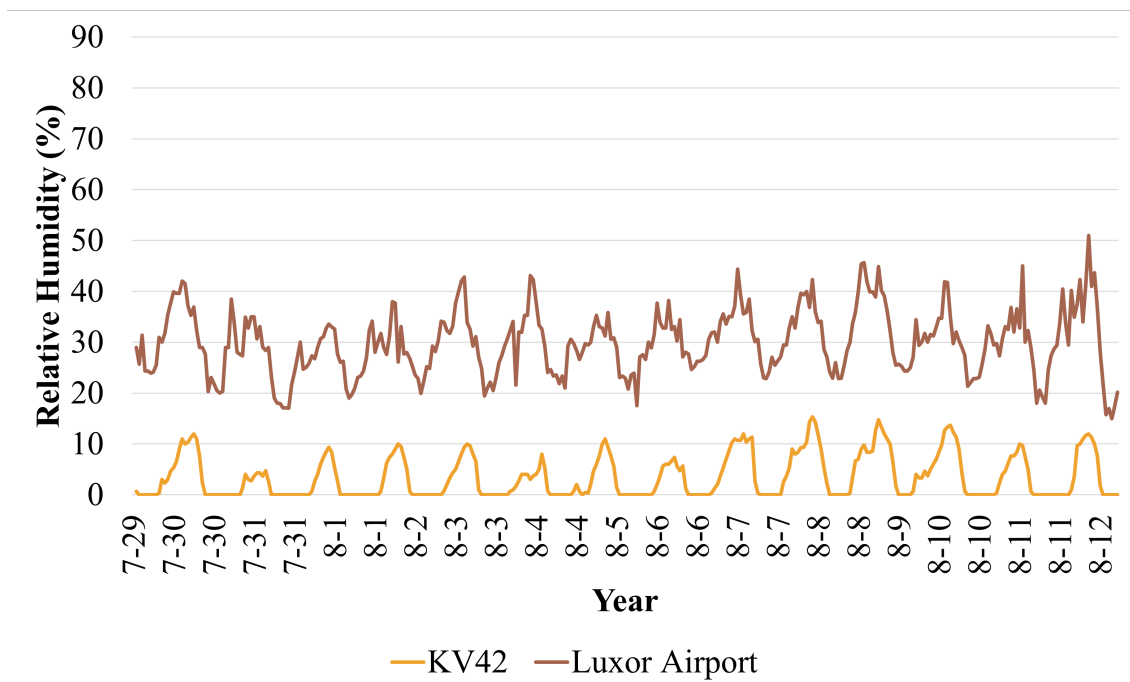


Figure 39: Relative Humidity time series for Summer 2019 from KV42 (Libelium weather station) and Luxor airport weather station

sites also rapidly drops after 2021, then slightly increases between 2022 and 2023 then drops to a low magnitude negative correlation. As well, there appears to small fluctuations between the maximum relative error in 2022 of approximately 70% to a minimum relative error of approximately 61% in 2024. This information provides some insights on the difference in relative humidity between the two sites not significantly changing over the years but the correlation has continued to decrease significantly over time. Similar to temperature, during May (Figure 40)), the relative humidity relationship analysis is very similar to that of April. The magnitude of the negative correlation slightly decreases from 2023 to 2024 and the value of the average relative error is greater ranging from around 75 to 90%.

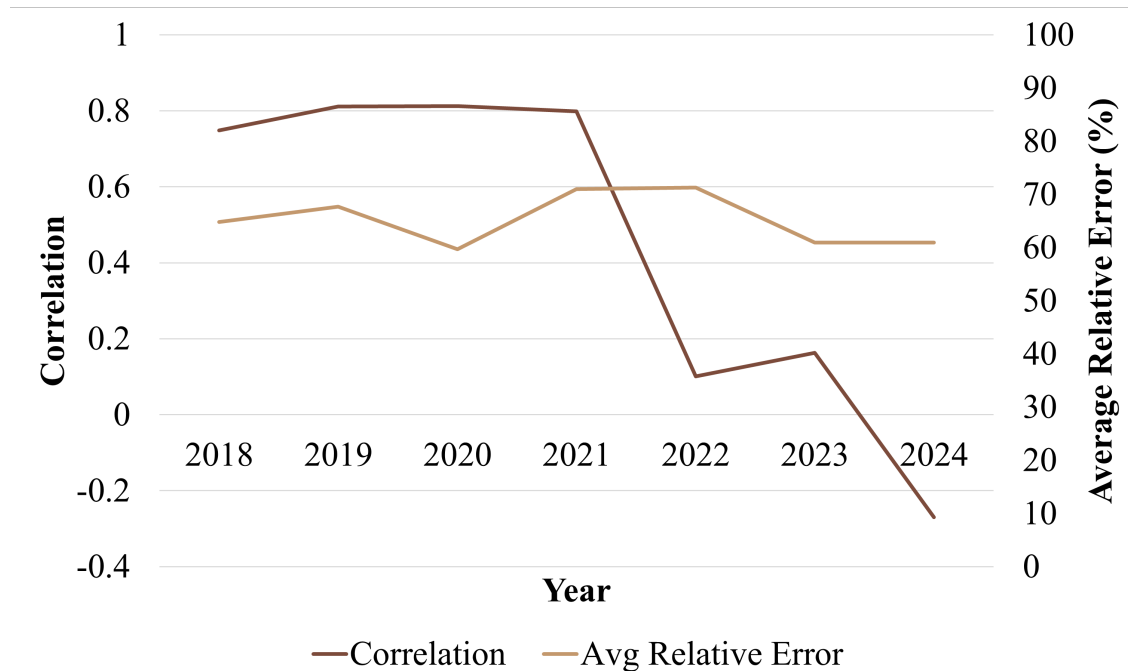


Figure 40: KV42 (Libelium weather station) versus Luxor airport weather station April relative humidity data: correlation and average relative error, 2018–2024

4.2 Temperature and Relative Humidity Hourly Comparisons

To get a better understanding of the direct hourly relationship between KV42 and Luxor during April and May, it is important to study the average differences on an hourly scale to identify variations in the diurnal cycle. There is a greater average difference between the two locations in relative humidity in comparison to average temperature as evident in Figures 42 and 44. The difference in temperature is very similar overall for both April and May, however it is important to note that for the years 2023 and 2024 there is a slightly greater difference for May than for April. The average difference between the two locations is greater across all years during May than in April. The average difference between the two months has an approximate range between 1 to 5%.

Another way to study the hourly difference between the two locations is to analyze their average diurnal cycles. In Figures 43 and 45, the average value for that particular hour across the years 2018 to 2024 from

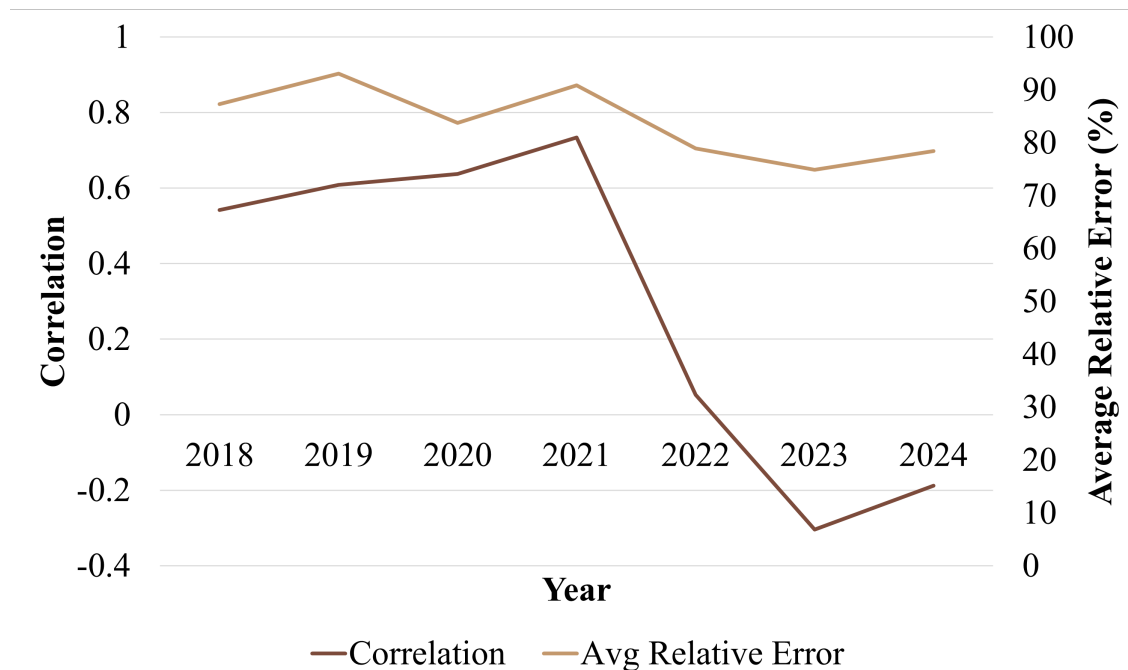


Figure 41: KV42 (Libelium weather station) versus Luxor airport weather station May relative humidity data: correlation and average relative error, 2018–2024

April to May is taken.

4.2.1 Temperature Hourly Comparison

In terms of temperature, the diurnal cycle at KV42 appears to have a lower amplitude and variance. Therefore, it is clear that the temperature cycle at Luxor has a greater net temperature variation during the daily period. As well from Figure 43, the average daily maximum is around 9 to 10 am at KV42, whereas the average daily maximum is around 1 to 2 pm at Luxor. Similarly, the average daily minimum is around 9 pm at KV42 and around 4 am at Luxor.

4.2.2 Relative Humidity Hourly Comparison

In terms of relative humidity, the diurnal cycle variation is greater at Luxor than at KV42. For the most part KV42 is dry, reaching a relative peak during night hours with a maximum around 9 to 10 pm and a relative trough during morning hours with a minimum around 8 to 9 am. In contrast, at Luxor, the peak in relative humidity is during the morning with the peak around 4 am and a trough during afternoon hours with a minimum around 1 to 2 PM. These findings provide some insight on how on a day to day basis, Luxor and KV42 on average vary between each other, allowing an understanding of why there may be variations in overall averages. As well, the above hourly comparisons provide information on how accurately Luxor's data can be a supplement for missing data at KV42 and if the change in climatic variables at Luxor can be used as an approximation at KV42.

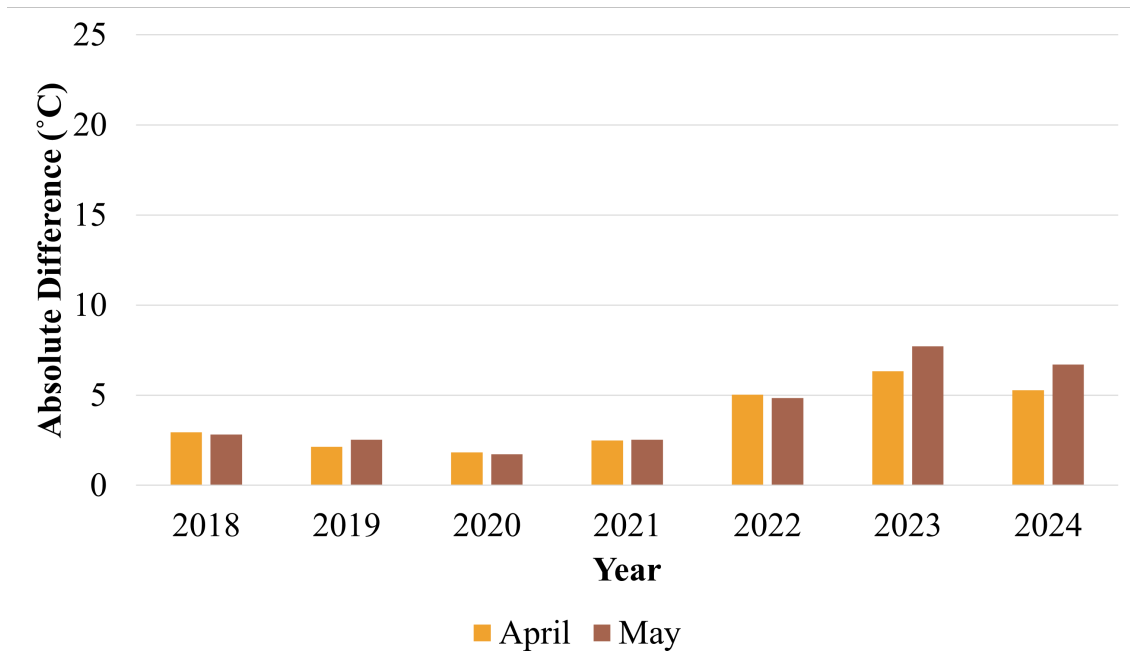


Figure 42: KV42 (Libelium weather station) versus Luxor Airport weather station: differences of monthly temperature averages computed from hourly data for April and May, 2018 to 2024

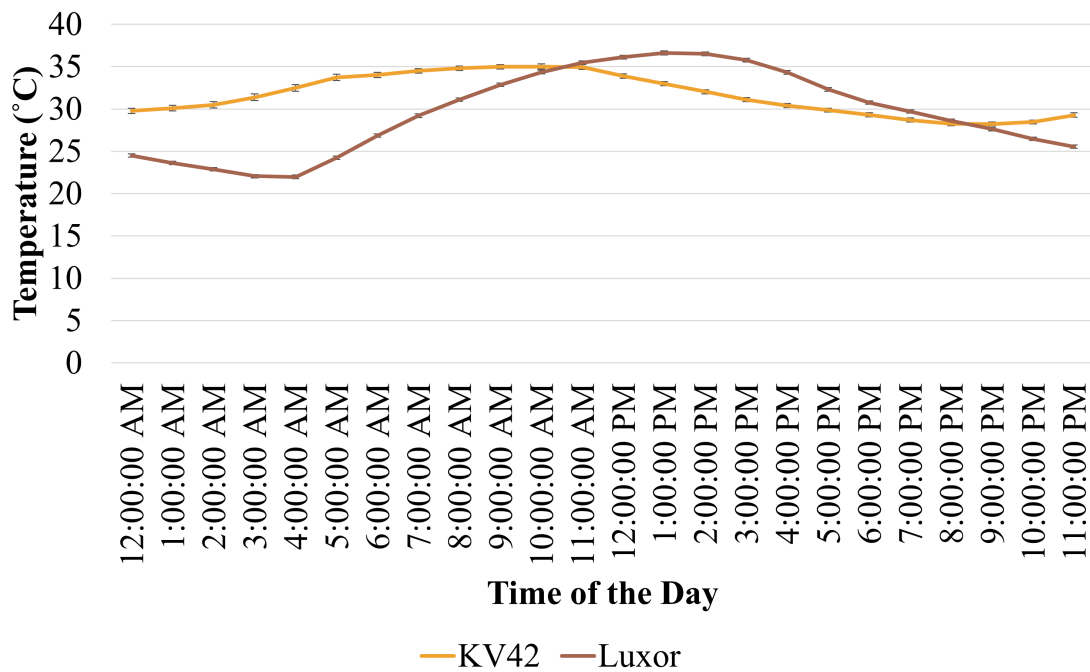


Figure 43: KV42 (Libelium weather station) versus Luxor Airport weather station: April–May hourly average temperatures, 2018 to 2024

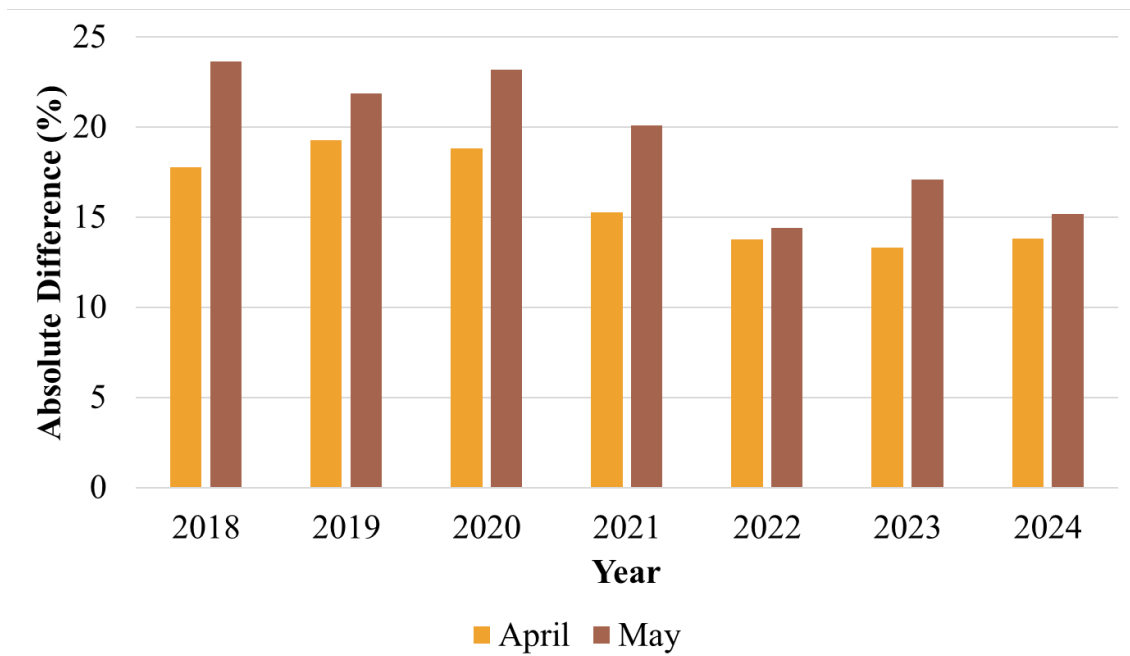


Figure 44: KV42 (Libelium weather station) versus Luxor Airport weather station: differences of monthly relative humidity averages computed from hourly data for April and May, 2018 to 2024

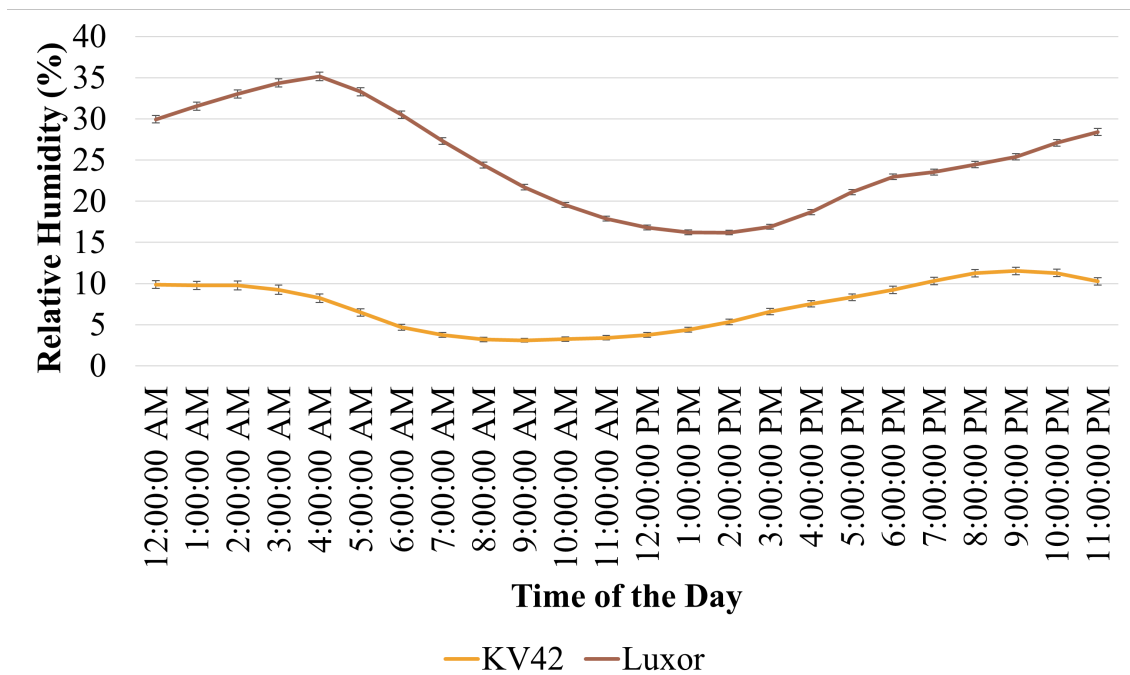


Figure 45: KV42 (Libelium weather station) versus Luxor Airport weather station: April–May hourly average relative humidity, 2018 to 2024

4.3 Temperature and Relative Humidity Trend Comparisons

Figures 46 and 48 show that the average April and May temperatures for each available year where Luxor has a temporal range from 1984 to 2024 and KV42 has a temporal range from 1984 to 2024. From there a linear trend can be calculated based off of these April and May averages for each year.

4.3.1 Temperature Trend Comparison

In Figure 46, the annual trend during May is greater than that during April for Luxor. As well, May is the warmer month and Luxor's May temperatures are increasing at a rate greater than that of April temperatures. The annual increase in temperature per decade is greater than the temperature trends at both April and May. To put these numbers into perspective, the current global annual temperature increase per year is around 0.20 degrees Celcius per decade based on NOAA's global climate report ([49]), This represents only 38% of the annual temperature increase, 45% of the May increase and 53% of the April temperature increase in Luxor. Therefore, temperatures in Luxor are increasing at a rate greater than the global average. It should be noted that the error margins for the April and May temperature trend are significant, however even on the lower side, the trend for both months in Luxor is greater than the average global annual trend.

In relation to KV42, there is not enough of a temporal range to infer a trend over a decade. However, comparisons between Luxor and KV42 temperature averages were done to understand if there is a similar pattern between the two to ultimately see if the trends at Luxor can be used to estimate the trends at KV42. For temperature, in Figure 46, although KV42's May average temperatures are warmer than Luxor, the peaks and troughs seem to align closely. Meanwhile, KV42's April average temperatures are also warmer than Luxor but average temperatures during 2021 to 2022 overlap with Luxor May temperatures. From years 2018 to 2020, it is clear that the patterns closely resemble each other when relating to Luxor and KV42's respective April and May average temperatures. However, the pattern changes where KV42 begins to deviate in 2021.

Figure 47 presents the hottest and coldest day value from April to May for each year, Luxor (1984 to 2024) and KV42 (2018 to 2024). The Luxor area will see the hottest and coldest day increase in temperature over time. It should be noted that the trend uncertainty is greater for the trend for the hottest day values than the trend for coldest day values. In terms of KV42 following Luxor max and min temperature patterns, the coldest day value for Luxor and KV42 follow very closely where the only differing factor is that KV42 has slightly warmer coldest days in comparison to Luxor. Notably, despite the data connectivity issues at KV42 beginning in 2021, the coldest day values at KV42 and Luxor Airport continue to correlate strongly. This relationship suggests that even with reduced sample sizes, the cold temperature patterns remain similar across both locations. In contrast, the hottest day value patterns of Luxor and KV42 do not align. For the most part, KV42's hottest day values are warmer than that at Luxor except in 2021.

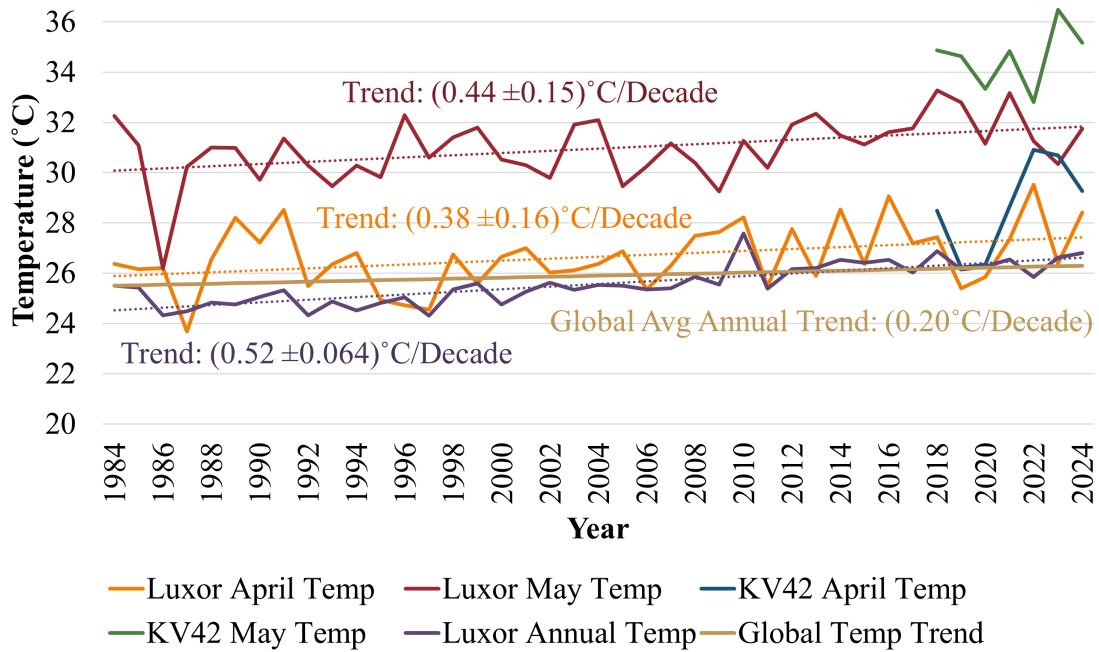


Figure 46: KV42 (Libelium weather station) and Luxor Airport weather station: April–May average temperatures compared with the global annual rate of temperature change [49]

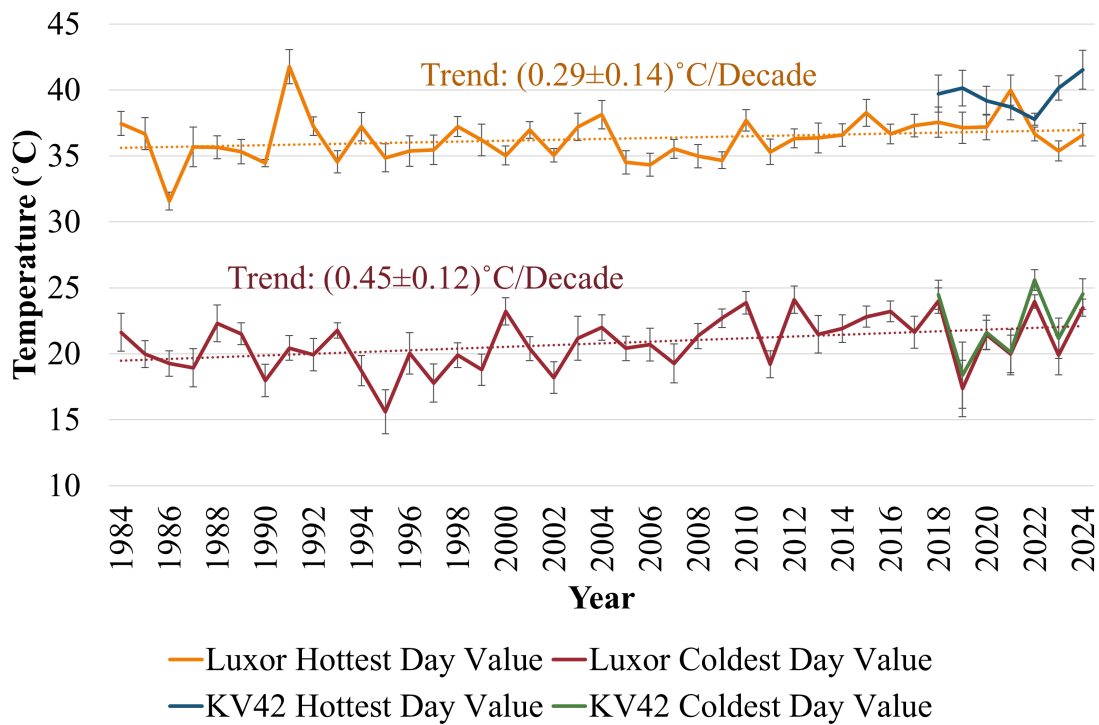


Figure 47: KV42 (Libelium weather station) versus Luxor Airport weather station: hottest and coolest April-May daily values

4.3.2 Relative Humidity Trend Comparison

In Figure 48, the annual, May and April relative humidity trend for Luxor is the same. In other words, there is the same decrease in relative humidity per decade during April, May and annually. It should be noted that in order of error margins, the annual trend has the lowest and April has the highest.

In terms of relative humidity, KV42's April averages follow a similar pattern to Luxor's May averages. In contrast, KV42's May averages does not follow any of the Luxor average patterns.

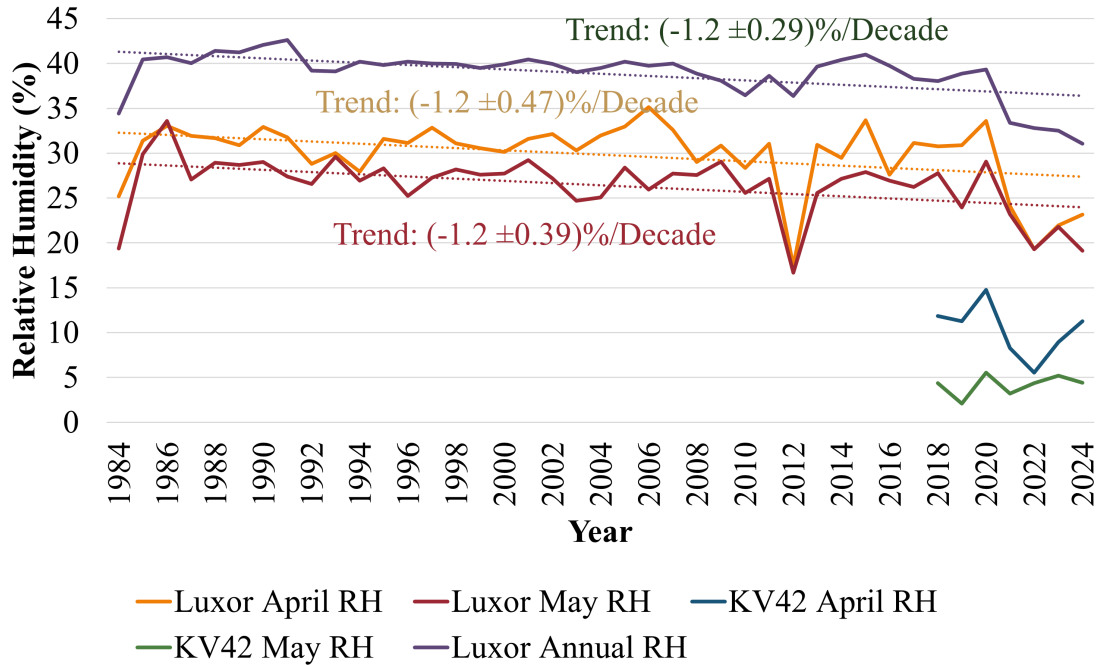


Figure 48: KV42 (Libelium weather station) versus Luxor Airport weather station: April-May relative humidity averages.

Figure 49 presents the most humid and least humid day value from April to May for each year. Both the most humid and least humid days in Luxor are decreasing in relative humidity over time. In terms of KV42 following Luxor maximum and minimum relative humidity, the most humid day value for KV42 is closer in value to the least humid day value in Luxor and does not seem to follow a close resemblance to each other in terms of peaks and troughs. The least humid day values for KV42 are practically zero. Overall, highlighting how dry KV42 is.

4.3.3 Max/Min Temperature and Relative Humidity Luxor Error Bars

To calculate the error bars for Figures 47 and 49, the period from the start of April to the end of May is divided into 6 intervals, around a week and a half for each interval. For each interval, the maximum and minimum values of temperature and relative humidity are recorded, providing 6 data points for each extreme. The standard error is then calculated to assess the variability of these extremes relative to their

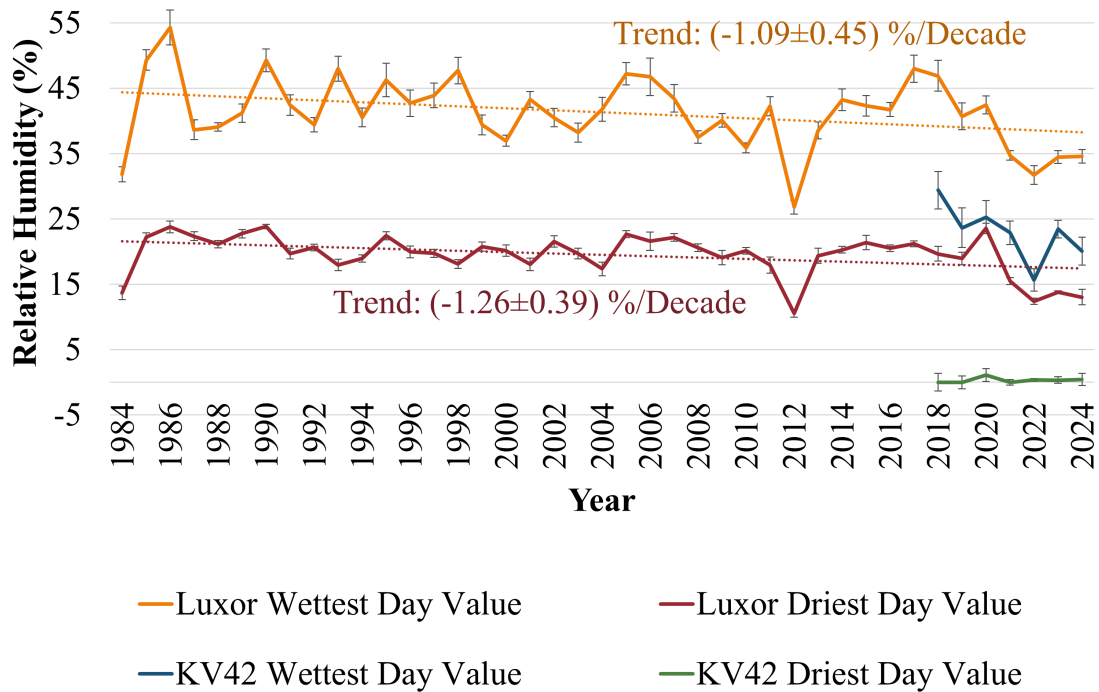


Figure 49: KV42 (Libelium weather station) versus Luxor Airport weather station: most humid and least humid April–May daily values

respective averages.

4.4 Detailed Relative Humidity Comparisons

In the above Figures it is clear that there is a better relationship between Luxor and KV42's temperature than relative humidity. Since it is known that KV42 is less humid, perhaps a formula could be found to estimate KV42's relative humidity from Luxor's. This is done through plotting the relationship between the two locations with KV42 relative humidity on the y-axis and Luxor on the x-axis as seen in Figures 50, 51, 52a and 52b. Only overlapping data periods, when both Luxor and KV42 have recorded values, are considered in this analysis. After plotting, the R-squared, also known as the coefficient of determination, is calculated. The R-squared is a statistical measure that defines the relation between the independent variable and the dependent variable [50]. The R-squared value can range from 0 to 1 where a value 0 suggests that the independent variable has no relation to the dependent variable and a value of 1 suggests that the dependent variable is entirely determined by the independent variable [50].

Figure 50 presents the relationship between the two locations for all relative humidity data between 2018 to 2024. The results show an R-squared of 0.4905 suggesting a weak relationship between the two locations' relative humidity when looking at the entirety of data.

To gather a better understanding of the relationship the entirety of the dataset was broken down into

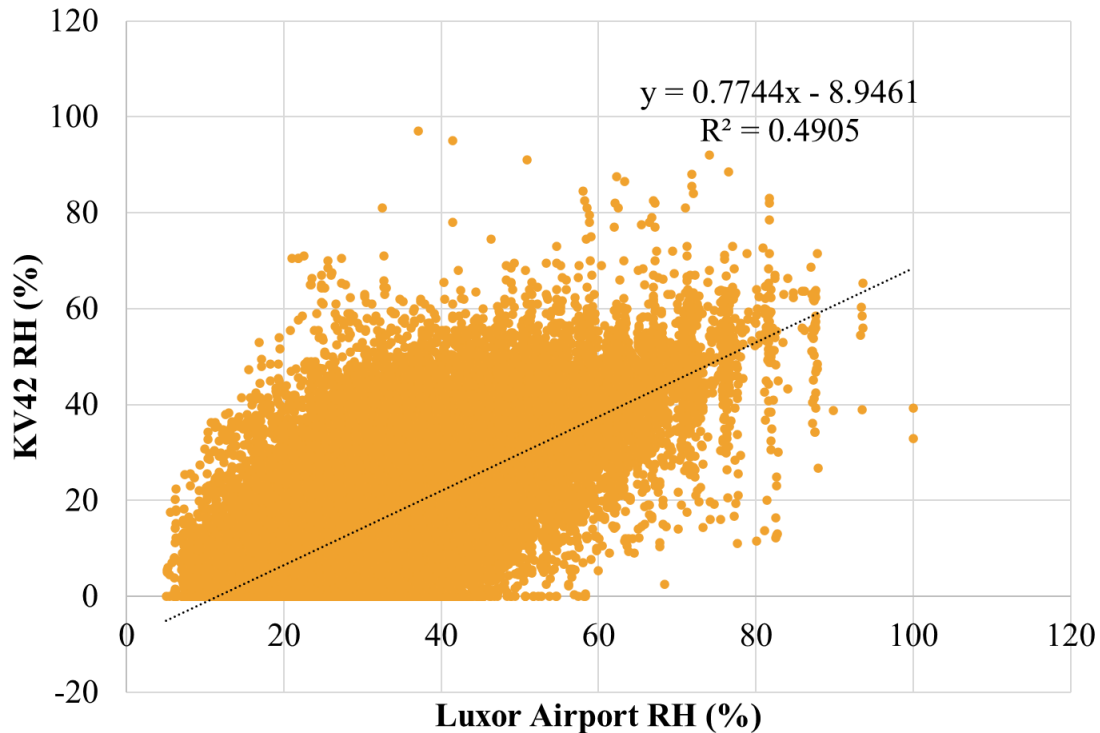


Figure 50: “KV42 (Libelium weather station) versus Luxor Airport weather station: annual relative humidity relationship, 2018–2024

smaller components. As mentioned previously, before the data issues presented themselves in 2019, 2020 and 2021 were the years that presented the best correlation and reduced relative error between the two sites. Therefore, Figure 51 presents all available data from 2019 to 2020. The results show a relatively stronger relationship with an R-squared of 0.7562 between the two locations’ relative humidity. Perhaps suggesting that with sufficient and accurate data, estimations can be made on KV42’s relative humidity based on Luxor’s relative humidity data.

To understand if there is a seasonal component to the relative humidity relationship between the two locations, Figure 52 are presented. When comparing the two figures a) and b), it is clear that both prove a weak relationship in relative humidity between the two stations. But it is important to note that the winter season has a far larger R-squared (a 0.4606 during winter and a 0.1924 during summer), indicting a better relative humidity relationship between the two locations during winter than summer. As well, the summer season has a very weak relative humidity relationship at an R-squared of 0.1924 providing insight that relative humidity is not correlated during the warmest months.

Analysis was also done to inquire if there was a relationship between wind direction/speed and relative humidity. If perhaps at certain wind speeds or directions, the relative humidity will vary accordingly. However, after analysis there appeared to not be any clear results, denoting that there lacks a relationship between the two variables. For evidence of said lack of results, view Figures A-1, A-2, A-3 and A-4 in the Appendix.

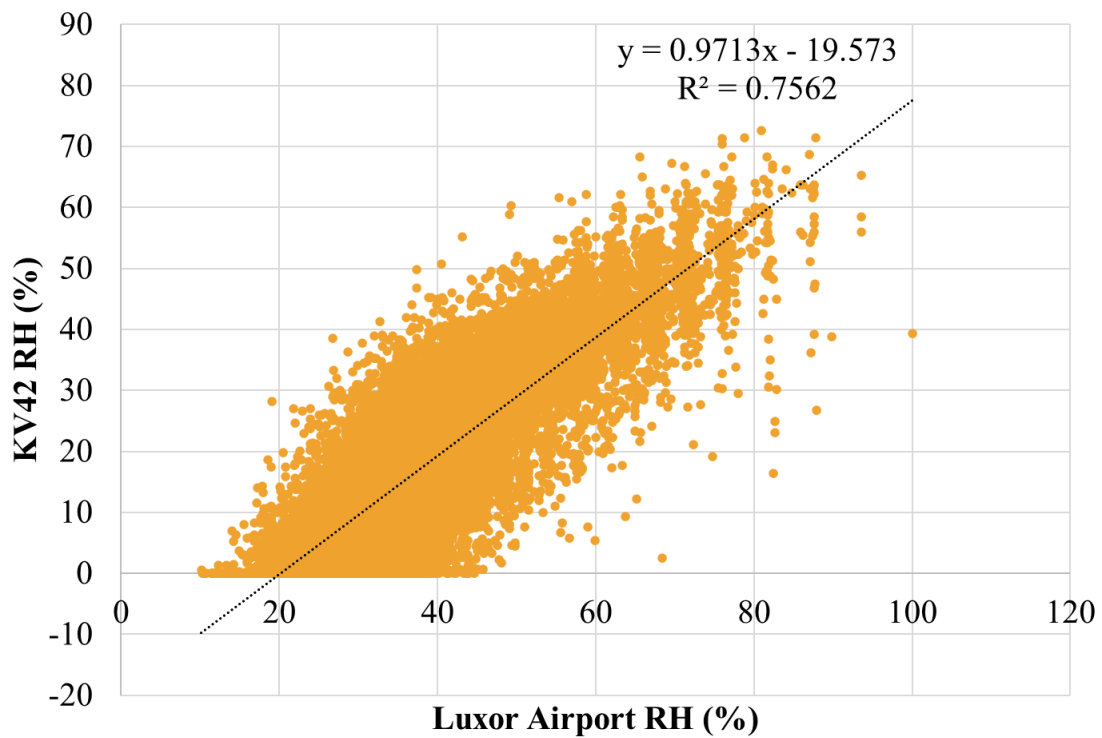
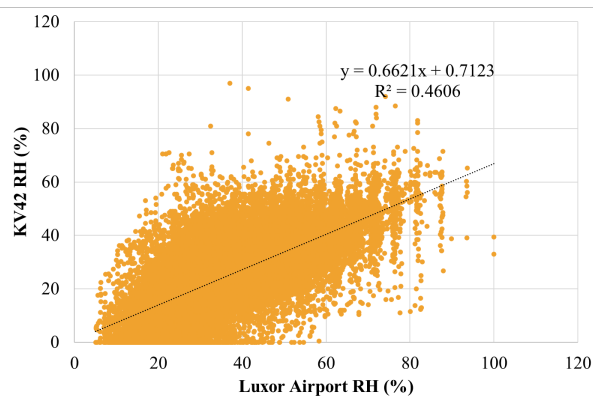
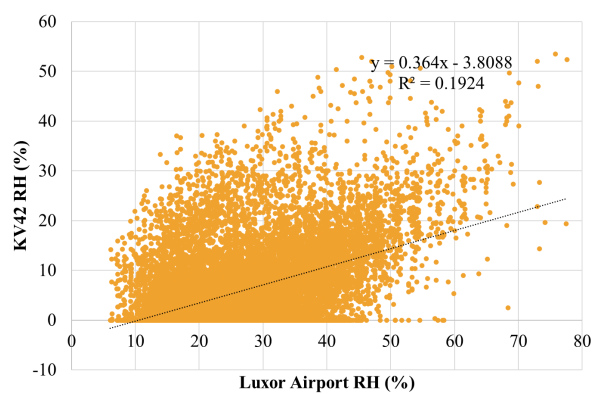


Figure 51: KV42 (Libelium weather station) versus Luxor Airport weather station: annual relative humidity relationship, 2019-2020



(a) KV42 (Libelium weather station) versus Luxor Airport weather station: Winter relative humidity relationship, 2018 to 2024



(b) KV42 (Libelium weather station) versus Luxor Airport weather station: Summer relative humidity relationship, 2018-2024

Figure 52: Winter and summer relative humidity relationships between Luxor airport and KV42

4.5 Summary of KV42 and Luxor Climate Comparisons

The comparative analyses between KV42 and Luxor demonstrates both the strengths and limitations of using regional weather station data to approximate local micro-climatic conditions. General temperature comparisons show strong correlations, with Luxor reliably capturing the temperature portion of the climatology experienced at KV42. However, there are differences on the small-scale temperature variations such as the time of peak daytime heating which indicates that local topography influences hourly temperature values.

In comparison to temperature, relative humidity comparisons reveal a greater divergence. KV42 frequently records lower relative humidity values, especially during the least humid months. This discrepancy is likely driven by the site's location, surrounded by large cliffs where the airflow and rock-surface heating differs from Luxor airport's environment.

Overall, the results indicate that Luxor's airport data provides a useful foundation for understanding climate trends in the surrounding area, but they cannot fully substitute for site-specific measurements when assessing for climate change driven deterioration. To perhaps understand this relationship further, these insights lead into a deeper examination of TT95's interior climate presented in the next chapter.

5 TT95 Interior Climate Variation Results

Changes in temperature and relative humidity can lead to deterioration even in underground archaeological locations. An article by Xia et al, highlights this phenomenon through a detailed study of the Qinling and Shunling tombs of the Southern Tang Dynasty [51]. Their long-term monitoring revealed that micro-climatic fluctuations, in particular vertical stratification in relative humidity and variance in temperature fluctuations depending on the positioning within the tomb (entrance versus the back) lead to rock deterioration [51]. The main contributor to deviations such as salt efflorescence, powdering and bio-deterioration is the airflow exchange that occurs between the interior and exterior [51]. The study used both long-term environmental monitoring and monthly short-term investigation to analyze the salt crystallization distribution and microbial growth within the two tomb locations [51]. Variation in climatic parameters can accelerate physical, chemical, biological deterioration processes which can cause irreversible damage on the tombs [51]. Thus, it is important to understand the magnitude of these variations to prevent further damages through protective measures such as microclimate control to mitigate tomb deterioration [51].

Previous analysis in this study explored how well regional climate analysis can predict localized climatic trends. This section, with the use of TT95 data will analyze how well outdoor stations can be used for underground predictions of temperature and relative humidity.

It should be noted first, that at the time of this study there was a limited amount of data. The data spans from the second half of 2022 to the first half of 2024 which can be visually seen in Figure 53. Thus, it should be taken into consideration that the following analysis is done only during this short period of time and may not accurately represent the overall relationship between KV42 and TT95 over a longer period of time.

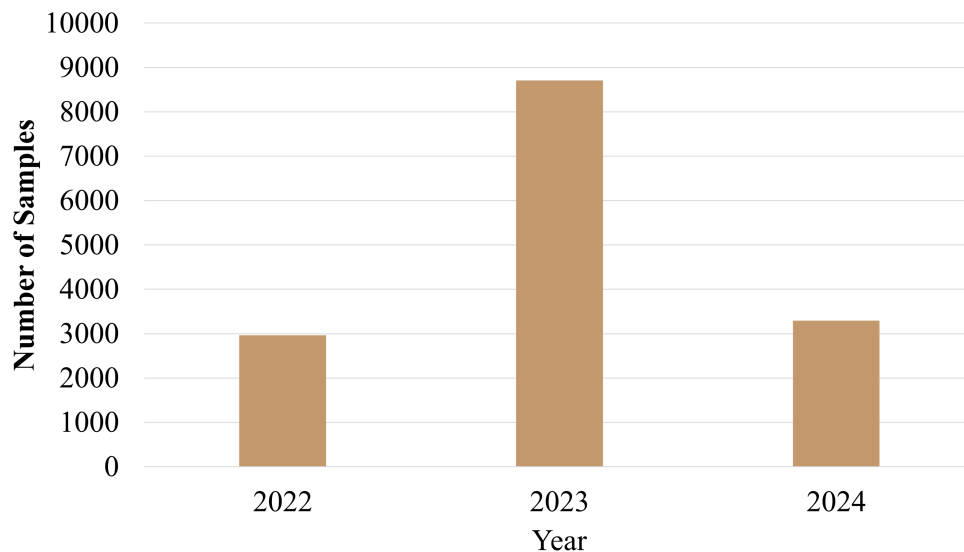


Figure 53: Number of hourly data samples for each year from 2022 to 2024 available from TT95's interior environmental monitoring station

5.1 Air Temperature Relative Error and Correlation Analysis

Figure 54 presents the relative error and correlation between KV42 and TT95 datasets, to acquire an understanding of how closely related the two sets of data are and if the data at KV42 can be used to supplement TT95. In other words, can outdoor stations be used to predict or represent data for underground stations. It should be noted that the correlation and relative error calculation is dependent on the comparison of hourly values from each station at the same hour. In this case, for temperature, the correlation between TT95 and KV42 is fairly decent ranging between 0.6 to 0.8 where the highest correlation is during 2023 with a value of 0.77. The average relative error is notable ranging from 20 to 30%. Where the average relative error is highest in 2022 and lowest in 2024.

These findings suggest that whilst outdoor stations such as KV42 could provide a reasonable approximation for temperature in a nearby underground station, TT95, caution must be taken due to the relatively high error margins. The moderate correlation suggest some relationship between the two locations and that the temperature variation at KV42 does somewhat track to those at TT95. However, the average relative error highlights that these values can diverge significantly from each other and that KV42's weather station cannot reliably represent TT95's conditions. Both external and internal factors can be the reasons for these differences such as seasonal weather patterns, changes in station maintenance and/or localized environmental conditions. From Figures 36 and 37 it is clear KV42 and Luxor have a relatively good correlation and a low average relative error from years 2018 to 2021 but this relationship decreases in strength significantly from the years 2022 to 2024. This suggests that perhaps the moderately weak relationship between KV42 and TT95 could be attributed to data collection issues at the time with both stations. Performing the correlation and average relative error analysis again but with Luxor and TT95 data provides similar results to that with KV42 and TT95 with the average correlation ranging from 0.6 to 0.7 as seen in Figure 55. The average relative error varies from 20 to 25%. These results show that TT95 has a slightly better relationship with KV42 than Luxor. The importance of the comparisons between KV42 and TT95 lies in the prospect that if subsurface temperature could be inferred from air temperature then perhaps rock temperature measurements can be collected less invasively.

5.2 Relative Humidity Relative Error and Correlation Analysis

Similar to the above temperature analysis between KV42 and TT95, Figure 56 presents the relative error and correlation between KV42 and TT95 datasets which provides insights into the relationship between the locations in terms of relative humidity. The correlation is low ranging from 0.4 to 0.5, whilst the average relative error ranged from around 30 to 60%.

This relatively weak correlation suggests that the two sites experience distinctly different local relative humidity conditions that are influenced by their own respective atmospheric conditions. The variability in the average relative humidity highlights how environmental factors such as rock moisture and wind circulation can alter the amount the allotment of moisture. The differences could also be attributed to measurement uncertainties or sensor issues in the respective Libelium systems used at each site. This large difference in

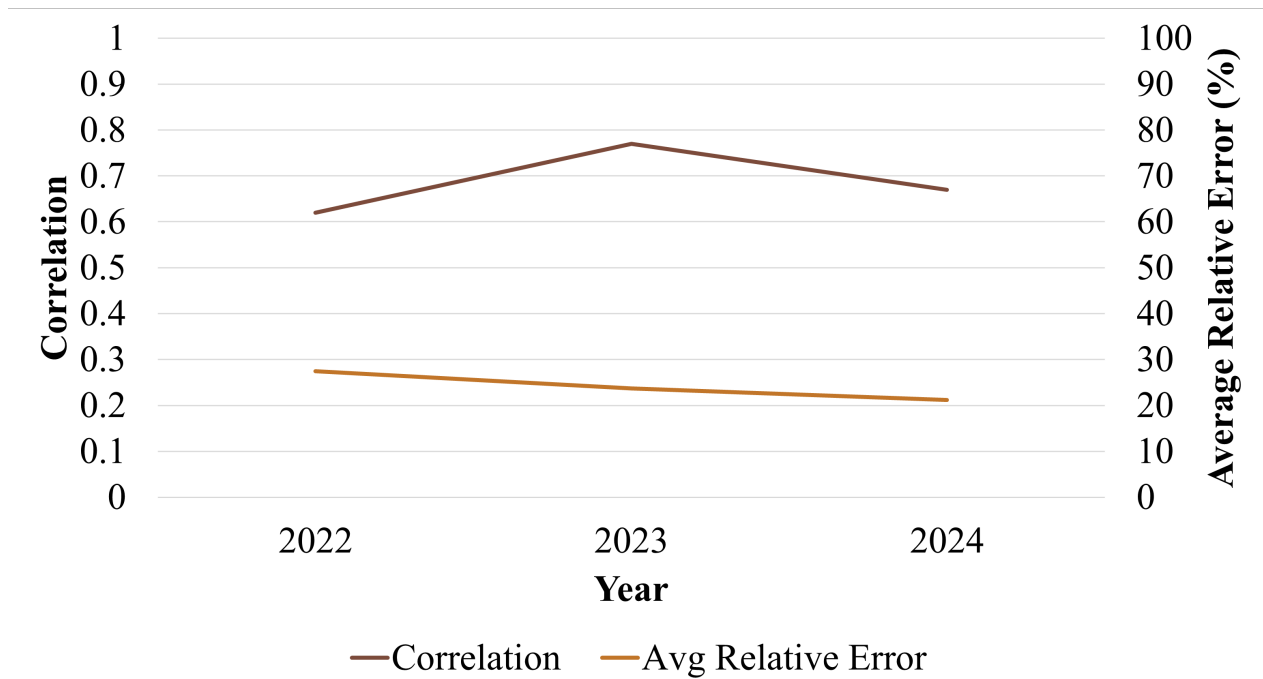


Figure 54: KV42 (Libelium weather station) versus TT95 (interior environmental monitoring station) annual temperature data correlation and average relative error, 2022-2024

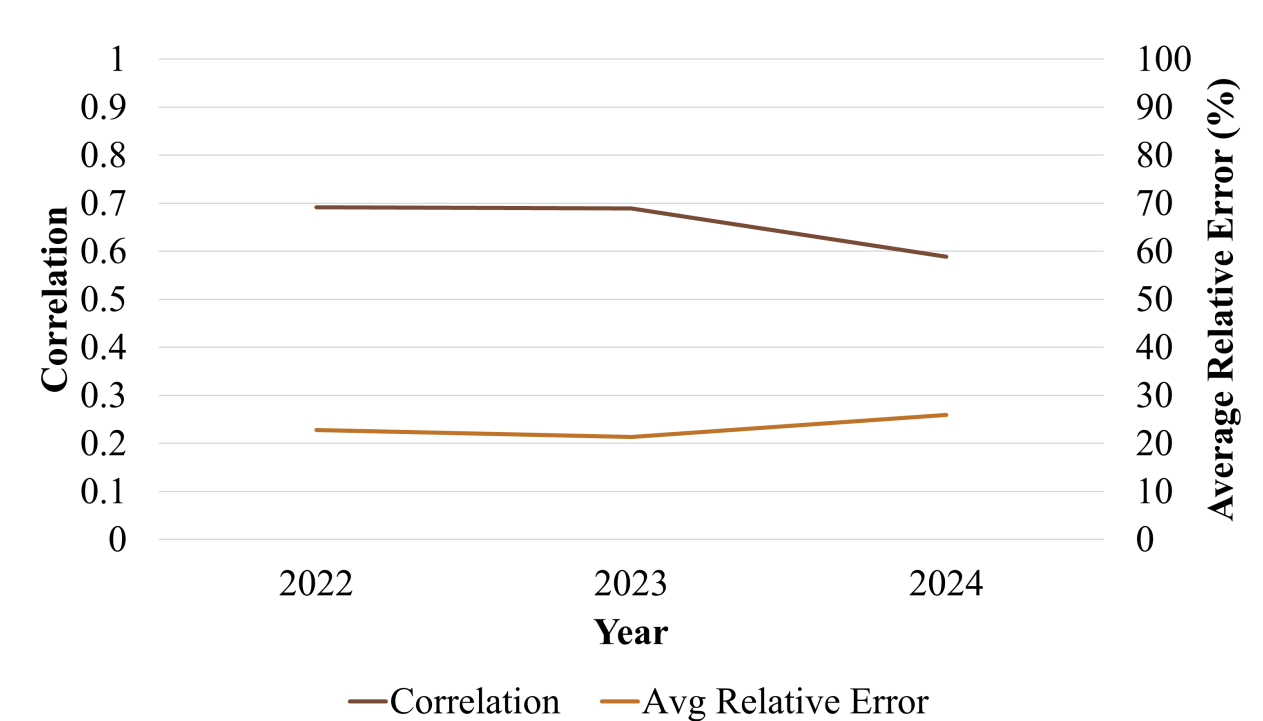


Figure 55: Luxor airport weather station versus TT95 (interior environmental monitoring station) annual temperature data correlation and average relative error, 2022-2024

relative humidity between the two sites underscores the importance of site-specific monitoring when assessing moisture related processes, since relying on outdoor stations may misrepresent underground conditions. Luxor and TT95 also showed a poor relationship, as seen in Figure 57, with each other with a correlation from 0 to 0.60 then an average relative error from 40 to 50%. Thus, it is clear that in terms of relative humidity, TT95 and KV42 have a better relationship than TT95 and Luxor.

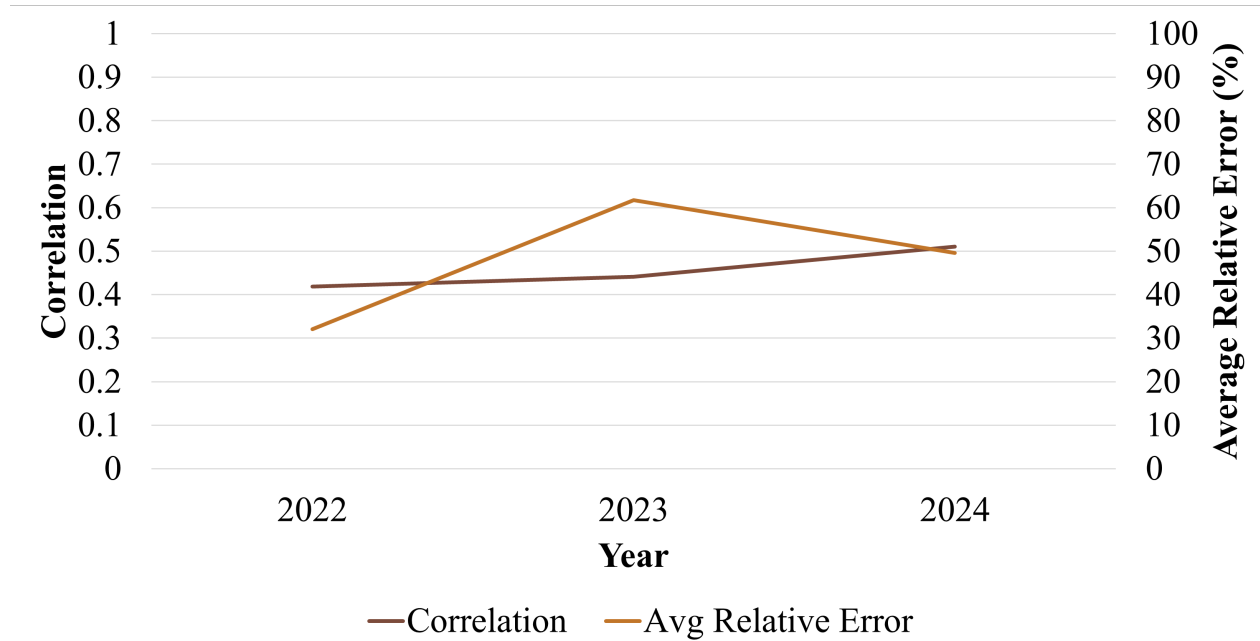


Figure 56: KV42 (Libelium weather station) versus TT95 (interior environmental monitoring station) annual relative humidity data correlation and average relative error, 2022-2024

5.3 Air Versus Rock Temperature Relative Error and Correlation Analysis

The Libelium uses the Decagon GS3 to measure rock temperature using a rock temperature sensor probe using a thermistor [32]. The rock temperature has an accuracy of $\pm 1^{\circ}\text{C}$ and is accurate within the temperature range of -40 to 60°C [32].

Understanding the relationship between air and rock temperature at an underground location such as TT95 is important in inferring how the rock within the structure relates to the internal temperature of the tomb. For example, if the air within the tomb were to warm, by how much would the rock warm as well. This relationship is explored in Figure 58, where the correlation varies from 0.90 to 1 and the average relative error varies from 1.40 to 2%. Such a strong relationship indicates that the rock temperature within TT95 responds closely to the air temperature with minuscule deviations. The air temperature can accurately predict the change in temperature of the rock, which is very significant for the conservation of the structure.

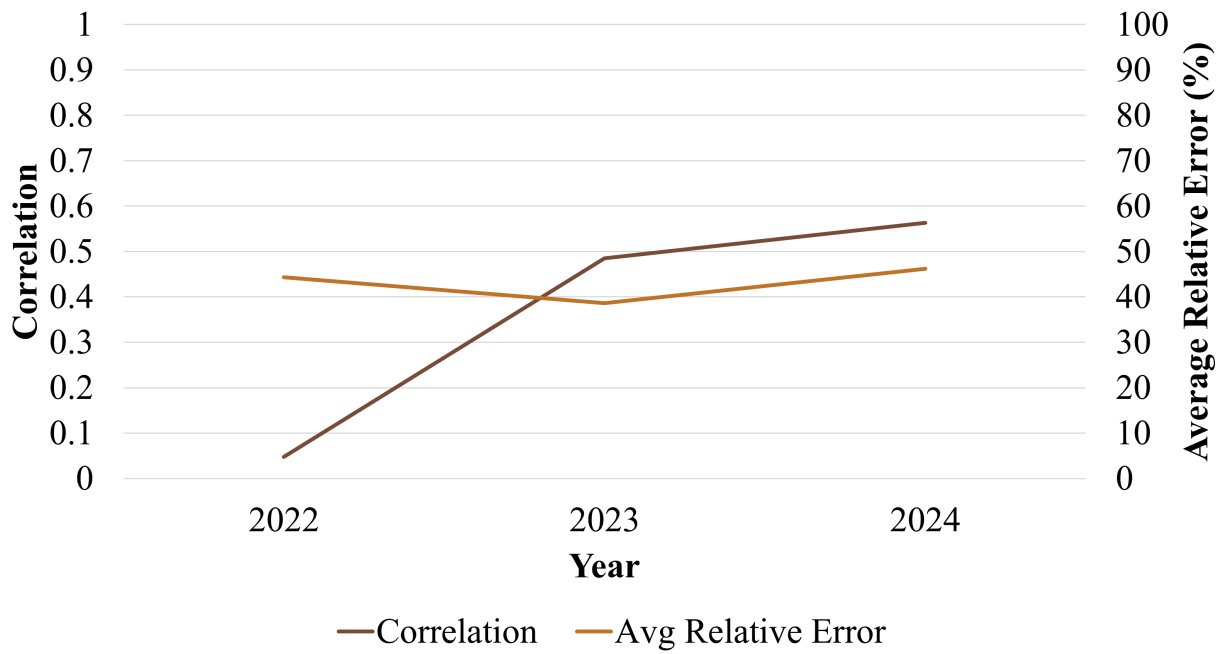


Figure 57: Luxor airport weather station versus TT95 (interior environmental monitoring station) annual relative humidity data correlation and average relative error, 2022-2024

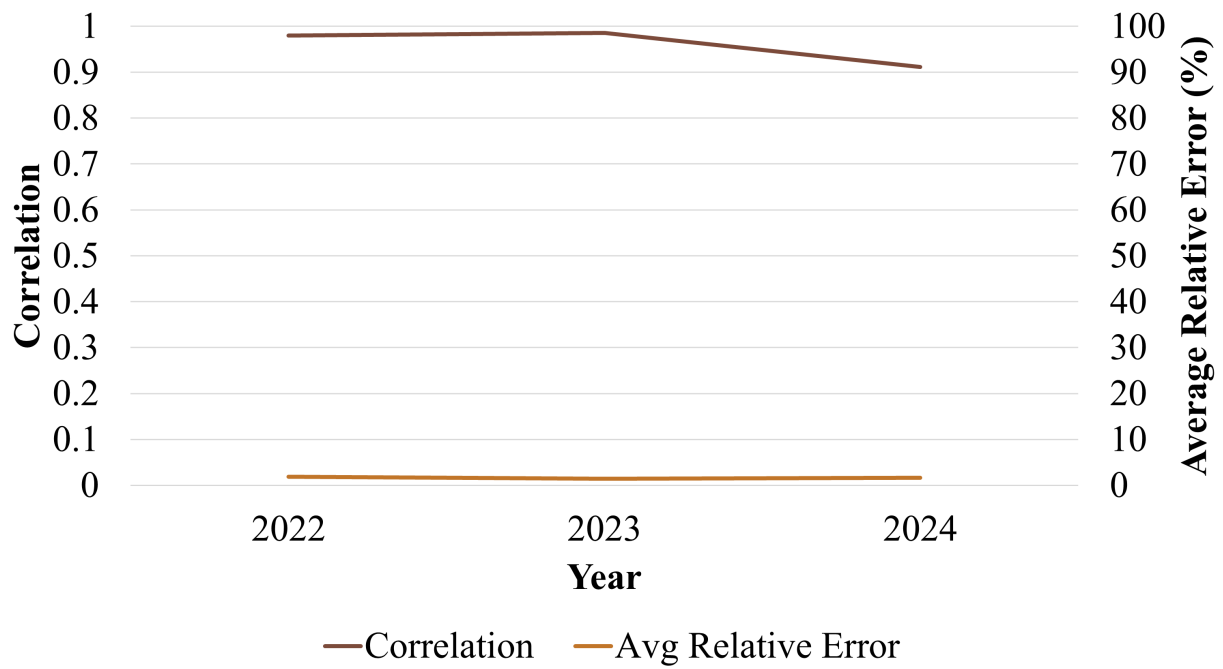


Figure 58: TT95's annual air temperature versus rock temperature data correlation and average relative error from 2022-2024

5.4 Summary of TT95 Interior Climate Findings

This section used TT95 data to evaluate how well outdoor weather stations can be used to predict underground temperature and relative humidity conditions. The comparisons show that TT95 has a closer relationship with KV42 than with Luxor. Perhaps this is because both TT95 and KV42 are influenced by similar local topography and micro-climatic variations within the Theban Necropolis. Luxor, on the other hand represents broader regional conditions and in this case, diverges from what is happening at the tomb level. However, it should be mentioned that although TT95 and KV42 have a moderately good relationship for temperature and relative humidity, the differences between the two case study locations such as external versus internal factors, highlights that the near surface measurements cannot be directly translated into conditions inside a tomb.

Overall, TT95's strong relationship between rock and air temperature highlights how climate within the tomb acts as a system where changes in air temperature can directly lead to changes in the tomb's structure. To explain further, variations in rock temperature can lead to periods of thermal expansion and contraction which can influence crack movement and overall stability. These findings highlight the limits of relying solely on regional stations for microclimate assessment, especially for underground structures such as tombs and reinforces the need for site-specific monitoring. This chapter provides an important factor to the broader discussion of this research in the next chapter.

6 Discussion

6.1 Interpretation of Temperature and Relative Humidity Rate of Change Maps

The rate of change maps, Figures 30 and 31, provide insights on the areas across Egypt that are the most affected by changes in temperature and relative humidity. As explained in section 2.1.3, changes in land use can influence climatic conditions locally. Therefore the assessment of these changes is vital in getting a grasp for the reasons as to why certain areas in Egypt are changing in climate more rapidly than others.

As seen in Figure 30, areas with the greatest temperature change across all seasons appears to be in northeastern Egypt, more specifically Cairo and Ismailia. Another area of note is Dakhla, since the area experiences a relatively greater change in temperature per decade during the first half of winter and the second half of summer. In contrast, areas with a relatively minimal rate of change in temperature such as Siwa, Baharia, Asyut and Kharga are more consistent across most or all seasons.

In terms of relative humidity, areas of decreasing relative humidity, as seen in Figure 31, are the most significant along the northern coast (Alexandria, Ismailia and Cairo) across all seasons. In contrast, the only area within the study area with increasing relative humidity across all seasons is Asyut, however, during winter months Dakhla also appears to be increasing in relative humidity over time.

To gain an understanding of perhaps why these areas are more susceptible to climatic changes, it is helpful to identify the changes in land-use over the period of 1984 to 2020. As evident in Figure 59, there are four areas that have visibly undergone significant changes from December 1984 to December 2020 within the study area.

In Area 1, Egypt's northern coast including Alexandria, Ismailia and Cairo, as better identifiable in Figure 60, a comparison of the image set reveals that the greenery visible in 1984 has expanded over time. The expansion consists primarily of rural urban development, including new residential buildings and agricultural land. In addition, circular farming patterns are visible in the 2020 image, which were absent in the 1984 image. These circular farming patterns are more commonly found in the southwest portion of Egypt. These crop circles use a form of irrigation called centre-pivot, the main purpose of this irrigation type is to conserve water [52]. Darker green circles are likely potato crops, lighter brown circles are likely wheat, medicinal, and aromatic plants, and lighter, tan-coloured circles are areas that have undergone controlled burning to clean up the plot for the next crop by removing excess plant matter [52]. Since a majority of Egypt receives minimal water, agricultural lands away from the Nile River are required to use water conserving methods [52]. In the more deserted areas, such as the southwest of Egypt, these circular farming patterns depend on the Nubian Sandstone Aquifer System which is buried under the sand and provide these agriculture patches with enough moisture to survive [52]. In the centre of the circular patterns are wells which draw up groundwater from the Nubian aquifer, which is then either sprayed or dipped out of long, rotating pipes that circulate the entire circle plot [52]. These aquifers are the only source of water for residents living here and since more than 95% of Egypt is inhabitable due to the heavily arid conditions, these aquifers are the main reason for habitation in Egypt's southwest [52].

Similar to Area 1, in Area 2 (near Farafra) and Area 3 (near Dakhla), as seen in Figures 61 and 62 respectively, a comparison of each set of images show an addition of greenery, composed of rural development. These areas of development show plots of agricultural land as well as the circular farming patterns.

Finally Area 4, as seen in 63, there is an extension of the green portion east of Daraw when comparing the set of images. This additional green portion of east is again areas of rural development and a few circular farming plots.

Across all areas and on a smaller degree other areas within the study area, there is a growth of rural development and agricultural plots. This growth is attested to Egypt's total population growth from 1984 to 2020 as seen in Figure 64. From this figure it is clear that Egypt's population has been steadily increasing where 1984 to 2020, the population had increased by 22%. The total population data was attained from the World Bank Group website ([53]) where the publisher of the data is the United Nations (UN) Population Division. The total population includes all residents within the country without the consideration of legal status and/or citizenship and the values shown in Figure 64 are taken mid-year [53].

The reason for this development is understood, but in the context of this research, the effects of the developments on climate must be analyzed. The Alexandria, Ismailia and Cairo area where there is a relatively significant amount of heating, is also the urban centre of Egypt. With continuous urban development, as evident through studies such as Halder et al (2021) and Arunab et al (2025), urbanization combined with climate change can produce urban island heat effect [54][55]. As mentioned above, Egyptian cities along the northern coast are continuing to expand, so the effects of rapid urban development became more potent [55]. From there an urban heat island can arise where urban centres will undergo increased temperatures relative to surrounding rural areas [55]. In addition, these urban heat islands are correlated with land-use changes, increased energy consumption, increased population and changes in micro-climates [55][54]. These elevated temperatures can consequently lead to accelerated drying which is confirmed through Figure 31.

Southwest of Baharia and northwest of Dakhla lies Farafra, which is the area highlighted in 61, where there was growth of rural development and circular farming patterns. The relative size of the development is minor compared to Area 1. Based on the Figures 30 and 31, Farafra is undergoing a moderate amount of warming per season and in terms of moisture, the area appears to be increasing in relative humidity slightly during the winter and moderately decreasing in relative humidity during the summer. These findings appear to be consistent with those from Zhao et al (2016), where they concluded that areas with significant agricultural development in Northeast China were undergoing localized cooling and wetting due to an increase in evapotranspiration [56]. The minor area in Farafra of rural development may be responsible for the weak influence. The slight winter increase in relative humidity could be due to irrigation and farming occurring during this time. Meanwhile, during the summer months, the effect of drying due to increasing temperatures may be greater than the rate of evapotranspiration.

Area 3, which covers the local surrounding area of Dakhla, similar to area 2, has an expansion of rural development and circular farming patterns. Relative to area 2, area 3 has a slightly large area of rural space, which helps to explain a greater amount of increasing in relative humidity during the winter months in comparison. The decreasing relative humidity during the summer in area 3 is similar to area 2. However,

the rate of temperature change is where the two areas become dissimilar. During the first half of winter and second half of summer there appears to be greater warming in area 3 than area 2. This variation in temperature may be due to differences in surrounding topography. Area 2, is surrounded by highly elevated mountainous areas which can cause winds that reach the mountain to undergo orographic lift (more detailed explanation of this process is explained in section 6.2). The air will dry and sink, which can influence the surface temperatures in the area.

Area 4, located north of Aswan, near Daraw, there is growth in rural development. It should be noted that the amount of rural development is minimal relative to other areas. Based on Figures 30 and 31, this area undergoes a moderate amount of change relative to the rest of Egypt. The reason for this is that although rural development could provide a minor amount of cooling and increasing relative humidity in the area, this effect does not overcome the heating and drying effects in the area.

Another aspect that could provide insights on the reason for increasing temperatures across a majority of Egypt, increasing carbon emissions. Incident solar radiation on the Earth's surface is either absorbed or reflected [57]. A partial portion of the absorbed radiation is remitted into the atmosphere [57]. However, greenhouse gases such as carbon dioxide, water vapour and methane absorb this radiation and subsequently re-emit leading to the warming of the Earth's surface and lower atmosphere [57]. The natural greenhouse effect is a vital component that allows for life on Earth.

However, the anthropogenic greenhouse effect also known as the enhanced greenhouse effect, began at the start of the Industrial Revolution where human activities led to a higher concentration of greenhouse gas emissions [57]. The main source of greenhouse gas emissions due to human activities is the burning of fossil fuels [57]. These excess emissions act as a blanket that insulates the Earth's atmosphere trapping heat from the sun within the atmosphere, and consequently, the Earth's surface [57].

From 2000 to 2022, Egypt has seen an 18% increase in carbon dioxide emissions due to fuel combustion [58]. This increase in emissions is linked closely to Egypt's growing energy demands. As the population increases and continuous development expansions, the amount of fossil fuels required consequently, increases. Ultimately, these increases will contribute significantly to Egypt's total contribution of carbon emissions. Egypt's main carbon emission contributor is the energy sector [58]. Power generation within Egypt relies on the burning of fossil fuels such as natural gas, coal and oil [58].

Arid areas such as Egypt, continue to be vulnerable to the effects of climate change [59]. A long-term drying over land is associated with the increase of aridity, reduction of soil moisture and a decrease in atmospheric relative humidity [59]. Areas with minimal water sources are susceptible to accelerated heating simply because the water bodies, including the ocean are unable to supply the required amount of moisture to keep consistent saturation levels across the land [59]. Another often overlooked symptom of excessive drying is the risk of weather changes. A warmer atmosphere, will absorb more water vapour and the increase in water vapour will lead to a positive feed loop since water vapour is a greenhouse gas [59]. In addition, the warmer atmosphere would be able to transport the extra absorbed moisture to storm systems in surrounding areas, which can lead to heavy rain events, dry spells and worsened flooding conditions [59].

On a separate note, changes in atmospheric temperature and humidity can also alter wind patterns which can further aggravate local drying conditions [59].

The Cultural Resources, Partnerships and Science within the Climate Change Response Program in the National US Park Service outlined the direct effects that climatic changes have on archaeological sites [60]. First, increasing temperatures across the globe can lead to accelerated thermal processes which can result in micro-cracking of the site [60]. Heritage sites that are newly exposed to environmental factors will deteriorate at a faster rate, and organic materials within these sites tend to more rapidly decay which could lead to a decrease in the site's structural integrity [60]. Secondly, an increase in relative humidity can also lead to an accelerated decay rate of organic materials and increased rate of mold growth in enclosed sites such as tombs [60]. Thirdly, heritage sites can become disturbed due to changes in seasons and land use, these changes can also lead to a reduction in site accessibility [60]. Finally, a decrease in relative humidity can cause a drying of the rock leading to a greater crack damage, these drier winds may also be more vulnerable to wind and thus, increase exposure to erosion [60].

Building upon the aforementioned impacts, the rate of change spatial maps developed in this study provide a spatial visualization of how temperature and relative humidity is changing over time across Egypt. The observed warming and decreasing relative humidity trends confirm that these threats as identified by the National US Park Service are not just theoretical but are active hazards present in regions within Egypt that are concentrated with cultural heritage sites [60]. Similar findings have been reported globally, where climate change has accelerated the deterioration of archaeological sites. A research article by Jorgen Hollesen from The National Museum of Denmark highlights how increasing temperatures can alter the rate of chemical and biological reactions leading to small changes in surrounding sediment that could increase the site's rate of degradation and corrosion [61]. This fact is important to this study since the temperature rate of change maps demonstrate that eastern portions of Egypt, such as the Luxor region and surrounding desert sites such as KV42 and TT95 experiences significant warming relative to the global average. The Middle East as a whole has been experiencing increasing temperatures since the early 1970's, where maximum temperatures have been increasing annually from 0.3 to 2.8°C and minimum temperatures have been also increasing annually from 0.4 to 2.8°C [62]. Another area with a similar arid climate to Egypt is Jordan, which has been especially experiencing increasing amounts of heatwaves [62]. Jordan is forecasted to continue experiencing an increase in temperature where the average annual temperature will be increased by 2°C by 2050 [62]. within Jordan is historical and archaeological sites located in Petra [63]. Similar to King's Valley, Petra also has deep valleys and is also susceptible to major climate-related threats such as flash floods, droughts and sandstorms [63]. A study by the Petra National Trust has recorded that Petra has undergone over-tourism, land-use changes and a lack of infrastructure maintenance which continues to threaten the lifespan of beloved archaeological monuments and sites [63].

Areas undergoing an increasing relative humidity trend such as Asyut and Dakhla will also cause harmful effects on local archaeological sites. A study by Basu et al (2021) identified how variation in moisture content can deteriorate building materials such as limestone. Although, this study is located in London, similar to Egypt, limestone is one of the more common building stones [64]. The methodology of this study

involved visual inspections of different limestone-made buildings near the University College London [64]. The inspection was used to identify cracking, flaking, scaling and detachment of the material [64] In particular, to classify surface decay, the colour, gloss and roughness was also noted [64]. The porosity of the limestone allowed for mineral swelling and consequently, moisture expansion which can lead to significant deterioration over time [64]

Overall, these spatial patterns provide the notion that it is imperative that localized climate trends are incorporated into preservation planning, as the accelerated warming and decreasing relative humidity across Egypt poses increasingly severe risks to the structural integrity of the archaeological sites across the country.



Figure 59: Satellite view of Egypt from Google Earth Pro (Dec 2020) highlighting four areas that have undergone significant changes from December 1984 to December 2020 within the study area. The 4 indicated regions are further examined in more detail in the following figures

6.2 Interpretation of Regional and Local Climate Differences

As presented in Sections 2, 3 and 4, Egypt has a spatially varying climate in terms of temperature and relative humidity. To better understand the spatial attributes that cause these variations, Egypt's elevation is



Figure 60: Satellite view of Egypt's Northern Coast near Alexandria (Area 1), from Google Earth Pro. Left: Dec 1984 and Right: Dec 2020



Figure 61: Satellite view of Egypt, specifically near Farafra (Area 2), from Google Earth Pro. Left: Dec 1984 and Right: Dec 2020



Figure 62: Satellite view of Egypt, specifically near Dakhla (Area 3), from Google Earth Pro. Left: Dec 1984 and Right: Dec 2020



Figure 63: Satellite view of Egypt, specifically near Aswan (Area 4), from Google Earth Pro. Left: Dec 1984 and Right: Dec 2020

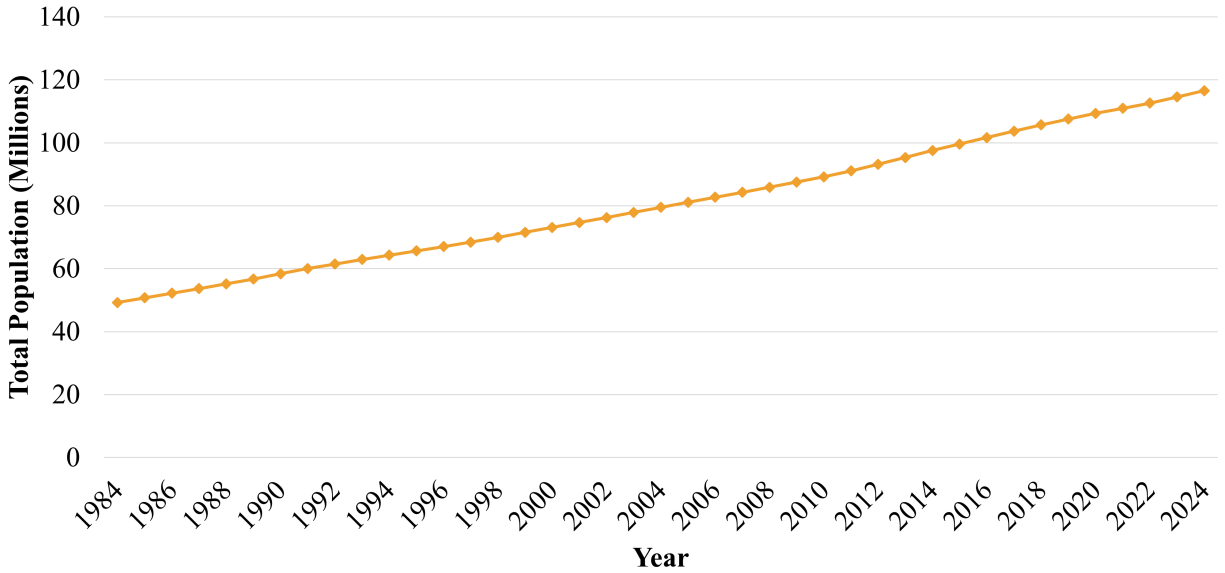


Figure 64: Total population in Egypt from 1984 to 2024. Data source: World Bank [53]

explored. The GTOPO30 digital elevation model (DEM) 30 arc-second DEM of Africa is used [65]. The GTOPO30 is a global DEM that was created by the U.S. Geological Survey's EROS Data Center [65]. The name of the DEM, GTOPO30 is derived from the fact that the resolution of the dataset is 30-arc seconds which is approximately 1 kilometer [65].

Overall, it is clear that there is a greater amount of spatial influence on relative humidity than temperature. Therefore, the elevation contours presented in Figure 66 can be compared with the relative humidity climatology maps Figures 24 to 27. Figures 24 and 25 presents the 1984 to 2024 and 2018 to 2024 relative humidity climate spatial maps, respectively. Climate wise there seems to not be a significant effect of the elevation on relative humidity when comparing to 66. In terms of the Luxor region, Figures 26 and 27 presents the relative humidity climatology from 2018 to 2024 and mentioned above there was no distinct relationship between relative humidity climatology and elevation. Mainly the trend follows that most northern areas near the coast are more humid than southern portions of Egypt.

The rate of change (per decade) in relative humidity from 1984 to 2024 is presented in Figure 31 . The main areas of interest are the anomalies in the relative humidity rate of change spatial map which is Dakhla and Asyut. Dakhla appears to be for the most part surrounded by higher elevation, where Dakhla is in a valley. In contrast, Asyut is on a higher elevation area. It should be noted that Dakhla is only increasing in relative humidity during the winter. Therefore, these contrasting topographical areas with similar increasing relative humidity signatures during the winter season suggests that perhaps elevation is not the primary contributor to the increases in relative humidity. Other reasons for the anomaly could be because of local climate, changes in land-use, and/or anthropogenic influences.

Another attribute that affects climate is wind direction and speed. To better understand on a closer resolution the wind climatology over Egypt, the IRI Monthly Wind Climatology ([66]) is analyzed. The

maps provided by IRI, as seen in Figure 65, showed the average monthly surface wind climatology for the inputted year using a climatological base period from 1991 to 2020 at around sea level pressure (1000 mb) [66]. According to this dataset, Egypt predominately experiences northerly winds throughout the year with small seasonal variations. To understand the monthly variations, Egypt is split in half horizontally into upper and lower Egypt to distinguish the wind climatology in the different parts of Egypt. In January and February, the upper portion of Egypt experiences winds from the northwest to the north-northwest, while the lower area experiences winds from the north to north-northeast. March brings a slight shift in the upper area to north to northwest, with the lower area remaining north to north-northeast. April winds are very similar to January and February for all of Egypt. In May, the upper area wind transitions from north-northwest to north-northeast, while the lower area continues with north to north-northeast winds. During June, the upper area is dominated with north to north-northwest winds, and the lower area by northerly winds. July and August maintains north to north-northwest winds across Egypt. September through November returns to the pattern of north to north-northwest in the upper area and north to north-northeast in the lower area. Finally, Decembers shows winds from north to northwest in the upper area and north to north-northwest in the lower area.

Visualizing the spatial variation in wind speed can be done through Figures 67 and 68. The wind speed data used is from the Global Wind Atlas ([67]) where they downscale large-scale wind climate data to acquire micro-scale wind climate data [67]. To explain further, the large-scale wind climate data is obtained through re-analysis atmospheric data, particularly in the fourth version of the Global Wind Atlas, the ERA5 dataset is used [67]. The ERA-5 data is acquired from the European Centre for Medium-Range Weather Forecasts (ECMWF) where the simulation period is from 2008 to 2017 [67]. This data has a resolution of approximately 30 kilometres then undergoes a generalization process where the wind climate data as a resolution of 3 kilometres which is the same spacing as the mesoscale data derived from the WRF (Weather Research and Forecasting) mesoscale model [67]. Then generalized wind climates applied into a modelling process is used to calculate the local wind climates for a resolution of 250 metres [67]. Such a small wind climate resolution allows for analysis of the differences in wind between Luxor and KV42.

When comparing Figures 67 and 66 it is evident that the wind speed contours follow closely with the elevation contours. The surrounding areas around high elevation areas tend to have a relatively higher wind speed. This is better seen in Figure 68, where the elevation contours closely follow wind peak areas. It should be noted that in this Figure it is evident that Luxor is located in an area of low wind and KV42 is located in an area of high wind. Since elevation and wind can have an effect on relative humidity, then perhaps this can help explain a parameter which causes the two locations to have such significantly varying relative humidity.

This contrast between Luxor and KV42 becomes more evident when considering their respective topography and climate. Based on Figure 66, Luxor is situated at an elevation of approximately 86 metres and is located on the Nile. The area appears to be relatively flat considering the lower wind speeds and the lack of rapidly changing elevation (mountainous areas). In contrast, KV42 is situated at an elevation of approximately 187 metres, but it should be noted that the KV42 weather station is held at a height. Surrounding KV42 is cliffs that vary in elevation of over 400 metres and therefore as northwesterly winds pass over the

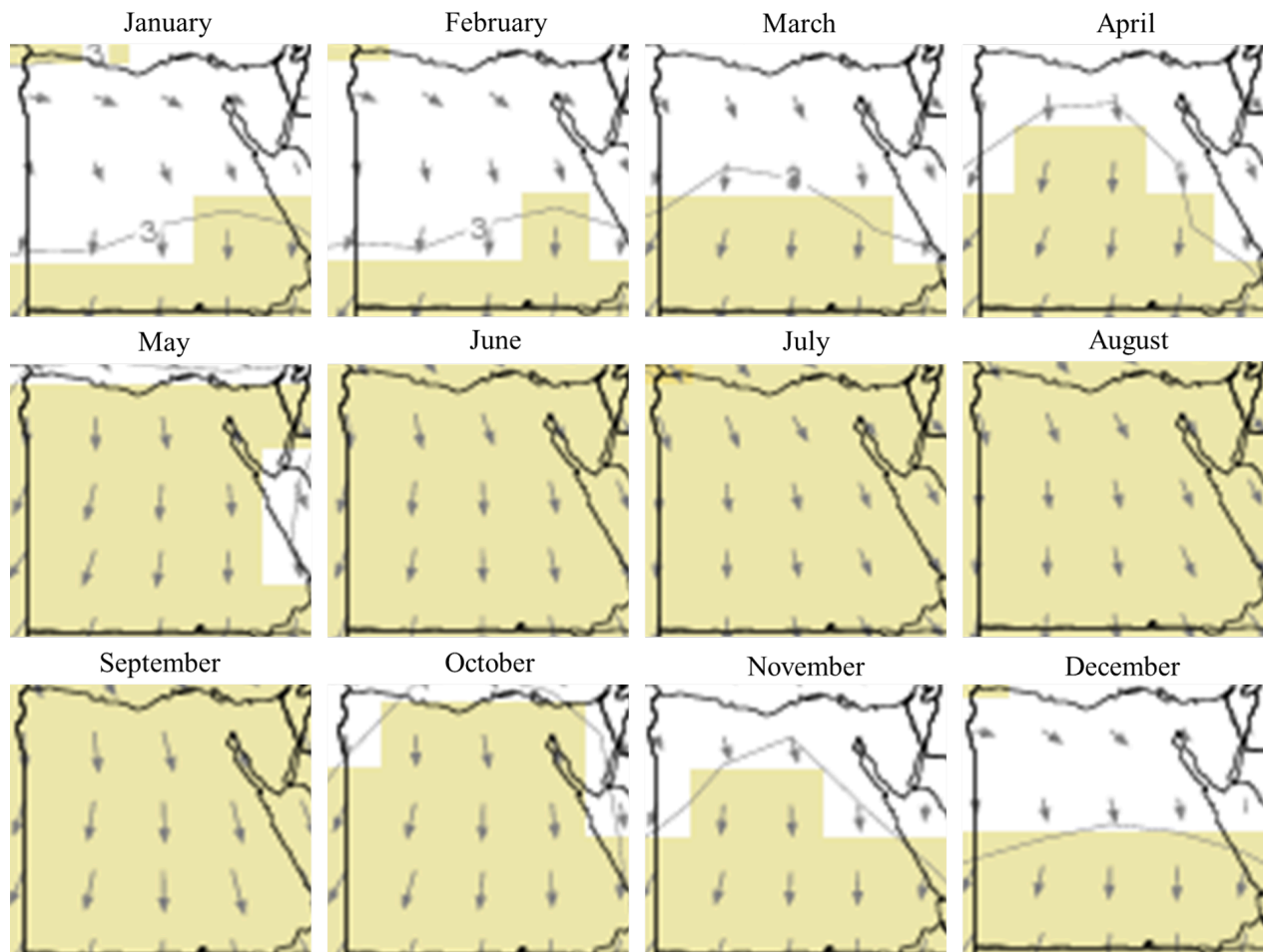


Figure 65: IRI Monthly Wind Climatology at 1000 mb. The white represents wind speed from 0 to 3 m/s and the light tan areas represent wind speed from greater than 3 m/s to 6 m/s. The arrows represent where the wind is coming from. Source: [66]

cliffs the air will rise. Relatively moist trade winds passing over the Nile River will ascend the eastern part of the cliffs and will then rapidly cool, condense and precipitate all moisture out [68]. The drier air will then fall down the mountain and warm up leading to further drying [68]. The orographic effect is a large component in the difference in the amount of relative humidity between Luxor and KV42 [68].

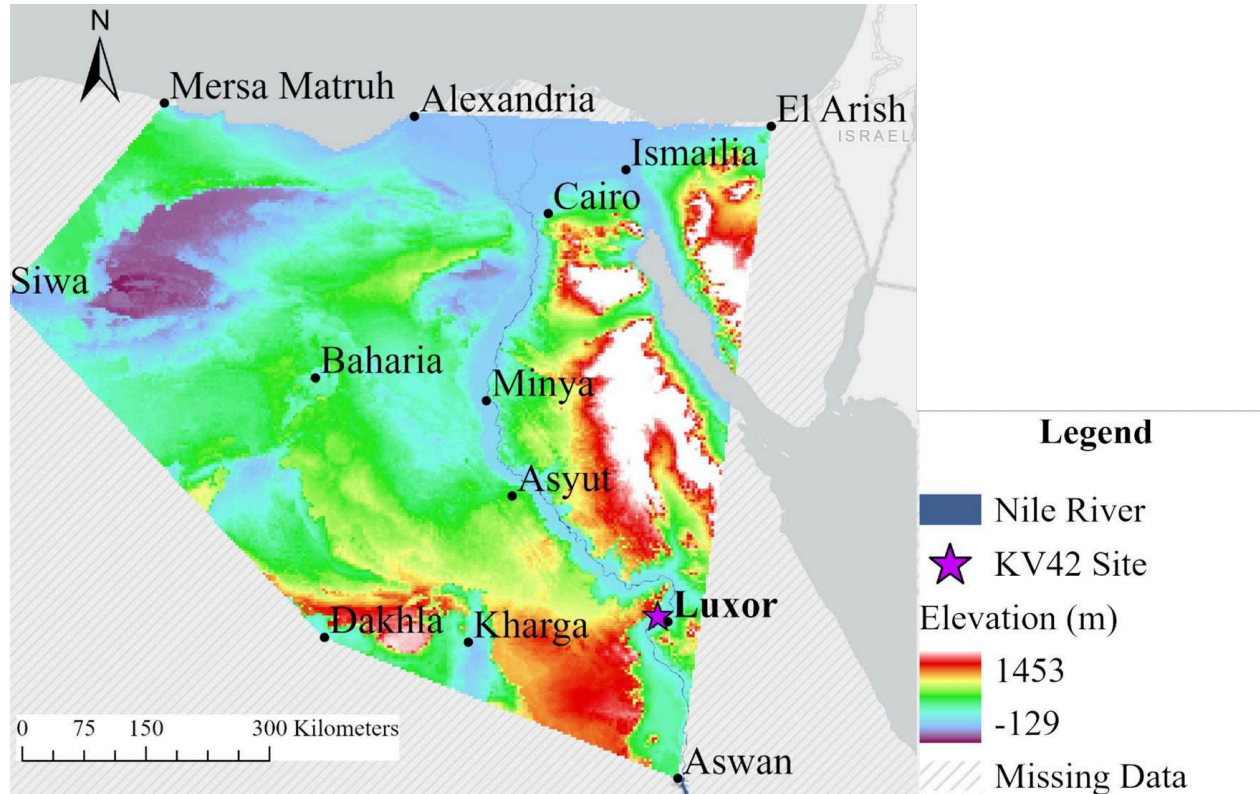


Figure 66: Elevation map of Egypt derived from the GTOPO30 digital elevation model (DEM) (Data is from [65])

6.3 Reliability of Regional Data for Microclimate Assessments

In an ideal situation, regional station data would be able to perfectly predict climate trends at archaeological sites with microclimate. Unfortunately through the results, it is clear that there are deviations between the regional station, Luxor and the archaeological site KV42. It should be noted that the methodology followed to confirm whether or not Luxor's climate data can be used to supplement KV42 is also applicable for other sites and nearby weather stations. Although it is clear that there is better correlation and similarity in temperature between the two sites than relative humidity, there are still issues with both.

Firstly, during periods of sufficient data such as during 2019 and 2020, it is clear that there is a close relationship in terms of the April and May diurnal temperature cycle as seen in Figures 34 and 35. In addition, again for the sufficient data years before 2022, the April and May temperatures at both sites have a high correlation (approximately 0.7 to 0.9) and low relative humidity (around 10%) as seen in Figures 36 and 37. This provides the notion that with sufficient data, during April and May, temperatures at both sites are strongly related and similar therefore, starting to provide reliability on the use of Luxor climate data to

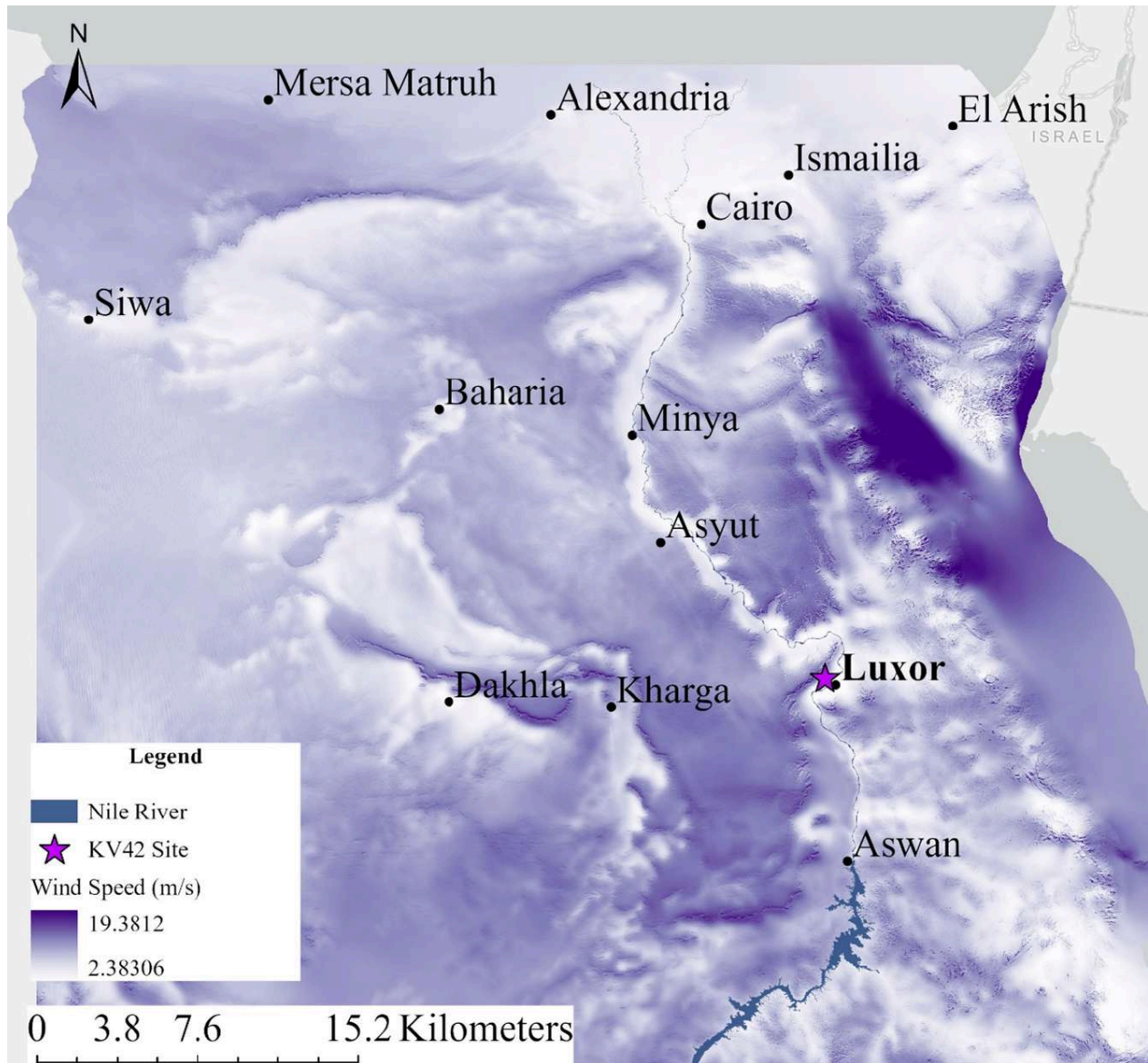


Figure 67: Wind speed data at 100 meters height across Egypt for 2008 to 2017. Data source: Global Wind Atlas [67]

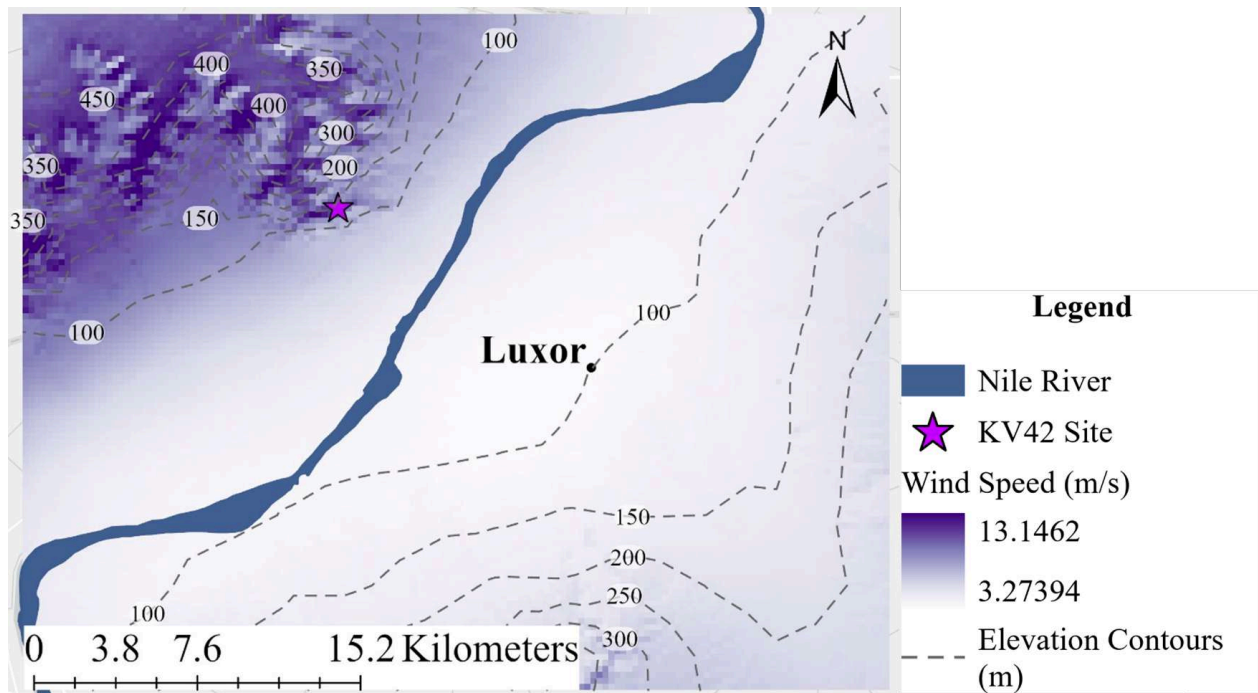


Figure 68: Wind speed data at 100 meters height for the Luxor region during 2008 to 2017 (Data source: Global Wind Atlas [67]) with elevation contours overlaid

predict climate KV42 during April and May from 2018 to 2021. In terms of an hourly temperature difference between April and May, it is clear from Figure 42 that from 2018 to 2021 there is less than 5 degrees celcius difference on average alluding to again how close the values are. However, it should be noted that the two locations do have varying periods of time in which there is a diurnal max and min as seen in Figure 43. Thus, it is the supplemented data is done using averages and not filling missing hourly data during the day since these values can vary.

The regional spatial interpolation did not fully capture the relative humidity conditions at KV42. The possible reasons for this include the KV42's cliff surroundings and higher elevation relative to Luxor Airport. The micro-environmental factors associated with KV42's location are not accurately represented in the regional interpolation, thus, it can be concluded that interpolation of relative humidity alone is not sufficient.

In terms of climate trends, as seen in Figure 46 from 2018 to 2021, it can be assumed that Luxor's April and May temperature trend lines would somewhat accurately predict the temperature trend at KV42. With this assumption, it can be predicted that KV42 would be increasing in temperature at a rate equal or near Luxor's. Therefore, this assumption would conclude that both locations are increasing at a rate of around double the global annual average during April and May. The repercussions for these relatively high rate of temperature increase will be furthered discussed in Section 7.1. In terms of the rates of change of hottest and coldest day values for April and May, the coldest day values for both Luxor and KV42 closely follows from 2018 to 2024 which means that Luxor's trend of increasing daily minimum temperatures is an accurate estimate of KV42's trend. In contrast, the hottest day values from 2018 to 2024 for both Luxor and KV42 does not follow a similar trend pattern. The values of the hottest day for the two locations have uncertainties

which over the years are close to each other or overlap, indicating that the values are somewhat close in value from 2018 to 2022. However, it does not closely represent the maximum temperature trend, indicating again that in terms of diurnal cycle maximum temperatures there is a variance in averages where KV42 is relatively warmer but the relative difference in temperature is not consistent.

7 Conclusions

7.1 Summary of Findings

The research done in this thesis was to work towards addressing a critical gap in climate informed heritage preservation: the lack of site specific climate data for archaeological sites in Egypt. Through a combination of NOAA weather station data, in-situ measurements from KV42 and TT95, as well as spatial interpolation done through the use of ArcGIS's Natural Neighbour technique, this study demonstrates how regional climate data can be used to approximate local microclimate conditions with reasonable demonstration.

The analysis revealed an overall warming and decreasing relative humidity trend across Egypt from 1984 to 2024. The average temperature increase of 0.35°C per decade exceeds the global average of 0.20°C (based on NOAA Global Climate Report [49]), which indicates that Egypt is experiencing climate change at an accelerated rate in comparison to the global average. The decreasing relative humidity trend has a stronger decrease during summer months, which presents several concerns considering the effects on structures made of natural materials such as sandstone and limestone. Changes in temperature and relative humidity can cause pH variations in buried archaeological material as well as a weakening of structural integrity due to heaving and cracking [1]. Porous material such as limestone can be physically altered due to fluctuating humidity, which can alter the dissolved salts within the material [1]. Luxor's dry and non-variable environment has allowed for the preservation of archaeological sites [1]. Yet, with changing climate, the structures that have survived for centuries may be at risk of increased damage rates [1]. Sandstone within temples continue to be degraded by salt crystallization caused by increasing temperatures leading to more rapid evaporative processes [1]. These findings are relevant for KV42 and TT95, which are constructed from limestone. Localized monitoring of the cliff stability at KV42 was done by Alcanio-Olivares et al (2019), with a range of sensors inside the open fracture behind the rock column as seen in Figure 3 [20]. These sensors measured air temperature, rock temperature, relative humidity and crack aperture [20]. Cyclic temperature variations had a strong correlation with the lateral fracture cycle of the column [20]. In addition, the fluctuation in relative humidity also proved to have an influence on the column, where possibly due to the swelling clay minerals the fracture apertures were able to expand and contract with the changes in relative humidity [20]. Therefore, rapid fluctuations in temperature and relative humidity will lead to weakening of the rock mass over time [20]. The collapse of the rock column poses dangerous implications since as mentioned in Section 1, the rock pillar is above the KV42 entrance, next to a ladder that tourists use to enter another tomb, KV34.

Comparative analyses between the two locations, KV42 and Luxor, showed that while regional data can reflect broader climatic pattern, it is unable to capture specific details of local micro-climates. For instance, KV42 is consistently less humid and a more consistent diurnal temperature cycle than Luxor, suggesting that site specific conditions such as elevation, sun exposure and surrounding terrain can play a significant role in local climate variation. These climatic differences highlight the importance of inputting available heritage site climate data when possible to increase the accuracy of regional dataset based spatial interpolation to approximate micro-climates. In a similar fashion, the analysis between KV42 and TT95 provided similar

findings. Even with KV42 and TT95 being only 1.5 kilometres apart from each other, the different dynamics at each location lead to variations in both temperature and relative humidity. Correlation and relative error between the two locations provided insights that in terms of temperature, a moderate relationship and for relative humidity, a weak relationship exists. A similar relationship is also found between Luxor and TT95. These results confirm that although, Luxor's and KV42's temperature data can be used to supplement TT95's missing data, it should be done with caution and concurrently with other data sets. It can be mildly assumed that due to increasing temperatures at both Luxor and KV42, that TT95 could also be experiencing a similar pattern. This finding is important since the strong relationship between air and rock temperature indicates that increasing air temperature within the tomb directly affects the rock conditions. Meanwhile, for relative humidity it is clear that neither KV42 nor Luxor can serve as a reliable substitute for TT95 data, since it appears that each of these sites vary differently in relative humidity. Therefore, it is evident that in this case, outdoor stations were unable to capture the unique micro-climatic variability of TT95 as an underground tomb, highlighting the vital need for localized measurements.

The spatial interpolated maps developed in this study effectively visually presented the magnitude and distribution of changes in climatic parameters: temperature and relative humidity, across Egypt. These maps highlight the main areas of concerns, undergoing greater changes in temperature and relative humidity. In addition, the spatial interpolation process demonstrated in this study proved a scalable framework for other heritage sites globally. As well, the uncertainty analysis presented in this research, highlighted the level of reliability of the interpolated data, providing insight on the limitations and potential of using regional climate data to approximate local areas.

A supplementary component of this study is the logistical and technical challenges associated with collecting weather data from remote archaeological sites such as KV42 and TT95. These challenges further emphasize the need for regional data to supplement and assess the reliability of the heritage site data.

With all of this in mind, the results of this study include both positive and negative outcomes. On the positive side, the interpolated spatial maps were able to capture regional warming and decreasing relative humidity trends across Egypt, proving context to the areas undergoing the greatest magnitude of changes. In addition, the results also revealed that the spatial interpolation of regional temperature climatology was able to accurately represent KV42's temperature climatology. However, the analysis also revealed negative results. For instance, the relative humidity was more difficult to represent accurately and the sparse weather network limited the spatial detail of the interpolated spatial fields. These mixed results highlighted both the benefits and challenges of using regional datasets to interpret micro-climates at archaeological sites.

7.2 Practical Recommendations for Site Preservation and Monitoring

The results found in this study highlight how the preservation of Egyptian archaeological sites should be viewed with critical consideration. The warming trends, as demonstrated previously, is accelerated in comparison to the global average, therefore it is vital that preservation strategies incorporate regional or local climate data. These preservation strategies should focus on mitigating environmental stressors that can

accelerate the degradation of the material.

First, weather stations such as KV42 and TT95 should be installed in various other heritage sites where the data can be studied by climatologists. These stations provide valuable data on temperature, humidity and wind trends, which are vital for the assessment of deterioration risks. However, as explained in this research, maintaining weather stations at these heritage sites, poses challenges such as connectivity issues, battery failures and limited access for repairs. To address these challenges, preservation experts should invest into technology that involves remote data monitoring, backup power systems and repair strategies.

Second, preservation efforts should focus on fluctuating periods of high temperatures and rapid drying, which poses significant risk on the structural integrity of heritage sites. For example, Luxor's summer months exhibit rapid diurnal fluctuations and relatively low humidity levels. As expressed by historian researchers such as Jorgen Hollesen (2022) increasing temperatures can alter the site's and its surrounding's chemical factors which can cause an increase in the rate of degradation [61]. Within Egypt, the study by Khater et al (2024), highlighted that climate change's impacts such as drying and warming will lead to scaling, material degradation and cracking of archaeological sites [1].

Third, spatial interpolation maps should be included into conservation planning to identify vulnerable regions. These maps can help to prioritize sites for preservation based on the rate of climatic change.

Fourth, preservation strategies should be altered for that specific heritage site's materials and features. For instance, limestone and sandstone structures may require different preservation and conservation treatments due to varying porosity or thermal characteristics. Detailed analysis should be done on these materials to provide insights of which preservation method is appropriate to apply. For instance, as explored through a study by Gandah (2019) is how vital it is that the preservation methods envisioned be tested in advance as to not further damage the site [26]. To do so, to increase the efficiency of the preservation method used, original construction techniques must be taken into consideration [26]. In addition, preserved sites should be regularly monitored.

Fifth, besides weather stations, archaeological sites should also implement monitoring systems that can analyze structural features and their changes. This includes the application of sensors to detect cracks and moisture infiltration. The data from these sensors, as well as climatic data, can provide a better view on the site and allow for a more effective conservation.

Most importantly, collaboration across different disciplines is essential. Preservation strategies must be built on information from climatologists, archaeologists, scientists and engineers. A multi-field approach can allow the use of predictive modelling to forecast future climate scenarios and assess the potential impact on archaeological sites. The combination of environmental and structural data with simulation tools can allow preservation experts to make decisions that are more informed and for the development of long-term strategies to protect cultural landmarks.

7.3 Suggestions for Policymakers and Preservation Agencies

Policymakers and heritage preservation agencies play a vital role in translating scientific research into policy. The findings of this research study highlights the urgency of the development of climate-informed preservation policies are both practical and effective.

One of the most important suggestions is the expansion of Egypt's weather monitoring system. The current coverage of weather stations with sufficient temporal data is sparse, particularly in cultural heritage regions such as the Theban Necropolis. Policymakers should consider funding for the installation and maintenance of weather stations at the most affected heritage sites. The data collected from these sites should be consistent, reliable and accessible with collection and information on the instruments available as well. These weather stations should have data be uploaded to an online database that allows researchers and scientists to analyze the climate data.

In addition, policymakers should promote international standards, such as UNESCO's guidelines ([69]), to ensure that the applied conservation techniques are aligned with the standards. Impactful collaboration such that done in 2024 between UNESCO and the National Museum of Egyptian Civilization (NMEC) must continue [70]. In 2024, the two corporations came together to sign the Implementation Partnership Agreement (IPA) geared at providing resources to the NMEC for conservation practices and much more [70]. As well as, incorporating climate risk assessments into preservation and conservation projects.

Additionally, local involvement is an integral part of ensuring that preservation efforts are sustainable in the long term. Preservation agencies should invest in training programs to allow local workers to learn the skills needed to operate and maintain weather station instruments.

Policymakers should consider research such as those by Aldosari et al (2017) and Elsayed (2021) which provide insights into innovative techniques that enhance the resilience of ancient structures to climate change [27][71]. To explain these studies in more detail, the study by Aldosari et al (2017) explores the use of calcium carbonate nanoparticles in an acrylic copolymer base as a consolidation and treatment to protect limestone [27]. The treatment was able to improve the mechanical strength of limestone and reduced the amount of water absorption [27]. The study by Elsayed (2021) explored the use of smart systems to detect damaged in ancient Egyptian monuments such as to name a few: ground penetrating radar (GPR), canonical biplot for microclimate detection, monitoring heritage system (MHS) and terrestrial laser scanning [71]. These methods allow for a better and quicker response to site deterioration, promotes visitor safety and allows for efficient monitoring [71]. However, trials should still be funded to evaluate the effectiveness of these treatments and methods, such as the two mentioned, over a period of time. If these methods are effective, the current preservation practices will be evolved and mitigate impending damages.

Finally, a important suggestion, most highlighted by this research is that policymakers should consider the integration of climate-informed preservation across the nation. This includes incorporating heritage conservation into climate change adaptation plans alongside disaster risk reduction frameworks. Through the recognition that cultural heritage sites are a critical component of a nation's identity, governments can ensure that preservation efforts are given the resources necessary for success.

7.4 Limitations of this Research

Although this research provides a framework for enhancing localized climate analysis for archaeological sites in Egypt, several limitations must be acknowledged to contextualize the findings and provide a better path for future work.

7.4.1 Data Availability and Temporal Gaps

A major limitation arises from the sparse availability of climate data across Egypt. NOAA weather stations are unevenly distributed, with many regions such as the Western Desert having incomplete or missing records. This uneven coverage introduces significant uncertainty into the spatial interpolation maps, especially in areas far from an available station.

Similarly, the KV42 and TT95 in-situ datasets contain significant temporal gaps due to connectivity failures, battery issues and SIM card malfunctions, and the logistical challenges of maintaining equipment at remote archaeological sites. These gaps restrict the ability to undergo long-term trend analysis at the site level and can hinder the accuracy of correlation assessments with regional data.

It should be also noted that efforts were made to obtain meteorological data from local Egyptian researchers, but these attempts were unsuccessful due to access restrictions and limited public availability. As a result, NOAA datasets and the in-situ stations at KV42 and TT95 are the only datasets used for analysis.

7.4.2 Spatial Interpolation Uncertainty

The Natural Neighbour interpolation method used in this research provided a smooth and clear climate surface, however, the accuracy of this interpolation is based on the density and distribution of the input stations. In regions with sparse coverage, the method may oversimplify localized topography, water bodies and land-use.

It is important to note that this study intentionally applied a simple interpolation method as a initial test of how well regional station data can represent local archaeological micro-climates. This is done in order to assess the method's effectiveness before attempting more sophisticated approaches in future research.

7.4.3 Sensor and Instrumentation Constraints

The Bosch BME280 sensors within the the DAQ used at KV42 and TT95 have known accuracy limitations, particularly for relative humidity under extremely dry conditions, such as that of Luxor. As a result, very low humidity measurements below the device's uncertainty of $\pm 3\%$ are not captured accurately.

In addition, the malfunctioning of the secondary battery at KV42 during the period of time from July 2023 until February 2025 introduced time inaccuracies of up to ± 5 days, which complicated the analysis between the local and regional datasets. Although corrective assumptions were applied during that time,

these adjustments may have also introduced uncertainty into the temporal comparisons. Since February 2025, this issue has been corrected through update of the hardware.

7.4.4 Limited Representation of Micro-climates

While the study compares regional data with two archaeological sites, KV42 and TT95 only represent a very small portion of archaeological sites in the Theban Necropolis and more broadly, Egypt. Micro-climates can vary dramatically over short distances depending on the location.

The findings done in this research cannot be simply generalized to all archaeological sites and additional case studies are required to better understand the bigger picture across Egypt.

7.4.5 Limited Climate Variables

This research focuses on temperature and relative humidity, which although are important climate stressors for understanding material degradation, they are not the only factors affecting archaeological sites. Variables such as wind, precipitation, ground moisture would provide more information but these variables were unavailable.

7.5 Continuation of the Research

While the research done in this study, provides findings which can be used for climate-informed heritage preservation, the data and results can be used for future research projects. First, the spatial interpolation technique, Natural Neighbour can be refined. Although, the Natural Neighbour methods is proved to be effective in this study, incorporating other variables such as elevation, land use and wind patterns can increase the accuracy of the spatially interpolated climate map.

It is important to note that although elevation is often incorporated into interpolation schemes, comparisons between KV42 and Luxor demonstrates that elevation alone cannot explain local temperature differences. KV42 sits at a higher elevation than Luxor Airport, yet it is often warmer due to its extremely dry environment and cliff surroundings. An alternative approach would to use potential temperature. however, this KV42 and Luxor comparison suggests that that temperature does not follow a dry adiabatic lapse rate in this region. This indicates that any future interpolation approach that incorporates elevation would also need to account for moisture availability. Due to this study's lack of high-resolution moisture datasets, further refinements should be left for future work.

Future work could also include developing a multiple regression model that incorporates elevation, wind speed, land use and other environmental variables. This model may be able help to explain local deviations, such as those observed at KV42 that cannot be captured through spatial interpolation alone. For instance, remote sensing products such as NASA's land-uses datasets could be used. Although these datasets have a course resolution, they may still provide valuable information on surface characteristics that influence

localized micro-climates.

In addition, future studies could incorporate air-moisture sensors that are able to directly measure the actual mixing ratio of the atmosphere. Unlike relative humidity, the actual mixing ratio is not dependent on temperature and therefore, provides a more conservative measure of the amount of water vapour in the atmosphere. If the actual mixing ratio were to remain constant with warming, this would help to explain the observed decrease in relative humidity across most of Egypt.

Second, the data from KV42 and TT95 provided valuable insights, but their data was limited by connectivity issues. Future research can be done to solve these issues by exploring alternative power sources and data storage methods to ensure that continuous and reliable data is being collection. In addition, having multiple weather sensors at varying depths, locations and orientations can provide more information on the site's micro-climatic conditions.

Third, the methodology used in this research can be used for other archaeological sites. Comparative studies across the globe would contribute to the development of a framework for climate-informed preservation

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Appendices

A Other Excel Formulas

This section outlines the key Excel formulas applied during the data processing and analysis. Each formula is accompanied by a brief explanation.

The process of organizing the NOAA weather station data:

First, blank spaces were added to account for missing data during particular hours. The yearly date and temperature is added and the following excel formulas are applied for each year:

```
=TEXT(DATEVALUE(MID([StartDateCell],1,10)) + INT((ROW([CurrentRow])-ROW([StartRow]))/24),  
"yyyy-mm-dd") & "T" & TEXT(MOD(ROW([CurrentRow])-ROW([StartRow]), 24), "00") & ":00:00"
```

Explanation

- Extracts the date from [StartDateCell].
- Calculates the number of days and hours based on the row position that has passed from the original start date.
- Reformat the result to match that of the original data.
- Creates a list of all dates (for each hour) that year.

```
=IFERROR(VLOOKUP(TEXT([TimestampCell], "yyyy-mm-ddThh:mm:ss"), [LookupRange], 2, FALSE), "")
```

Explanation

- Searches to see if there is a matching date in the curated list of all dates and the dates with data.
- Returns the corresponding data if there is data at the particular date, otherwise a blank cell is returned.

The above Excel formulas are used to organize temperature and dew point temperature data from 1984 to 2024.

The provided data is in the format of +TEMP,Q where TEMP is the temperature or dew point temperature are represented as tenths of degrees celcius (i.e., 70 represents 7 degrees celcius) and Q is the quality number. The two values are separated into different columns with the use of the Text to Columns tool where the delimiter is the comma.

To allow for the accurate averages of these values to be calculated for each year the following Excel formulas are used:

=IF (ISBLANK([RawTempCell]), NA(), [RawTempCell]/10)

Explanation

- Checks if [RawTempCell] is blank.
- If blank, #N/A is returned to indicate missing data.
- If not blank, divides value in [RawTempCell] by 10 to get units of degree celcius

The above process is done for all locations with sufficient data as outlined in previous sections.

B Additional Figures

Relationship between KV42's relative humidity and wind direction/speed for 2019 and 2020.

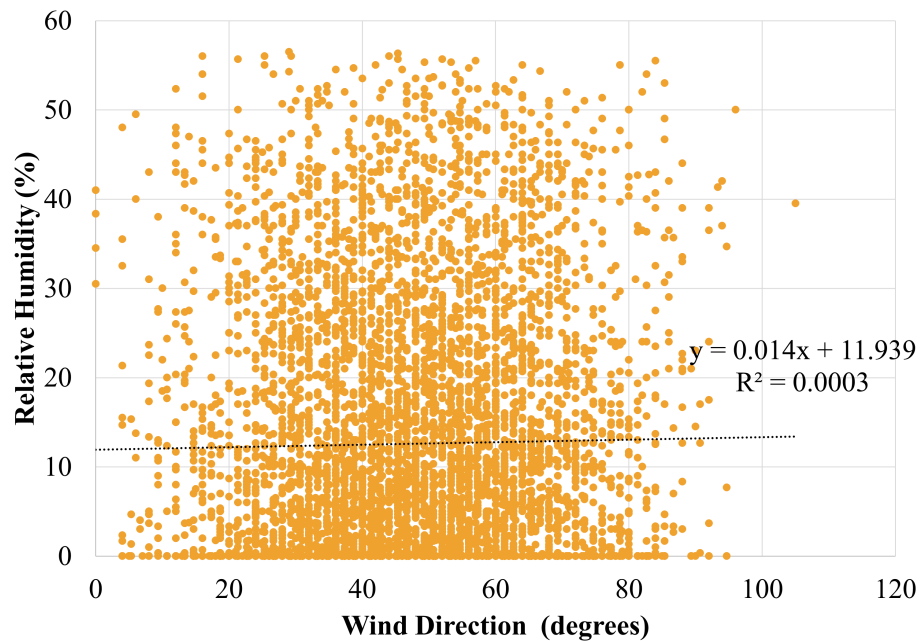


Figure A-1: Relationship between KV42's relative humidity and wind direction during 2019

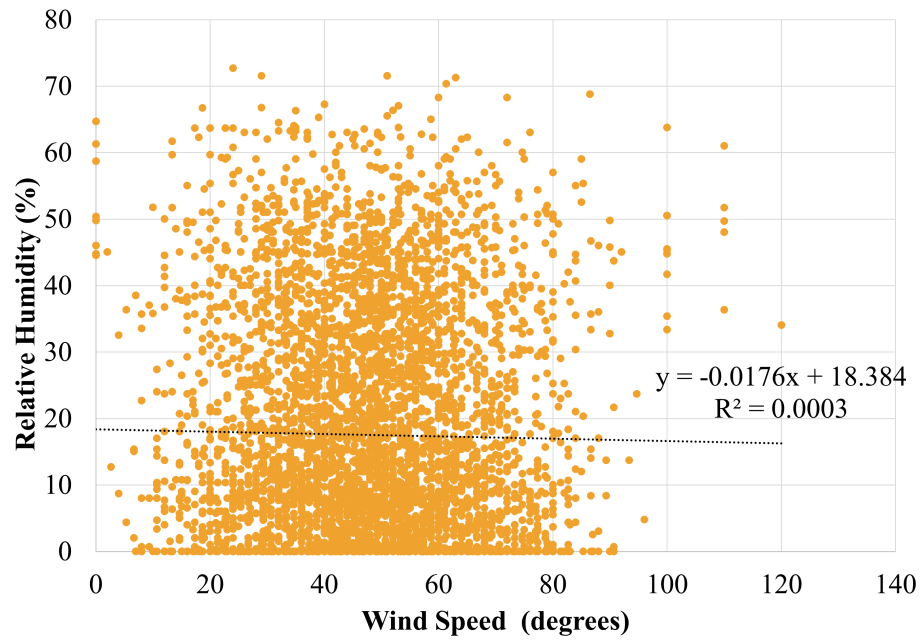


Figure A-2: Relationship between KV42's relative humidity and wind speed during 2020

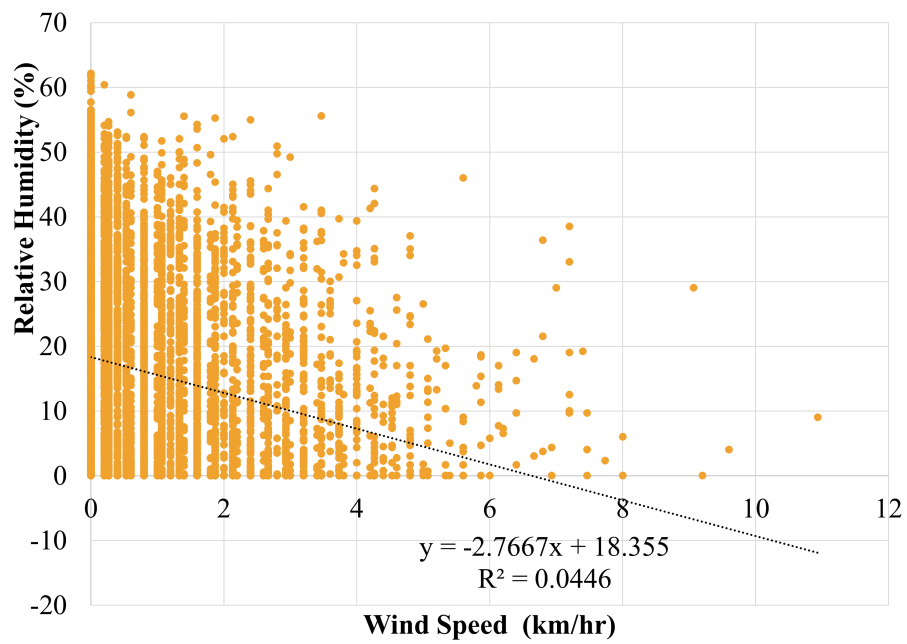


Figure A-3: Relationship between KV42's relative humidity and wind speed during 2019

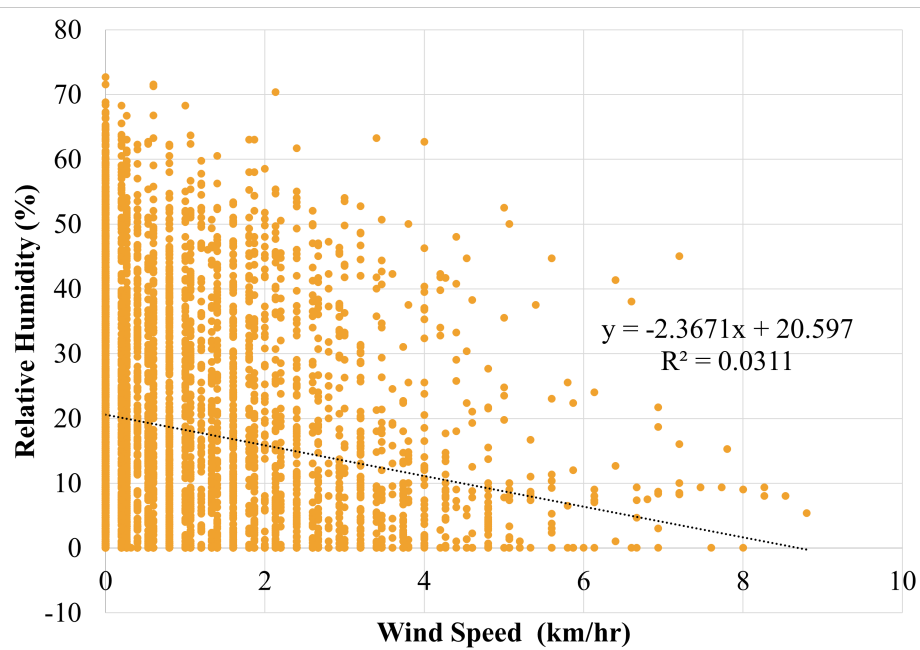


Figure A-4: Relationship between KV42's relative humidity and wind speed during 2020