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Diploma Thesis

Tracing the Links between Forest Cover and Terrestrial Precipitation: Case of Four City Areas in the Czech Republic

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DIPLOMA THESIS ASSIGNMENT

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Landscape Engineering
Landscape Planning

Thesis title

Tracing the links between forest cover and terrestrial precipitation: case of four city areas in the Czech Republic

Objectives of thesis

The main goal of the thesis to analyse changes in precipitation and temperature due to land cover changes and changes in forest cover in four city areas in the Czech Republic

Methodology

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AUTHOR'S DECLARATION

I hereby declare that this Diploma Thesis is my original work, except where otherwise acknowledged in the text, under the guidance of prof. RNDr. Dana Komínková, Ph.D. I have listed all the literature and publications from which I have acquired information. This thesis has not been submitted or published earlier and shall not, in future, be submitted by me for obtaining any other degree from this or any other University or Institution.

Date : _______________ Signature : ____________________

Swati Surampally

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ABSTRACT

The aim of this study is to augment the research in the forest-precipitation dynamics at the local scale so as to have scientific evidence underpinning the shift to "water-cycle" centered urban planning process rather than the traditional "rapid- drainage" based planning. The fact that forests play an important role in the large scale water cycle as well as the small scale water cycle is established through the literature review with a focus on the theory of Biotic Pump.

The main goal of the study is to analyse the relationship between the changes in the forest-cover and changes in the precipitation amount and pattern within a 10 km buffer around four different cities in the Czech Republic - Most, Prague, Třeboň and Brno.

Long term climate data is analysed using statistical tests to determine the annual and seasonal trends within each study area and then juxtaposed with the land cover data to ascertain the forest-precipitation correlation. Although the analyses revealed no statistically significant trends, neither for precipitation nor for forest cover, yet positive relationships are evident between the land cover and local climatic conditions when the four study areas are compared, given that the climatic zones and elevation of the four study areas are similar.

The climate trends in the four study areas are also compared with the National, Continental and Global trends to evaluate the role of land cover in influencing the local climatic conditions.

The analyses of land cover and precipitation trends done in this study is vital to help shift our focus from carbon-centered role of the forests to hydrological based ecosystem service of the forests which will enable us to plan the appropriate mitigation measures against the abrupt climate change.

Key Words: Climate, Land-cover, Hydrology, Urbanization, Ecosystem Services.

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1 | INTRODUCTION

Earth has gone through many phases of climate change in the past due to minor changes in the Earth's orbit (NASA, 2019) but the current phase of global climate change is largely attributed to the anthropogenic activities (National Research Council, 2010). We have disrupted the ecology of life on Earth to a great extent but if we carefully analyse the disruptions caused by us and understand the mechanisms of various life sustaining processes, there is still hope that we can act to help the Earth recover. One of the global physical processes effected by climate change due to rise in global temperature is the hydrological cycle. Precipitation (rain/ snow/ hail) patterns across the globe have been affected, there have been frequent instances of draughts and floods across various parts of the world damaging various life forms. There is an alarming water crisis at many places. It is anticipated that the effects of hydrological imbalance due to climate change would result into more severe damages than the changes in the global temperatures (Bengtsson L, 2010). With the increasing water crisis, it is very important to critically look at the hydrological cycles at various scales to understand the complex mechanisms involved and the factors that affect these cycles.

Our Forests and Water both are under threat. Understanding their inter-relationships is very crucial at this point of time. The regulatory ecosystem services of the forests have majorly been studied with respect to carbon sequestration, groundwater recharge, erosion control, purification of water & air, but their influence on the atmospheric water cycle has been underestimated until recently and is still not widely realised. The principles and processes underlying the Forest-Rainfall relationship are complex and not widely recognised (Ellison et al, 2017). Researchers do agree that changes in land cover does affect the water cycle but there still is some speculation about what extent it gets affected. But there is an urgent need to draw the attention towards this function of the Forests as it may help understand the current events of severe floods and draughts across the globe and can further lead us to mitigate them as well as plan our landscapes in accordance. Our Landscape Planning/ Management decisions should be rooted from a sound understanding of the landscape ecology only then we will be able to regulate the adverse effects of the climate change. Planners and the governing institutions need to integrate the scientific ecological studies in order arrive at decisions that would indeed result in some positive outcomes when fighting against the climate change (Ellison et al, 2017). In the present scenario, the focus is mainly in context of the greenhouse gases causing the climate change ignoring the effects of loss of natural vegetation on the water cycles which is evident from the IPCC (Intergovernmental Panel on Climate Change) reports from 2007 and 2013 which do not recognise the impacts of vegetation and water on the climate change. Hence it is extremely important to shift our focus towards natural vegetation for a sustainable water cycle on local as well as on global scales (Hesslerová, 2019).

2 | DEFINING THE CONCEPT AND IT'S IMPORTANCE

2.1. Forests and the Hydrological Cycle

Hydrological cycle is defined as "the sequence of conditions through which water passes from vapor in the atmosphere through precipitation upon land or water surfaces and ultimately back into the atmosphere as a result of evaporation and transpiration" ("hydrological cycle", 2019). Of the total water available on Earth, only 0.001% is present as atmospheric moisture resulting from evaporation and transpiration, yet it plays a significant role in the availability of water for the terrestrial life as it is derived in the form of precipitation.

Recent calculations have revealed that approximately 1,17,600 cubic kilometres of water falls on the terrestrial surface every year and out of this, only 45,800 cubic kilometres is derived from the oceans and the remaining part, which is the larger part is derived from the land itself, i.e. through evapotranspiration (ET) – evaporation of water from soil or water surfaces and by the transpiration of vegetation as seen in Figure 1. Hence, forests/trees play a vital role in the hydrological cycle through the process of transpiration, which contributes to the atmospheric moisture. It is estimated that a large canopy tree in the Amazon forest can transpire up to 1000 litres of water per day (Jordan & Kline, 1977). But due to extensive deforestation for agricultural land, pastures and urbanization, there is a huge loss in the amount of water going through evapotranspiration in the hydrological cycle which is affecting the availability of water on the land.

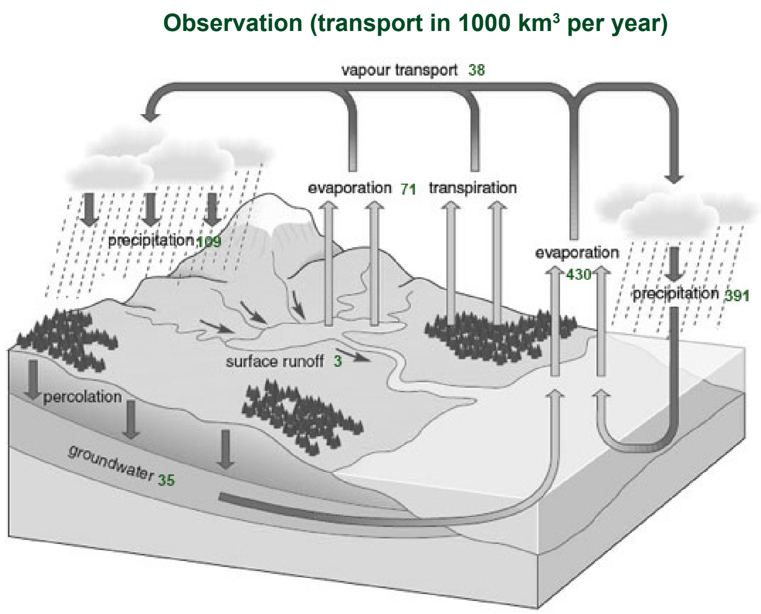


Figure 1. THE GLOBAL WATER CYCLE. Adapted from "The global atmospheric water cycle" by L Bengtsson, 2010, Environmental Research Letters, 5: p.2. © 2010 by IOP Publishing Ltd.

Although the rate of transpiration from the plants depends on the temperature, relative humidity, wind movement, soil moisture, the type of plant/tree, and the amount of incoming solar radiation, natural forests generally have higher rates of transpiration due to high leaf area index. Apart from influencing the hydrological cycle through transpiration, recent studies have revealed another major function of the forests - transportation of atmospheric moisture from oceans to the land. It is very important to explore this aspect of the forests which had not been scientifically explained until recently. The principles underlying this function of the forests can be understood through the Biotic Pump Theory proposed by Makarieva & Gorshkov (2007), which works on a continental scale.

2.2. The Continental Hydrological Cycle

According to the Biotic Pump Theory, low-level air moves from areas with weak evaporation to areas with more intensive evaporation. Due to the high leaf area index, natural forests maintain high evaporation fluxes, which support the ascending air motion over the forest and "suck in" moist air from the ocean (Makarieva & Gorshkov, 2007). The water vapour as a result of evapotranspiration rises and meets the cooler air at higher levels of atmosphere condenses and this condensation leads to reduced atmospheric pressure. During condensation as water vapour transits from gas to liquid phase, the water molecules come closer together and the space between these molecules disappears which causes the reduction in the air pressure. As a result, the surrounding air (atmospheric moisture from ocean) moves into the reduced pressure zone because winds tend to flow from areas with high pressure to areas with low pressure. This implies that in order to bring the precipitation on the inland areas from the ocean, it is necessary to maintain the process of condensation on the land, keeping it in the low-pressure zone.

The crux of this concept is condensation being the driver of atmospheric circulation. This factor had been overlooked by the climatologists until this concept was formulated (Bunyard, 2015). According to Makarieva and Gorshkov, an important aspect to consider for this concept is that it works only in case of undisturbed natural forests which have an immediate border with the ocean or at least within 600 km from the coastline. And in case of continuous natural forests from the coastline, the atmospheric moisture does not depend on the distance from the ocean, it travels up to several thousands of kilometres inland as seen in Figure 2. On the contrary, in case of non-forested coastlines, the mean distance to which the air fluxes can transport moisture is limited only to several hundreds of kilometres. In extreme cases like a desert where there is no water for evaporation, the low level air moves to the ocean and the area becomes permanently closed for any humid air to travel from the oceans. On the other hand, in case of the Amazon forest, the climate is wet thousands of kilometres inland from the ocean which is possible only because of the Amazon forest being a continuous forest cover from the coast (Makarieva et al, 2009). The trees not only transpire moisture but also release some aerosols into the atmosphere which help the water vapor to condense and ultimately lead to precipitation. When compared to the ocean water surface in the same latitude as Amazon forest, the rate of condensation is lower although there is speculation that even marine organisms release some natural biological aerosols. The major factor here is the initiation of the condensation, until the rate of condensation stays higher on the land, the direction of moisture transport will be from ocean to land and this can reverse in case there is higher condensation over the oceans (Biotic Regulation, 2016). The efficiency of this function of the natural forests as biotic pump also depends on factors like season and geographical conditions - temperature, solar radiation, size, and location of the forest area with respect to the major oceanic condensation zones (Makarieva et al, 2013). Changes in the air fluxes with differing factors are illustrated in Figure 2.

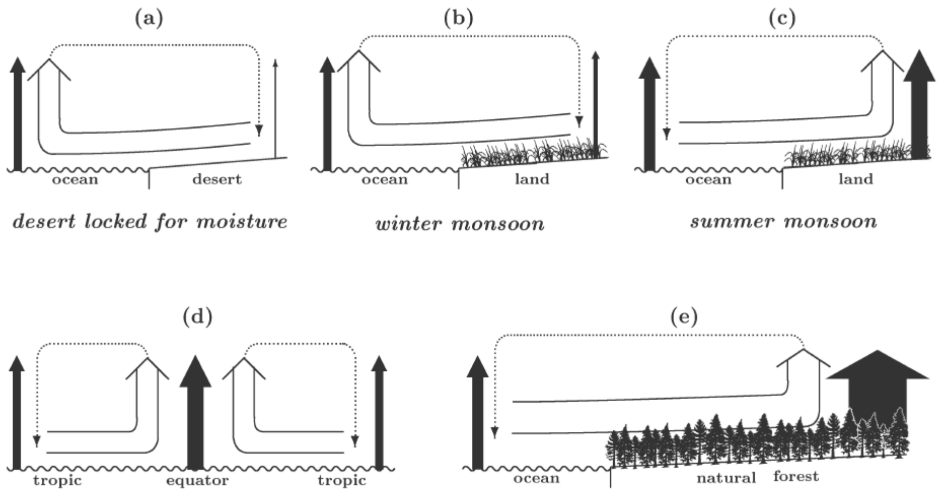


Figure 2. MOVEMENT OF AIR FLUXES. Adapted from "Biotic pump of atmospheric moisture as driver of the hydrological cycle on land", by A.M. Makarieva & V.G. Gorshkov, 2007, Hydrology and Earth System Sciences, 11: p.1025. © 2007 by A.M. Makarieva & V.G. Gorshkov.

"Black arrows: evaporation flux, arrow width schematically indicates the magnitude of this flux (evaporative force). Empty arrows: horizontal and ascending fluxes of moisture-laden air in the lower atmosphere. Dotted arrows: compensating horizontal and descending air fluxes in the upper atmosphere; after condensation of water vapor and precipitation they are depleted of moisture. (a) Deserts: evaporation on land is close to zero, so the low-level air moves from land to the ocean year-round, thus "locking" desert for moisture. (b) Winter monsoon: evaporation from the warmer oceanic surface is larger than evaporation from the colder land surface; the low-level air moves from land to the ocean. (c) Summer monsoon: evaporation from the warmer land surface is larger than evaporation from the colder oceanic surface; the low-level air moves from ocean to land. (d) Hadley circulation (trade winds): evaporation is more intensive on the equator, where the solar flux is larger than in the higher latitudes; low-level air moves towards the equator year-round; seasonal displacements of the convergence zone follow the displacement of the area with maximum insolation. (e) Biotic pump of atmospheric moisture: evaporation fluxes regulated by natural forests exceed oceanic evaporation fluxes to the degree when the arising ocean-to-land fluxes of moist air become large enough to compensate losses of water to runoff in the entire river basin year-round" (Makarieva & Gorshkov, 2007, p.1025)

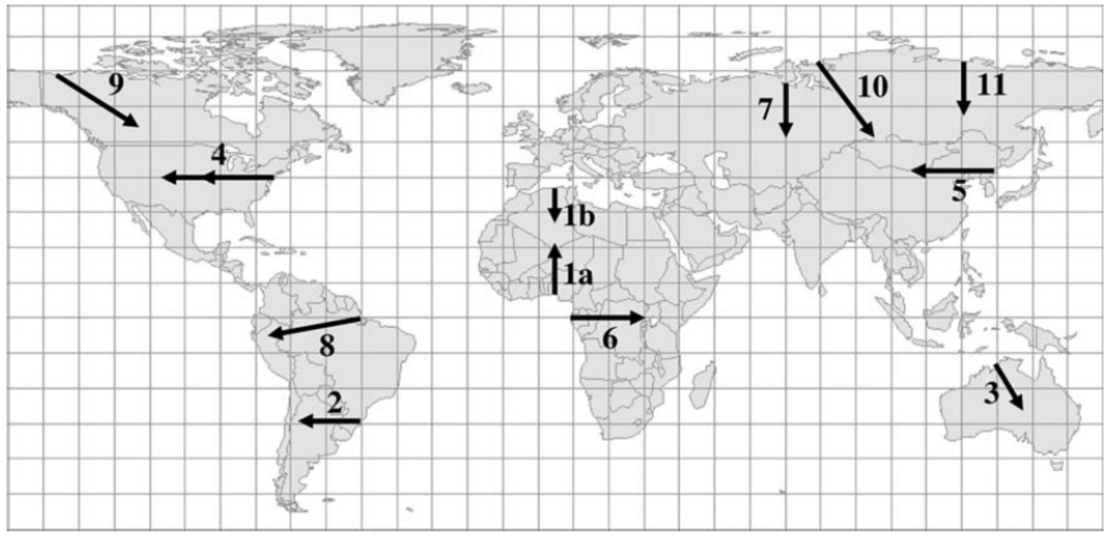


Figure 3. LOCATION OF TRANSECTS FOR STUDY ACROSS DIFFERENT GEOGRAPHICAL REGIONS. Adapted from "Precipitation on land versus distance from the ocean: Evidence for a forest pump of atmospheric moisture", by A.M. Makarieva et al, 2009, Ecological Complexity, 6: p.303. © 2008 by Elsevier B.V.

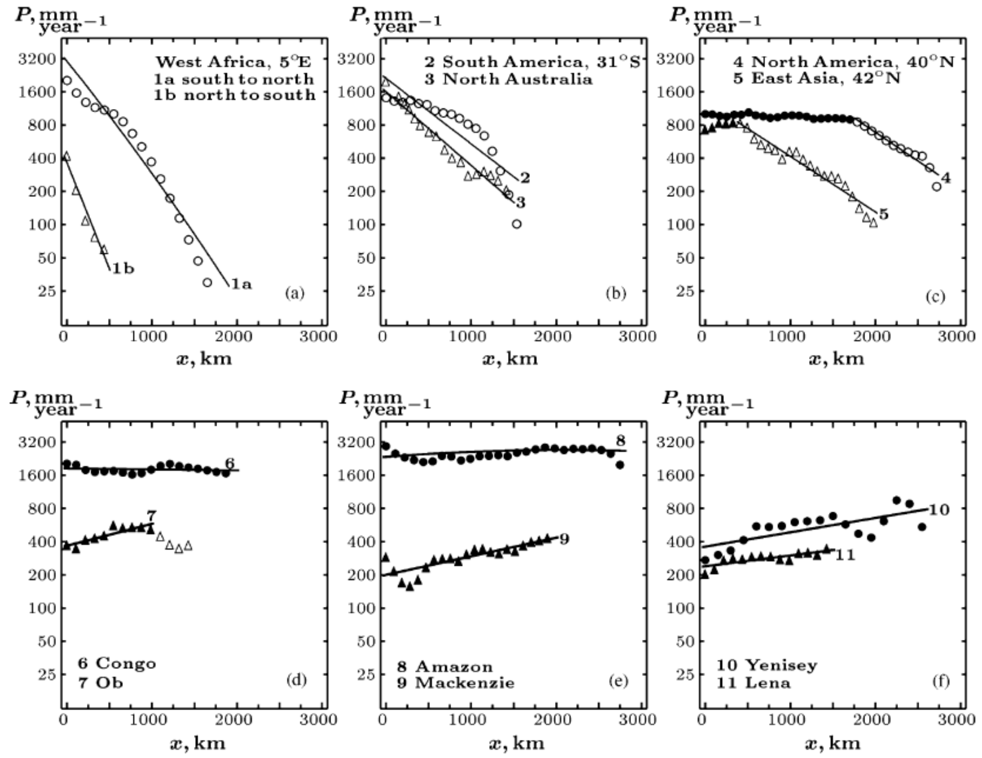


Figure 4. GRAPHS REPRESENTING PRECIPITATION VERSUS DISTANCE FROM THE COAST FOR EACH OF THE TRANSECTS. Adapted from "Precipitation on land versus distance from the ocean: Evidence for a forest pump of atmospheric moisture", by A.M. Makarieva et al, 2009, Ecological Complexity, 6: p.304. © 2008 by Elsevier B.V.

Figure 3 and Figure 4 from the study by Makarieva et al (2009), depict that the annual precipitation remains constant or sometimes increases with the distance from the oceanic coast in case of forested regions and in case of non-forested regions, the precipitation decreases exponentially as the distance from the coast increases. This is due to the high transpiration fluxes developed by the forests.

2.3. The Local Hydrological Cycle, Solar Energy and Soil Moisture

While the continental hydrological cycle is based on the horizontal movement of the moisture across large distances, the local hydrological cycle is essentially based on the vertical movement of the moisture and recycles water within a watershed, this cycle occurs over the seas and oceans as well as over the land as seen in Figure 5. It is estimated that about 50 to 65% of the precipitation that falls on the land goes into the repeated creation of precipitation over the land (Kravčík et al, 2007).

The evaporation and transpiration from the land is again the key source here. It is vital to maintain soil moisture and vegetation in the order to keep the circulation of small amounts of water circulating over the region (Kravčík et al, 2007).

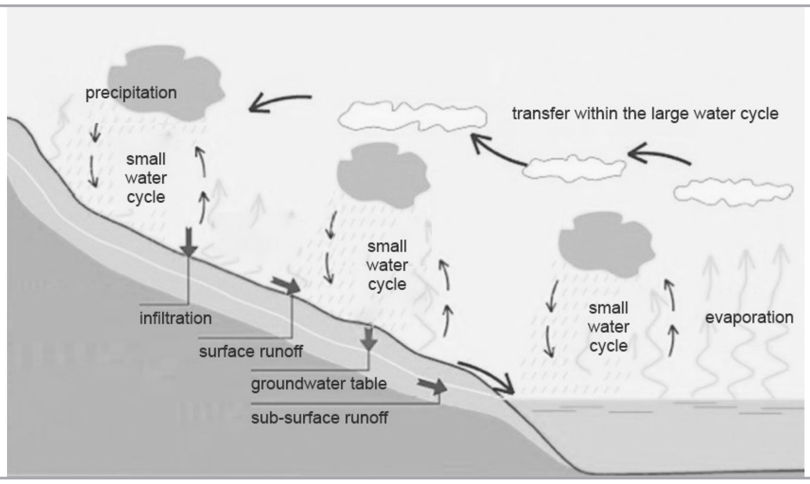


Figure 5. THE LARGE AND THE SMALL WATER CYCLES. Adapted from "Water for the Recovery of the Climate - A New Water Paradigm", by M Kravčík et al, 2007, Waterparadigm, p. 20. © 2007 by ML.

To ensure a stable cycle of evapotranspiration and precipitation on land, it is essential to maintain the water availability on land. It is a closed cycle, when the land is drained due to urbanization or agriculture, there is an increase in the amount of run-off water from the territory, the water is no more available for evaporation, the cycle is opened, and it ultimately affects the precipitation. The decrease in precipitation further affects the growth of vegetation and the situation keeps deteriorating thereafter. The solar energy falling on the land surface with low vegetation gets converted to sensible heat which otherwise would have been converted into latent heat through evapotranspiration. This solar energy converting to sensible heat implies an increase in the land surface temperature and radiation of heat absorbed by the surrounding man-made infrastructure since there is no dense vegetation to convert the water into water vapor. In densely urbanized areas, this causes Urban Heat Island Effect - the surface and air temperature of the urban area tends to be higher than the surrounding suburban and rural areas. This further creates a huge difference in the temperatures of day and night. As a result, air currents increase, and the water vapor is drifted away by the warm air and most of the water evaporated in the area is lost. There is a disruption in the rainfall patterns, light and frequent precipitations are replaced by heavy and infrequent precipitation from the oceans. To maintain the functioning of the local/regional water cycle it is vital to maintain dense tree cover as well as water bodies in the region (Kravčík et al, 2007).

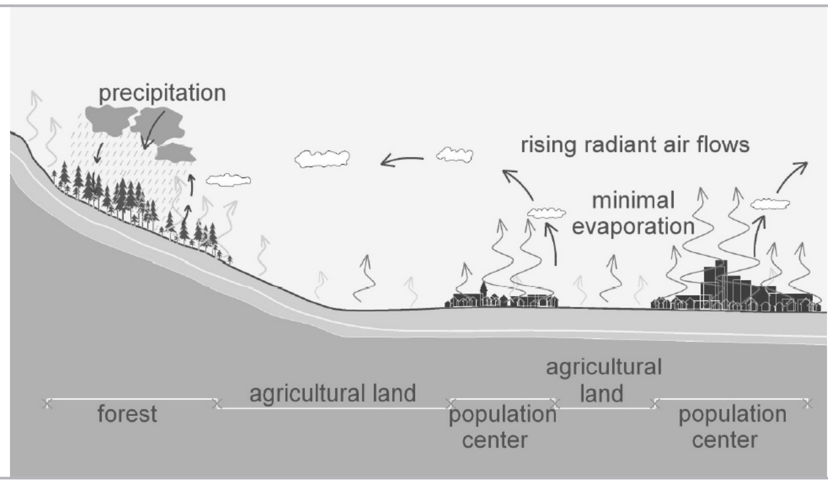


Figure 6. IMPACT OF CHANGES IN LAND COVER ON THE SMALL WATER CYCLE. Adapted from "Water for the Recovery of the Climate - A New Water Paradigm", by M Kravčík et al, 2007, Waterparadigm, p. 58. © 2007 by ML.

As seen in Figure 6, since there is decrease in water in a particular region due to deforestation, there is increase in the temperature which leads to adverse rainfall patterns not only in the region but also affects the neighbouring regions because the rising radiant flows as seen in the figure, pushes the clouds towards cooler environments. Dense tree cover is essential not only for the evapotranspiration but it also helps in maintaining the terrestrial temperature due to shade as well as due to evapotranspiration which reduces the sensible heat. As seen in the Figure 7, the surface temperature of the forest cover is the least followed by water surface in a mixed landscape and the difference in temperatures is of nearly 20 °C.

Forests also protect the water in the soil from intense evaporation by solar energy. The soil moisture in turn facilitates the growth of the vegetation. Deforestation on the other hand can cause soil compaction and hardening, soil erosions, reduction in water groundwater infiltration and increase in run-off which can sometimes lead to floods as well. The ecosystem services of the vegetation on the land extend in various directions and inter links various processes to maintain the water budget.

Other water retaining ecosystems on the land like wetlands, peat bogs, wet meadows have been removed and drained from large parts of the land across the world to make the land usable for agriculture and urbanisation. This has led to increase in the surface temperatures as well reduction in the evapotranspiration. Wetlands are as essential as forests for their ecosystem service of moistening the atmosphere through evapotranspiration and regulating the regional and global temperatures as well as formation of water vapor and clouds as seen in Figure 7 (Pokorný et al, 2016).

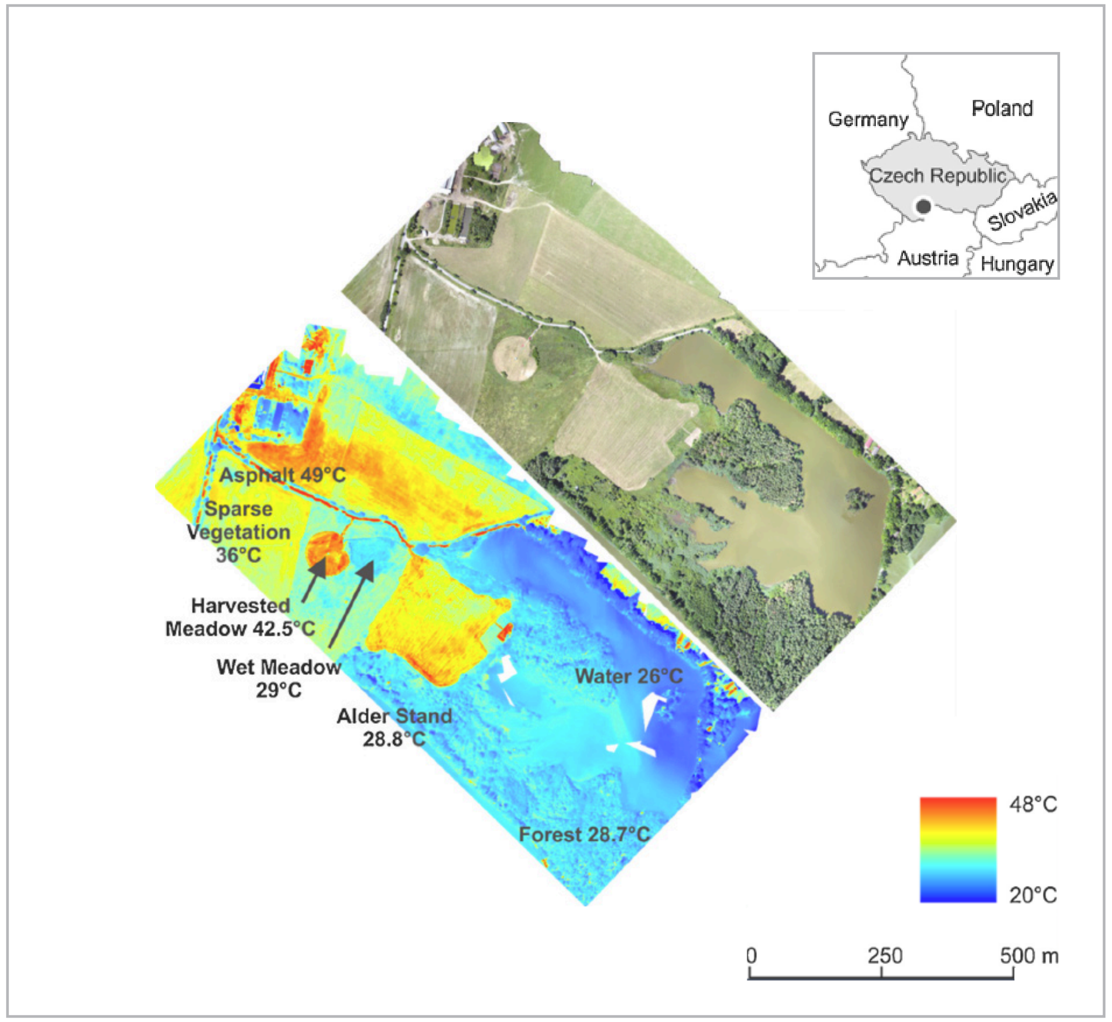


Figure 7. SURFACE TEMPERATURE DISTRIBUTION IN A MIXED LANDSCAPE. Adapted from "Trees, forests and water: Cool insights for a hot world", by D Ellison et al, 2017, Global Environmental Change, 43: p.55. © 2017 by Ellison et al.

3 | BACKGROUND: STUDIES ON FORESTS AND HYDROLOGICAL CYCLE

The notion that forests influence the terrestrial hydrological cycle has a long history. In ancient Greece, Theophrastus (371–287 BCE) argued that Greece had experienced climatic change due to the draining of marshes and extension of agriculture (Bennette & Barton, 2018 ex. Glacken,1976). People have realized the relationship between deforestation and scanty rainfall at different places in the world at different periods of time. Tribal, indigenous people who live in the forests and worship them, have intuitively known the working of the nature and that rainfall will recede with loss of vegetation (Smart Biotic Pump, 2018).

A modern take on this concept started from the 15th century and continues to the present day.

"The Genoese-Spanish explorer Christopher Columbus (1451–1506) reasoned that the intense mid-day rains in the American tropics were induced by the dense tropical forest foliage which had a high moisture content that was recycled. He also argued that deforestation in the tropics led to declining rainfall. The idea that forests strongly influence rainfall emerged in the early modern era (1450–1750) in response to the Scientific Revolution and European exploration and expansion throughout the world (Grove 1995). Columbus's ideas reflected a widely-held belief that deforestation in the Canary Islands, Madeira and Azores Islands during European colonization caused a decline in overall rainfall. Naturalists in the 1600s and 1700s argued similarly that deforestation on the islands of St. Helena and Mauritius and in the Caribbean led to similar rainfall declines" (Bennette & Barton, 2018, p.2).

Although many speculated theses connections, there wasn't a unified agreement by the scientists on this idea until the early nineteenth century as some of the critics indicated that deforestation rather had a positive effect on the climate. For example, Georges-Louis Leclerc (1707-1788) who was an influential French biologist, based on his philosophical view, expressed that deforestation, farming and stream management in the newly colonized continents would eventually improve the impoverished fauna (Spamer & McCourt, 2006). Similarly, Thomas Jefferson (1743-1826), who was an American Statesman, Architect and a naturalist, held the idea that due to climatic changes caused by settlements, American cold and moist climate would improve and become more tolerable (Kingsland, 2011).

Alexander von Humboldt (1769-1859) who was the father of meteorology, ecology and physical geography, suggested that forests have a connection with the rainfall, in a more scientific manner. There were many researchers who wrote about the forests-rainfall influences although it was criticized most of the times. George Perkins Marsh (1801-1882), in his book Man and Nature: Or, Physical Geography as Modified by Human Action (1864) presented his view on how throughout the history humans changed the regional climate due to deforestation. This concept of Forests-Rainfall-Climate gained momentum in the 1800's as the colonization spread in the world which caused deforestation leading to reduced rainfall. But the concept declined globally due to criticism by hydrologists and researchers as there were no appropriate scientific evidences. The methodologies adopted were questioned in terms of their validity.

The Forest-Rainfall concept revived in the late 20th century as climate-modelling evolved and with the studies of effects of increased emissions of CO2. Issues emerging from deforestation were widely discussed and further advancement in science acknowledged the global warming rooted in forest loss. The role of forests in mitigating the pollution and their connection with rainfall was re-established through further understanding of the biology and mechanism of transpiration by trees. The increase in regional and global temperatures was linked with the loss of evaporation by trees due to deforestation leading to disruptions in the hydrological cycles. The criticism on the idea that forests influence rainfall continues to the present time. Ellison et al (2012), discuss the two school of thoughts – Supply-side and Demand-side which argue whether the impact of forests on water yield is positive or negative. From the Demand-side, Csaba et al (2013), present their view that man-made afforestation at dryland edges reduce the stream flow in the watersheds due to higher water use by the trees. The Demand-side commentators do not take into consideration that this consumption of water by trees is eventually used up in the evapotranspiration by the trees, providing precipitation on a larger scale. The Supply-side on the other hand recognizes the positive impact of forests on the hydrological cycle on a larger scale. There has not been a unified statement from the researchers mainly because of the difference in scales in which the analyses have been framed.

Many studies have been carried out for a long time analysing the contribution of vegetation to the atmospheric moisture through transpiration but the most significant concept in the recent times is the Biotic Pump Theory, proposed by the two Russian scientists Makarieva and Gorshkov (2007) which postulates the role of forests in transporting the moisture from the oceans to the inland and being the main driving force for precipitation on the land as discussed in the section 2.2. Their articles on this subject have drawn attention of many researchers like Bunyard et al (2014, 2015), Meesters et al (2009), Jaramillo et al (2018) to look at the factors driving climate change from a new perspective. And there have been further studies done by these researchers based on this theory analysing the Forest-Rainfall dynamics at various scales and with different methodologies. The following sections give a summary of some of these studies.

3.1. Studies by Makarieva and Gorshkov

Makarieva and Gorshkov have a sequence of research papers starting from the conception of biotic pump and the following papers make in-depth analyses demonstrating the quantitative justification underlying the theory. Makarieva and Gorshkov (2007) outlines the concept of biotic pump based on the geophysical and ecological principles to indicate the role of forests in transporting the moisture from the oceans. They take the case of various transects on land at different geographic locations and compare the ocean-to-land moisture transport on forested versus non-forested land regions. They demonstrate this on a continental scale to express the exponential weakening of precipitation with distance from the ocean in case of non-forested territories. Applying the physical principles, they establish the vertical and horizontal movements of air fluxes from ocean to land in presence of natural forests.

In context of ecological principles, they describe the ecological system of natural forests and that only natural forests having huge expanses adjoining the coast would function as biotic moisture pump and not planted forests or any other types of vegetation. Native species communities in natural forests over a hundred millions of years have developed a complex set of genetically encoded biophysical and morphological traits that aid storage as well as extraction of soil moisture and also maintain a non-trivial balance wherein the evapotranspiration by the trees is intense enough for the forest to act as a biotic pump and at the same time soil moisture never gets depleted. Some of the other traits that the natural forests possess are the biogenic aerosols produced by the trees which help to control the intensity of water vapor condensation over the forests; the height stature of the trees maintain the vertical temperature gradient under the forest canopy regulating the amount of soil moisture evaporation as well as resist high velocity winds due to surface friction. Other species like bacteria, fungi and animals, all form a part of this complex ecosystem structure of the natural forests which enable its function as a biotic pump. Planted forests do not possess such traits and hence are unable to maintain the required moisture levels and fail to act as biotic pumps (Hance, 2012). This signifies the importance of content wide natural forests to tackle desertification of the land masses.

Makarieva and Gorshkov (2008) establish the physics underlying the biotic pump through mathematical calculations of air fluxes. They state that in case of undisturbed natural forests with continuous canopy of tall trees, "the area of the evaporating surface of leaves is tens of times larger than the area of the canopy projection onto the ground" (Makarieva & Gorshkov, 2008). This implies that forest evapotranspiration is significantly higher compared to evaporation from an open area which leads to the pull of moisture from oceans to the land even when the land and ocean temperatures differ. And this transported moisture compensates for the river runoff at any distance from the ocean throughout the year (Makarieva & Gorshkov, 2008). This is demonstrated through the correlation of annual precipitation and the distance from the ocean for selected forested and non-forested geographical areas as depicted in Figures 2 and 3. Makarieva et al (2013), demonstrate the seasonal variability and the efficiency of forests to pump moisture from the ocean. The precipitation patterns are not constant throughout the year, they vary with seasons, with changes in the atmospheric temperatures. They compare the precipitation patterns between seasonal - boreal forests and the evergreen - equatorial forests. In boreal forests, the distance up to which ocean to land moisture is transported is minimal during the winters and increases up to five times during the summers as the forest is active while in case of equatorial forests, the annual precipitation remains constant most of the year, but the coefficient of variation for monthly precipitation declines exponentially towards the continent interior. This is concluded by analysing the monthly precipitation levels across equatorial rainforest and boreal forest transects at different geographic locations. Monthly precipitation versus distance from the coast are plotted to prove the existence of forest biotic pump and its seasonal variations. This explains that during the winters when the solar energy is low, the evaporation over the forest canopy is low as compared to the oceans and thus the moist air flows from the land to the ocean, creating a dry atmosphere on the land during the winters. But the evaporation does not stop from the forest due to the soil moisture reserves from the wet period. This soil moisture reserve can be maintained only by the natural forests due to their ecological capabilities evolved over the millions of years. Makarieva et al (2013) thus state that forests have evolved over the years to generate rainfall.

3.2. True or False

Afforestation results in positive water yield or negative water yield? As mentioned by Ellison et al (2012), there are two school of thoughts regarding the effect of forests on water yield. The Demand-side as presented by them are of the opinion that afforestation reduces downstream water availability as the trees consume the water while the Supply-side state that afforestation improves water availability on regional and /or global scales. The comparisons have been put forward in wrong context because the Demand-side commentators present their views which are mostly based on the impacts of industrial monoculture afforestation projects.

For example, a report by Karumbidza & Menne (2011), put forward the impacts on water resources due to an industrial tree plantation project carried out by a Norwegian company in Tanzania. They present the negative impacts on local hydrological conditions caused by alien pine and eucalyptus tree plantations on natural grasslands. The report although recognises that the water consumed by the plantation will eventually return back as precipitation but not necessarily at the plantation site. The contributed air moisture will benefit other areas depriving the downstream areas with water. The selection of tree type for plantation becomes critical here because Eucalyptus is an evergreen tree which consumes high amount of water all year round and can lead to soil degradation in the tropics and subtropics. Tang et al (2007),

suggest through their study in China that eucalyptus can be beneficial when planted on small areas and are not suitable for forest cover restoration. Natural and mixed-forests yield better hydrological functions than monocultures.

The Supply-side as presented by Ellison et al (2012) assert that large scale forests increase the amount of precipitation but may not observable or accountable on a smaller scale. The arguments on these two sides are in very different context and are not comparable. The important point here is that inappropriate afforestation practices can cause damage to the local environmental conditions on a short-term scale and hence afforestation plans need to consider the regional ecological conditions in order to benefit local and regional scales.

Makarieva et al (2014) state that restoration of forests will increase local rainfall as well as contribute in the ocean to land moisture transport on a continental scale.

3.2.1. Studies Underpinning the Biotic Pump Theory

Bunyard et al (2014) and Bunyard et al (2015) present two different kinds of experiments which are attempts to validate the physics underlying the Biotic Pump Theory. The former study is based on the actual data collected from a meteorological station to analyse the relationship between the evaporative force generated by the forests and the resulting wind flow from the oceans. The meteorological station is located in the lowlands of Caribbean Costa Rica with majority of the area being a primary tropical forest and rest of the area a secondary forest. Using the principles of thermodynamics, the data has been analysed to prove that the trade winds (a wind blowing almost constantly in one direction) are influenced by changes in the evaporative force over the forest canopy.

The latter study is an experiment done in a laboratory set up to test the physics underlying the Biotic Pump Theory. A specially designed apparatus is set up to investigate whether the horizontal flow of wind is driven by condensation induced atmospheric pressure as stated by Makarieva and Gorshkov. And the experiment succeeds in demonstrating that it is the “condensation and not buoyancy is the major mechanism driving airflow, thus lending strong support to one of the main tenets of the Biotic Pump Theory” (Bunyard, 2015). Although this experiment is based on model built in the lab and is on a micro level but according to the researchers, the same laws of physics work at the macro level as well and therefore the fundamentals of the mechanism should not be any different in the atmosphere at large. But there could be other factors adding up on a larger scale, we cannot ignore them and accept this to be the ideal situation at all scales. These studies demonstrate that forests act as a biotic pump to extract moisture from the oceans to the inland continental areas influenced by the decreased atmospheric pressure followed by condensation. Such studies are very crucial for further implications of this theory.

3.2.2. Studies Challenging the Biotic Pump Theory

The article by Meesters et al (2009) questions the role of forests in redirecting the atmospheric circulation of winds although they might be influential to some extent. According to them, atmospheric circulation determines where forests can grow and not vice-versa. And the second point that they make through their study is that although atmospheric circulation is influenced by evaporation, condensation and surface differential heating, the first two are secondary factors and differential heating at surface is the most important factor. They question the physical foundations of the biotic pump theory by making comparisons between the traditional theory and the proposed evaporative force theory.

The researchers also state that Makarieva and Gorshkov have ignored "complex spatio-temporal atmospheric flow patterns as the ascending and descending branches of the Hadley Circulation, the shielding effect of mountain ranges, organized convection around forested islands, etc., all of which are fundamental to understanding precipitation regimes and vegetation zonation" (Meester et al, 2009).

But according to Makarieva and Gorshkov (2009), the theory of evaporative force does not replace or contradict the traditional theory but it in-fact fills the gap in understanding certain atmospheric processes. They explain it through the example of hurricanes which develop near isothermal surfaces, implying that the traditional theory of differential heating does not fails to explain this phenomenon. "The evaporative force concept that relates wind velocities to spatial differences in the intensity of condensation rather than heating provides a unifying explanation to both hurricanes and tornadoes as well as to stationary circulation patterns" (Makarieva & Gorshkov, 2009).

Makarieva and Gorshkov state that since the modern circulation models do not consider the physics of forest moisture pump, there have been large discrepancies in their calculations of water budget for river basins, for example, as per the models the amount of moisture transported from the oceans to the Amazon river basin tends to be twice less than the estimated Amazon run-off. Biotic pump theory hence solves this unresolved puzzle (Makarieva & Gorshkov, 2009).

A recent study by Jaramillo et al (2018) try to prove that the hypothesis of forest biotic pump is wrong through mechanical and thermodynamic analyses. They suggest that "Makarieva & Gorshkov's theory is invalid, because it fails to include the other component of the Newton's third law pair, namely, the downward force of the dry air on the water vapor. Since these two forces cancel, their net effect on the moist atmosphere as a whole is zero. Thus, they have no effect on geophysical fluid dynamics." (Jaramillo et al, 2018). They criticize the theory of condensation induced atmospheric dynamics.

The article by Makarieva et al (2018) justifies their theory with the equations of hydrodynamics and state that the atmospheric power is largely influenced by the condensation induced atmospheric dynamics and that the effect of the differential heating is very small in comparison.

3.3. Methodologies Adapted in Various Studies

In the studies by Makarieva and Gorshkov (Makarieva & Gorshkov 2007; Makarieva & Gorshkov 2010; Makarieva et al. 2009; Makarieva et al. 2013), they firstly indicate the presence of a biotic pump in natural forests by plotting distance from the ocean versus amount of precipitation for various forested and non-forested transects across the world. They further prove the hypothesis through physical principles deconstructing the mechanisms of air motions as well as the biological principles grounded in plant physiology.

The detailed study by Kravčík et al (2007), uses a thermal camera to demonstrate the temperature regulating function of the vegetation by taking the pictures of plants vs ground, plantation vs man-made infrastructures and landscapes with different types of landcover. The temperature differences are visually depicted to illustrate the impact of vegetation on the regional water and temperature gradients. They also use graphs to show the trends in temperature on drained land versus natural land and also compare urban areas with vegetated areas. As seen Figure 7, the surface temperature of area covered by asphalt was almost double the temperature of the area covered with forests and water within the same landscape.

Ellison et al (2012), study the source of precipitation across major river basins in the world. They calculate the percentage of precipitation derived from local, terrestrial, oceanic and polar sources based on the secondary data collected for over a 50 year time period and also calculate the contribution of each of these sources on the average annual precipitation for various river basins considering the seasonal variability as well. They further calculate the ratios of terrestrial to local average precipitation and evapotranspiration multiplier to understand the trends. For example, in the Mississippi River basin as depicted in Figure 8, indicates that precipitation derived from the total terrestrial source is almost double the amount derived from oceanic sources during spring and summer, and almost equal during fall and winter. There is a high seasonal variability in the contributions of the local sources to the total terrestrial precipitation.

Similarly, calculations across other river basins also indicate that the evapotranspiration during the summer months is a major contributor in the total terrestrial precipitation and local sources do not seem to be as significant. Oceanic sources contributions vary among different river basins and in most cases exceeds the total terrestrial contributions but only marginally.

The study by Bunyard et al (2014), use the same physical principles as proposed by Markarieva and Gorshkov. They use real time data from a meteorological station to do the calculations and depict the relationship between the wind speed and evaporative force by plotting graphs for each month of 3 months study. They infer that the air flow from trade winds follow the changes in the evaporative forces which is evident from the graphs as seen in Figure 8.

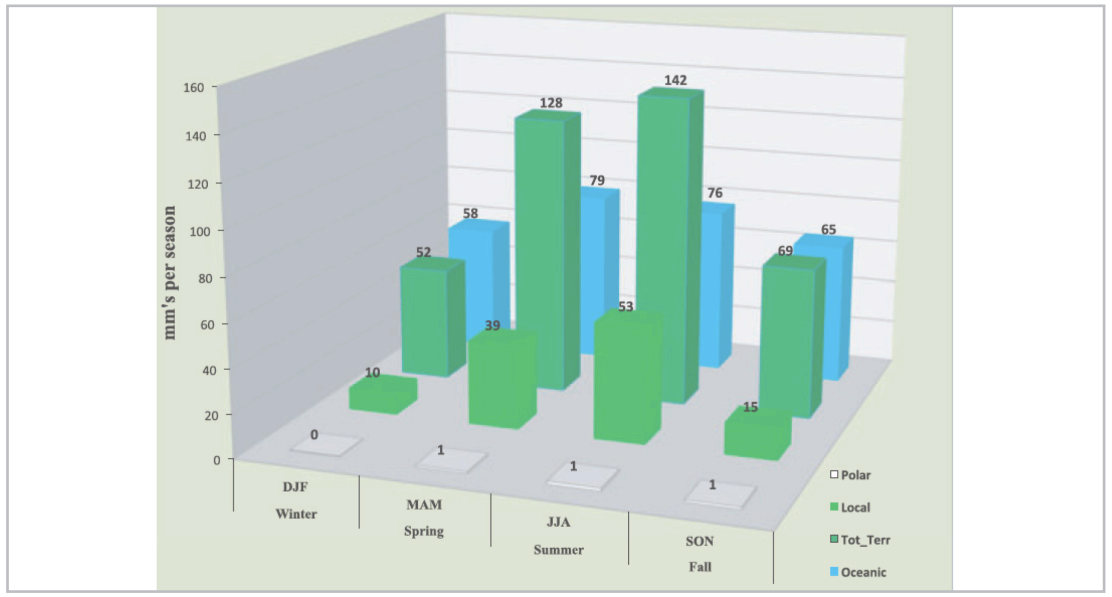


Figure 8. AVERAGE ESTIMATED PRECIPITATION IN % AND MM PER SEASON IN THE MISSISSIPPI RIVER BASIN (1948–1997). Adapted from "On the forest cover-water yield debate: from demand- to supply-side thinking" by D Ellison et al, 2012, Global Change Biology, 18: p.815. © 2011 by Blackwell Publishing Ltd.

Another approach adapted is a laboratory experiment as presented in the study by Bunyard et al (2015). An enclosed apparatus was designed and built to test if condensation of water vapor at a sufficiently high rate results in a uni-directional airflow. Newton's laws of physics are used to calculate the rate of condensation inside the apparatus and about more than hundred experiments with varying conditions were conducted to arrive at the results which showed a significant correlation between airflow and the rate of condensation.

> *"The rotary air flows created appear to be consistent both in direction and velocity with the biotic pump hypothesis, the critical factor being the rate change in the partial pressure of water vapor in the enclosed body of atmospheric air. Air density changes, in terms of kinetic energy, are found to be orders of magnitude smaller than the kinetic energy of partial pressure change"(Bunyard et al, 2015, p.10922).*

3.4. Limitations of the Various Studies

For the study done through an experiment in a laboratory, although the researchers claim that the same dynamics would work on a larger scale, yet there are numerous factors that can emerge on an atmospheric scale. Biology and the physics underlying the concept of biotic pump theory are complex matters, hence a laboratory experiment may not be a strong evidence.

In another study, the results are drawn using the real time data from a biological station in a tropical forest and the principles of thermodynamics. But the study is limited only to the dynamics of the airflow and the evaporative pressure for a few months, and does not calculate the annual water budget of the river basin. The precipitation dynamics are not incorporated and hence the results only indicate a conjecture towards the biotic pump hypothesis. On the other hand, the study done by Ellison et al (2012) they project the precipitation dynamics and sources of annual precipitation for various river basins but they do not consider the dynamics of airflow and hence again it only suggests towards a possibility of biotic pump system. The study was limited only to analyse only the weight of oceanic, terrestrial and local sources of precipitation.

The study by Meesters et al (2009) comments only on driving forces of the atmospheric circulation and does not address the problems of moisture transport and the spatial distribution of precipitation. The working of the ecological processes and underlying mechanisms are very complex and pose as limitations for the researchers to deconstruct them and analyse. Factors affecting them vary with varying scales of geographical area being analysed. The scale of the study in this context is crucial.

3.5. Re-Examining the Processes Underlying Global Water Cycle

There is a shift in understanding the mechanisms involved in the water cycles and the driving forces but still there is not enough study to figure out the complete picture because the processes involved are complex and variable. Although the ideas are largely recognized but there are many factors which need in-depth analysis for further evaluations.

For example, as perceived from the data that large part of the precipitation on the land is derived from the land itself, but the amount of this precipitation depends on factors like topography, other geographical conditions, change in land-use within the river basins as well outside the river basins, varying stomatal behaviour of trees, abundance of biological and non-biological aerosols in the atmosphere, pollution levels, dynamics of ice crystals due to biological ice-nucleating particles emitted from decaying leaves, and atmospheric circulation of winds induced by temperature gradients. Sheil (2018) suggest that now it is known what factors influence and affect the hydrological cycles but interdisciplinary research is needed to analyse these linkages to accurately understand the biology of water cycles at different levels.

3.6. From Theory to Practicality

The role of forests to mitigate climate change was widely viewed as pools that sink carbon dioxide from the atmosphere but there has been a shift in understanding their function as facilitators of terrestrial rainfall and temperature regulators as more important aspects compared to carbon sequestration. And it is important that this change in the perspective should now be applied into practice by adopting preventive measures and developing strategies for sustainable planning. It is necessary to spread the awareness from the scientific community to other disciplines like planners and governing institutions so that efforts are made in the right direction.

When planning on wider scale, it is important to consider the effects of land cover change not limited by the geographical boundaries. In case of natural forests acting as a biotic pump on continental scales, the policy level decisions taken in one country can have implications on areas stretching to countries further inland. For planning strategies on such wide scale, we would need involvement of organisations and institutions which can co-ordinate decisions across political boundaries, for example – International Union of Forest Research Organizations (IUFRO), The Centre for International Forestry Research (CIFOR), United Nations Framework Convention on Climate Change (UNFCCC). Current framework of international policies is based on carbon related issues and do not recognize the relationship of forests with water and energy cycles. We need these essential policies on local/regional level as well as on global scale. In order to tackle climate change with this perspective, a choreographed and coordinated system of measures needs to be followed by countries and progress towards a common goal.

Ellison et al (2017) state that "most water assessment tools still do not consider flows of atmospheric moisture. Land planning tools for ecosystem services, however, are beginning to integrate the nuances of the "right tree in the right place" as a well-understood function" (Ellison et al, 2017). Climate simulation models can be very useful tool in this context but they have not been accurately built yet. They need to be cross examined with real time data to evaluate their predictions. Technological advancement is equally important and need to be developed involving experts from multiple disciplinary so that all the key processes are considered and the theories are well tested before implementation.

4 | URBAN FORESTS AND PRECIPITATION

Many cities around the world are facing water scarcity. With the depleting levels of groundwater, it is very important to take measures to maintain the water retaining capacity of the urban landscapes. There are extreme weather events like floods and draughts recurring in many parts of the world. A regulated precipitation pattern is very essential to tackle these problems. One of the major contributors for such weather events is considered to be the reduction in evaporation as trees are replaced by the buildings and other urban surfaces. This has been previously mentioned in section 1.3, how the conversion of solar energy into latent by plants is replaced by conversion into sensible heat by the urban surfaces. This ultimately affects the weather and climate by altering the rates of precipitation and local wind patterns. The only solution to mitigate such problems is through extensive vegetation.

Governments, institutions and people around the world are taking initiatives to develop green infrastructures like forests, wetlands and other green spaces in their cities for sustainable urban development. The benefits of dense vegetation/forests have been well recognized because of their ability to regulate land degradation and soil erosion, regulate the temperature by providing shade, provide healthy spaces for exercising and recreation, and biodiversity conservation. Especially in the urban environments, trees are beneficial as they control the levels of air pollution as well as noise pollution, and as they add beauty in the concrete jungles. Many cities have adopted plantation drives and other strategies towards greener and cleaner environments but one aspect that is not yet been much recognized is the ability of the forests to influence the precipitation patterns. Although many understand their importance in terms of absorbing the rainfall and retaining the water in the landscape but an important ecosystem service that they provide by inducing the rainfall is still not very well recognized, understood or implied in the planning process. Trees through evapotranspiration generate water vapor contributing to the small water cycle in the local area which further induces precipitation either in the same area or the moisture might get transported to the neighbouring areas but it is a very important aspect which needs to be studied for addressing the terrestrial water availability problems faced by the world today.

The analysis of spatial distribution of rainfall with respect to the forest cover in an urban setting is important for reducing run-off, flooding or landslides and as well as for maintaining the water balance in a landscape. In section 1.3, the effects of vegetation on the small hydrological cycle has been discussed, but then how does afforestation or presence of forested area in a city influence the spatial distribution of rainfall? Relatively little research has been done in this context. The biotic pump theory is applicable in case of large scale forests stretching from a coast but the question whether forests in coastal urban areas influence moisture transport and spatial distribution of rainfall in cities needs to be addressed.

For example, in case of Mumbai which is a coastal metropolitan city located on the west coast of India. According to the article from a newspaper (Pinto, 2019) the rain data from 2019 monsoon season showed that the maximum rainfall was recorded in the suburban areas (compared to all artificial areas). These is a huge expanse of green cover around these areas, they surround a national park which has small hills as well and some other areas have water bodies while the city side has more built up areas and very less green cover. This clearly indicates that the clouds are observed more towards the areas with dense vegetation and partly also due to the topography. Although the hills are very small, they result in orographic enhancement of the rainfall (orographic lift occurs when an air mass is forced from a low elevation to a higher elevation as it moves over rising terrain (Pinto, 2019). Wind patterns are also to be considered along with the above-mentioned factors.

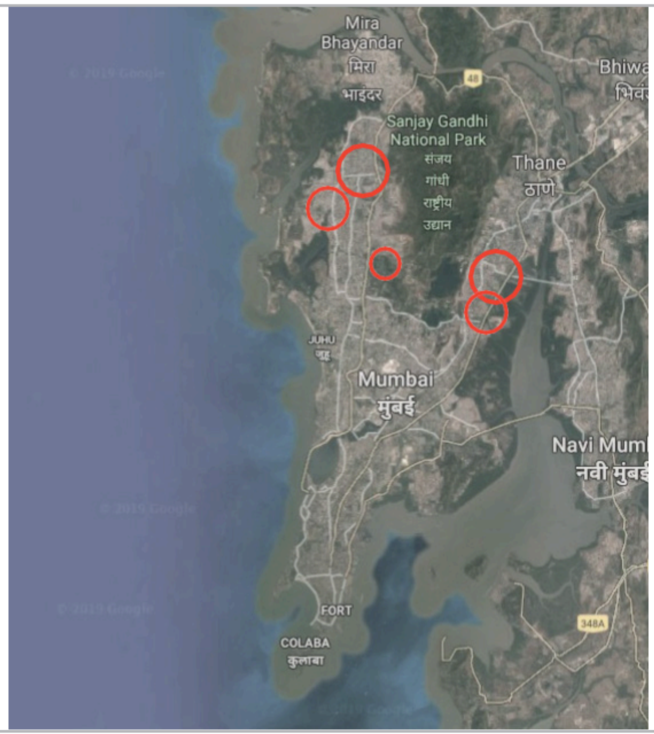


Figure 9. MAP OF MUMBAI – AREAS WITH MAXIMUM RAINFALL 2019.

As seen in Figure 9, the southern part of the city is very densely urbanized and there is hardly any green cover. The difference in the precipitation levels is visible between the vegetated and non-vegetated areas although it is a coastal city.

The afforestation programs in the cities are mainly based on the carbon cycle. In context of water, urban forest ecosystem services are attributed only to avoided run-off, flooding, rainfall interception and water quality. Although transpiration is considered as an ecosystem service but the planning or conservation goals are not focused on this aspect and neither are the rainfall patterns seen as linked with the forest cover.

Water security is attracting the global attention now and many nature-based solutions are being analysed and employed. There are a few freely available models for quantifying the urban and peri-urban forest benefits, for example – i -Tree, developed by United States Forest Service which is being used globally for assessing and valuing the impact of trees and forests - from the scale of local forest parcels to regional landscapes - on environmental quality, human health and well-being, but none of these models consider the forest-rainfall connection.

“Although the links between forests and water are recognized, however, they are not adequately accounted for in the indicators used for monitoring. Indicator 6.6.1, for example, includes only swamp forests, mangroves, and forests temporarily or permanently inundated by water (UN-Water, 2017). These forests undoubtedly have a role in disaster risk reduction, but other forests with potentially significant value for water-related ecosystem services are unrecognized, such as forests managed for water supply and other forest types known to have strong roles in hydrological cycles (e.g. riparian and cloud forests)” (Nagabhatla et al, 2018, p.49).

The indicator 6.6.1 mentioned by Nagabhatla et al (2018) is an indicator developed UN-Water for target 6.6 which aims at protecting and restoring water-related ecosystems by 2020 as they are important for improving water quantity. Indicator 6.6.1 is basically ecosystem health monitoring tool to be used by the UN countries to monitor the target progress. The target includes water-related ecosystems such as vegetated wetlands, rivers, lakes, reservoirs and groundwater, as well as those occurring in mountains and forests, which play a special role in storing freshwater and maintaining water quality. (Target 6.6 – Ecosystems, n.d.). There is no consideration of the forest-rainfall connection as a major factor in their target/ indicator.

It would be really beneficial to have an indicator on land cover - rainfall distribution in the urban watersheds especially because urban areas are under immediate threat and need urgent attention. It is not very clear whether the presence of a forested area within the city will cause rain within the same area or attract moisture and cause rainfall, as was seen in case of river basins in Figure 8, where local area evapotranspiration was not a major contributor but other environmental benefits of urban forests in general have been assessed and a lot of cities are adapting policy changes to protect or develop urban forests. The urban areas not only benefit from trees within the city and peri-urban forests but also from faraway forests. In fact, faraway forests might have a greater impact on the rainfall generation than the forests in the watersheds around cities. For example, São Paulo in Brazil witnessed a devastating water shortage in 2015 due to deforestation in the Amazon forest (Watts, 2017).

Each of these three forests - inner forests, nearby forests and faraway forests have different kinds of environmental impacts and all of them are necessary for the ecology of the cities as seen in Figure 10. Inner forest is all the trees spread in the city - along the sidewalks and parks. These green spaces affect the microclimate of the city, it helps replenish the groundwater, absorb pollution as well as provide potential for recreation. The nearby forests capture and filter drinking water, absorb pollution and, prevent flooding and landslides. Faraway forests – up to hundreds or thousands of kilometres can affect the city environment. These undisturbed forests are essential for one very important function which is generating rains in the region.

"A 2005 study by NASA found that deforestation in the Amazon region of South America influences rainfall from Mexico to Texas and in the Gulf of Mexico, while forest loss in Central Africa affects precipitation patterns in the upper and lower U.S Midwest. Similarly, deforestation in Southeast Asia was found to impact rainfall in China and the Balkan Peninsula. It is important to note that such changes primarily occur in certain seasons and that the combination of deforestation in these areas enhances rain in one region while reducing it in another" (Bettwy, 2005).

Figure 10. ENVIRONMENTAL BENEFITS OF DIFFERENT SCALES OF FORESTS ON THE CITY. Adapted from "45 Cities Pursue a New Urban Strategy: Protecting Forests Near and Far" by J-R Pool et al, 2018, World Resources Institute.

In the city of Beijing, China, data collected on the distribution of precipitation from about ten years showed that the areas receiving maximum rainfall were all in and around the peri-urban forest area (Zhang, 2017).

As our forests and water are both under threat, their relationship needs immediate attention as they can help restore a lot of environmental disturbances caused by anthropogenic activities. And as most of the world population resides in the cities that are at the tip of water scarcity, restoring urban forests can benefit the hydrological cycle which will eventually curb the water crisis at large. This nature-based solution needs more study especially on forest-rainfall connection in the urban forests. It is a challenge to balance the green cover and the built areas as cities are oriented towards economy but before planning and strategizing the sustainable development goals, urban ecosystem services needs to be scrutinized, looking beyond the carbon-centered mitigation as it can lead to economic gains in the long run.

Although there are studies which link the forest-rainfall connection on a continental scale, connections on a local scale are difficult to determine but is an opportunity for research.

5.1. Global Scenario

Temperature Trend - On a global scale, there has been a consistent increase in the mean temperatures since the end of the 19th century and has been rapidly increasing since 1970s while the precipitation trend has been varying from Northern Hemisphere to the Southern Hemisphere. It is difficult to generalise the global precipitation trend as it has high spatial and temporal variability. The last decade (2006-2015) was the warmest decade on record. The change in global annual temperature ranges from 0.09°C/decade to 0.24°C/decade during the time period 1961-2016 (NASA, 2020).

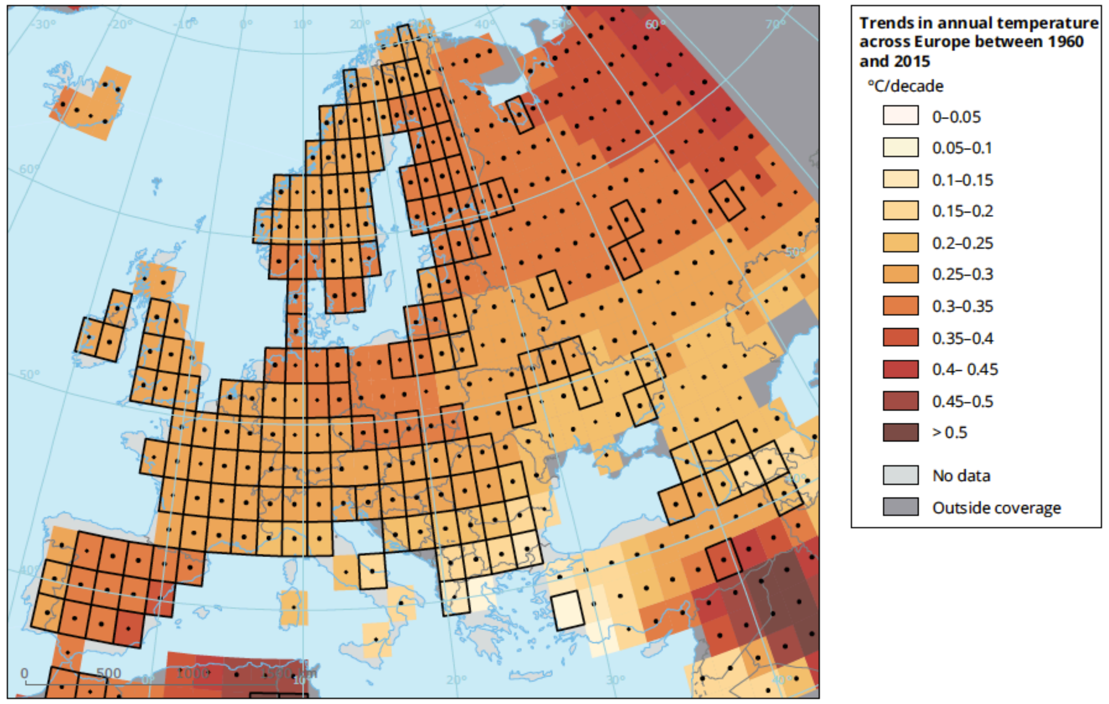
Precipitation Trend – the global mean precipitation values do not indicate any statistically significant trend for the time period 1979-2014 but there are patterns of increasing and decreasing trends across the globe (Adler et al, 2017). The trends for the time period 1979-2008 show an increase over the subtropical oceans and a decrease along the equatorial oceans and hence the overall trend is flat (Wang et al, 2016).

Forest Cover - Hansen et al (2013) examined the changes in the global forest cover for a period of 12 years (2000-2012) which indicated a global forest loss of 2.3 million square kilometres and a gain of 0.8 million square kilometres. Some regions exhibited accelerating losses while some regions showed gains in the forest cover.

5.2. European Scenario

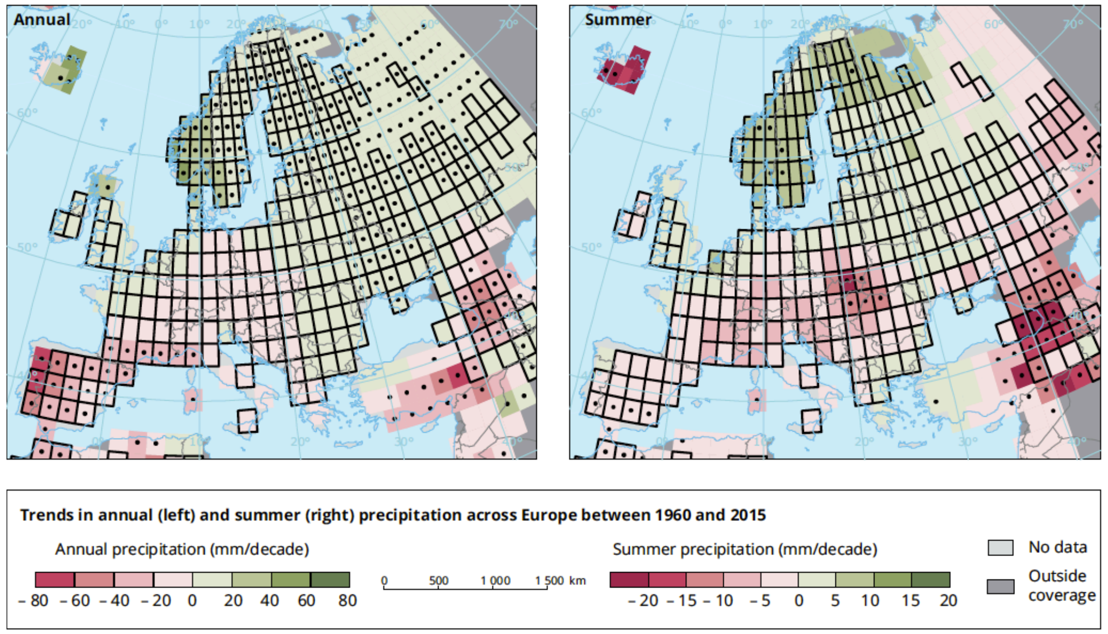
Temperature Trend - In the European context, the rate of change in annual temperature ranges from 0.05°C/decade to 0.4°C/decade as seen in Figure 11, which is higher than the change in global average temperatures. Summer temperatures in the last three decades have been record high since past 2000 years, more affected areas being Iberian Peninsula, Central Europe and North-eastern Europe. Winter temperatures are more affected in the Scandinavia (EEA, 2017).

Precipitation Trend - In case of precipitation, there have been variations at sub-continental level – increase in precipitation in the Scandinavian region and decrease in the Iberian Peninsula in the 20th century as seen in Figure 12. Climate models have projected a statistically significant increase in the annual precipitation for large parts of Central Europe and Northern Europe, and decrease in the Southern Europe. On an average, heavy precipitation events have been more frequent across Europe but it has been more intense in the Northern and North-eastern Europe. But not all changes are statistically significant (EEA, 2017).



Note: Grid boxes outlined with solid black lines contain at least three stations and so are likely to be more representative of the grid box than those that are not outlined. Significance (at the 5 % level) of the long-term trend is shown by a black dot (which is the case for almost all grid boxes in this map).

Figure 11. TRENDS IN ANNUAL TEMPERATURE ACROSS EUROPE BETWEEN 1960 AND 2015. Adapted from "Climate change, impacts and vulnerability in Europe 2016", 2017, EEA, p.75. © 2017 by EEA.



Note: Boxes that have a thick outline contain at least three stations. Black dots represent high confidence in the long-term trend in that box (at the 5 % level).

Figure 12. TRENDS IN ANNUAL AND SUMMER PRECIPITATION ACROSS EUROPE BETWEEN 1960 AND 2015. Adapted from "Climate change, impacts and vulnerability in Europe 2016", 2017, EEA, p.81. © 2017 by EEA.

Forest Cover – Forest cover in the Northern Europe had always been dominant but there has been a significant increase in the forest cover across Western Europe post Second World War but the increase has been substantially low in the Central, Eastern and Southern Europe. These changes have been in effect mainly due to the large-scale afforestation programmes (EEA, 2018).

5.3. The Czech Republic Scenario

"The climate of the country corresponds to the Atlantic-continental area of the temperate climate zone of the northern hemisphere. The average annual temperature varies from 1.0 °C to 9.4 °C in dependence on geographic factors. Atmospheric precipitation is amongst the most variable climatic elements. Heavy precipitation is connected especially with the occurrence of low-pressure areas and fronts over Central Europe" (Ministry of the Environment of the Czech Republic, 2009).

Temperature Trend – The annual average temperatures in the Czech Republic increased by 0.8°C in the time period 1991-2008 as compared to the time period 1961-1990 as seen in Figure 13. The winter and summer trends are higher than the trends in autumn (ClimateChangePost, 2020). And it is projected that the annual temperature will increase by 1.0 °C by 2030 (Ministry of the Environment of the Czech Republic, 2015).

Precipitation Trend – The average territorial precipitation in the Czech Republic increased by 2.9% compared to the normal values in the period 1991-2008, with significant increases in summer and winter precipitations and a decrease during the autumn, in comparison to the period 1961-1990 as seen in Figure 14. This reflects the trend with annual average precipitation values across the country but there is a high territorial variability associated with it (Ministry of the Environment of the Czech Republic, 2009).

Forest Cover – Czech Republic has a large extent of forest cover. As of 2007, about 33.62% of the total area of the country is under forest cover (Ministry of the Environment of the Czech Republic, 2009). The area of forest cover has significantly increased since the 1950s as seen in the Figure 15.

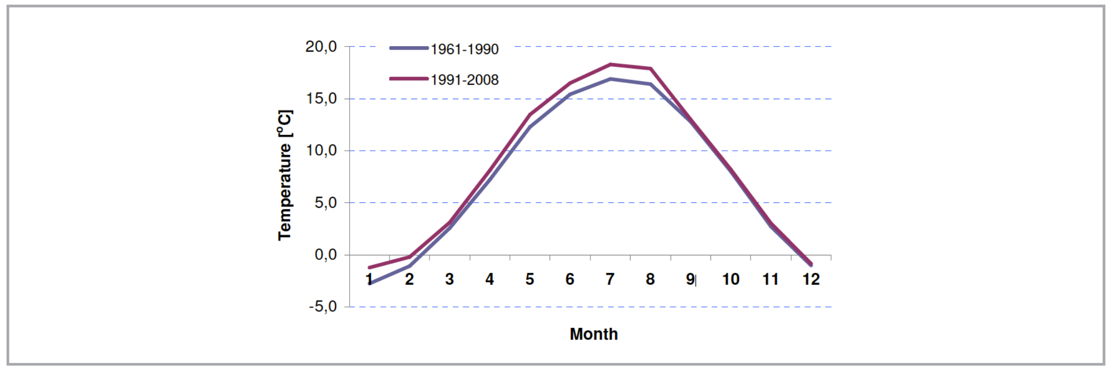


Figure 13. ANNUAL VARIATION IN THE AVERAGE AIR TEMPERATURES IN THE CZECH REPUBLIC IN THE PERIODS 1961-1990 AND 1991-2008. Adapted from "Fifth National Communication of The Czech Republic on The UN Framework Convention on Climate Change Including Supplementary Information Pursuant To Article 7.2 Of The Kyoto Protocol", 2009, Ministry of the Environment of the Czech Republic, p.24.

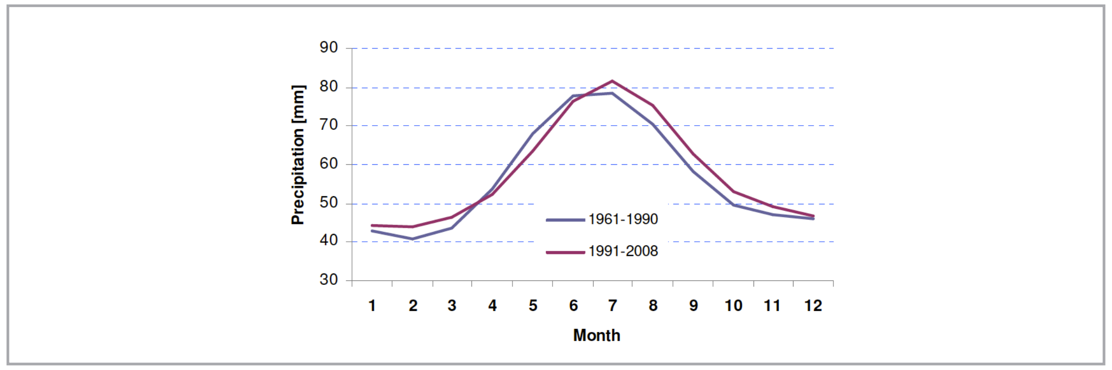


Figure 14. ANNUAL VARIATION IN THE AVERAGE TERRITORIAL PRECIPITATION IN THE CZECH REPUBLIC IN THE PERIODS 1961-1990 AND 1991-2008. Adapted from "Fifth National Communication of The Czech Republic on The UN Framework Convention on Climate Change Including Supplementary Information Pursuant To Article 7.2 Of The Kyoto Protocol", 2009, Ministry of the Environment of the Czech Republic, p.26.

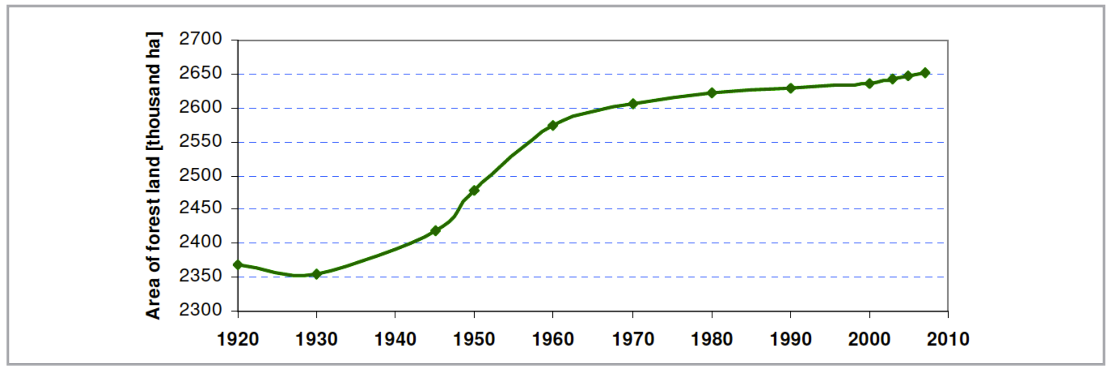


Figure 15. TRENDS IN THE FOREST COVER IN CZECH REPUBLIC IN THE PERIOD 1920 TO 2007. Adapted from "Fifth National Communication Of The Czech Republic On The Un Framework Convention On Climate Change Including Supplementary Information Pursuant To Article 7.2 Of The Kyoto Protocol", 2009, Ministry of the Environment of the Czech Republic, p.48.

The main goals of the study are:

i. To analyse the relationship between changes in the forest-cover and changes in the precipitation amount and pattern within four different cities in the Czech Republic.

ii. To compare the forest-precipitation dynamics between the four study areas.

The main objectives of this analytical study are:

i. To determine the annual trends of the meteorological elements with historical data for each study area.

ii. To assess if there are any significant differences between the climate trends of the four study areas.

iii. To evaluate if there is an increase in the heavy precipitation events for each study area.

iv. To compute the changes in the landcover over time for each of the location.

v. To analyse if there is a positive relationship between the changes in forest cover and changes in the amount of local precipitation.

vi. To examine the effects of landcover on the local climate conditions by comparing the four locations.

For the analysis of this study, two types of data sets have been obtained -

i. Climate data-set with daily values of six meteorological elements - average temperature, minimum temperature, maximum temperature, precipitation, relative air-humidity, and number of sunshine hours, for a period of 55 years (1961-2016).

ii. Landcover data-set and Changes in landcover data-set which includes artificial surfaces, agricultural areas, forest areas, shrub / other herbaceous vegetation associations, open areas with little / no vegetation, wetland areas, and water bodies, for a period of 28 years (1990-2018).

7.1. Climate Data

The climatological data has been sourced from the Czech Hydrometeorological Institute (CHMI) and obtained from ENKI, o.p.s., who purchased it in 2017. The technical series consists of daily values of six meteorological elements for selected 4 points out of 768 points of regular 10 x 10 km grid network (grid points of outputs use regional climate model ALADIN-Climate / CZ) for the period 1961 – 2016.

This Regional Climate Model (RCM) - ALADIN is based on a numerical forecasting model for Central Europe, with the ability to simulate climatic characteristics with a resolution of 10-25 km, which works in conjecture with the global model. The simulations are first performed using the Global Circulation Model (GCM) which provides the necessary information on the development of large-scale processes in the atmosphere (103km scale). The results are then processed by the RCM, which provides precise and detailed regionalization of the results, up to the scale of 101–102 km (P Hesslerová, Personal Communication, March 3, 2020).

But due to the uncertainties of GCM model outputs and regional downscaling methods, RCM outputs for the territory of the Czech Republic are burdened with a higher degree of uncertainty than the outputs of models for the European continent with respect to the global scale (P Hesslerová, personal communication, March 3, 2020).

Quality control, homogenization and interpolation of the missing values was performed on the daily values of all the basic meteorological elements datasets in Czech Republic. All these methods and steps help to eliminate non-climatic errors in order to devoid them of any false trend detections (Štěpánek et al., 2009).

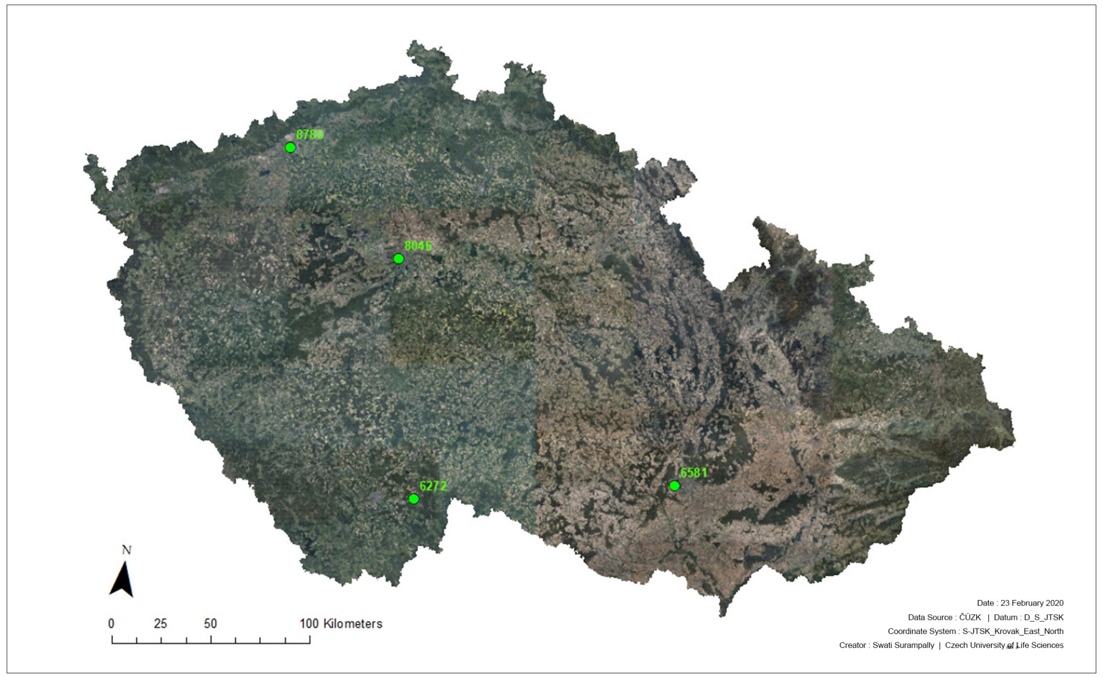


Figure 16. LOCATION OF THE SELECTED FOUR POINTS IN THE CZECH REPUBLIC FROM THE GRID NETWORK SOURCED FOR THE INPUT DATA FOR THIS STUDY.

Following are the input stations for calculation of individual grid points:

i. **6272** - Třeboň, Tábor, Rudolfov, Byňov, České Budějovice, Jindřichův Hradec

ii. **6581** - Brno - Žabovřesky, Brno - Pisárky, Brno - Veveří, Brno - Tuřany, Troubsko

iii. **8046** - Praha - Klementinum, Praha - Karlov, Praha - Kbely, Praha - Libuš, Praha – Ruzyně

iv. **8780** – Most - Kopisty, Kadaň - Tušimice, Jirkov, Žatec, Žatec - Velemyšleves

7.2. Land Cover Data

The data for the landcover and changes in landcover has been acquired from CORINE Land Cover (CLC) for the years 1990, 2000, 2006, 2012 and 2018. CLC is a geographic land-cover/land-use database from the CORINE programme undertaken by the European Environment Agency (EEA).

CLC was realised based on the visual interpretation of satellite images (SPOT, LANDSAT TM and MSS). Ancillary data (aerial photographs, topographic or vegetation

maps, statistics, local knowledge) were used to refine interpretation and the assignment of the territory into the categories of the CORINE Land Cover nomenclature (EEA,1995).

The database is organised in 3 levels and 44 classes as seen in Figure 12. For the purpose of this study, Level 1 classes have been considered for all categories except for Forests and seminatural areas where Level 2 has been considered as this study requires to distinguish Forests, Shrub and/or other herbaceous vegetation associations, and Open spaces with little / no vegetation.

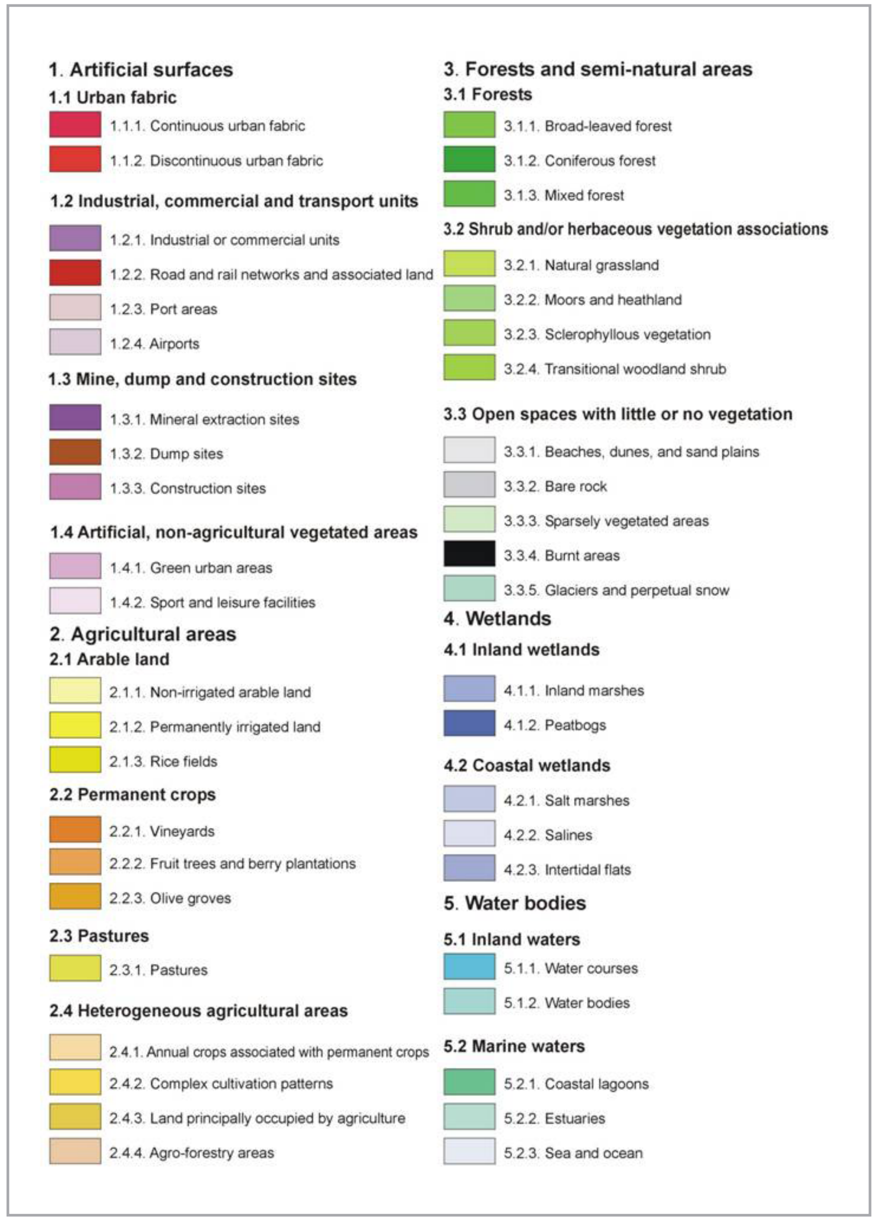


Figure 17. CORINE LAND COVER CLASSES. Reprinted from “Land Copernicus”. Adapted from “Corine Land Cover Classes” by Copernicus Land Monitoring Service. Retrieved from https://land.copernicus.eu/Corinelandcoverclasses.eps.75dpi.png/view.

In the database, the smallest surfaces mapped (minimum mapping units, MMU) correspond to 25 hectares. Linear features less than 100 m in width are not considered. The scale of the output product was fixed at 1:100.000. Thus, the location precision of the CLC database is 100 m (EEA, 1995).

Another set of data used for this study is the CORINE Land Cover Changes (CLCC).

> *"CLCC are derived from satellite imagery by the direct mapping of changes based on image-to-image comparison. Change mapping applies a 5 ha MMU to pick up much more detail in CLCC layer than in CLC status layer. Two European validation studies have shown that the achieved accuracy is above the specified minimum (85 %) for CLC, as well as for CLCC" (Büttner, 2014).*

7.3. Methodology

7.3.1. Methodology for Climate Data

The monthly and annual means were calculated for each of the meteorological elements from the daily measures data-set using the Average function in Microsoft Excel 2020 v.16.34.

The average function measures the central tendency, which is the location of the centre of a group of numbers in a statistical distribution.

For a data set consisting of the values a_1, a_2, ... a_n, the Average can be defined as (Eq.1):

$$A = \frac{1}{n}\sum_{i=1}^{n} a_i = \frac{a_1 + a_2 + \cdots + a_n}{n} \tag{1}$$

Where A is the average, a is observed value from sample, Σ is the sum of values in the average equation, n is the final count of all values and i =1.

Trend Test of the Data –

To analyse the annual trends for each meteorological element over time for each location, Mann-Kendall test was employed using XLSTAT 2020 v.1.1.64525.

Mann-Kendall test is a non-parametric statistical test used to identify a trend in a time series dataset which is recommended by the World Meteorological Organisation. This test determines if the time series has statistically significant increasing or decreasing trend (Yu et al, 2002).

The null hypothesis for this test is that there is no trend in the series. The three alternative hypotheses are that there is a negative, non-null, or positive trend. The Mann-Kendall tests are based on the calculation of Kendall's tau measure of association between two samples, which is itself based on the ranks with the samples. The computations assume that the observations are independent. The S statistic used for the test and its variance are given by:

$$S = \sum_{i=1}^{x-1}\sum_{j=i+1}^{x} \operatorname{sgn}(x_j - x_i) \tag{2}$$

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \tag{3}$$

Where n is the number of observations and x_i (i = 1. . . n) are the independent observations. A positive Kendall's tau value indicates an increasing trend in the series and negative Kendall's tau value indicates a decreasing trend.

The results are illustrated through charts and tables.

Homogeneity Test of the Data –

Pettitt's Homogeneity test was employed to identify the time at which the shift in the mean values of each meteorological element occurs at each location. Both annual and seasonal values were tested. The Pettitt's test is a nonparametric test that requires no assumption about the distribution of data. The null hypothesis is that the data are homogeneous. The alternative hypothesis is that there is a date at which there is a change in the data. The test was computed with XLSTAT 2020 v.1.1.64525. Pettitt's test is defined as:

$$K_T = \max |U_{t,T}| , \tag{4}$$

where

$$U_{t,T} = \sum_{i=1}^{t}\sum_{j=t+1}^{T} \operatorname{sgn}(X_i - X_j) \tag{5}$$

The change-point of the series is located at K_T, provided that the statistic is significant. The significance probability of K_T is approximated for $p \leq 0.05$ with:

$$p \simeq 2 \ \exp\left(\frac{-6\ K_T^2}{T^3 + T^2}\right) \tag{6}$$

If the p-value is less than the preassigned significance level α, the null hypothesis is rejected and the data is divided into two sub-series (before and after the location of the change point) with two different distribution functions.

Comparison Test of the data –

Kruskal-Wallis test is a rank-based non-parametric test that was used to determine if there are statistically significant differences between the means of each meteorological element across the four locations.

The null hypothesis is that the samples come from the same population and the alternative hypothesis is that the samples come from different populations. The calculation of the K static in the Kruskal-Wallis test is defined by:

$$K = \frac{12}{N(N+1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3(N+1) \tag{7}$$

where n_i is the size of sample i, N is the sum of the n_i's, and R_i is the sum of the ranks for sample i. When there are ties, the mean ranks are used for the corresponding observations.

The p-value associated with the K-value, determines if the null hypothesis is rejected, in that case, atleast one group is different from the others. Using multiple comparison procedures, the group/s responsible for rejecting the null hypothesis can be identified.

7.3.2. Methodology for Land Cover Data

Both the landcover data sets were recategorized according to the desired levels and type of classification and visualised for the respective study areas in ArcGIS software. The categorial areas were calculated which are illustrated through pie-charts with percentages of landcover.

The percentages of forest cover were further analysed with the changes in precipitation over years through graphs to evaluate their relationship.

8 | STUDY AREAS

The locations for this study were selected based on the following criteria:

i. Similar Elevational Gradient
ii. Similar Climatic Zone
iii. Availability of Historical Climatic Data

The extent of the four study areas was marked as a buffer of 10 kilometres radius around the meteorological stations from where the climate data was collected. These areas are around four major towns in the Czech Republic – Most, Prague, Třeboň and Brno as seen in Figure 18.

The Czech Republic lies in the Temperate climate zone, which is characterised by mild summers and cold, cloudy and humid winters. As seen in Figure 19, climatic zones in the Czech Republic can be broadly classified into five categories, which is largely based on the differences in the altitude and topography. The latitude difference is negligible across the country. As seen in Figure 19, the four study areas fall into nearly similar climatic zones: Warm – Hot – Dry zone but the landscape character varies significantly between the study areas.

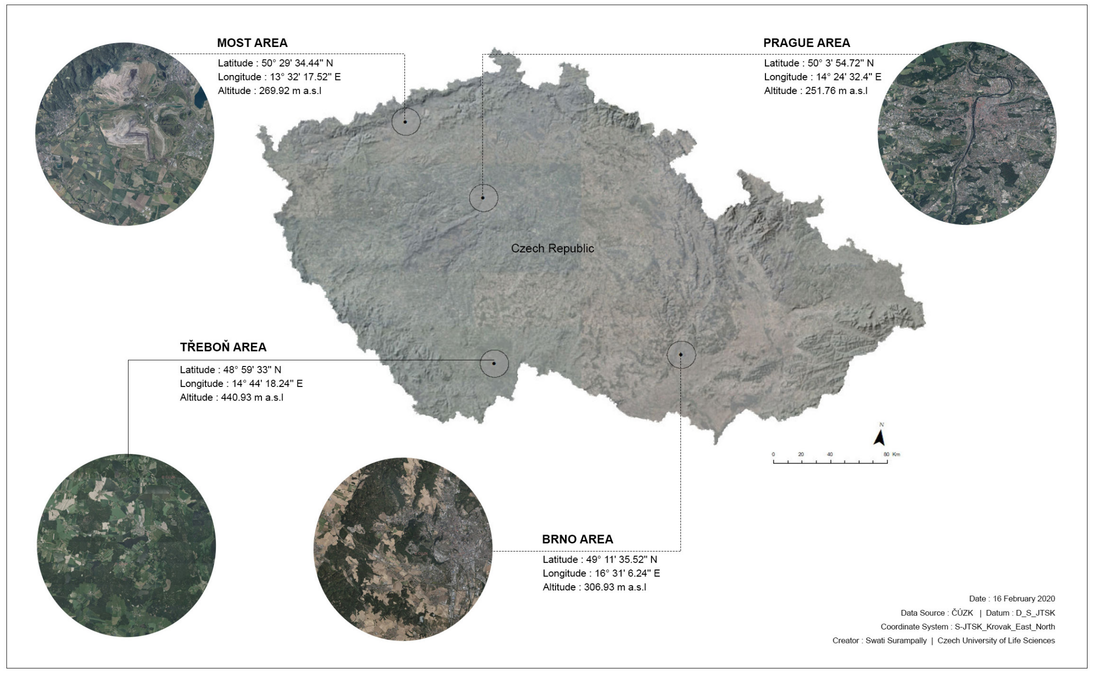


Figure 18. LOCATION OF THE FOUR STUDY AREAS IN CZECH REPUBLIC.

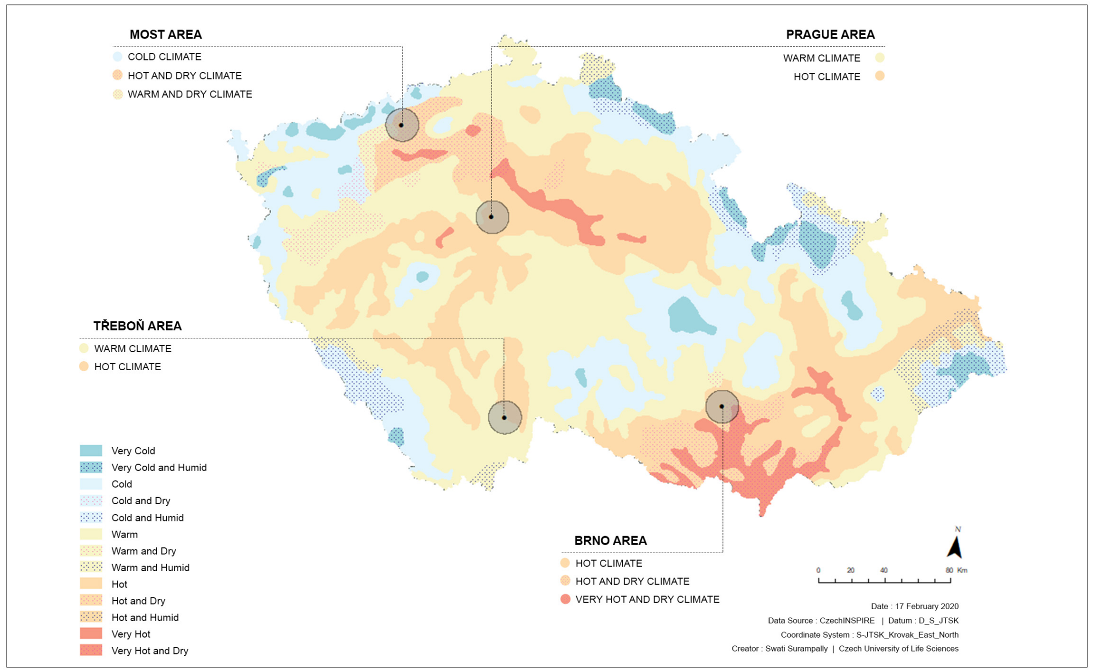


Figure 19. CLIMATE ZONES MAP OF CZECH REPUBLIC WITH LOCATION OF STUDY AREAS

Within the European climate zones, the Czech Republic falls under the continental moderate climate zone, a sub-type of the temperate climate. In the study done by European Environmental Agency, 2019, climate data analysed over a period of 40 years (1975-2016), a northward shift of the agro-climate zones is quite evident. Figure 19 indicates the climate zones within the Czech Republic and are relative to the areas within the boundary of the country. For example, the climate zone - Very Hot and Dry doesnot indicate a desert like climate but the hottest and the driest zone in the country.

8.1. Most Area – Land Cover and Climate

The city of Most is located in the North-western part of the Czech Republic, in the undulating landscape between the Ore Mountains (Krušné hory) and the Bohemian Uplands (The České středohoří) with elevational gradient ranging between 230 to 420 m a.s.l. Brown coal mines were discovered here historically, and due to the mining activities, the landscape character of this area has been in a constant flux. Although the mining activities here began as early as 13th century, it reached its peak in the second half of the 20th century which caused significant environmental degradation. In 1964, the historical town of Most was demolished in order to expand the mining activities and a new town was developed in the vicinity. Today, the environmental conditions have improved as a result of reclamations (Chodějovská et al, 2014).

The climate data of 55 years (1961-2016), indicates that the area of Most receives maximum rainfall during the summer months (June to August) with an average of 64.3 mm total precipitation per month. The lowest precipitation is during February with total precipitation of 29 mm. The temperature reaches its maximum levels during summer months (June to August), with averages ranging from 22.3°C to 24.3°C and minimum temperatures in the winter (December to February) with averages ranging from -2.9°C to -4.0°C. The general climatic conditions for the area of Most based on this data can be seen in the Figure 20.

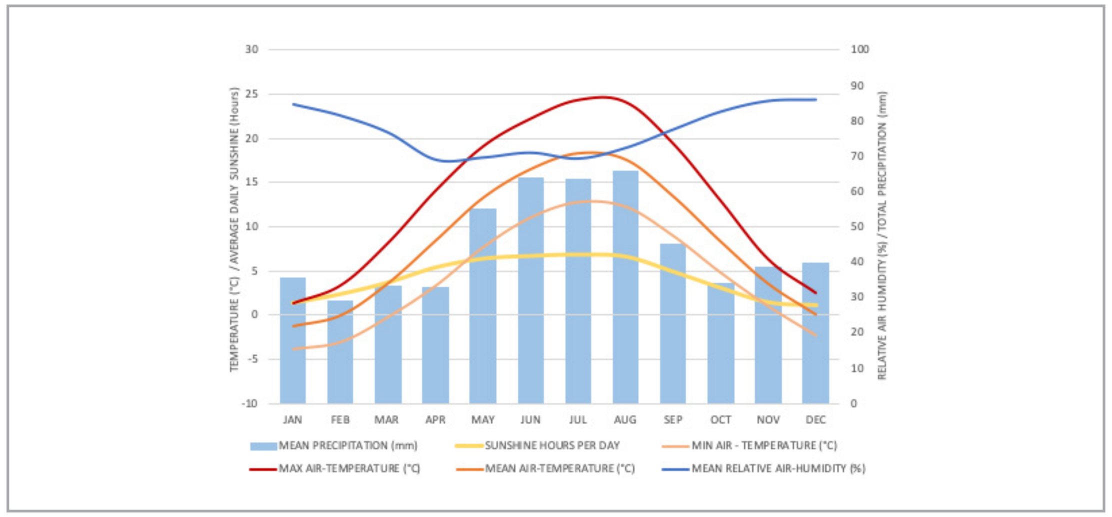


Figure 20. CLIMATE GRAPH OF MOST AREA BASED ON CLIMATE DATA FROM 1961-2016

8.2. Prague Area – Land Cover and Climate

Prague, the capital city of the Czech Republic is located in the central part of the Bohemian Massif with elevational gradient ranging between 177 to 399 m a.s.l. The landscape of the city is characterised by natural elements like the Vltava River and surrounding hillocks. Over the centuries of human settlement spreading in all directions, the surrounding greenery, fields, meadows, forests, vineyards and gardens were slowly consumed up for the urban development. The development accelerated during the latter half of 19th century and early 20th century and even today the urban sprawl is a big threat to the remaining green belt around the city (Chodějovská et al, 2015). From 1985 - 2000, the built-up areas increased by 8 fold and the transport infrastructure increased 10 fold. The land conversion for urban fabric was majorly from the agricultural land (Pazúr et al, 2016).

According to the historical climate data (1961-2016) of Prague area, the maximum rainfall during the summer months (June to August) is about 63.7 mm of total precipitation per month. The driest month is February with total precipitation of about 19 mm. The maximum temperatures during summer (June to August) range between 23.3°C to 25.3°C while the minimum temperatures during winter (December to February) range between -0.8°C to -2.4°C. Figure 21 depicts the general climatic conditions for the area of Prague.

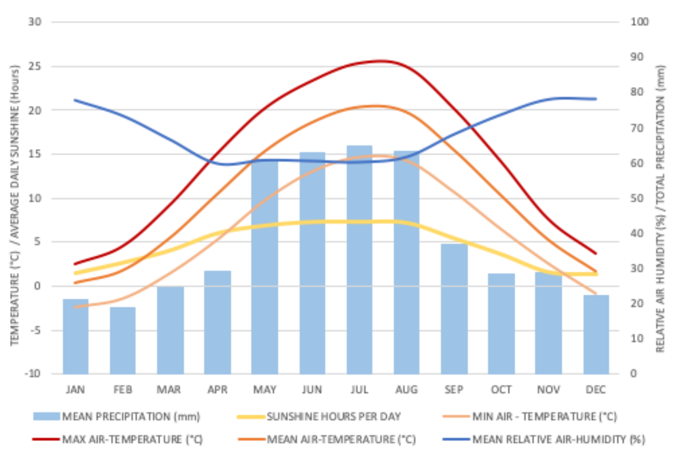


Figure 21. CLIMATE GRAPH OF PRAGUE AREA BASED ON CLIMATE DATA FROM 1961-2016

8.3. Třeboň Area – Land Cover and Climate

Třeboň is a town located in the South-western part of the Czech Republic. The landscape around the town is defined by ponds, wetlands, marshes and forest areas. The terrain is mostly flat with elevational gradient ranging between 400 to 500 m a.s.l. The natural systems in this region remain very slightly modified because the soil was not suitable for agriculture and the region was spared from extensive development. The pond systems in this region fall under the Ramsar Convention on wetlands and consists of 12 declared and 2 proposed – especially rare biotopes. The region also houses some nature reserves and protected areas which are more recent, dating back to the late 20th century (Chodějovská et al, 2015).

The climate data from 1961-2016, indicates maximum precipitation in the area of Třeboň during the summer months (June to August) with an average of 86.0 mm of total precipitation per month. The lowest precipitation is during February with 26.8 mm total precipitation. The maximum temperatures range between 22.1°C to 24.1°C during summer (June to August) and the lowest temperatures range between -3.6°C to -5.2°C during the winter (December to February).

The climate graph for Třeboň area in the Figure 22 gives a general idea about the climatic conditions there.

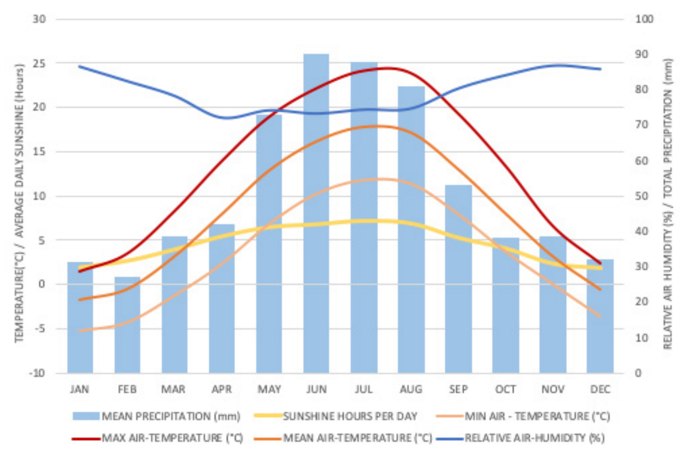


Figure 22. CLIMATE GRAPH OF TŘEBOŇ AREA BASED ON CLIMATE DATA FROM 1961-2016

8.4. Brno Area – Land Cover and Climate

Brno is located in the South-eastern part of the Czech Republic, between the Bohemian-Moravian forested highlands and the fertile South Moravian lowlands with vineyards. The elevational gradient ranges from 189 to 497 m a.s.l. Although the urban area has been expanding since the beginning of the 19th century, a large extent of forested area remains intact due to unsuitable conditions for agricultural activities in the northern and western extents of the city. Almost a tenth of area is still occupied by gardens and orchards which can be attributed to the existence of many garden colonies from the medieval times (Buček and Kirchner, 2011). According to the study by Demek et al (2007), 60% of the studied territory of Brno and its surroundings indicated a stability in the land-use for the period of about 250 years, which is quite unprecedented.

The climate data of 55 years (1961-2016), indicates that the area of Brno receives maximum rainfall during the summer months (June to August) with an average of 67.9 mm total precipitation per month. The lowest precipitation is during February with total precipitation of 26.6 mm. The temperature reaches its maximum levels during summer months (June to August), with averages ranging from 22.6°C to 24.7°C and minimum temperatures in the winter (December to February) with averages ranging from -3.6°C to -5.4°C. The general climatic conditions for the area of Brno is depicted in the Figure 23.

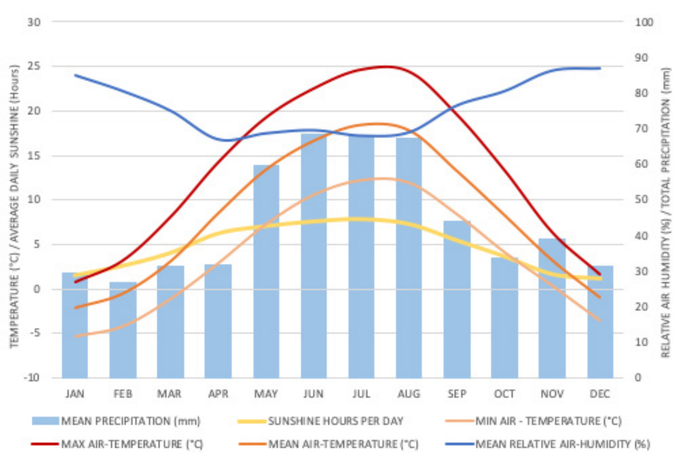


Figure 23. CLIMATE GRAPH OF BRNO AREA BASED ON CLIMATE DATA FROM 1961-2016

9 | RESULTS

Mann-Kendall statistical test was used to determine if there is a statistically significant trend for each of the six meteorological elements in each of the four study areas. The results are demonstrated through tables showing the values of the test results and graphs depicting the patterns and trend slopes for each meteorological element.

The p-value in the table determines if the null hypothesis is to be accepted or rejected. If the p-value is greater than the significance value of 0.05, the null hypothesis is accepted that there is no trend in the series and if the p-value is less than 0.05, the alternative hypothesis is accepted that there is a statistically significant trend in the series. The Kendall's tau value determines if the trend is increasing or decreasing. A positive Kendall's tau indicates an increasing trend and a negative value indicates a decreasing trend.

To analyse if there is a particular time period during which there was a significant shift in the values of each of the meteorological element, Pettitt's test was employed. The results are again represented through tables and graphs.

The table mentions the p-values for each element which determines whether to accept or reject the null hypothesis as well as the year of shift which specifies from which year the values show a shift. The corresponding graphs determine whether there is an upward shift or a downward shift along with the year of break point.

To examine if there is an increase in the number of days with heavy precipitation for each of the study areas, three categories are used:

i. Number of days with precipitation greater than or equal to 10 mm
ii. Number of days with precipitation greater than or equal to 20 mm
iii. Number of days with precipitation greater than or equal to 30 mm

The results are presented through graphs showing the trend and tables showing Mann-Kendall test results which was used to determine if these trends are statistically significant.

The changes in the land cover are represented through maps each of the study area for each year the data was recorded along with graphs showing the changes in percentage of land cover and a graph indicating the temperature and precipitation trends over time. Another set of maps represent the exact polygons of areas that got converted from one type of land cover to another along with the year of change. These maps are supported with climate graphs for the specific years which also highlights the maximum and minimum amount of precipitation during the specific years.

Now to compare the trends among the four study areas, Kruskal-Wallis test was used. The results are presented through three types of graphs for each of the meteorological element:

i. A Line graph plotting the trend in the values for each location.

ii. A Scatter graph plotting the range within which the values exist for each location.

iii. A Demšar graph, also called as Critical Differences plot – to visualize the pairwise differences after performing the Kruskal-Wallis test followed by a post-hoc procedure.

The changes in the land cover are compared using the stacked bar graphs over time for each location. Finally, the changes in the forest cover are plotted against the changes in precipitation for each location to examine the forest-precipitation dynamics across the four study areas.

9.1. Most Area

Annual Climate Trends in Most Area:

The values of the Mann-Kendall test as seen in Table 1, show that there is a statistically significant trend for all the meteorological elements in Most except for precipitation which shows an increase but the trend is not statistically significant. While all the elements show an increasing trend, relative air-humidity shows a decreasing trend for Most which can be seen in the Figure 24.

Table 1. MANN-KENDALL TEST VALUES FOR EACH METEOROLOGICAL ELEMENT IN MOST AREA

METEOROLOGICAL ELEMENT	KENDALL'S TAU	p-VALUE	SEN'S SLOPE	NULL-HYPOTHESIS	TREND
Max. Air-Temperature	0.468	<0.0001	0.041	rejected	increasing - significant
Mean Air-Temperature	0.461	<0.0001	0.035	rejected	increasing - significant
Min. Air-Temperature	0.406	<0.0001	0.028	rejected	increasing - significant
Sunshine Hours	0.255	0.006	3.282	rejected	increasing - significant
Relative Air-Humidity	-0.301	0.001	-0.067	rejected	decreasing - significant
Precipitation	0.161	0.081	1.496	not rejected	increasing - not significant

Null Hypothesis: There is no trend in the series; Alternative Hypothesis: There is a trend in the series. Significance level **α = 0.05.**

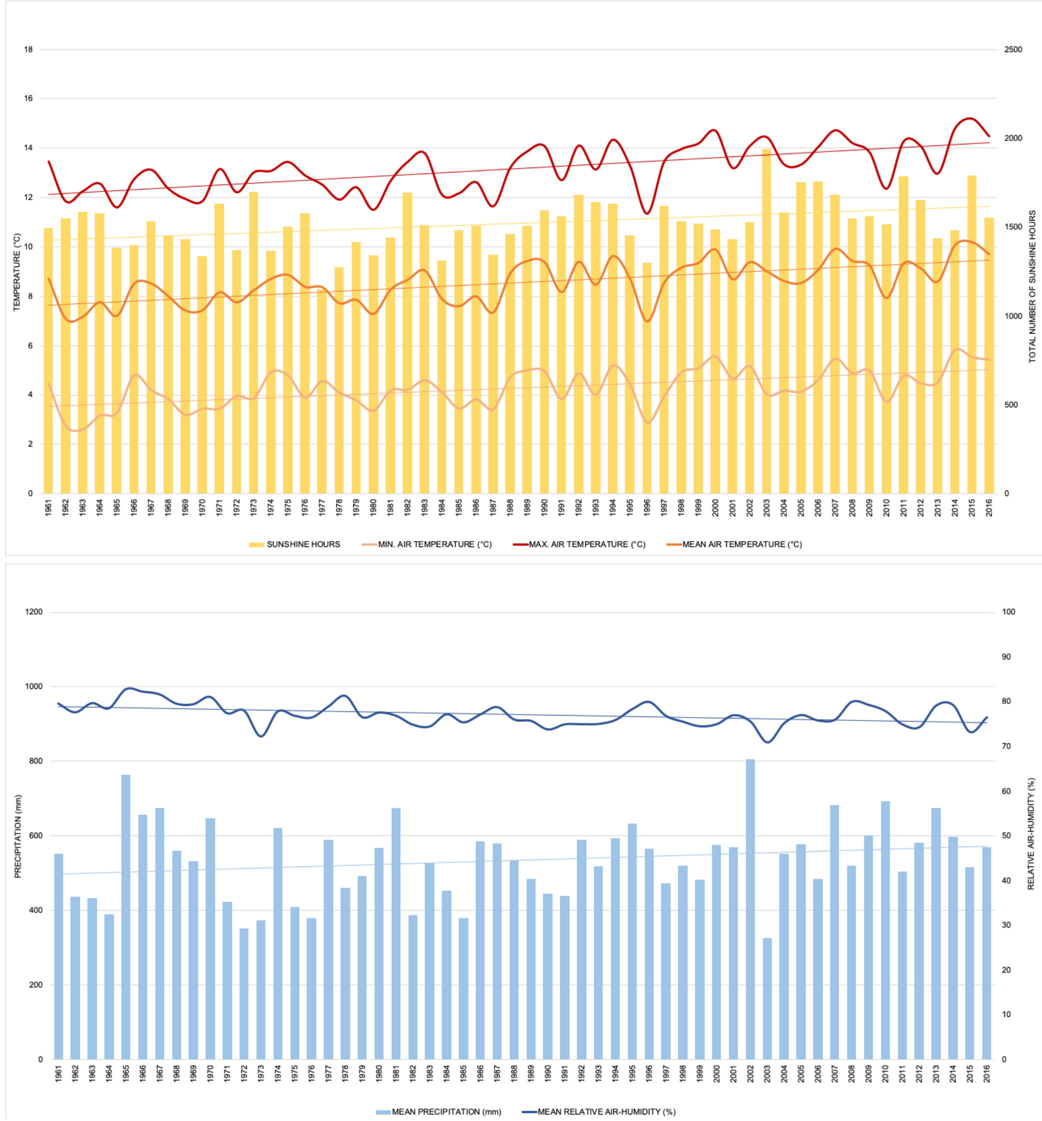


Figure 24. GRAPH OF CLIMATIC TRENDS IN MOST AREA FROM 1961-2016.

Change-Points in the Mean/Sum Values of the Meteorological Elements in Most Area:

According to the results of Pettitt's test, there is a statistically significant shift in the mean/sum values for all the meteorological elements in Most except for the precipitation as seen in Figure 25. The earliest shift can be seen in the values of relative air-humidity which also has a downward shift while all other elements have an upward shift and comparatively occur in a later period of time as inferred from Table 2. Relative air-humidity is affected either with changes in the moisture content in the atmosphere or with changes in the temperature. In this case, the shift in values of air-humidity precedes the shift in the temperature values which indicates that probably there was a decrease in the moisture content in the atmosphere during that time which can be due to the deforestation related to the mining activities in Most.

Table 2. PETTITT'S TEST VALUES FOR EACH METEOROLOGICAL ELEMENT IN MOST AREA

METEOROLOGICAL ELEMENT	p-VALUE	SHIFT	YEAR OF SHIFT	NULL-HYPOTHESIS
Max. Air-Temperature	<0.0001	Upward	1987	rejected
Mean Air-Temperature	<0.0001	Upward	1987	rejected
Min. Air-Temperature	0.000	Upward	1987	rejected
Sunshine Hours	0.003	Upward	1989	rejected
Relative Air-Humidity	0.003	Downward	1980	rejected
Precipitation	0.250	None	-	not rejected

Null Hypothesis: Data are homogeneous; Alternative Hypothesis: There is a date at which there is change in the data. Significance level α = 0.05.

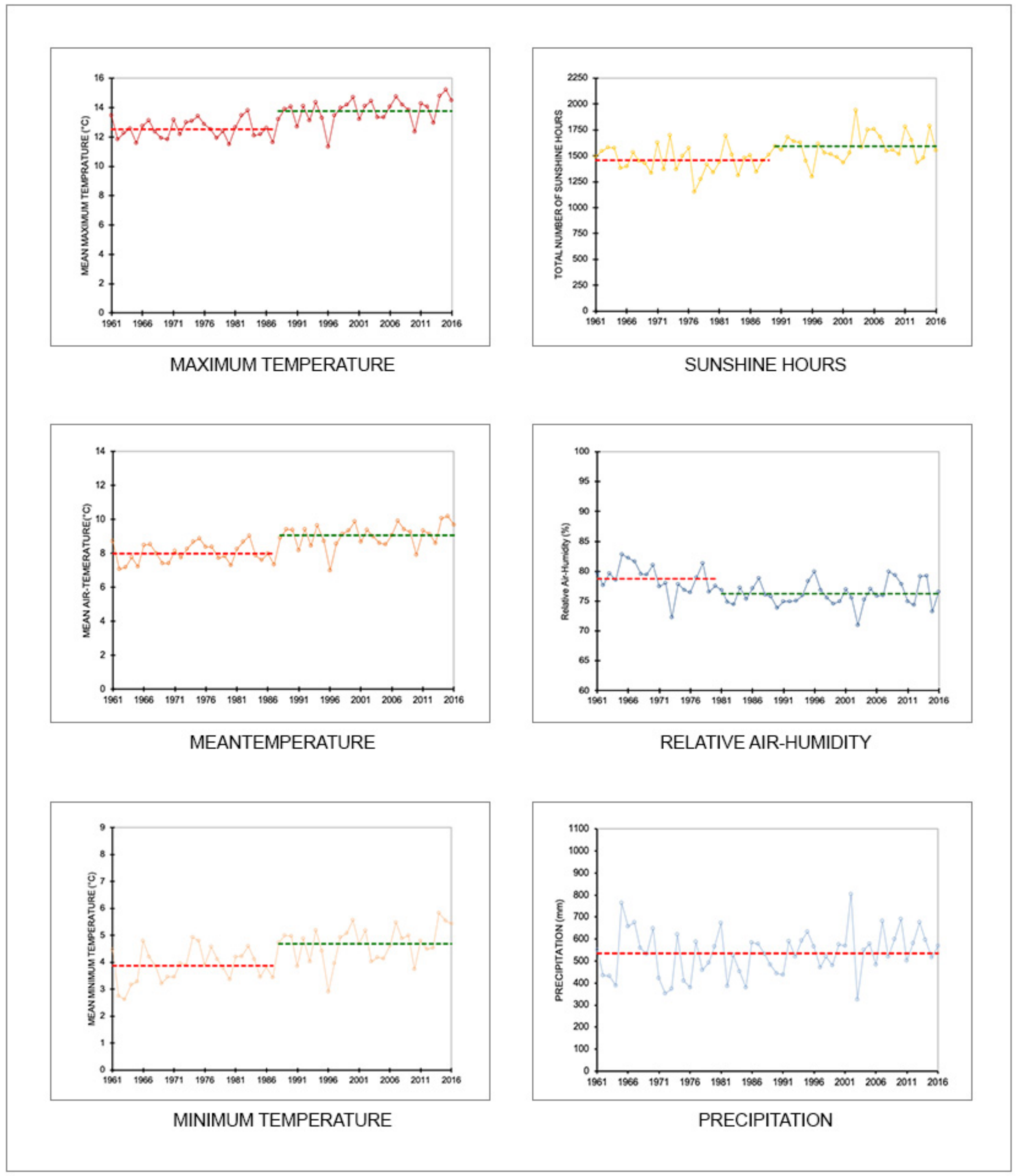


Figure 25. SIGNIFICANT CHANGE-POINTS IN THE MEAN / SUM VALUES FOR EACH OF THE METEOROLOGICAL ELEMENT IN MOST AREA FROM 1961-2016.

Trend in the Number of Heavy Precipitation Days in Most Area:

According to the Mann-Kendall statistical test results as seen in Table 3, there is an increasing trend for all the three classes but the trend is not statistically significant only in case of days with precipitation greater than 20 mm. Although the annual precipitation trend in Most does not show a statistically significant increase, the number of days with heavy precipitation does. This implies that there have been more frequent heavy precipitation events. Figure 26 illustrates the increase in this trend.

Table 3. MANN-KENDALL TEST VALUES FOR NUMBER OF HEAVY PRECIPITATION DAYS IN MOST AREA

CATEGORY	KENDALL'S TAU	p-VALUE	SEN'S SLOPE	NULL-HYPOTHESIS	TREND
Days > 10 mm	0.208	0.028	0.077	rejected	increasing - significant
Days > 20 mm	0.177	0.074	0.000	not rejected	increasing - not significant
Days > 30 mm	0.281	0.008	0.000	rejected	increasing - significant

Null Hypothesis: There is no trend in the series; Alternative Hypothesis: There is a trend in the series. Significance level **α = 0.05.**

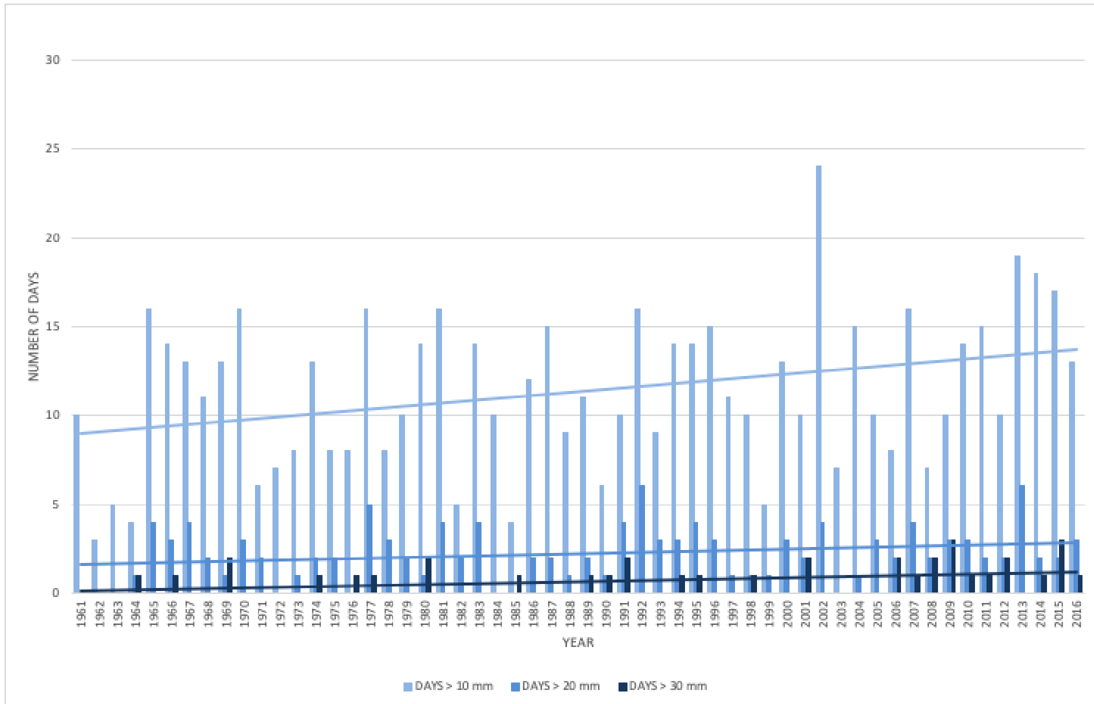


Figure 26. TREND IN THE NUMBER OF HEAVY PRECIPITATION DAYS IN MOST AREA FROM 1961-2016.

Land-Cover (1990-2018) with Annual Precipitation and Mean-Temperature Graph (1990-2016) in Most Area:

Almost half of the land cover within the study area of Most is occupied by agriculture, followed by artificial surfaces and forest area. As seen in Figure 27, there is an increase in the percentage of forest cover by about 13% during the time period 1990 to 2018.

The lowest amount of total precipitation when compared across decades was during the 1970s (1971-1980). Although the temperature values have been consistently increasing with every decade, the highest change in the temperature values has been during 2010s (2001-2010) to 2020s (2011-2016).

Changes in the Land-Cover with Changes in the Seasonal Climatic Conditions Over Time Within the Study Area of Most:

Largest land cover conversion to forest cover has been during the years 2000 to 2006 and 2006 to 2012. Figure 28 shows the land cover types that changed during 1990 to 2018 in the Most study area recorded at four time intervals. Majorly, shrub/other herbaceous vegetation area got converted into forest area.

There has been an increase in the winter precipitation as well as summer precipitation. There is an increase in the maximum monthly precipitation from 80.5 mm in 1990 to 130.9 mm in 2000 and 71.4 mm in 2006 to 104.2 mm in 2012 but overall statistical values from 1990-2016 does not show any significant increase in the precipitation values. There is an increase in mean temperature over all the four seasons but the increase is statistically significant only for autumn season.

Figure 27. LAND COVER PERCENTAGES (1990-2018) WITH TEMPERATURE – PRECIPITATION GRAPH (1990-2016) FOR MOST AREA.

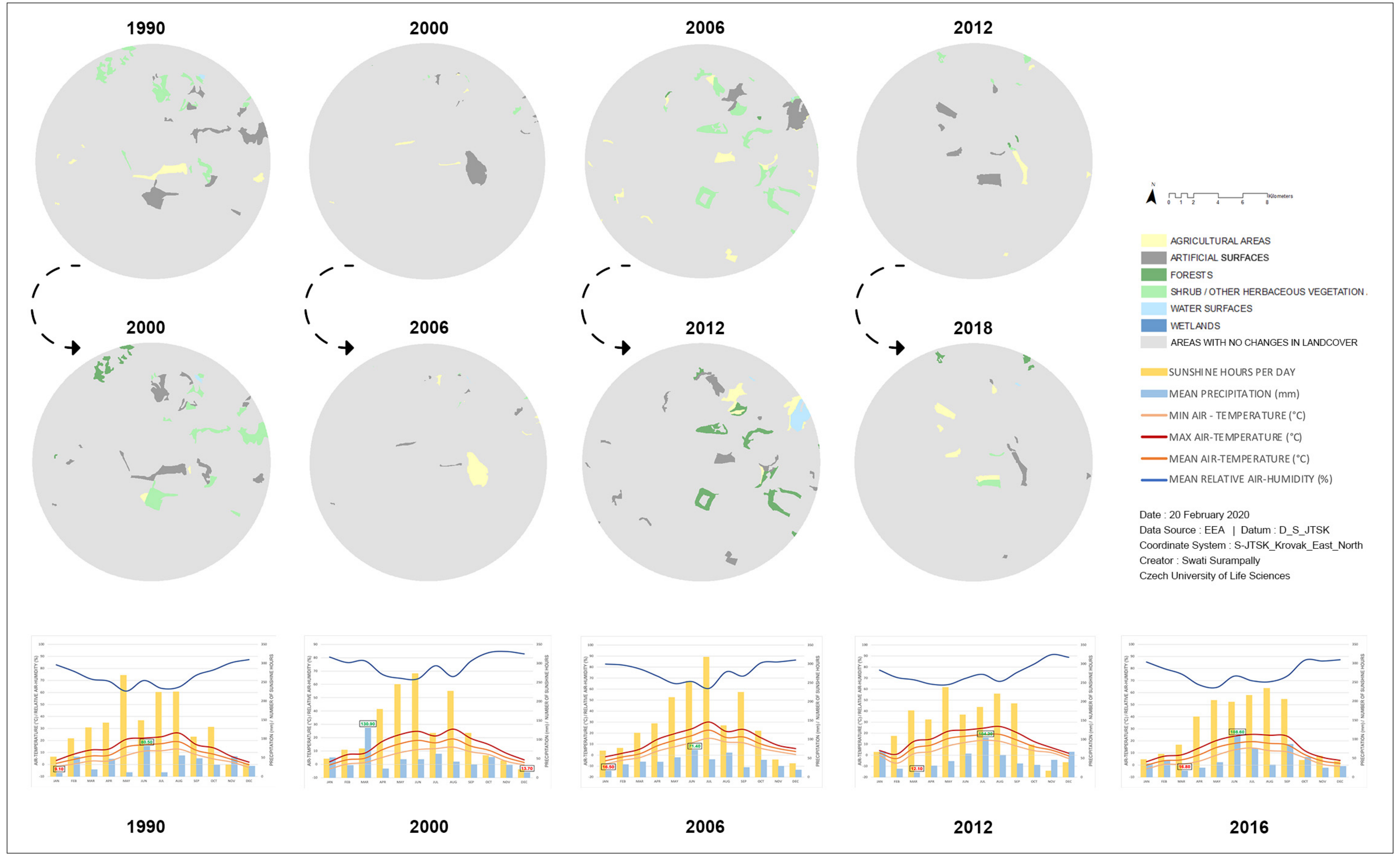


Figure 28. CHANGES IN THE LAND COVER (1990-2018) WITH CHANGES IN THE SEASONAL CLIMATIC CONDITIONS (1990-2016) FOR MOST AREA.

9.2. Prague Area

Annual Climate Trends in Prague Area:

In Prague area, the values of temperature and sunshine hours show a statistically significant increase over time. Relative air-humidity shows a significant decrease in the trend. Precipitation values show a decrease as well but it is not a statistically significant trend as inferred from the results of Mann-Kendall test which are represented in Figure 29 and Table 4.

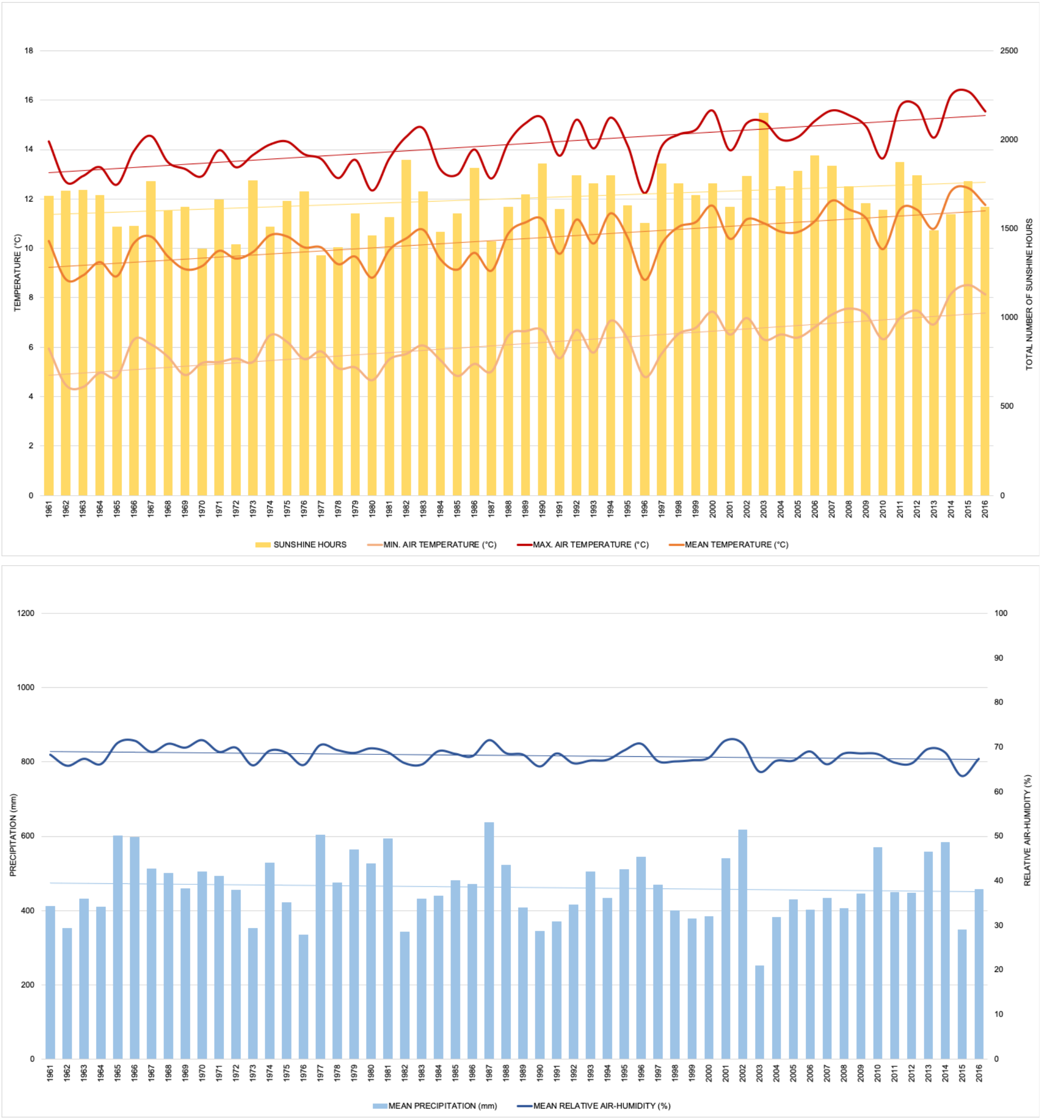


Figure 29. GRAPH OF CLIMATIC TRENDS IN PRAGUE AREA FROM 1961-2016.

Table 4. MANN-KENDALL TEST VALUES FOR EACH METEOROLOGICAL ELEMENT IN PRAGUE AREA

METEOROLOGICAL ELEMENT	KENDALL'S TAU	p-VALUE	SEN'S SLOPE	NULL-HYPOTHESIS	TREND
Max. Air-Temperature	0.494	<0.0001	0.044	rejected	increasing - significant
Mean Air-Temperature	0.526	<0.0001	0.043	rejected	increasing - significant
Min. Air-Temperature	0.566	<0.0001	0.047	rejected	increasing - significant
Sunshine Hours	0.222	0.016	3.061	rejected	increasing - significant
Relative Air-Humidity	-0.182	0.048	-0.033	rejected	decreasing - significant
Precipitation	-0.044	0.641	-0.356	not rejected	decreasing - not significant

Null Hypothesis: There is no trend in the series; Alternative Hypothesis: There is a trend in the series. Significance level **α = 0.05.**

Change-Points in the Mean/Sum Values of the Meteorological Elements in Prague Area:

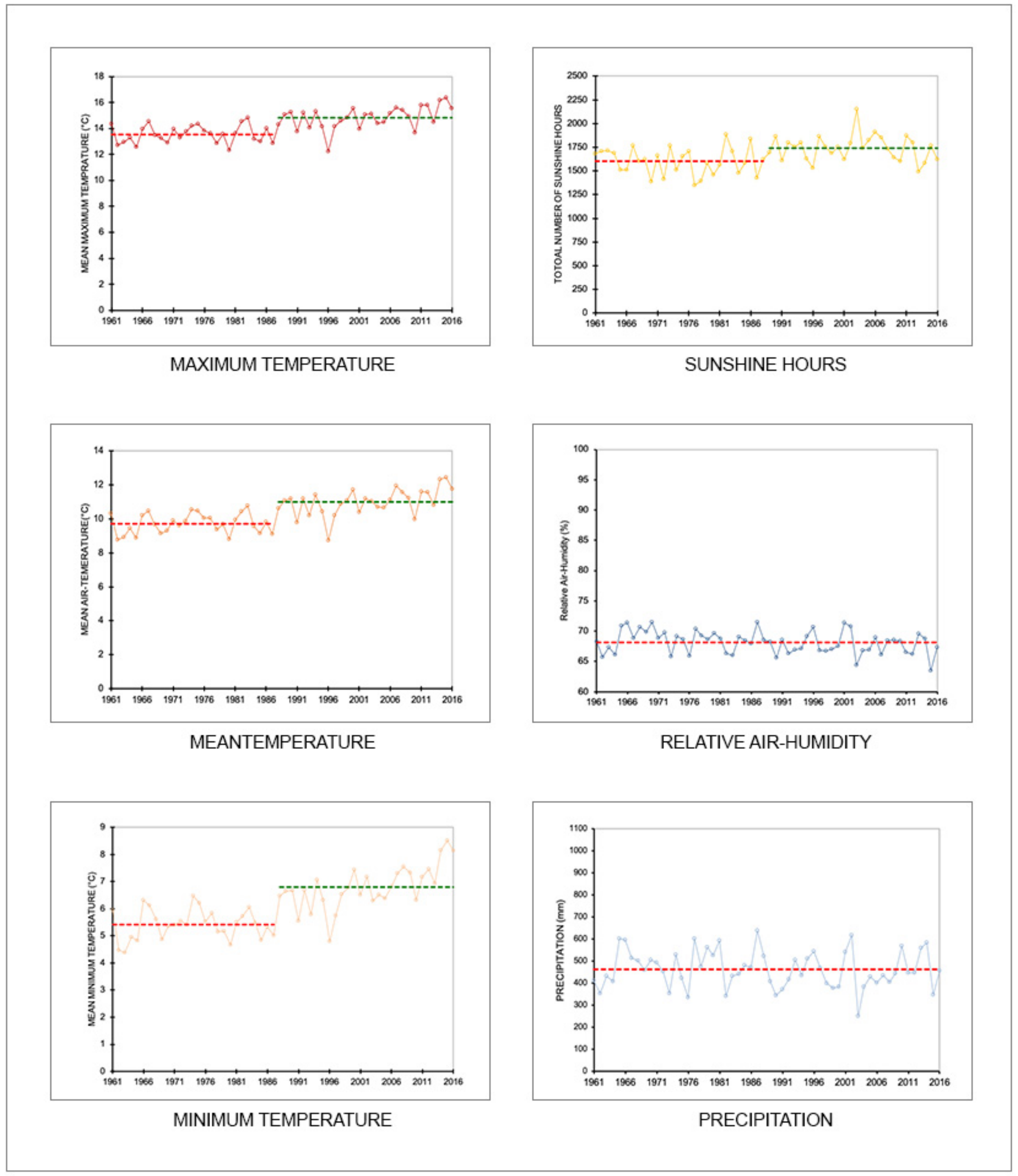


Figure 30. SIGNIFICANT CHANGE-POINTS IN THE MEAN / SUM VALUES FOR EACH OF THE METEOROLOGICAL ELEMENT IN PRAGUE AREA FROM 1961-2016.

According to the Pettitt's test results for Prague area as seen in Table 5 an depicted in Figure 30, there is a statistically significant upward shift in the mean/sum values of temperature and sunshine hours occurring during the same period of time while there is no significant shift in the mean/sum values of relative air-humidity and precipitation.

Table 5. PETTITT'S TEST VALUES FOR EACH METEOROLOGICAL ELEMENT IN PRAGUE AREA

METEOROLOGICAL ELEMENT	p-VALUE	SHIFT	YEAR OF SHIFT	NULL-HYPOTHESIS
Max. Air-Temperature	<0.0001	Upward	1987	rejected
Mean Air-Temperature	<0.0001	Upward	1987	rejected
Min. Air-Temperature	<0.0001	Upward	1987	rejected
Sunshine Hours	0.006	Upward	1988	rejected
Relative Air-Humidity	0.283	None	-	not rejected
Precipitation	0.897	None	-	not rejected

Null Hypothesis: Data are homogeneous; Alternative Hypothesis: There is a date at which there is change in the data. Significance level α = 0.05.

Trend in the Number of Heavy Precipitation Days in Prague Area:

All the three classes of number of days with heavy precipitation show a decreasing trend in Prague but they are not statistically significant as inferred from the Mann-Kendall test results in Table 6 and trends seen in Figure 31.

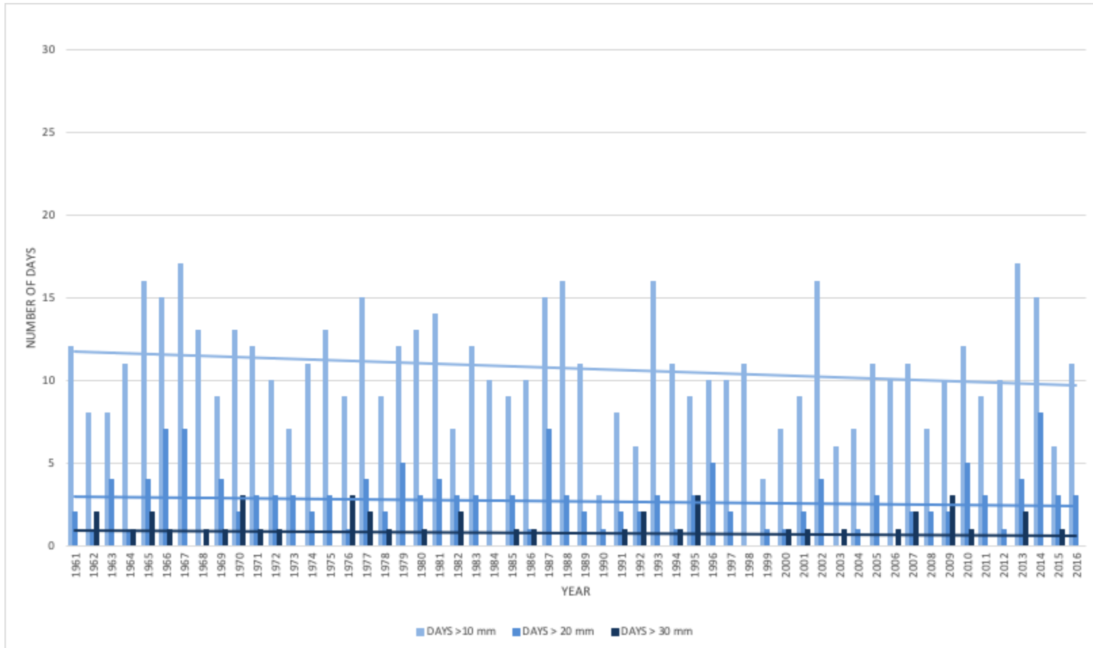


Figure 31. TREND IN THE NUMBER OF HEAVY PRECIPITATION DAYS IN PRAGUE AREA FROM 1961-2016.

Table 6. MANN-KENDALL TEST VALUES FOR NUMBER OF HEAVY PRECIPITATION DAYS IN PRAGUE AREA

FACTOR	KENDALL'S TAU	p-VALUE	SEN'S SLOPE	NULL-HYPOTHESIS	TREND
Days > 10 mm	-0.129	0.177	-0.034	not rejected	decreasing - not significant
Days > 20 mm	-0.076	0.440	0.000	not rejected	decreasing - not significant
Days > 30 mm	-0.097	0.353	0.000	not rejected	decreasing - not significant

Null Hypothesis: There is no trend in the series; Alternative Hypothesis: There is a trend in the series. Significance level **α = 0.05.**

Land-Cover (1990-2018) with Annual Precipitation and Mean-Temperature Graph (1990-2016) in Prague Area:

More than half of the land cover within the study area around Prague is artificial area and the remaining area consists of majorly agriculture and forest areas. As seen in Figure 32, there is a decrease in the percentage of forest cover by 2% from the year 1990 to 2018.

The lowest amount of precipitation was during the 1990s (1991-2000) when compared across the decades and the temperature values have been consistently increasing with every decade but the highest change in the temperature values has been during 2010s (2001-2010) to 2020s (2011-2016).

Changes in the Land-Cover with Changes in the Seasonal Climatic Conditions Over Time Within the Study Area of Prague:

There have been no significant land cover conversions to forests over time in Prague area. Mainly the land cover conversions have been from agriculture areas to artificial areas.

Although there is an overall decreasing tendency in the annual values of precipitation (1961-2016) but during the years 1990-2016 as seen in Figure 33, there is an increase in the seasonal precipitation values (summer, winter, autumn and spring months) but this increase is not statistically significant. The mean temperatures have a significant increase during summer and autumn but for winter and spring the increase is not statistically significant.

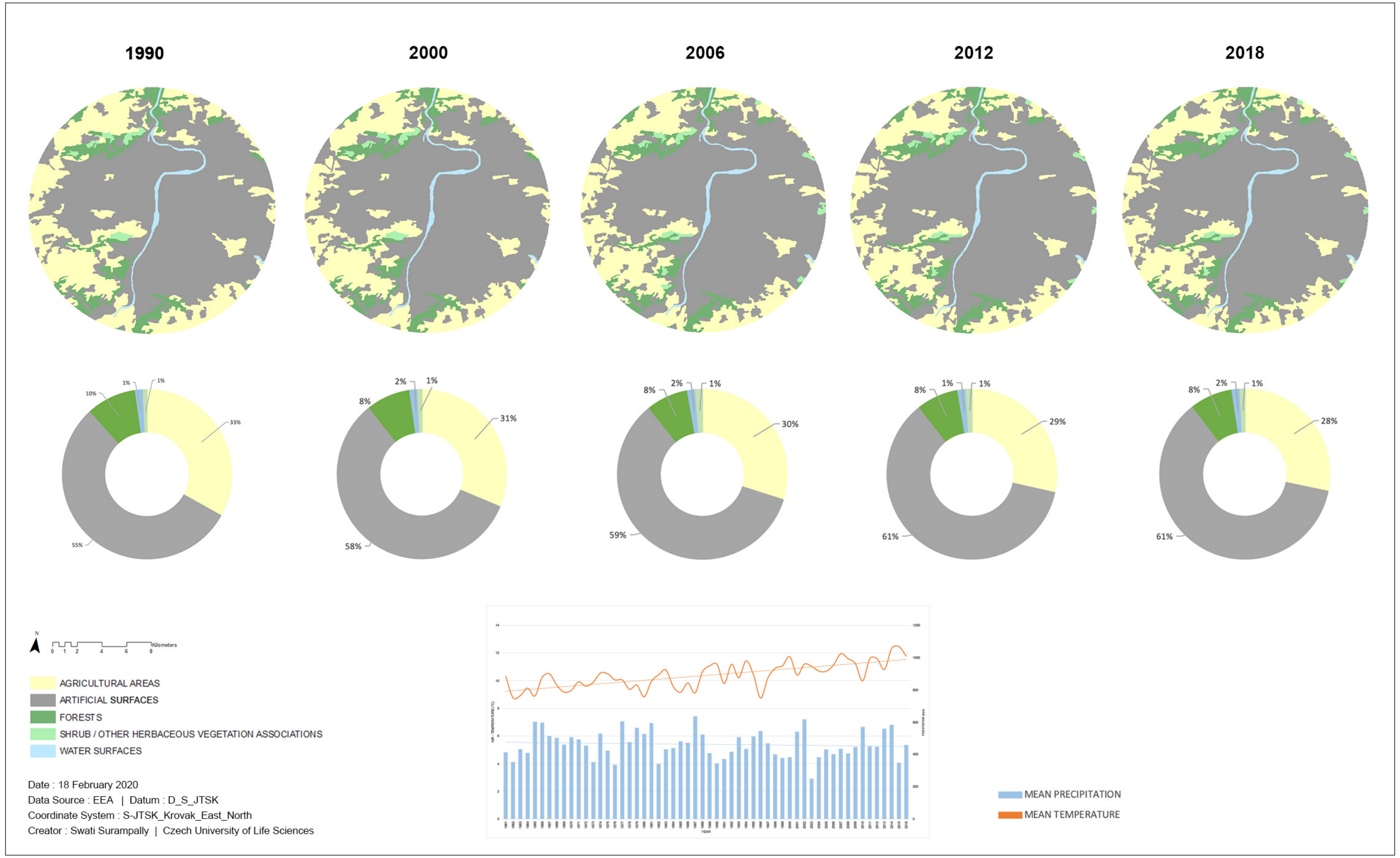


Figure 32. LAND COVER PERCENTAGES (1990-2018) WITH TEMPERATURE – PRECIPITATION GRAPH (1990-2016) FOR PRAGUE AREA.

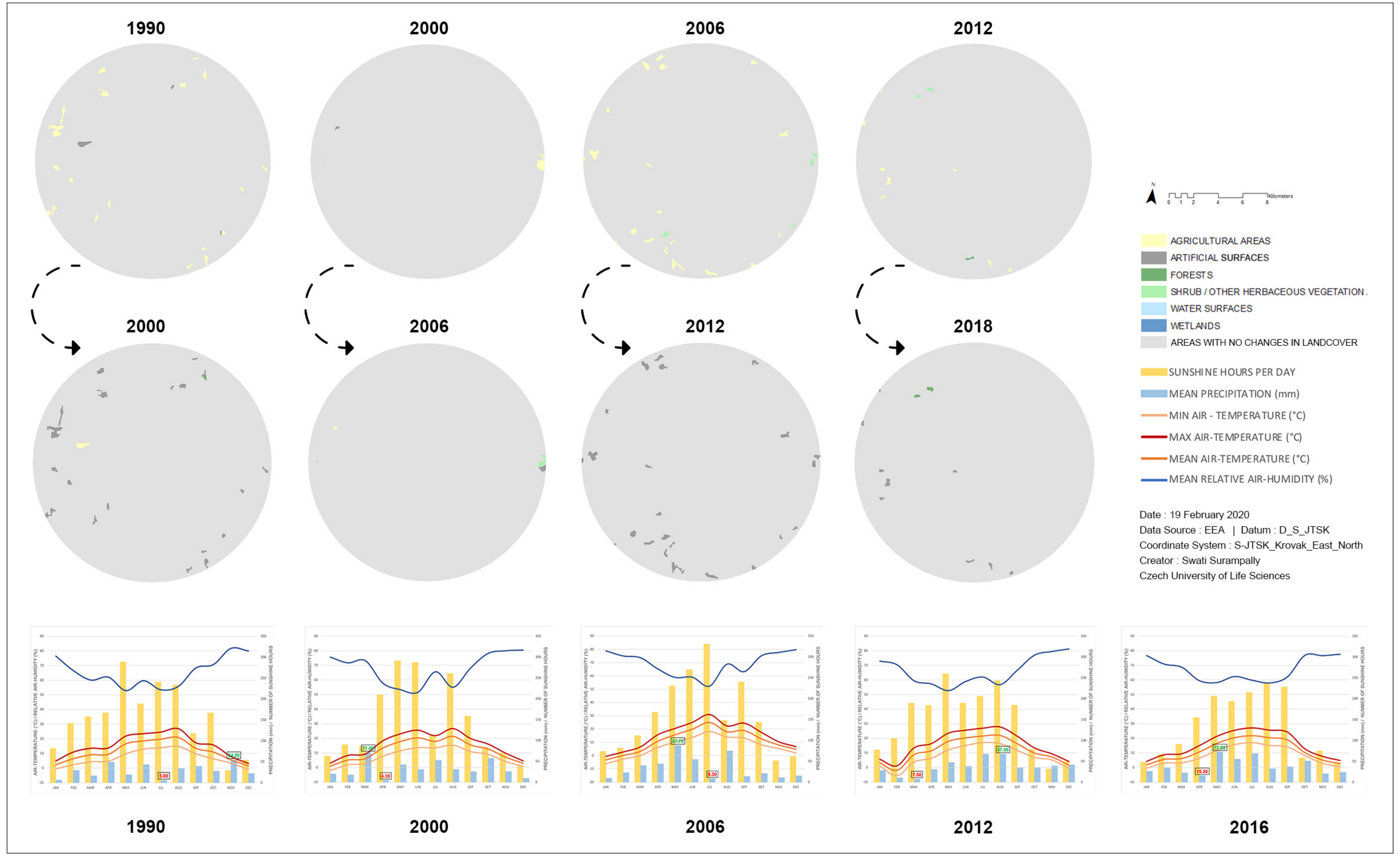


Figure 33. CHANGES IN THE LAND COVER (1990-2018) WITH CHANGES IN THE SEASONAL CLIMATIC CONDITIONS (1990-2016) FOR PRAGUE AREA.

9.3. Třeboň Area

Annual Climate Trends in Třeboň Area:

In the Třeboň area, the trend in the temperature values show a statistically significant increase and relative air-humidity shows a statistically significant decrease over time as seen in Figure 34. Precipitation and Sunshine hours have increasing values over time but are not statistically significant as inferred from the values of Mann-Kendall test listed in Table 7.

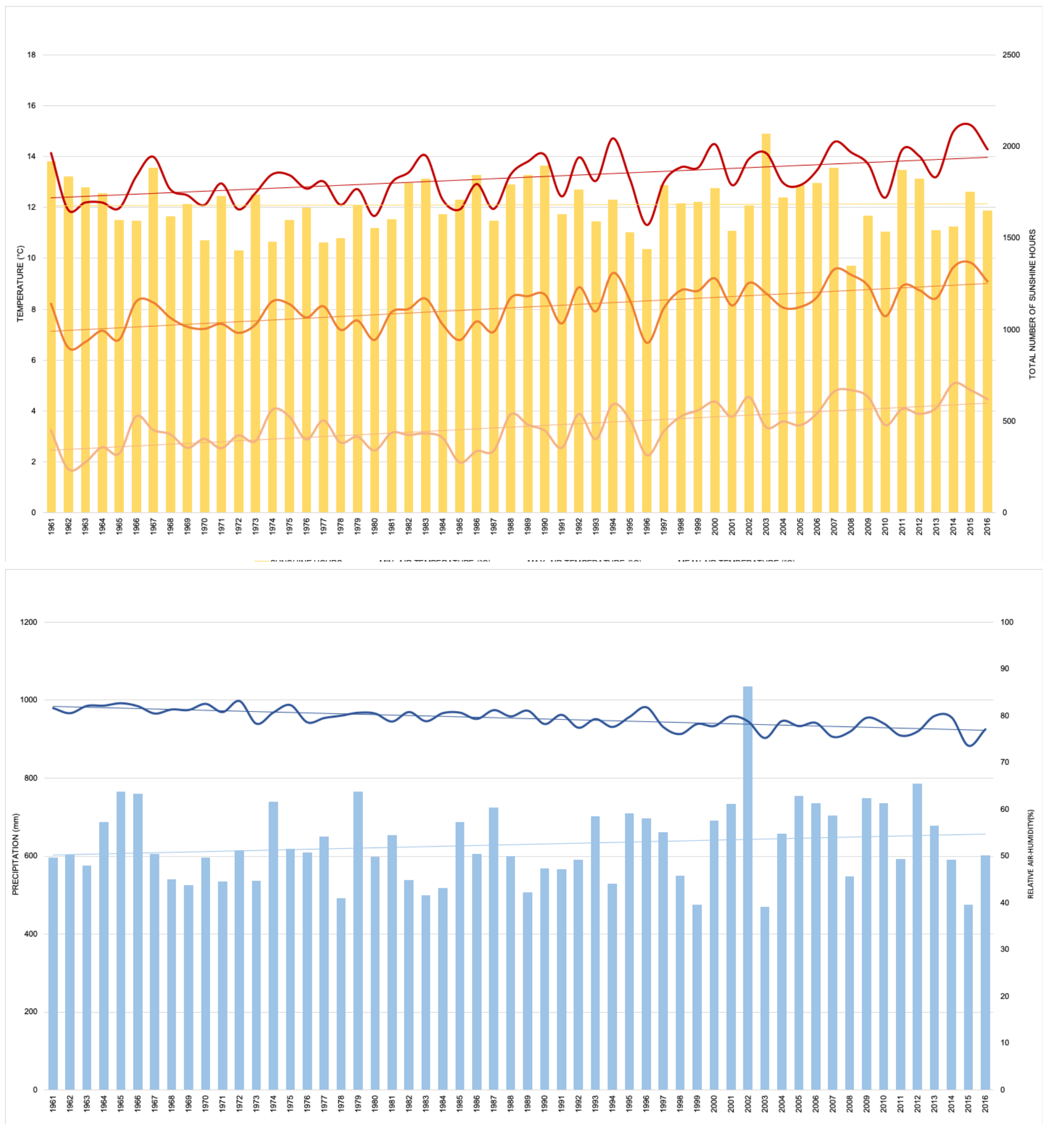


Figure 34. GRAPH OF CLIMATIC TRENDS IN TŘEBOŇ AREA FROM 1961-2016.

Table 7. MANN-KENDALL TEST VALUES FOR EACH METEOROLOGICAL ELEMENT IN TŘEBOŇ AREA

METEOROLOGICAL ELEMENT	KENDALL'S TAU	p-VALUE	SEN'S SLOPE	NULL-HYPOTHESIS	TREND
Max. Air-Temperature	0.377	<0.0001	0.032	rejected	increasing - significant
Mean Air-Temperature	0.488	<0.0001	0.036	rejected	increasing - significant
Min. Air-Temperature	0.484	<0.0001	0.034	rejected	increasing - significant
Sunshine Hours	0.025	0.794	0.433	not rejected	increasing - not significant
Relative Air-Humidity	-0.523	<0.0001	-0.092	rejected	decreasing - significant
Precipitation	0.088	0.340	0.854	not rejected	increasing - not significant

Null Hypothesis: There is no trend in the series; Alternative Hypothesis: There is a trend in the series. Significance level **α = 0.05.**

Change-Points in the Mean/Sum Values of the Meteorological Elements in Třeboň Area:

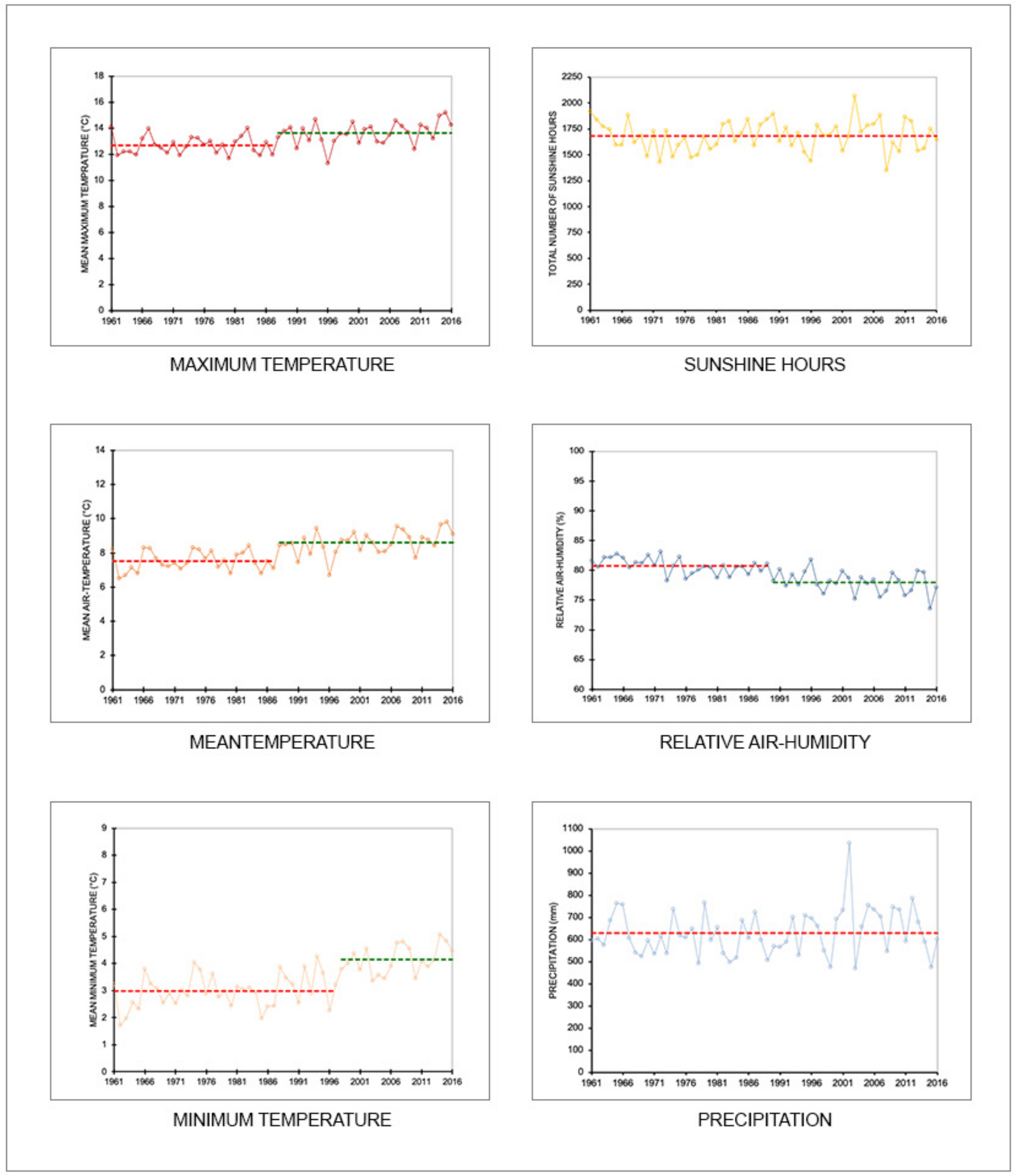


Figure 35. SIGNIFICANT CHANGE-POINTS IN THE MEAN / SUM VALUES FOR EACH OF THE METEOROLOGICAL ELEMENT IN TŘEBOŇ AREA FROM 1961-2016.

There is a statistically significant upward shift in the values of temperature but the shift in the minimum air-temperature occurred a decade after the shift in the values of mean and maximum air-temperatures as evident from the Pettitt's test results in Table 8. There is a statistically significant downward shift in the values of relative air-humidity occurring in nearly the same time period as mean and maximum air-temperature shifts. And there is no shift in the values of sunshine hours and precipitation.

Table 8. PETTITT'S TEST VALUES FOR EACH METEOROLOGICAL ELEMENT IN TŘEBOŇ AREA

METEOROLOGICAL ELEMENT	p-VALUE	SHIFT	YEAR OF SHIFT	NULL-HYPOTHESIS
Max. Air-Temperature	0.000	Upward	1987	rejected
Mean Air-Temperature	<0.0001	Upward	1987	rejected
Min. Air-Temperature	<0.0001	Upward	1997	rejected
Sunshine Hours	0.987	None	-	not rejected
Relative Air-Humidity	<0.0001	Downward	1989	rejected
Precipitation	0.665	None	-	not rejected

Null Hypothesis: Data are homogeneous; Alternative Hypothesis: There is a date at which there is change in the data. Significance level **α = 0.05.**

Trend in the Number of Heavy Precipitation Days in Třeboň Area:

All the three classes of number of days with heavy precipitation show an increasing tendency in case of Třeboň as seen in Figure 36 but the increase is not statistically significant as evident from Table9.

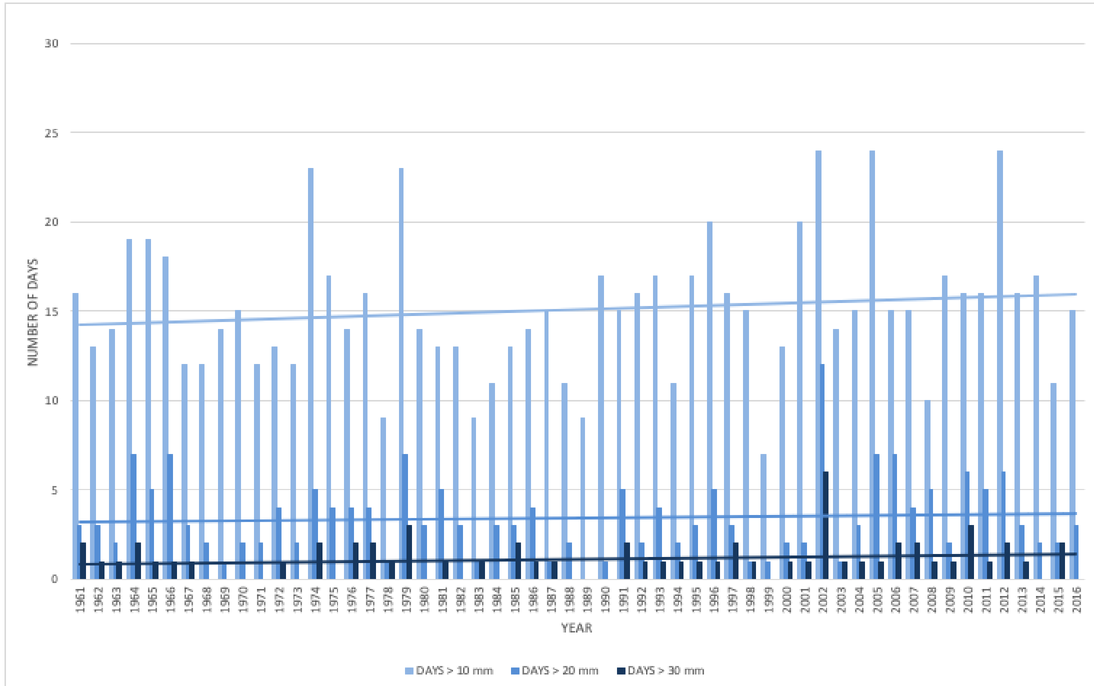


Figure 36. TREND IN THE NUMBER OF HEAVY PRECIPITATION DAYS IN TŘEBOŇ AREA FROM 1961-2016.

Table 9. MANN-KENDALL TEST VALUES FOR NUMBER OF HEAVY PRECIPITATION DAYS IN TŘEBOŇ AREA

FACTOR	KENDALL'S TAU	p-VALUE	SEN'S SLOPE	NULL-HYPOTHESIS	TREND
Days > 10 mm	0.111	0.241	0.031	not rejected	increasing - not significant
Days > 20 mm	0.016	0.869	0.000	not rejected	increasing - not significant
Days > 30 mm	0.111	0.284	0.000	not rejected	increasing - not significant

Null Hypothesis: There is no trend in the series; Alternative Hypothesis: There is a trend in the series. Significance level **α = 0.05.**

Land-Cover (1990-2018) with Annual Precipitation and Mean-Temperature Graph (1990-2016) in Třeboň Area:

More than half of the land cover within the study area around Třeboň is forest cover and the remaining area consists of agricultural areas majorly. As seen in Figure 37, there is an increase in the percentage of forest cover by 12% from the year 1990 to 2018.

The lowest precipitation has been during the decade 1980s (1981-1990) and the temperature values have been consistently increasing every decade with the highest change in the temperature values has during 2010s (2001-2010) to 2020s (2011-2016).

Changes in the Land-Cover with Changes in the Seasonal Climatic Conditions Over Time Within the Study Area of Třeboň:

Major conversions of land cover to forests has been during the period 1990 to 2000 where mostly shrub/other herbaceous vegetation were converted to forests. And the forest cover has been more or less consistent after that. No other major conversions in the land cover occurred after that as seen in Figure 38.

There is an increase in the summer, winter and spring precipitation and a decrease in the autumn precipitation values from 1990-2016 but these changes are not statistically significant. And in case of seasonal mean temperatures, there is an increase in the values during all four seasons but the increase is statistically significant only for autumn mean temperatures.

Figure 37. LAND COVER PERCENTAGES (1990-2018) WITH TEMPERATURE – PRECIPITATION GRAPH (1990-2016) FOR TŘEBOŇ AREA.

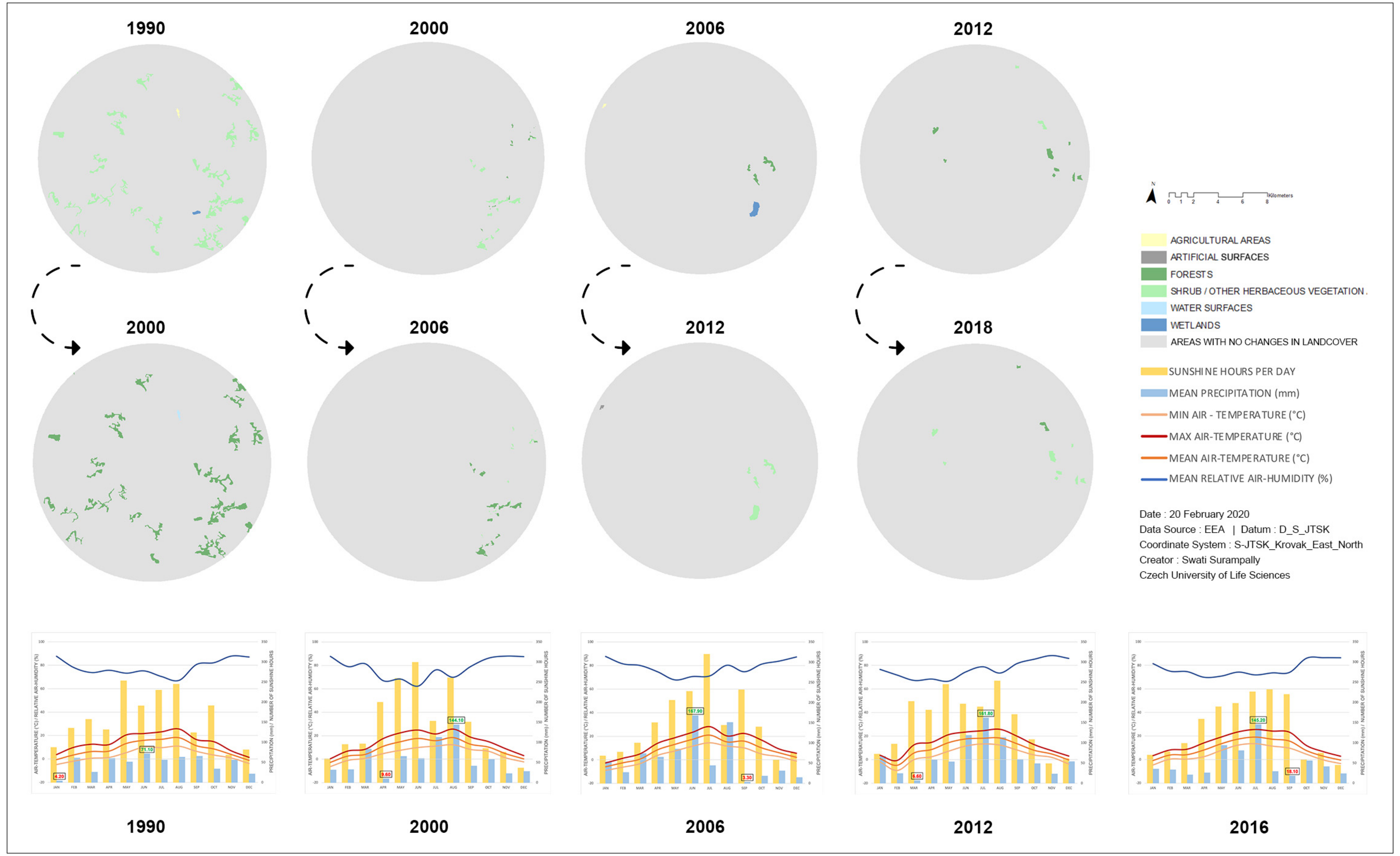


Figure 38. CHANGES IN THE LAND COVER (1990-2018) WITH CHANGES IN THE SEASONAL CLIMATIC CONDITIONS (1990-2016) FOR TŘEBOŇ AREA.

9.4. Brno Area

Annual Climate Trends in Brno Area:

In accordance to the results of Mann-Kendall test as listed in Table 10, there is a statistically significant trend for all the meteorological elements in Brno area except for precipitation which although shows an increase but the trend is not statistically significant. All the elements show an increasing trend except for relative air-humidity and precipitation which show a decreasing trend as seen in Figure 39.

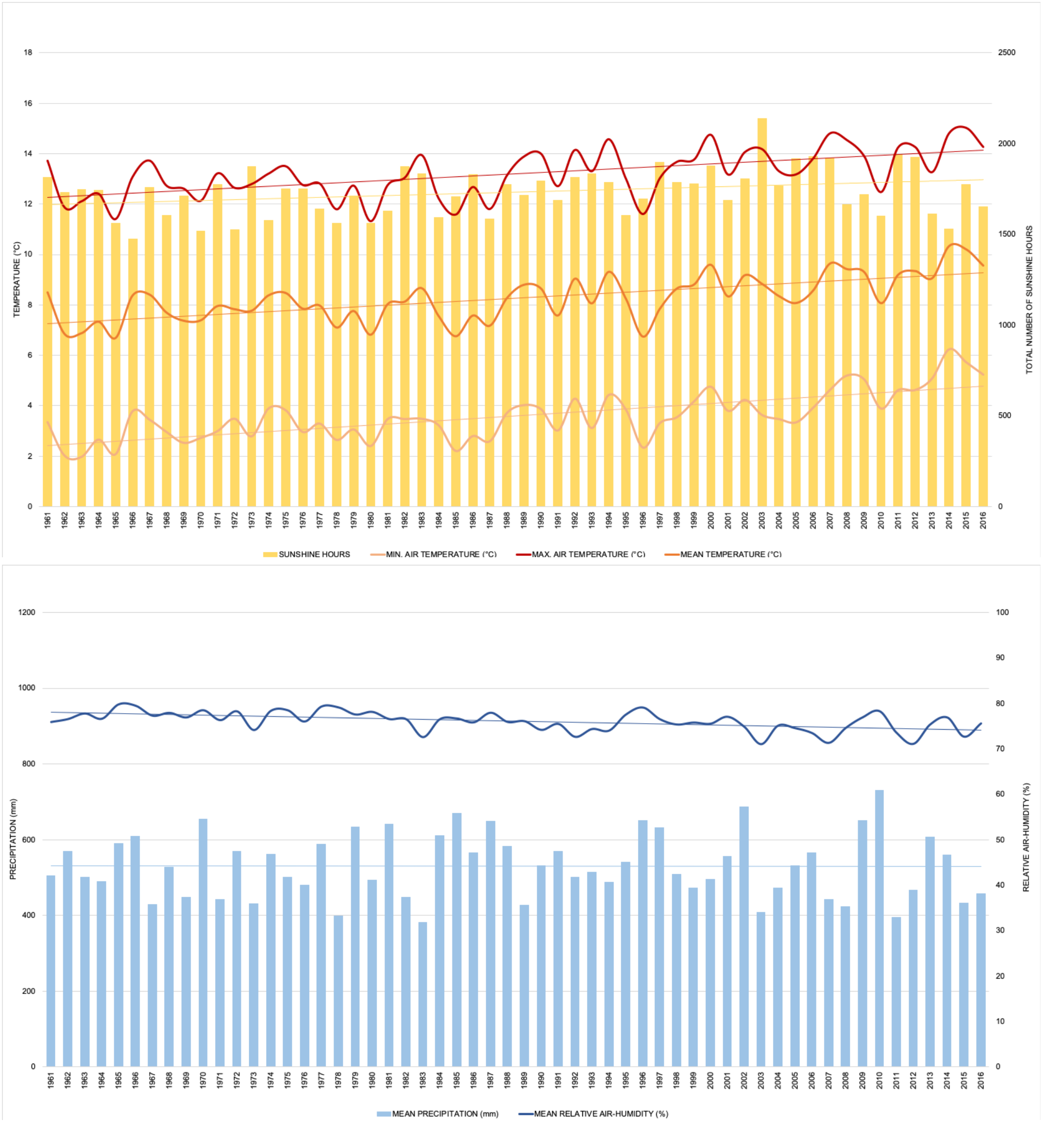


Figure 39. GRAPH OF CLIMATIC TRENDS IN BRNO AREA FROM 1961-2016.

Table 10. MANN-KENDALL TEST VALUES FOR EACH METEOROLOGICAL ELEMENT IN BRNO AREA

METEOROLOGICAL ELEMENT	KENDALL'S TAU	p-VALUE	SEN'S SLOPE	NULL-HYPOTHESIS	TREND
Max. Air-Temperature	0.442	<0.0001	0.035	rejected	increasing - significant
Mean Air-Temperature	0.491	<0.0001	0.038	rejected	increasing - significant
Min. Air-Temperature	0.543	<0.0001	0.043	rejected	increasing - significant
Sunshine Hours	0.204	0.027	2.435	rejected	increasing - significant
Relative Air-Humidity	-0.383	<0.0001	-0.071	rejected	decreasing - significant
Precipitation	-0.039	0.677	-0.225	not rejected	decreasing - not significant

Null Hypothesis: There is no trend in the series; Alternative Hypothesis: There is a trend in the series. Significance level **α = 0.05.**

Change-Points in the Mean/Sum Values of the Meteorological Elements in Brno Area:

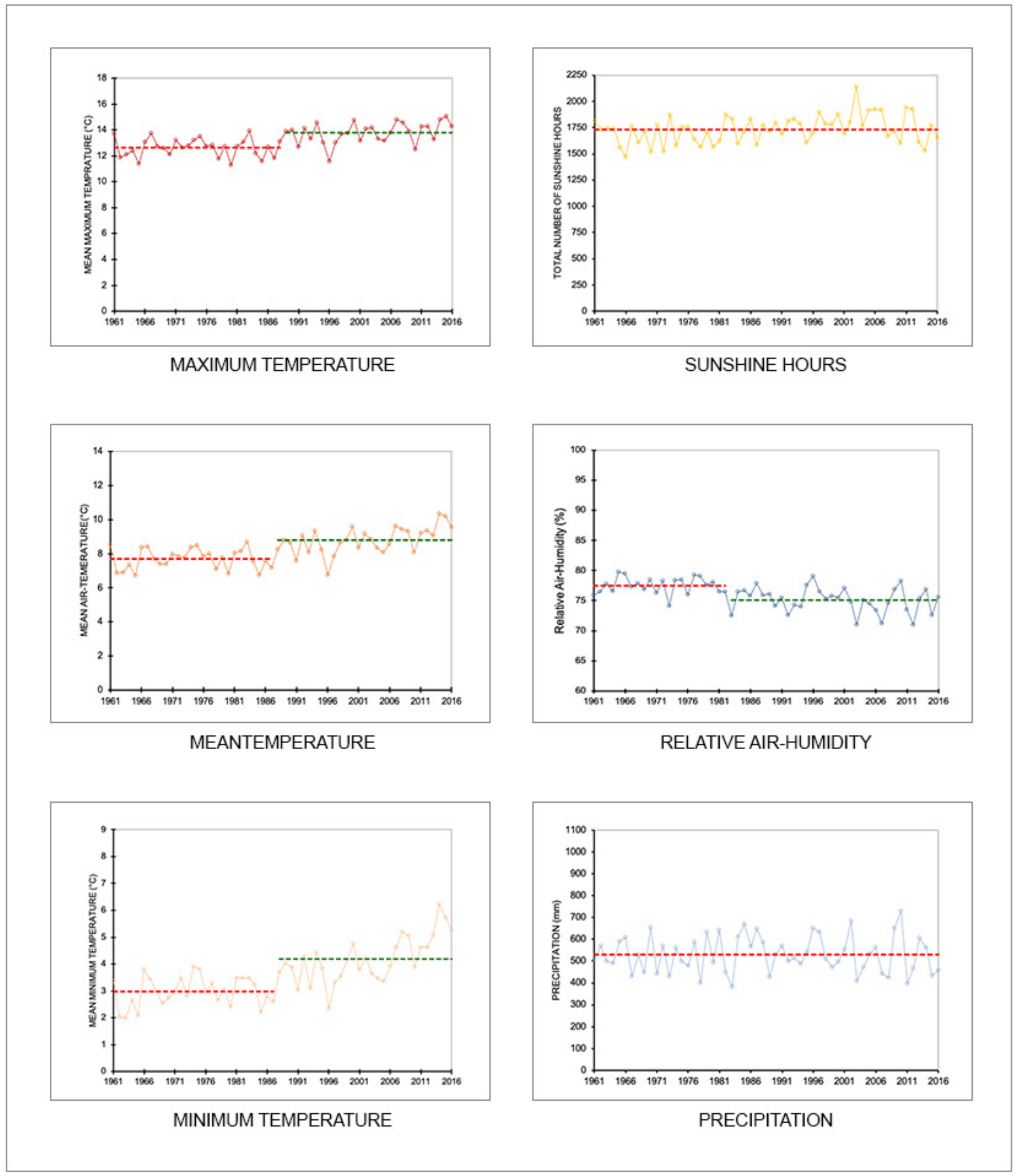


Figure 40. SIGNIFICANT CHANGE-POINTS IN THE MEAN / SUM VALUES FOR EACH OF THE METEOROLOGICAL ELEMENT IN BRNO AREA FROM 1961-2016.

There is a statistically significant upward shift in the mean values of temperature and a statistically significant downward shift in the mean values of relative air-humidity which seems to have occurred five years earlier than the shift in temperature values. While there are no significant shifts in values of sunshine hours and precipitation. The early change in relative air-humidity is similar as in case of Most but since we do not have any data on the land cover changes before 1990s, it cannot be justified whether the change is related to changes in atmospheric moisture content caused by changes in land cover.

Table 11. PETTITT'S TEST VALUES FOR EACH METEOROLOGICAL ELEMENT IN BRNO AREA

METEOROLOGICAL ELEMENT	p-VALUE	SHIFT	YEAR OF SHIFT	NULL-HYPOTHESIS
Max. Air-Temperature	<0.0001	Upward	1988	rejected
Mean Air-Temperature	<0.0001	Upward	1987	rejected
Min. Air-Temperature	<0.0001	Upward	1987	rejected
Sunshine Hours	0.051	None	-	not rejected
Relative Air-Humidity	0.000	Downward	1982	rejected
Precipitation	0.414	None	-	not rejected

Null Hypothesis: Data are homogeneous; Alternative Hypothesis: There is a date at which there is change in the data. Significance level **α = 0.05.**

Trend in the Number of Heavy Precipitation Days in Brno Area:

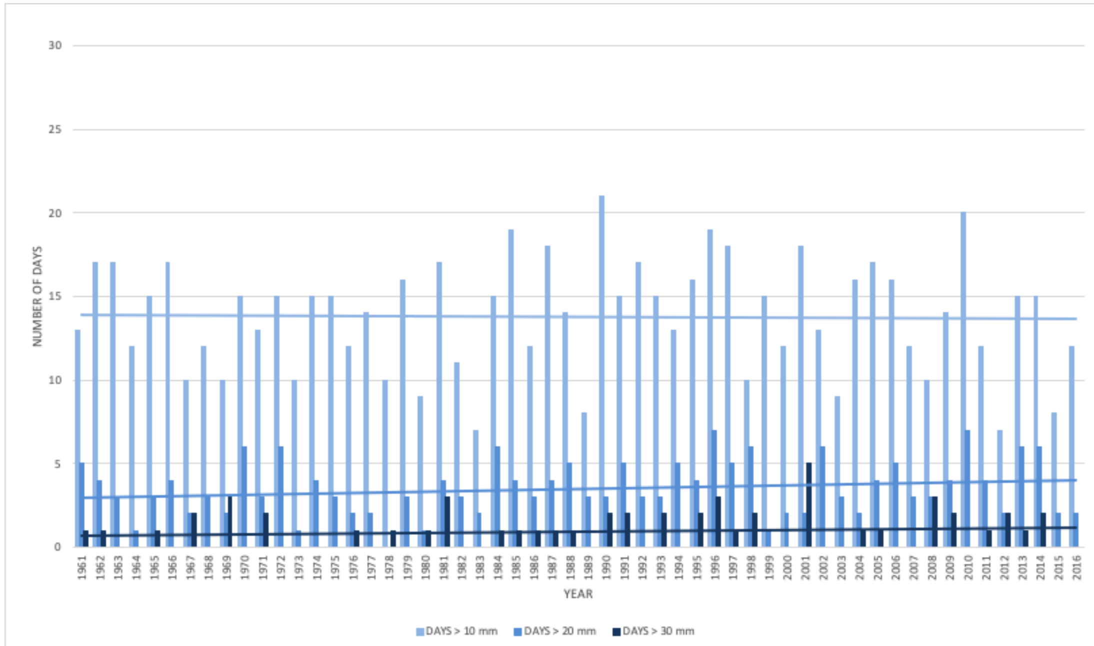


Figure 41. TREND IN THE NUMBER OF HEAVY PRECIPITATION DAYS IN BRNO AREA FROM 1961-2016.

The number of days with precipitation greater than 10 mm shows a decreasing trend while number of days with precipitation greater than 20 mm and 30 mm shows an increasing trend as seen in Figure 41. None of the three classes indicate a statistically significant trend in case of Brno as seen in the Table 12.

Table 12. MANN-KENDALL TEST VALUES FOR NUMBER OF HEAVY PRECIPITATION DAYS IN BRNO AREA

FACTOR	KENDALL'S TAU	p-VALUE	SEN'S SLOPE	NULL-HYPOTHESIS	TREND
Days > 10 mm	-0.017	0.859	0.000	not rejected	decreasing - not significant
Days > 20 mm	0.119	0.226	0.000	not rejected	increasing - not significant
Days > 30 mm	0.102	0.323	0.000	not rejected	increasing - not significant

Null Hypothesis: There is no trend in the series; Alternative Hypothesis: There is a trend in the series. Significance level **α = 0.05.**

Land-Cover (1990-2018) with Annual Precipitation and Mean-Temperature Graph (1990-2016) in Brno Area:

Nearly half of the land cover within the study area around Brno is under agriculture, followed by a forest cover and artificial areas. The percentage of forest cover in this case, as seen in Figure 42 has been constant throughout, except for an increase and decrease of about 2% during 1990-2006.

The lowest precipitation has been during the decade 1970s (1971-1980) while the temperature values have been consistently increasing with every decade with the highest change in the temperature values has during 2010s (2001-2010) to 2020s (2011-2016).

Changes in the Land-Cover with Changes in the Seasonal Climatic Conditions Over Time Within the Study Area of Brno:

There were some minor land conversions from shrub/other herbaceous vegetation to forests in the time period 1990-2000 and again some conversions from forests to shrub/other herbaceous vegetation from 2000-2006. Other land conversions include changes from agricultural use to artificial surfaces as seen in Figure 43.

There is an increase in the summer and winter precipitation and a decrease in the autumn and spring precipitation values from 1990-2016 but these changes are not statistically significant. There is a statistically significant increase in the summer and autumn mean temperatures but for winter and spring although there is an increase but not statistically significant.

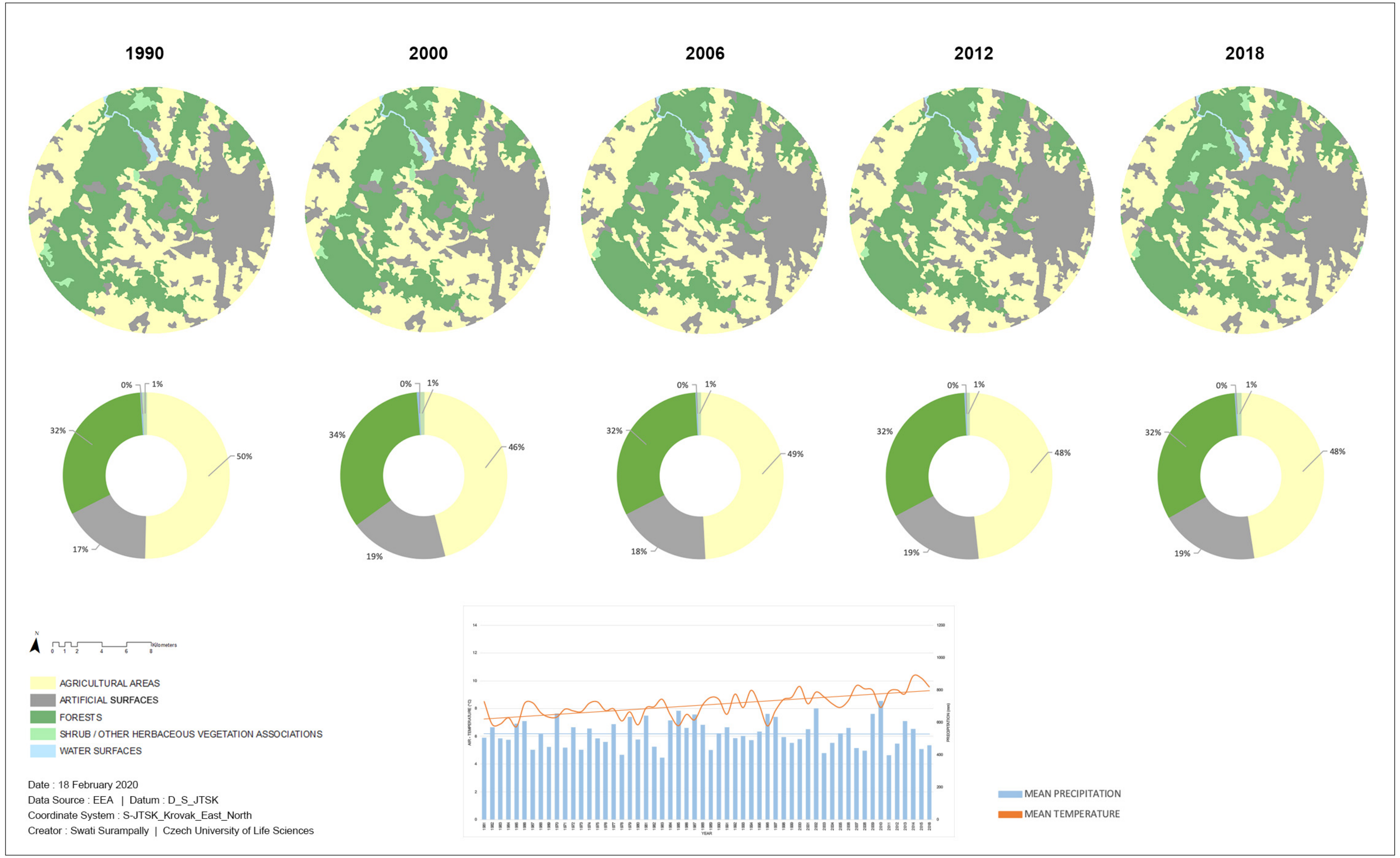


Figure 42. LAND COVER PERCENTAGES (1990-2018) WITH TEMPERATURE – PRECIPITATION GRAPH (1990-2016) FOR BRNO AREA.

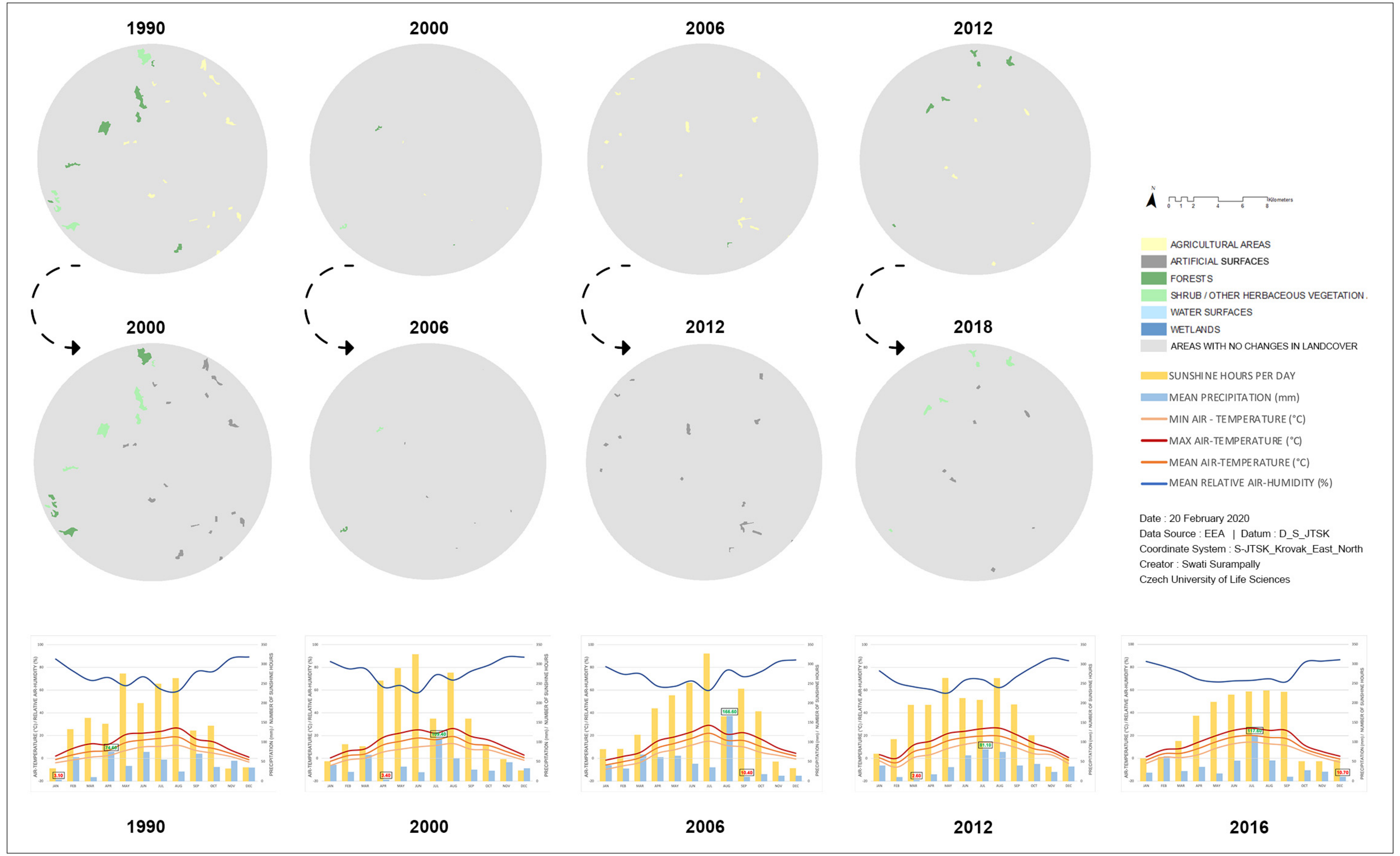


Figure 43. CHANGES IN THE LAND COVER (1990-2018) WITH CHANGES IN THE SEASONAL CLIMATIC CONDITIONS (1990-2016) FOR BRNO AREA.

9.5. Comparison of Annual Climate Trends of the Four Study Areas

Mean Air-Temperature:

The p-value for the Kruskal-Wallis test applied to mean air-temperature across the four study areas is < 0.0001 which is lower than the significance level of 0.05 and hence the null hypothesis is rejected which implies that the mean values of the four groups are significantly different.

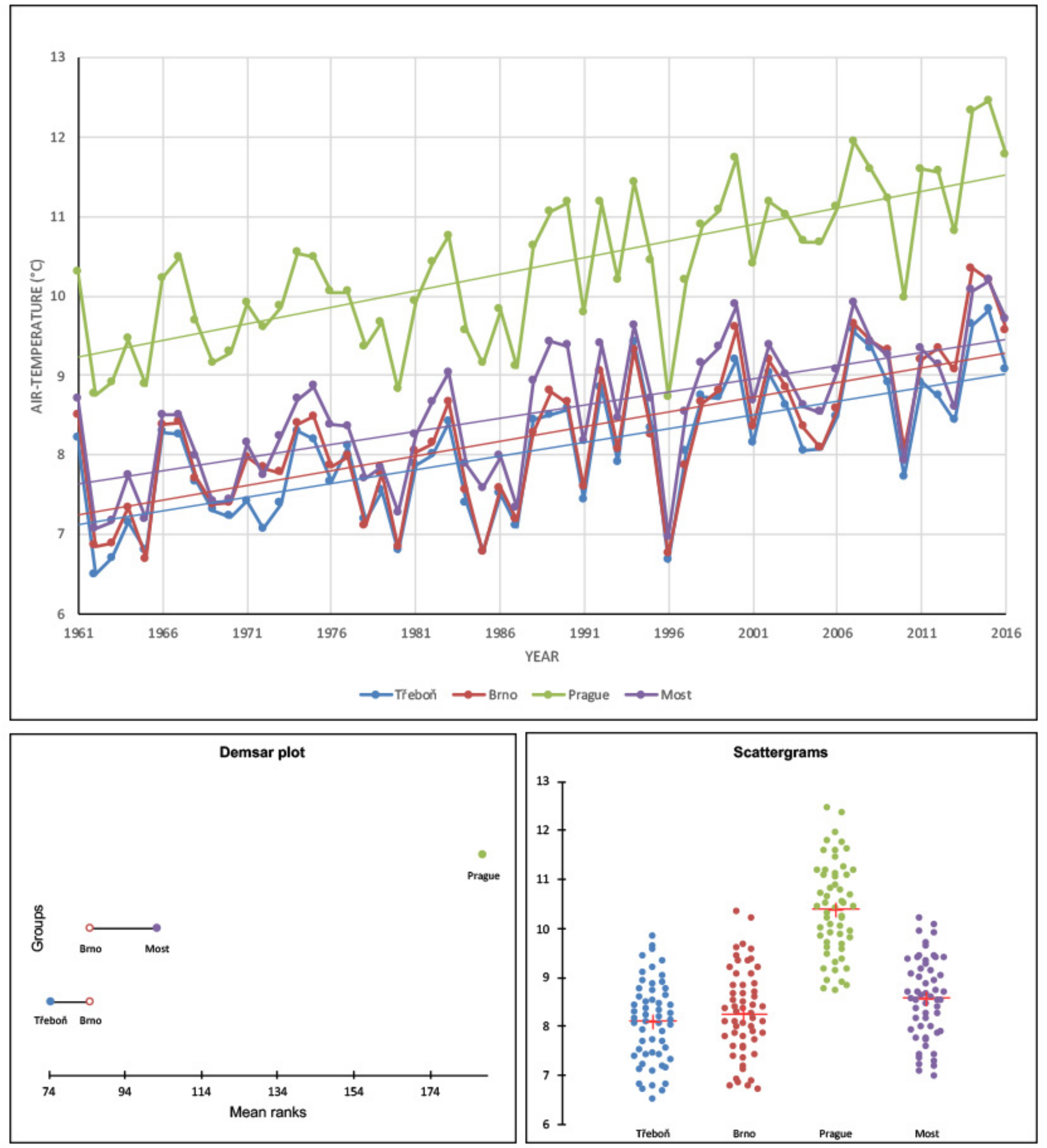


Figure 44. GRAPHS COMPARING TRENDS AND VALUES OF MEAN AIR-TEMPERATURE ACROSS THE FOUR STUDY AREAS FROM 1961-2016.

From the multiple pairwise comparisons as seen in Table 13, it can be inferred that mean values of Prague is distinctively different from the mean values of Třeboň, Brno and Most which are nearly similar. From the line graph and scatter graph in Figure 44, it is also evident that the values of mean air-temperature in Prague are higher by about 2.2°C than the other three places

Table 13. MULTIPLE PAIRWISE COMPARISONS USING THE STEEL-DWASS-CRITCHLOW-FLIGNER PROCEDURE FOR MEAN AIR -TEMPERATURE ACROSS THE FOUR STUDY AREAS.

Sample	Groups		
Třeboň	A		
Brno	A	B	
Most		B	
Prague			C

Maximum Air-Temperature:

The p-value for the Kruskal-Wallis test for maximum air-temperature across the four study areas is < 0.0001 which is lower than the significance level of 0.05, hence the null hypothesis is rejected which implies that the mean values of the four groups are significantly different.

From the multiple pairwise comparisons as seen in Table 14, it can be inferred that mean values of Prague is distinctively different the mean values of Třeboň, Brno and Most. From the line graph and scatter graph in Figure 45, it is evident that the values of maximum air-temperature in Prague are higher by about 1°C than the other three places.

Table 14. MULTIPLE PAIRWISE COMPARISONS USING THE STEEL-DWASS-CRITCHLOW-FLIGNER PROCEDURE FOR MAXIMUM AIR -TEMPERATURE ACROSS THE FOUR STUDY AREAS.

Sample	Groups	
Třeboň	A	
Most	A	
Brno	A	
Prague		B

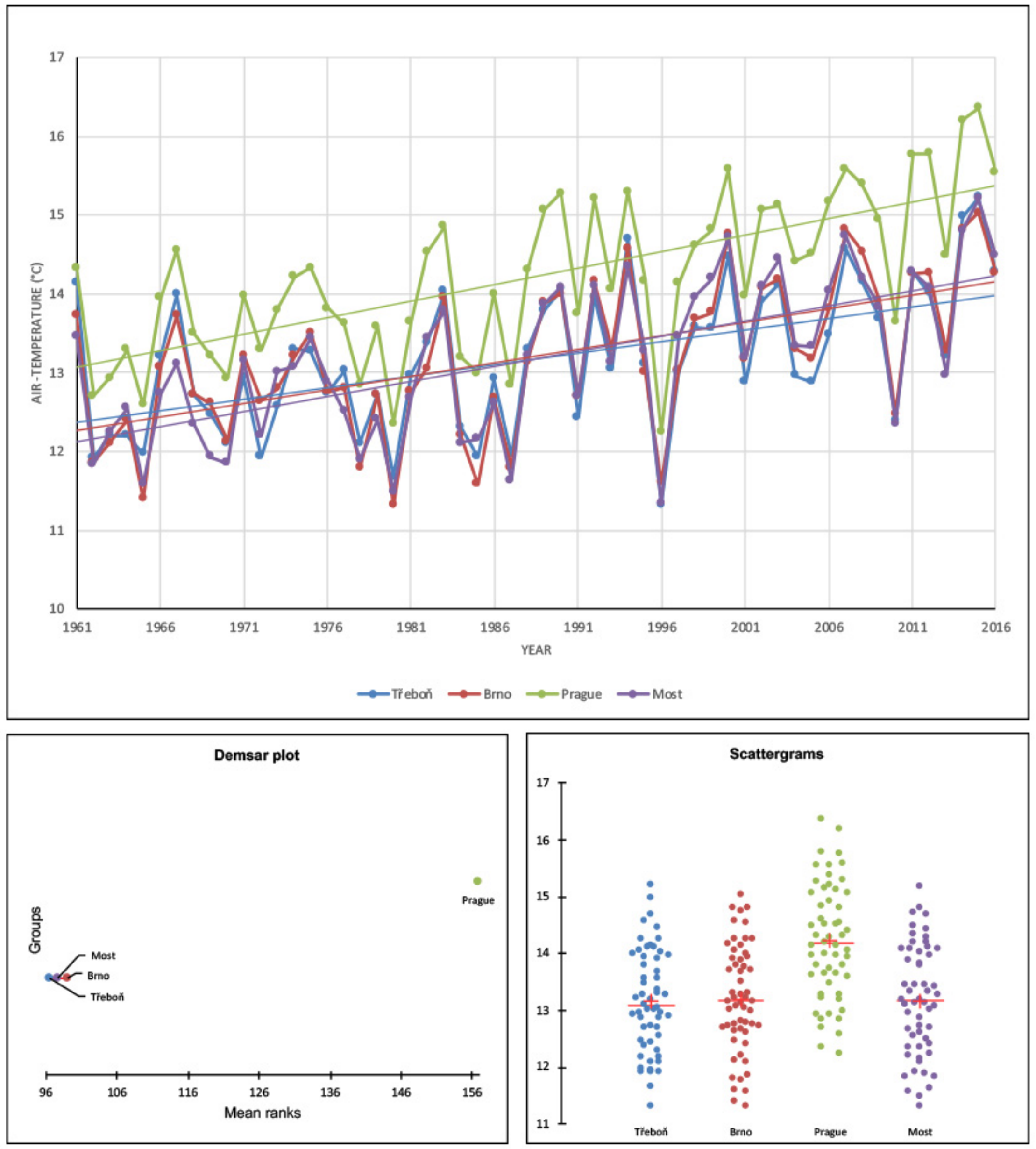


Figure 44. GRAPHS COMPARING TRENDS AND VALUES OF MEAN AIR-TEMPERATURE ACROSS THE FOUR STUDY AREAS FROM 1961-2016.

Minimum Air-Temperature:

The p-value for the Kruskal-Wallis test for maximum air-temperature across the four study areas is < 0.0001 which is lower than the significance level of 0.05, hence the null hypothesis is rejected which implies that the mean values of the four groups are significantly different. From the multiple pairwise comparisons as seen in Table 15, it can be inferred that mean values of Třeboň and Brno are similar and that of Prague and Most are significantly different. From the line graph and scatter graph as seen in Figure 46, it is evident that minimum air-temperature values are the lowest for Třeboň and Brno, followed by Most which are about 1°C higher and are the highest in case of Prague which are about 3°C higher than values for Třeboň and Brno.

Table 15. MULTIPLE PAIRWISE COMPARISONS USING THE STEEL-DWASS-CRITCHLOW-FLIGNER PROCEDURE FOR MINIMUM AIR -TEMPERATURE ACROSS THE FOUR STUDY AREAS.

Sample	Groups		
Třeboň	A		
Brno	A		
Most		B	
Prague			C

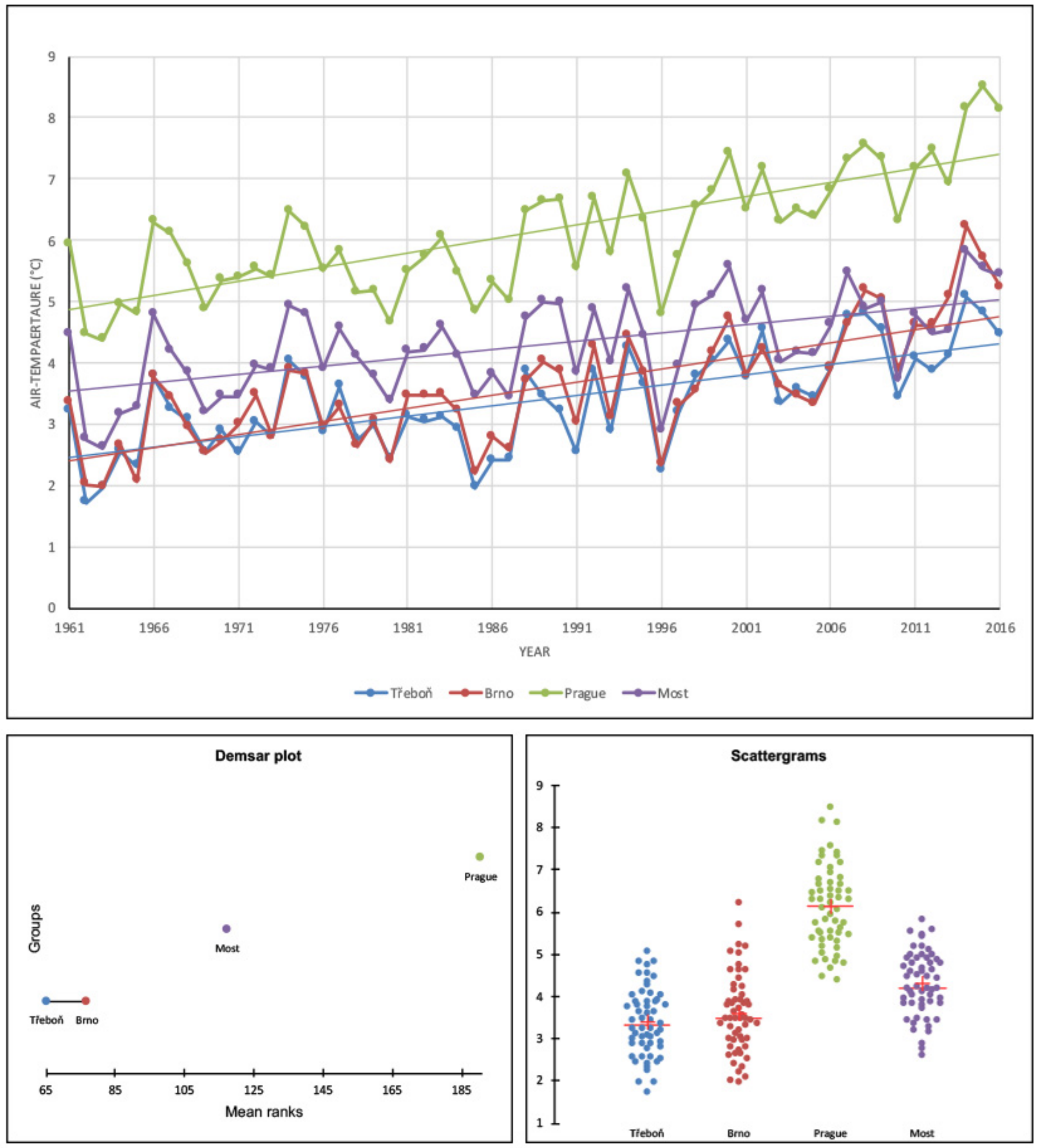


Figure 46. GRAPHS COMPARING TRENDS AND VALUES OF MINIMUM AIR-TEMPERATURE ACROSS THE FOUR STUDY AREAS FROM 1961-2016.

Number of Sunshine Hours:

The p-value for the Kruskal-Wallis test for number of sunshine hours across the four study areas is < 0.0001 which is lower than the significance level of 0.05 and hence the null hypothesis is rejected which implies that the mean values of the four groups are significantly different. From the multiple pairwise comparisons as seen in table 16, it can be inferred that sum values for Most are significantly different than Třeboň, Brno and Prague. From the line graph and scatter graph as seen in Figure 47, it is evident that number of sunshine hours are the lowest for Most by about 200 hours and for Třeboň, Brno and Prague, the values are quite similar.

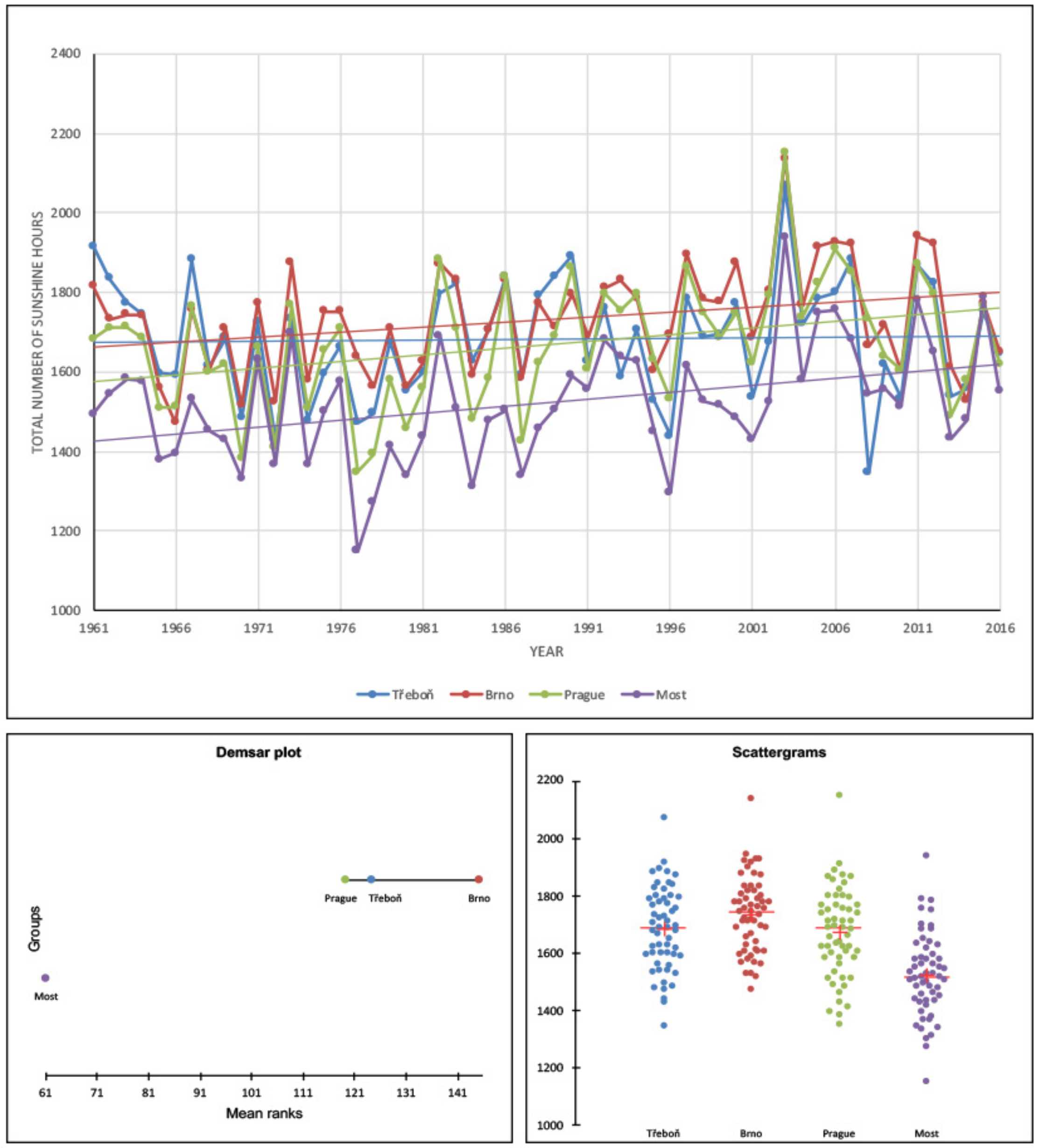


Figure 47. GRAPHS COMPARING TRENDS AND VALUES OF SUNSHINE HOURS ACROSS THE FOUR STUDY AREAS FROM 1961-2016.

Table 16. MULTIPLE PAIRWISE COMPARISONS USING THE STEEL-DWASS-CRITCHLOW-FLIGNER PROCEDURE FOR SUNSHINE HOURS ACROSS FOUR STUDY AREAS.

Sample	Groups	
Most	A	
Prague		B
Třeboň		B
Brno		B

Relative Air-Humidity:

The p-value for the Kruskal-Wallis test for relative air-humidity across the four study areas is < 0.0001 which is lower than the significance level of 0.05 and hence the null hypothesis is rejected which implies that the mean values of the four groups are significantly different.

From the multiple pairwise comparisons as seen in table 17, it can be inferred that the mean values for Most and Brno are similar, while the values for Prague and Most are significantly different. The values as seen in figure 48, for Most and Brno are lower by about 3% from Třeboň and higher from Prague by about 8%.

Table 17. MULTIPLE PAIRWISE COMPARISONS USING THE STEEL-DWASS-CRITCHLOW-FLIGNER PROCEDURE FOR RELATIVE AIR-HUMIDITY ACROSS THE FOUR STUDY AREAS.

Sample	Groups		
Prague	A		
Brno		B	
Most		B	
Třeboň			C

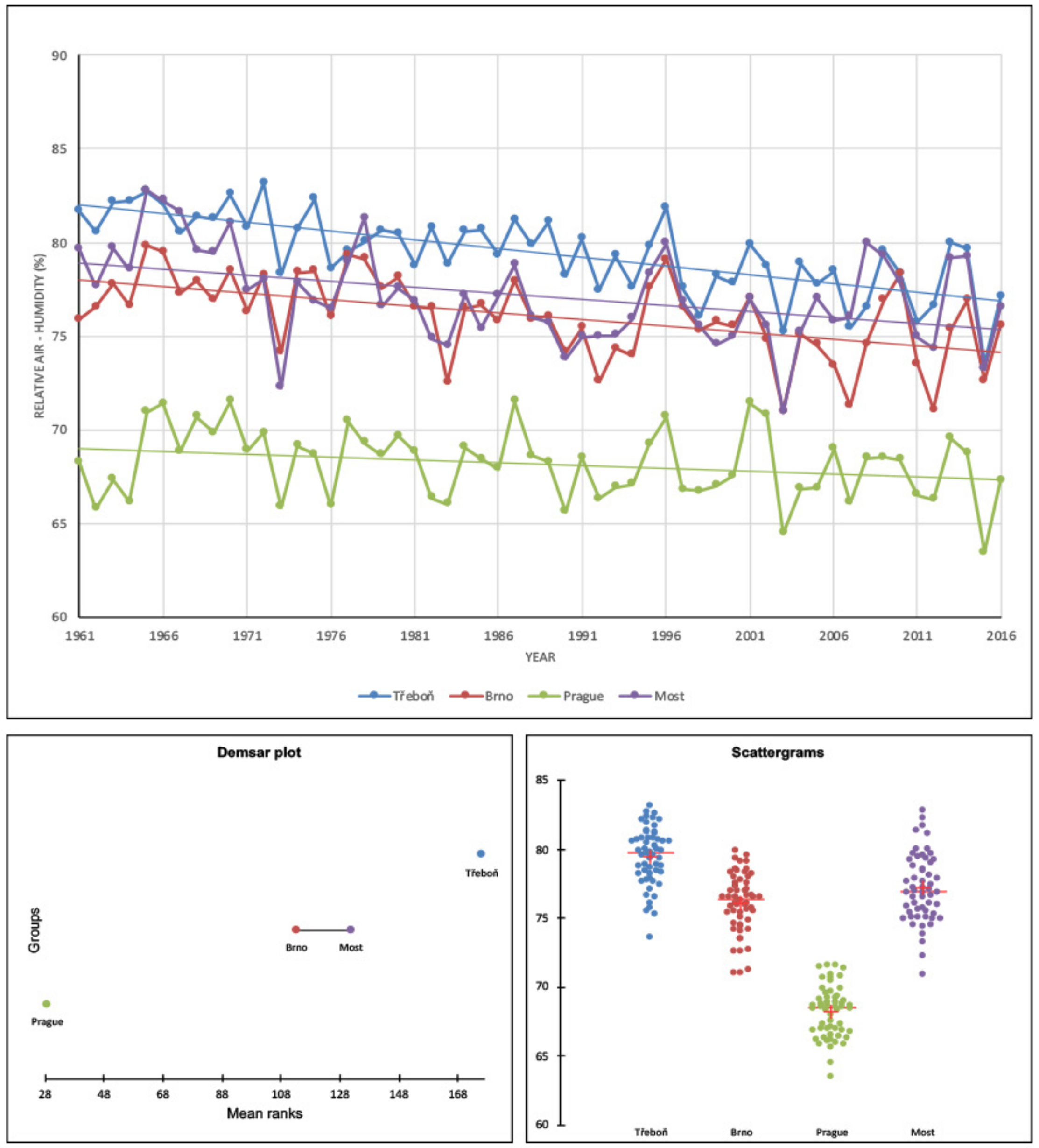


Figure 48. GRAPHS COMPARING TRENDS AND VALUES OF RELATIVE AIR-HUMIDITY ACROSS THE FOUR STUDY AREAS FROM 1961-2016

Precipitation:

The p-value for the Kruskal-Wallis test for precipitation across the four study areas is < 0.0001 which is lower than the significance level of 0.05 and hence the null hypothesis is rejected which implies that the mean values of the four groups are significantly different.

From the multiple pairwise comparisons as seen in table 18, it can be inferred that the sum values for Most and Brno are similar, while the values for Prague and Most are significantly different. The values as seen in figure 48, for Most and Brno are lower by about 100 mm from Třeboň and higher from Prague by about 60 mm.

Table 18. MULTIPLE PAIRWISE COMPARISONS USING THE STEEL-DWASS-CRITCHLOW-FLIGNER PROCEDURE FOR PRECIPITATION ACROSS THE FOUR STUDY AREAS.

Sample	Groups		
Prague	A		
Brno		B	
Most		B	
Třeboň			C

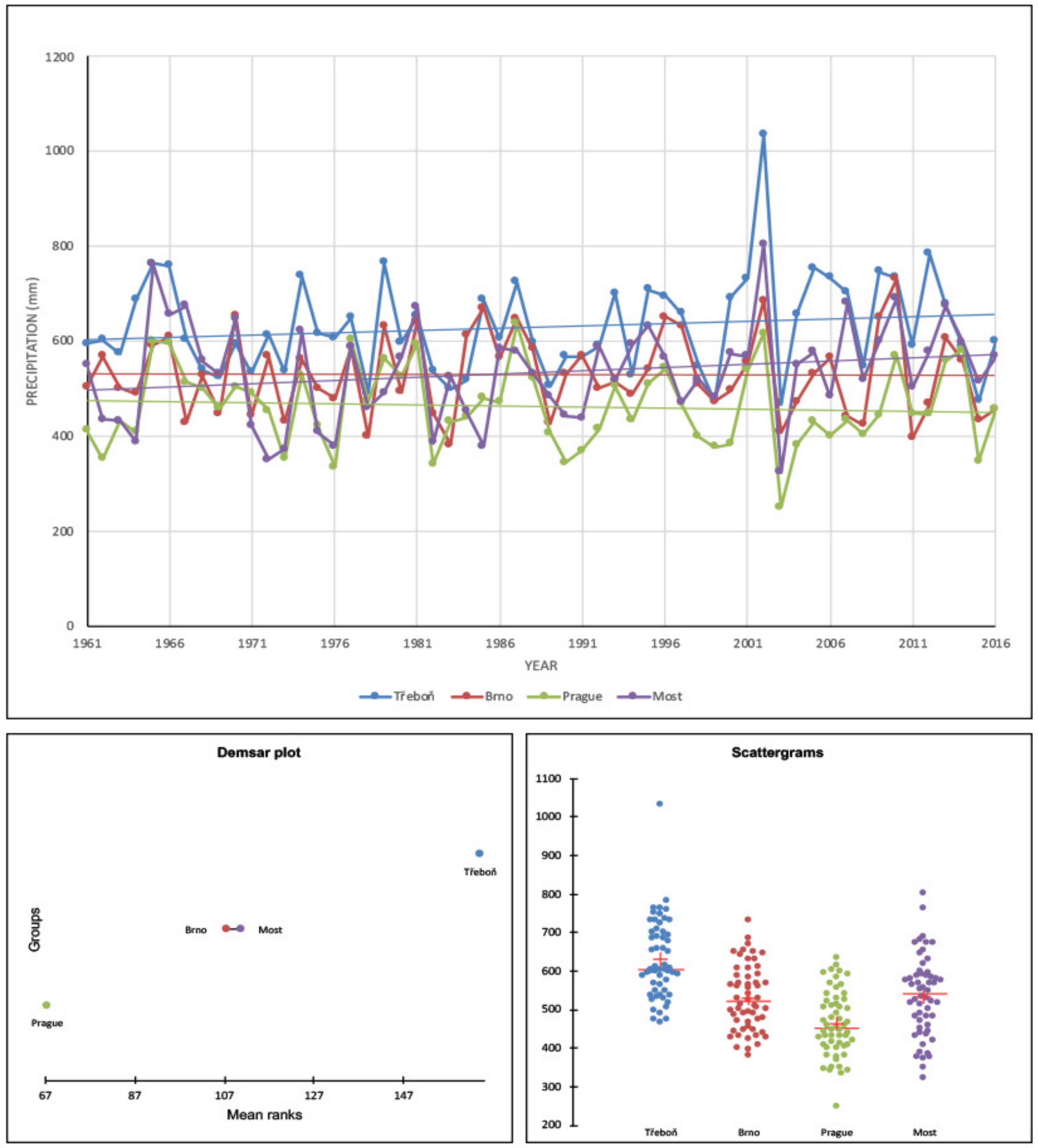


Figure 49. GRAPHS COMPARING TRENDS AND VALUES OF PRECIPITATION ACROSS THE FOUR STUDY AREAS FROM 1961-2016.

9.6. Changes in the Land-Cover Over Time in the Four Study Areas

Land cover when compared across the four study areas as seen in Figure 50, it can be inferred that Třeboň has the highest percentage of forests and water surfaces, and lowest percentage of artificial surfaces as land cover and also is the only area with wetlands among the four study areas and also the one with all types of land cover. There has been an increase in the forest cover in Třeboň from 1990 to 2000 and has been consistent thereafter.

Prague has the highest percentage of artificial surfaces and lowest percentage of forests as land cover among the four study areas. There has been a decrease in the forest cover in Prague from 1990 to 2000 and has been consistent thereafter. Most is the only place among the four study areas which had a consistently increasing forest cover from 1990 to 2018.

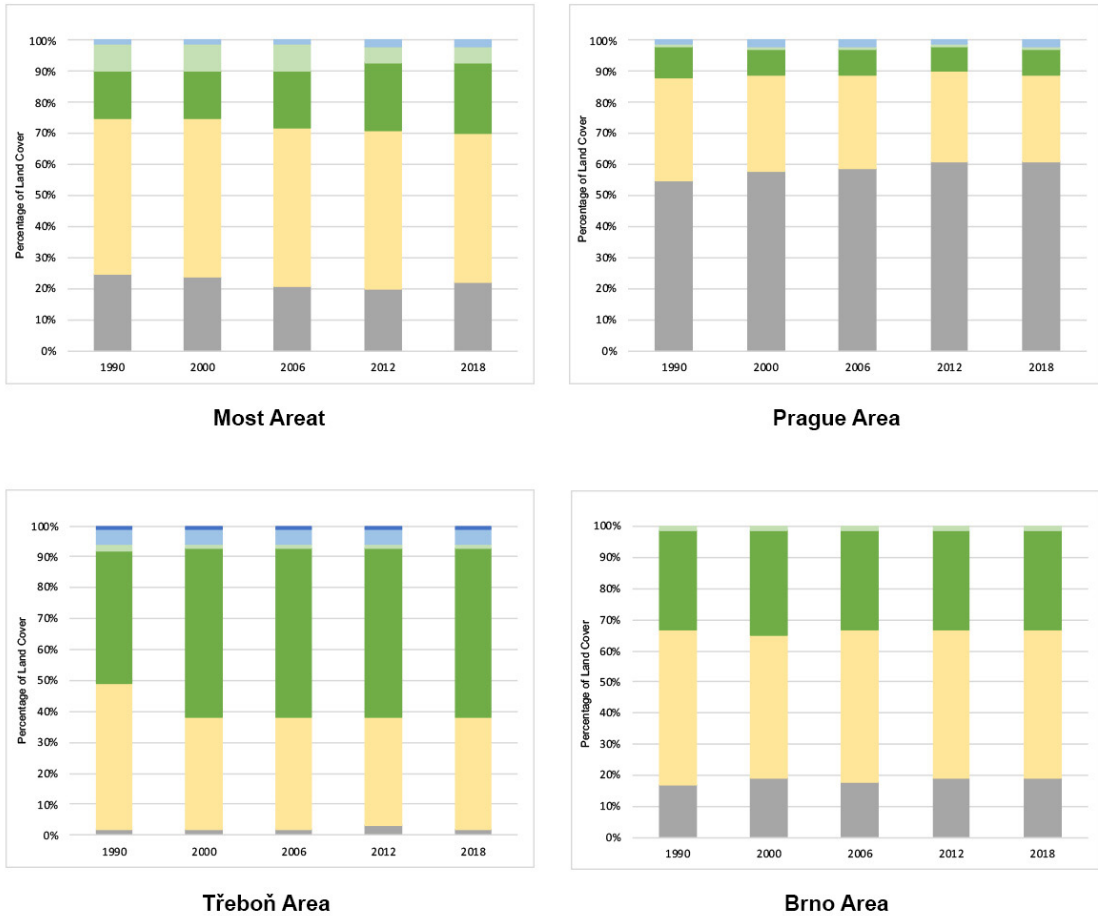
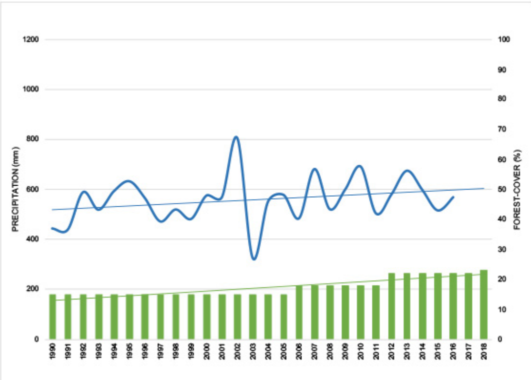


Figure 50. GRAPHS ILLUSTRATING THE CHANGES IN PERCENTAGES OF LAND COVERS OVER TIME WITHIN THE FOUR STUDY AREAS.

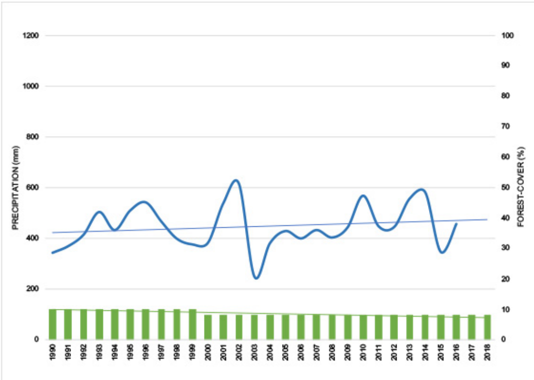
9.7. Forest – Precipitation Dynamics Over Time in the Four Study Areas

As seen in the Figure 51, there is a positive relationship between precipitation trend and forest cover trend for all the study areas except for Prague which indicates a negative relationship.

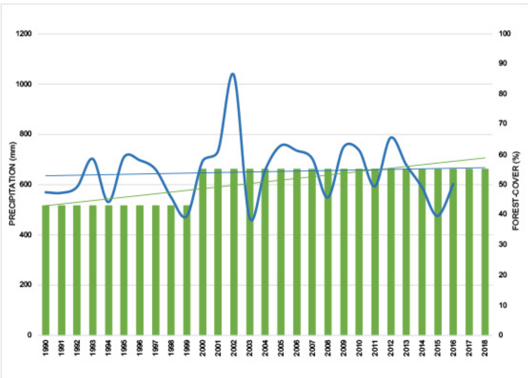
In case of Most and Třeboň, there is an increase in the precipitation with increase in the forest cover and in case of Brno, there is a decrease in the precipitation along with decrease in the forest cover; whereas in case of Prague, there is an increase in the precipitation with decrease in the forest cover, although overall precipitation trend from 1961-2016 shows a decreasing trend in Prague as seen in Figure 29.



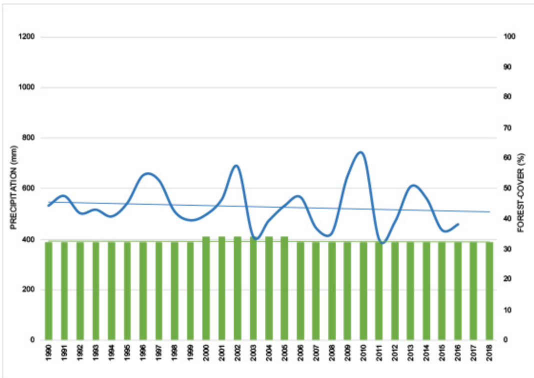
Most Area



Prague Area



Třeboň Area



Brno Area

Figure 51. GRAPHS SHOWING THE RELATIONSHIP BETWEEN TRENDS IN PRECIPITATION AND TRENDS IN THE FOREST COVER FROM 1990-2018 IN THE FOUR STUDY AREAS.

10 | DISCUSSION

The statistical analyses with respect to the precipitation trends generated unexpected results in which no significant changes in the precipitation trends was found during 1961 to 2016 in any of the four study areas. The line graph (Figure 49) indicated increasing precipitation values for Most and Třeboň while decreasing values were indicated for Prague and Brno. Unlike precipitation, the temperature values indicated a significantly increasing trend across all the four locations. This suggests that the trends in temperature are consistent and hence predictable but in case of precipitation, there are uncertainties and hence it is important to analyse the heavy precipitation events.

Even in case of number of days with heavy precipitation analysed in this study, there were no significant trends for any of the study areas except for Most where there is a statistically significant increase. While Třeboň and Brno indicate insignificant increase in the number of the days with extreme precipitation, Prague area indicated an insignificant decrease in the trend. The number of sunshine hours across Most, Prague and Brno showed a significantly increasing trend while for Třeboň the increase was not statistically significant. With respect to the trends in relative air-humidity, there is a significantly decreasing trend across all the four locations. From the analyses of the climate data, significant trends can be inferred for all the meteorological elements except for precipitation.

From the values of the temperature and precipitation trends for Global, Continental and the National trends as mentioned in Chapter 5 it is evident that the temperature values for Europe and the Czech Republic exceed the Global trend values, and in case of precipitation, the values vary across Europe which indicate increase as well decrease compared to the Global trend. The precipitation values for Czech Republic however show an increase compared to the Global trend but are within the range of European trend values.

According to the report by EEA (2017), during the time period 1960 to 2015, the trends in the annual temperatures across Europe and the Czech Republic can be seen in Table 19 along with the trends in the four study areas based on the meteorological data from 1961 to 2016. Adler et al (2017) specify that there is no significant Global trend in case of precipitation and the values for trend in temperature across the globe indicate an increase (NASA,2020) as listed in Table 19.

The annual temperature trend of Most and Třeboň are within the trend range of the Czech Republic and European trend values but exceed the range of Global trend values. In case of Prague and Most, the annual temperature trends exceed National, Continental as well as the Global trends.

Table 19. TABLE SHOWING TRENDS IN ANNUAL TEMPERATURE AND ANNUAL PRECIPITATION FROM 1961-2016.

LOCATION	CHANGE IN ANNUAL TEMPERATURE (°C /decade)	CHANGE IN ANNUAL PRECIPITATION (mm/decade)
Globe	0.09 to 0.24 (NASA,2020)	0 (Adler et al,2017)
Europe	0.05 to 0.40 (EEA, 2017)	80 to -80 (EEA, 2017)
Czech Republic	0.25 to 0.30 (EEA, 2017)	0 to 20 (EEA, 2017)
Most Area	0.35	58.80
Prague Area	0.45	-17.88
Třeboň Area	0.34	40.92
Brno Area	0.41	-30.80

The trends in the annual precipitation values for Most and Třeboň exceed the National and Global trend values but are within the range of European trend values. On the other hand, the trend values for Prague and Brno are lower than the National and Global values but are within the range of European trend values. There is a possibility of difference in the method of calculation of the trend values for Global, Continental/ National and the study areas and hence the values are only indicative.

The analyses for precipitation were carried out in context of the annual trends. Since these trends were found to be insignificant in all the study areas, seasonal trends are analysed to examine if there any statistically significant trends within the seasons over time:

Most Area:

As a result of the Mann-Kendall test as seen in Table 20, the summer precipitation shows a statistically significant increase and other seasons do not indicate any significant trends. Figure 52 depicts that there is an increase in the precipitation during autumn while there is a decreasing trend over winter and spring seasons.

The annual precipitation trend for Most as seen in Figure 24 shows an overall increase but not statistically significant and the increase in number of days with heavy precipitation shows a statistically significant increase in the trend as seen in Figure 26.

Table 20. MANN-KENDALL TEST VALUES FOR SEASONAL PRECIPITATION IN MOST AREA FROM 1961-2016.

SEASON	KENDALL'S TAU	p-VALUE	SEN'S SLOPE	NULL-HYPOTHESIS	TREND
Summer	0.264	0.004	1.154	rejected	increasing - signifcant
Autumn	0.173	0.059	0.642	not rejected	increasing - not signifcant
Winter	-0.020	0.827	-0.062	not rejected	decreasing - not signifcant
Spring	-0.004	0.966	-0.029	not rejected	decreasing - not signifcant

Null Hypothesis : There is no trend in the series; Alternative Hypothesis : There is a trend in the series. Significance level **α = 0.05.**

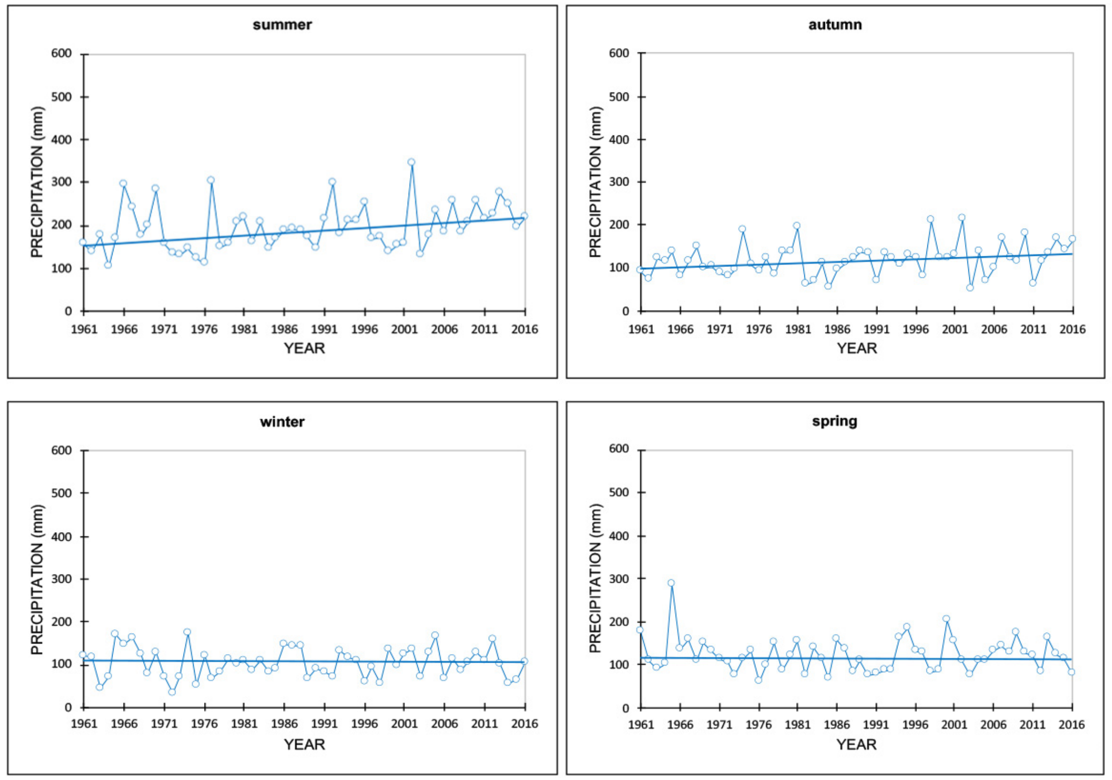


Figure 52. SEASONAL TRENDS IN PRECIPITATION FROM 1961-2016 IN MOST AREA.

Prague Area:

The seasonal precipitation trends as seen in Figure 53 depict an increasing trend during summer and winter and a decreasing trend during autumn and spring. None of the values indicate a statistically significant trend as seen in Table 21 from the Mann-Kendall test.

The annual trend as seen in Figure 29 as well as the number of days with heavy precipitation as seen in Figure 31 in Prague show an overall insignificant decrease in the trend.

Table 21. MANN-KENDALL TEST VALUES FOR SEASONAL PRECIPITATION IN PRAGUE AREA FROM 1961-2016.

SEASON	KENDALL'S TAU	p-VALUE	SEN'S SLOPE	NULL-HYPOTHESIS	TREND
Summer	0.027	0.772	0.092	not rejected	increasing - not signifcant
Autumn	-0.023	0.805	-0.121	not rejected	decreasing - not signifcant
Winter	0.122	0.184	0.219	not rejected	increasing - not signifcant
Spring	-0.142	0.123	-0.485	not rejected	decreasing - not signifcant

Null Hypothesis: There is no trend in the series; Alternative Hypothesis: There is a trend in the series. Significance level α = 0.05.

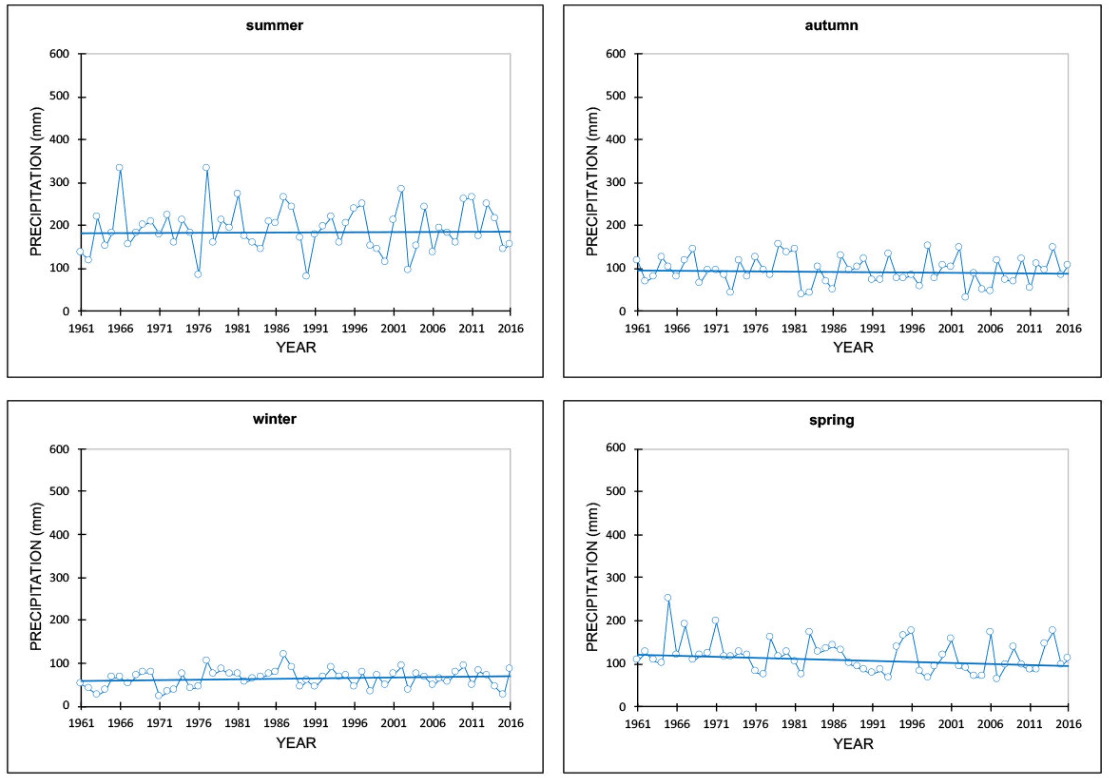


Figure 53. SEASONAL TRENDS IN PRECIPITATION FROM 1961-2016 IN PRAGUE AREA.

Třeboň Area:

Seasonal precipitation values in Třeboň as seen in Figure 54 during summer, autumn and winter show an increase while spring values show a decrease but none of them indicate a statistically significant trend as seen in Table 22 listing the Mann-Kendall test results.

The annual precipitation trend as well as the number of days with heavy precipitation in Třeboň show increasing trends but are not statistically significant as seen in Figure 34 and Figure 36.

Table 22. MANN-KENDALL TEST VALUES FOR SEASONAL PRECIPITATION IN TŘEBOŇ AREA FROM 1961-2016.

SEASON	KENDALL'S TAU	p-VALUE	SEN'S SLOPE	NULL-HYPOTHESIS	TREND
Summer	0.071	0.437	0.512	not rejected	increasing - not signifcant
Autumn	0.129	0.162	0.333	not rejected	increasing - not signifcant
Winter	0.156	0.090	0.383	not rejected	increasing - not signifcant
Spring	-0.057	0.534	-0.179	not rejected	decreasing - not signifcant

Null Hypothesis: There is no trend in the series; Alternative Hypothesis: There is a trend in the series. Significance level α = 0.05.

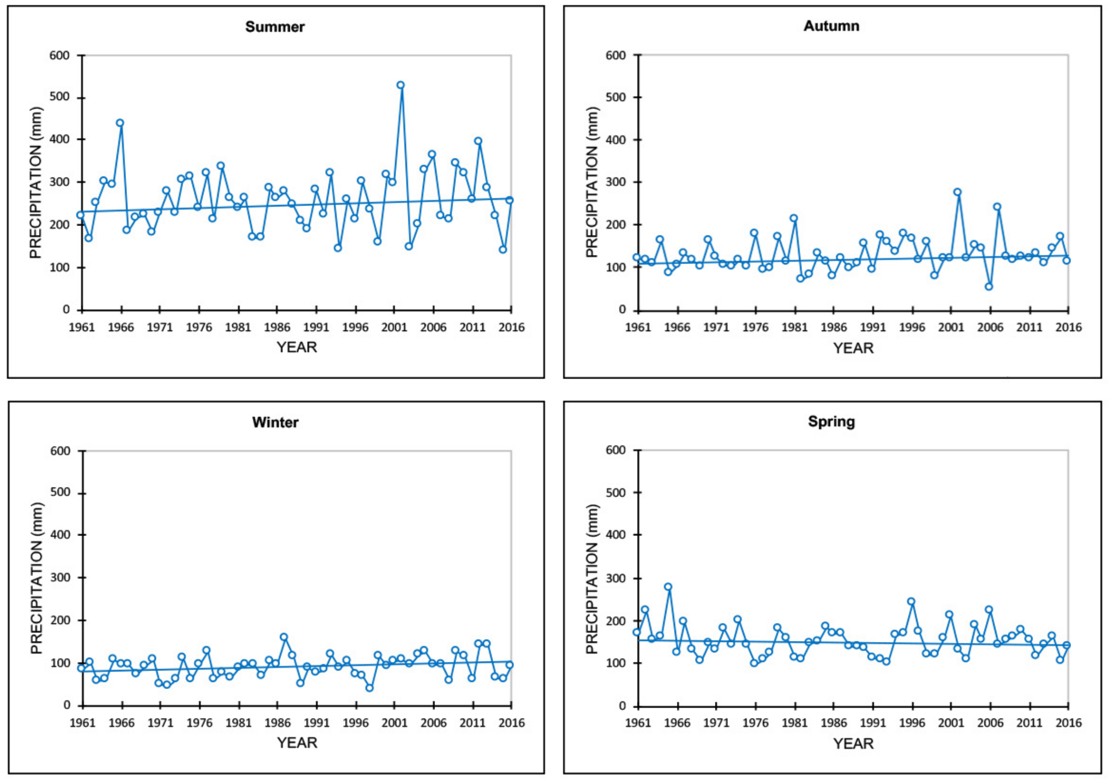


Figure 54. SEASONAL TRENDS IN PRECIPITATION FROM 1961-2016 IN TŘEBOŇ AREA.

Brno Area:

Summer and winter precipitation trends in Brno show an increase and the trends for autumn and spring show a decrease as seen in Figure 55. These trends are not statistically significant as seen from the Mann-Kendall results in Table 23.

The annual precipitation trend in Brno showed an overall decrease over time as seen in Figure 39 but the number of days with heavy precipitation as seen in Figure 41 showed an increasing trend but none of these values were statistically significant.

Table 23. MANN-KENDALL TEST VALUES FOR SEASONAL PRECIPITATION IN BRNO AREA FROM 1961-2016.

SEASON	KENDALL'S TAU	p-VALUE	SEN'S SLOPE	NULL-HYPOTHESIS	TREND
Summer	0.092	0.316	0.514	not rejected	increasing - not significant
Autumn	-0.034	0.708	-0.074	not rejected	decreasing - not significant
Winter	-0.019	0.832	-0.066	not rejected	decreasing - not significant
Spring	-0.064	0.489	-0.222	not rejected	decreasing - not significant

Null Hypothesis: There is no trend in the series; Alternative Hypothesis: There is a trend in the series. Significance level α = 0.05.

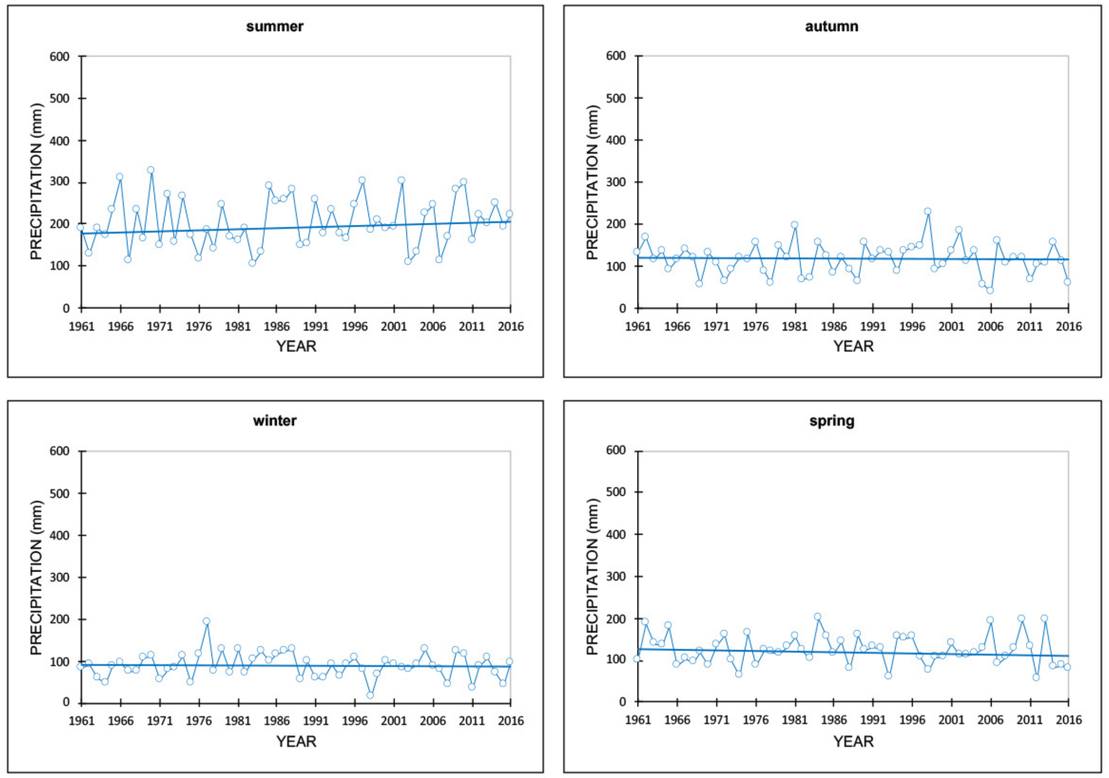
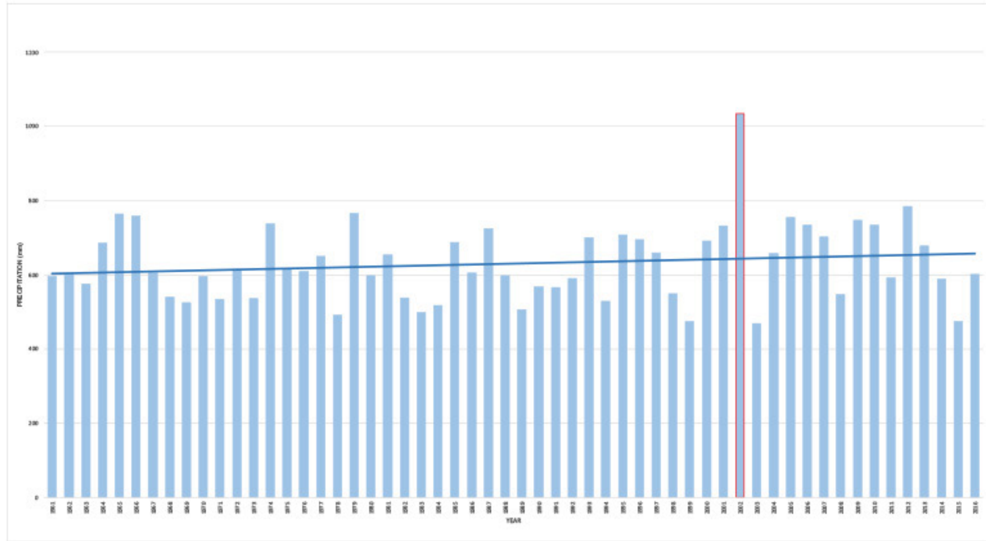


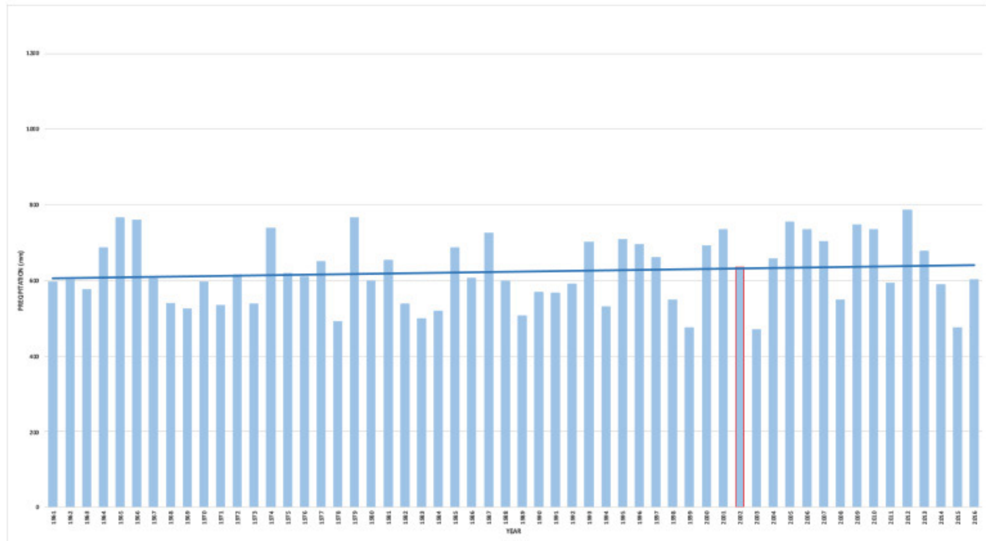
Figure 55. SEASONAL TRENDS IN PRECIPITATION FROM 1961-2016 IN BRNO AREA.

According to the statistical analyses of the seasonal precipitation, only Most showed a statistically significant increase in the summer precipitation and there were no significant seasonal trends for any of the study areas.

The trend in the precipitation at a local scale can also be affected due to the extreme events like in case of Třeboň which had extreme precipitation in 2002 causing floods. To investigate if the trend had a significant effect due to one extreme event, the precipitation value for 2002 was replaced with normal precipitation value. But as seen in Figure 52, there was no significant difference in the trend caused by one extreme event which was in fact a millennial flood in this case.



Graph with actual values



Graph with interpolated values

Figure 56. GRAPHS SHOWING ANNUAL PRECIPITATION TREND IN TŘEBOŇ FROM 1961-2016 WITH ACTUAL VALUE AND INTERPOLATED VALUE FOR THE YEAR 2002.

A probable technical issue in case of the climate data is that there are possibilities of some uncertainties in the dataset due to methods used to downscale Global climate model to Regional climate model as mentioned in the section 6.1. Also, the climate data used in this study is a model gridded output which is basically data derived from interpolated and weighted means of values from a set of meteorological stations in a particular area. Since the values are averaged, the influence on the precipitation data is more important than on the temperature data because precipitation varies discontinuously in space and time. But the grid data is preferred than the station data since it overcomes the scale mismatch between the climate models and station observations (Hofstra et al, 2010). This study is based on the annual average values which dilutes the extreme values and daily amplitudes. Although total sum values are used in case of precipitation, yet even an extreme value like a millennial flood does not significantly alter the long-term trend.

With respect to the forest cover, as seen in Figure 15, the area under forest cover in the Czech Republic had a significant increase between the years 1950 to 1980 and no sharp changes thereafter. Accordingly, the land cover data from the four study areas does not indicate any significant changes in the forest cover during the time period 1990 to 2018. There were not only large scale changes in the forest cover but also large scale agricultural land drainage programme was carried out in the Czech Republic during 1970s and 1980s where more than 10,000 km2 of wet meadows, floodplains were drained by systematic drainage systems (J Pokorný, Personal Communication, April 3, 2020). Until 1989, 2700 km2 of meadows and pastures, 800,000 km of balks, 350 km2 of bosques and Groves, 30,000 km of green line vegetation were removed. As per the records from the Agricultural Water Management Administration from 1959-89, about 10,848 km2 of land in the Czech Republic is drained by drain-pipe drainage system and about another 4,500 km2 of unregistered drained agricultural land (Vašků, 2011). Hence it would be more beneficial to analyse the land-cover and precipitation dynamics for the time period 1950-1990 but it is not in the scope of this study since the land-cover data from this time period is very difficult to realise.

The land cover data is based on the ancillary data like Topographic maps, Thematic land cover maps, Statistical information on land cover and Aerial photographs. The data has an accuracy of about 85% (Jaffrain et al, 2017) and hence there is a possibility of some discrepancies in the dataset. These have been some of the limitations of the analyses done in this study. One important component which is missing in the analyses of this study is the data on evapotranspiration. Land surfaces are altered due to changes in the land cover and it causes a significant effect on the local terrestrial evapotranspiration (Chen et al, 2019). Changes in evapotranspiration linked with changes in the land cover can be analysed with changes in the local precipitation which would be a stronger evidence to determine how changes in the land cover affect the precipitation.

SUMMARY OF THE FOUR STUDY AREAS:

As evident from the table 24, Třeboň area which has forest as the dominant land cover has the highest average annual precipitation and the lowest average annual temperature, followed by Most and Brno where the dominant land cover is agriculture and lowest average annual precipitation and highest average annual temperature is in Prague. This could be primarily due to the artificial surface as the dominant land cover in Prague since all the four study areas are located nearly in the same climate zones as seen in Figure 19 and also there are not significant elevational differences, there is a high probability of land cover influencing the local climatic conditions.

Table 24. CLIMATE AND LAND COVER SUMMARY FOR THE FOUR STUDY AREAS

LOCATION	AVG. ANNUAL PRECIPITATION (mm)	PRECIPITATION TREND	AVG. ANNUAL TEMPERATURE (°C)	TEMPERATURE TREND	DOMINANT LAND COVER
Most Area	534.93	Increasing (not signiificant)	8.54	Increasing (significant)	Agriculture
Prague Area	462.72	Decreasing (not significant)	10.38	Increasing (significant)	Artifical Surface
Třeboň Area	630.17	Increasing (not signiificant)	8.07	Increasing (significant)	Forest
Brno Area	530.15	Decreasing (not significant)	8.26	Increasing (significant)	Agriculture

Although the trend is not statistically significant, the precipitation values show an increase in Most and Třeboň. In case of Most, there is an increase in the forest cover owing to the forest reclamations post mining (Skalos, 2015) and hence possibly the corresponding local precipitation indicates an increase as well. But to demonstrate the effects of the land reclamation measures like forest reclamations and hydrological reclamations on the local climate, data from the individual meteorological station will be required instead of the grid data but there is no free access to this data in the Czech Republic. In Třeboň area, there is an increase of about 12% in the forest cover during 1961-2018 and accordingly, increasing values for the precipitation persist are evident.

Prague is under rapid urbanisation and its effects are noticeable from the decreasing forest cover and the subsequent decrease in the precipitation values since urbanisation of areas surrounding Prague begin after 1990. The land cover in Brno has been more or less consistent. Even though the area under natural land cover in Brno is slightly more than that of Most, the precipitation values in Brno show a decrease while they show an increase in Most. This could be possibly due to the location of Brno, which is around the warmest and driest regions of the Czech Republic (Figure 19). In three out of four cases, there is a positive relationship between the forest cover and precipitation amount. In case of Prague, the graph as seen in Figure 51, shows a negative relationship – the precipitation seems to increase as the forest cover shows a decrease for the time period 1990-2016 but the precipitation trend on a longer time period – from 1961 to 2016 shows a decreasing trend. And hence, it can be inferred that the relationship in fact is positive in nature.

As mentioned by Kravčík et al (2007) that as the land is drained due to urbanisation or agriculture, the amount of run-off from the territory increases and the water is no more available for evaporation which ultimately affects the hydrological cycle within the territory - is quite evident from the climate and precipitation analyses of the four study areas. Not only precipitation but also the temperature increases due to the Urban Heat Island effect which is also evident in case of Prague where air-temperature values are significantly higher than the other three study areas due to the large extent of artificial surfaces. The increase in the temperature values is usually attributed to the Green House Gas emissions but land-cover significantly contributes to the changes in the land surface temperatures and loss of water in the landscape. Kravčík et al (2007) also mention about how light and frequent precipitations are replaced by heavy and infrequent precipitation patterns. This also evident from the increasing trend in number days with heavy precipitation. Most, Třeboň and Brno all indicate an increasing trend but it is unexpected that Prague indicates a decreasing trend in this context. Also, as indicated by Pokorný et al (2016) about wetlands being as important as forests for regulating the local climate, it can be seen in case of Třeboň where there are wetlands along with the forests and corresponding the climatic conditions show higher precipitation amount as well as lower temperatures as compared to the other three study areas where there are no wetlands and also lesser forest cover.

It is evident that forests play a vital role in regulating the local climatic conditions, but urban areas do not have enough space available for forest plantations within the city but the peri-urban forests as mentioned by Zhang et al (2017) which contribute hugely to the local precipitation, need to be protected from the pressures of urban sprawl. Afforestation drives are extremely important in the urban areas. The brown fields in the urban areas can be all utilised for this purpose. Also to compensate for the lack of space for forests within the urban areas, different strategies and technologies could be used to increase the permeability in the territory. For example the Sponge City Plans being employed in China where the city plans are being focussed more towards nature-based urban run-off control systems instead of the existing “rapid-draining” approaches in the urban areas (Jia et al, 2017). To investigate more definite relationships between forest cover and precipitation on a local scale, further research can be done with historical land cover change data which could be challenging since the data has to be generated from various aerial photographs from the archives. Another way ahead could be in context of planning and design strategies in the urban areas so as to contain the storm water within the territory as well as to make it available for evapotranspiration. Last but not the least, policies regarding protecting and planting the forests with focus on the hydrological cycle.

11 | CONCLUSION

Four areas in the Czech Republic – Most, Prague, Třeboň and Brno were selected based on similar climatic conditions and elevations for this analytical study which aimed at determining the relationship between changes in land cover and changes in the local precipitation.

Climatic trends were determined for each of the study areas based on 55 years (1961-2016) of climate data sourced from the Czech Hydrometeorological Institute and 28 years (1990-2018) of land cover data sourced from the Corine Land Cover project by European Environmental Agency. The statistical tests employed for analysing the climate trends determined significant increase in the annual temperature values across all the four study areas while the annual precipitation values did not indicate any significant trends for any of the study area. Most and Třeboň showed increasing precipitation values over time while Prague and Brno showed decreasing precipitation values over time. The number of days with heavy precipitation also showed an increase for Most, Třeboň and Brno but on the contrary showed a decrease in case of Prague.

Although there were no significant changes neither in the forest cover nor in the precipitation trends in any of the four study areas during the specified period of time, yet the climatic trends seem to be affected by the local land cover types and proportions when the four study areas are compared. Třeboň with the highest forest cover and highest land cover types which also included wetlands showed lowest temperature values and highest precipitation values while Prague with the highest artificial surface as land cover showed the highest temperature values and lowest precipitation values. Also the relationship between the changes in the forest cover and changes in the precipitation values indicates a positive relationship in all the study areas except Prague during 1990-2016 but the long term precipitation trend (1961-2016) does indicate a positive relationship.

Our city plans need to consider the ecosystem services of the vegetated land cover in context of the water cycle so as to formulate appropriate mitigation measures for the water crisis that many cities in the world face today.

The indigenous people living in the forests have always been aware of the fact that deforestation will lead to decline in the amount of rainfall but we in the civilized society have to prove the same concept using statistical analyses. The message being simple – PLANT MORE TREES TO FIGHT THE CLIMATE CHANGE. Although individual trees or plantations do not facilitate the biotic pump as a natural forest would do yet they are extremely important to sustain the small scale hydrological cycle and to mitigate the water crisis in our continually expanding urban areas.

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CLIMATE DATA – Annual Averages/Sums of Each Meteorological Element for Each Study Area from 1961-2016.

	MINIMUM AIR - TEMPERATURE (°C)				MAXIMUM AIR - TEMPERATURE (°C)			
YEAR	TŘEBOŇ	BRNO	PRAGUE	MOST	TŘEBOŇ	BRNO	PRAGUE	MOST
1961	3.24	3.35	5.94	4.46	14.13	13.72	14.34	13.46
1962	1.72	2.03	4.47	2.76	11.92	11.87	12.70	11.84
1963	1.97	1.98	4.39	2.62	12.20	12.11	12.93	12.25
1964	2.57	2.66	4.96	3.18	12.20	12.41	13.29	12.55
1965	2.32	2.09	4.81	3.29	11.98	11.40	12.59	11.59
1966	3.79	3.78	6.31	4.80	13.22	13.08	13.95	12.74
1967	3.25	3.45	6.11	4.21	13.99	13.73	14.56	13.12
1968	3.08	2.96	5.61	3.84	12.72	12.73	13.49	12.35
1969	2.55	2.54	4.88	3.21	12.48	12.61	13.22	11.93
1970	2.90	2.73	5.36	3.46	12.10	12.13	12.93	11.85
1971	2.53	3.00	5.40	3.46	12.94	13.22	13.98	13.15
1972	3.04	3.49	5.54	3.97	11.93	12.64	13.29	12.20
1973	2.81	2.79	5.41	3.89	12.57	12.79	13.79	13.01
1974	4.05	3.90	6.48	4.93	13.31	13.21	14.21	13.08
1975	3.77	3.82	6.21	4.80	13.27	13.50	14.33	13.44
1976	2.88	2.97	5.52	3.91	12.74	12.76	13.82	12.89
1977	3.63	3.29	5.83	4.58	13.02	12.81	13.62	12.51
1978	2.76	2.65	5.15	4.11	12.11	11.79	12.85	11.91
1979	2.99	3.06	5.18	3.79	12.72	12.73	13.59	12.40
1980	2.45	2.41	4.67	3.38	11.68	11.31	12.35	11.49
1981	3.14	3.48	5.51	4.19	12.97	12.76	13.65	12.67
1982	3.06	3.48	5.73	4.22	13.38	13.05	14.53	13.45
1983	3.12	3.48	6.06	4.60	14.04	13.95	14.85	13.79
1984	2.94	3.22	5.47	4.13	12.31	12.21	13.20	12.11
1985	1.98	2.21	4.84	3.46	11.93	11.58	13.00	12.16
1986	2.42	2.80	5.32	3.83	12.92	12.67	14.01	12.61
1987	2.44	2.60	5.02	3.44	11.95	11.80	12.84	11.63
1988	3.87	3.71	6.48	4.73	13.30	13.13	14.30	13.20
1989	3.46	4.03	6.65	5.00	13.80	13.89	15.07	13.88
1990	3.22	3.87	6.67	4.97	14.06	14.01	15.28	14.08
1991	2.55	3.02	5.55	3.85	12.44	12.71	13.76	12.70
1992	3.88	4.28	6.70	4.88	13.96	14.15	15.22	14.11
1993	2.89	3.12	5.78	4.02	13.05	13.31	14.06	13.13
1994	4.26	4.43	7.07	5.20	14.71	14.58	15.30	14.35
1995	3.65	3.84	6.32	4.43	13.11	13.00	14.16	13.28
1996	2.26	2.35	4.80	2.90	11.32	11.60	12.24	11.33
1997	3.20	3.32	5.74	3.96	13.01	13.03	14.14	13.46
1998	3.79	3.55	6.54	4.93	13.58	13.68	14.62	13.96
1999	4.03	4.17	6.78	5.09	13.56	13.77	14.81	14.20
2000	4.37	4.75	7.43	5.57	14.48	14.75	15.58	14.71
2001	3.78	3.80	6.51	4.68	12.88	13.17	13.98	13.19
2002	4.55	4.23	7.17	5.17	13.91	14.07	15.08	14.09
2003	3.36	3.64	6.30	4.03	14.13	14.18	15.12	14.45
2004	3.59	3.47	6.51	4.18	12.97	13.30	14.41	13.34
2005	3.44	3.35	6.39	4.15	12.88	13.18	14.52	13.33
2006	3.91	3.92	6.81	4.62	13.47	13.81	15.17	14.05
2007	4.77	4.63	7.31	5.48	14.57	14.82	15.59	14.73
2008	4.82	5.20	7.55	4.89	14.16	14.54	15.40	14.21
2009	4.54	5.05	7.33	5.00	13.69	13.91	14.94	13.84
2010	3.44	3.89	6.32	3.74	12.39	12.47	13.66	12.35
2011	4.08	4.62	7.18	4.79	14.27	14.25	15.77	14.28
2012	3.89	4.63	7.47	4.49	14.01	14.27	15.78	14.08
2013	4.13	5.09	6.92	4.53	13.21	13.27	14.49	12.97
2014	5.08	6.23	8.16	5.83	14.98	14.83	16.20	14.81
2015	4.83	5.72	8.50	5.54	15.23	15.03	16.36	15.20
2016	4.46	5.23	8.13	5.44	14.28	14.27	15.55	14.49

YEAR	MEAN AIR - TEMPERATURE (°C)				TOTAL PRECIPITATION (mm)			
	TŘEBOŇ	BRNO	PRAGUE	MOST	TŘEBOŇ	BRNO	PRAGUE	MOST
1961	8.20	8.50	10.30	8.71	595.50	504.70	412.00	550.10
1962	6.49	6.86	8.75	7.07	602.40	568.80	352.00	435.30
1963	6.70	6.89	8.91	7.16	575.00	500.70	431.40	432.60
1964	7.15	7.34	9.45	7.74	686.30	490.30	409.20	388.60
1965	6.80	6.70	8.88	7.20	764.30	590.90	600.90	762.90
1966	8.29	8.38	10.22	8.50	758.90	608.30	597.00	655.70
1967	8.26	8.41	10.48	8.51	604.90	429.20	513.00	674.60
1968	7.66	7.70	9.67	7.99	539.40	527.50	500.60	558.80
1969	7.30	7.38	9.16	7.41	524.10	447.80	459.30	530.80
1970	7.22	7.40	9.29	7.42	595.20	653.50	504.40	646.60
1971	7.42	7.97	9.91	8.15	533.40	442.60	491.50	422.40
1972	7.07	7.84	9.59	7.74	613.60	568.60	454.10	351.00
1973	7.39	7.78	9.87	8.23	536.60	430.90	351.90	372.00
1974	8.30	8.39	10.54	8.69	737.80	561.40	528.50	620.70
1975	8.19	8.48	10.49	8.86	617.30	500.40	421.60	408.70
1976	7.67	7.86	10.05	8.37	608.00	479.50	334.80	379.10
1977	8.10	7.98	10.04	8.36	649.90	587.60	602.90	588.00
1978	7.18	7.11	9.37	7.71	491.80	399.50	474.60	459.50
1979	7.55	7.76	9.67	7.84	765.00	632.90	563.40	490.90
1980	6.79	6.83	8.82	7.27	598.10	492.50	525.40	566.80
1981	7.88	8.04	9.94	8.26	653.40	641.50	594.00	673.20
1982	8.00	8.14	10.41	8.66	537.60	448.40	341.60	386.70
1983	8.41	8.67	10.75	9.04	499.10	381.30	430.70	525.70
1984	7.39	7.56	9.56	7.88	518.10	611.50	439.70	452.30
1985	6.78	6.77	9.15	7.58	686.80	670.50	480.70	378.80
1986	7.51	7.59	9.83	7.98	605.60	565.20	470.70	585.10
1987	7.10	7.19	9.10	7.33	724.30	647.90	636.70	578.50
1988	8.44	8.28	10.62	8.93	598.60	583.10	522.20	532.90
1989	8.50	8.80	11.06	9.43	505.90	428.00	407.60	483.60
1990	8.57	8.66	11.18	9.37	568.20	531.20	344.20	443.10
1991	7.43	7.59	9.79	8.16	566.00	569.30	370.00	438.20
1992	8.85	9.04	11.17	9.39	589.90	501.30	415.50	588.50
1993	7.91	8.07	10.21	8.46	701.00	515.10	504.80	518.20
1994	9.41	9.32	11.43	9.62	529.30	488.50	433.70	592.50
1995	8.34	8.25	10.44	8.70	708.60	541.20	510.70	632.10
1996	6.67	6.75	8.73	6.97	695.50	650.80	542.90	565.40
1997	8.04	7.86	10.20	8.54	659.60	632.00	467.90	471.40
1998	8.74	8.66	10.88	9.15	548.50	508.40	399.90	519.10
1999	8.71	8.81	11.07	9.35	473.90	473.40	377.20	481.20
2000	9.20	9.59	11.73	9.88	691.00	495.50	383.00	574.90
2001	8.14	8.35	10.40	8.68	733.00	555.70	539.80	568.30
2002	9.03	9.19	11.19	9.38	1034.30	685.70	616.60	804.60
2003	8.61	8.84	11.02	9.00	468.30	408.60	250.10	324.80
2004	8.06	8.35	10.68	8.61	656.90	473.10	382.00	551.70
2005	8.08	8.08	10.67	8.53	753.80	531.60	429.90	577.40
2006	8.48	8.58	11.12	9.06	734.20	564.50	400.80	483.80
2007	9.55	9.65	11.94	9.92	702.50	441.50	433.70	680.80
2008	9.34	9.42	11.59	9.42	547.50	423.80	404.40	520.20
2009	8.90	9.31	11.23	9.24	747.20	651.00	444.20	599.50
2010	7.72	8.08	9.98	7.92	734.50	730.70	569.00	690.80
2011	8.91	9.20	11.59	9.33	592.20	395.70	448.40	502.90
2012	8.74	9.35	11.57	9.12	784.80	467.70	445.90	579.80
2013	8.43	9.07	10.81	8.59	677.80	607.10	558.00	674.20
2014	9.64	10.34	12.33	10.06	589.00	559.30	582.50	597.30
2015	9.82	10.20	12.45	10.19	474.30	433.70	347.40	515.30
2016	9.08	9.57	11.77	9.70	601.00	457.20	457.60	568.30

YEAR	MEAN RELATIVE AIR - HUMIDITY (%)				NUMBER OF SUNSHINE HOURS			
	TŘEBOŇ	BRNO	PRAGUE	MOST	TŘEBOŇ	BRNO	PRAGUE	MOST
1961	81.66	75.88	68.23	79.59	1916.20	1815.90	1684.10	1494.20
1962	80.57	76.54	65.75	77.64	1836.10	1732.70	1710.30	1546.70
1963	82.14	77.77	67.31	79.68	1773.90	1745.60	1714.00	1582.50
1964	82.20	76.61	66.13	78.55	1744.20	1742.20	1686.50	1576.50
1965	82.71	79.81	70.91	82.78	1597.60	1560.70	1510.50	1379.40
1966	82.07	79.49	71.37	82.25	1592.90	1473.40	1511.60	1396.10
1967	80.49	77.29	68.85	81.63	1883.50	1758.40	1764.00	1531.20
1968	81.37	77.91	70.69	79.56	1615.60	1604.50	1600.10	1453.00
1969	81.26	76.90	69.83	79.45	1685.30	1710.70	1621.20	1429.50
1970	82.57	78.49	71.50	81.06	1484.10	1516.70	1383.50	1333.10
1971	80.81	76.30	68.86	77.44	1725.60	1774.50	1661.80	1629.90
1972	83.18	78.24	69.81	78.03	1428.70	1526.40	1411.00	1368.60
1973	78.28	74.10	65.84	72.24	1733.70	1873.80	1768.20	1697.20
1974	80.73	78.37	69.14	77.83	1477.80	1578.90	1508.70	1365.50
1975	82.31	78.47	68.66	76.86	1597.60	1752.50	1653.20	1499.90
1976	78.59	76.00	65.91	76.47	1663.30	1751.80	1708.60	1577.20
1977	79.52	79.33	70.41	78.94	1473.20	1639.10	1347.80	1148.90
1978	80.04	79.12	69.27	81.30	1496.00	1563.20	1394.70	1273.90
1979	80.65	77.55	68.63	76.57	1675.80	1710.00	1581.60	1413.50
1980	80.48	78.12	69.67	77.58	1553.00	1563.20	1459.40	1339.10
1981	78.77	76.53	68.78	76.87	1600.10	1627.00	1561.10	1438.40
1982	80.81	76.49	66.33	74.87	1797.60	1873.30	1885.10	1691.60
1983	78.83	72.53	66.02	74.47	1824.10	1832.40	1708.70	1509.50
1984	80.58	76.51	69.04	77.19	1628.30	1593.10	1479.80	1311.90
1985	80.68	76.66	68.41	75.39	1705.70	1708.10	1582.80	1478.90
1986	79.33	75.81	67.90	77.17	1841.40	1831.50	1841.00	1505.00
1987	81.22	77.94	71.50	78.79	1591.80	1585.30	1426.60	1341.70
1988	79.87	75.89	68.58	76.02	1791.20	1774.30	1621.60	1459.30
1989	81.10	76.06	68.25	75.71	1841.80	1714.10	1692.50	1506.70
1990	78.23	74.13	65.59	73.81	1892.80	1796.10	1865.70	1591.10
1991	80.21	75.45	68.51	74.95	1628.20	1688.80	1607.20	1558.30
1992	77.42	72.58	66.30	74.98	1763.00	1812.70	1797.10	1681.00
1993	79.28	74.32	66.91	75.04	1588.40	1832.00	1754.40	1638.10
1994	77.60	73.97	67.09	75.92	1708.20	1786.20	1796.10	1628.80
1995	79.76	77.54	69.19	78.36	1527.50	1604.40	1630.60	1450.20
1996	81.85	79.10	70.69	79.94	1439.20	1694.50	1531.60	1297.20
1997	77.57	76.52	66.79	76.81	1786.40	1896.20	1864.80	1617.00
1998	76.06	75.33	66.72	75.53	1689.60	1785.10	1751.30	1528.60
1999	78.23	75.76	66.98	74.52	1694.50	1776.90	1686.90	1517.00
2000	77.79	75.50	67.52	74.99	1772.00	1876.70	1751.40	1484.60
2001	79.90	77.04	71.40	76.98	1537.10	1687.50	1622.30	1432.40
2002	78.77	74.81	70.75	75.55	1676.60	1804.80	1792.60	1524.90
2003	75.20	70.96	64.43	70.91	2068.80	2137.20	2150.90	1938.90
2004	78.86	75.07	66.85	75.23	1720.60	1767.40	1738.20	1578.70
2005	77.77	74.52	66.89	77.02	1785.30	1916.10	1823.00	1751.30
2006	78.45	73.43	68.96	75.80	1799.00	1928.00	1909.90	1756.10
2007	75.45	71.25	66.09	75.99	1882.00	1921.50	1853.20	1681.80
2008	76.55	74.56	68.48	79.97	1345.80	1665.90	1735.20	1545.80
2009	79.57	76.92	68.53	79.28	1620.30	1720.00	1639.50	1558.50
2010	78.35	78.28	68.38	77.87	1534.70	1602.00	1604.50	1514.10
2011	75.73	73.51	66.48	74.92	1868.10	1941.40	1871.20	1782.10
2012	76.61	71.03	66.23	74.34	1823.20	1923.80	1797.40	1650.30
2013	79.96	75.35	69.52	79.15	1540.50	1612.20	1490.20	1433.70
2014	79.67	76.89	68.76	79.23	1559.90	1527.90	1580.10	1479.90
2015	73.53	72.62	63.44	73.24	1751.90	1774.10	1766.90	1788.50
2016	77.08	75.56	67.29	76.53	1646.60	1652.70	1620.60	1550.80