The Climate of Cities

By

Matthew J. Downing

Advised by

Professor William Preston

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Social Sciences Department

College of Liberal Arts

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Research Proposal

As the world begins to look toward the human population's impact upon the natural systems it is becoming apparent that almost every human action alters the climate of the Earth. Cities in particular have an interesting impact upon the climate, both locally and otherwise. While there are similarities between global climate and climate within cities, differences abound. The impact of cities is multi-faceted with many interconnections affecting local weather, surrounding natural resources, even human health.

In accordance with the senior project graduation requirement at Cal Poly, San Luis Obispo, it is my intent to research and present a survey of the climate of cities. I will investigate the factors influencing the climate within cities as well as explore the climate's impact on the city's surrounding areas. This will be done using knowledge I have gained during my education at Cal Poly along with information researched in scientific journals, textbooks, and reliable Internet sources. The results of this research will be presented in a scholarly paper of at least 25 pages submitted to my faculty advisor William Preston, Ph.D.

Annotated Bibliography

Brazel, Anthony J. and Melvin G. Marcus. 1987. Heat enhancement by longwave wall emittance. American Geographical Society 77(4): 440-455.

Brazel and Marcus present a look at the emittance of longwave radiation from walls of urban areas and steep-sided cirques. They make specific reference to the temperature of walls as compared to adjacent ambient air temperatures. The longwave emittance is also put into the perspective of snow thaw at bases of cirques, reflecting what happens to urban snow. This article will be helpful in my project because it highlights the thermal conductivity of and heat radiation from built-up urban structures as opposed to some naturally occurring environments.

Chandler, T. J. 1962. London's urban climate. The Geographical Journal 128(3): 279-298.

Chandler gives an in-depth look at the factors contributing to London's climate at the time of publication. Many of the topics, such as urban pollution, urban fog, and changes in urban wind patterns, still have great relevance to today's urban climates. Chandler's mention of the reduction of sunshine interacting with the urban environment backs up other ideas about the climate of cities such as air pollution reflecting and absorbing incoming radiation. This will be helpful to my project because it is a real world example of how a city's climate is altered when the natural landscape is changed into urban centers.

Christopherson, Robert W. 2006. Geosystems: an introduction to physical geography. 6th ed. Upper Saddle River: Pearson Education, Inc.

Christopherson presents an introduction to the world of physical geography including many concepts involved in climate creation. He provides straightforward explanation of some complex ideas to facilitate a better understanding of the natural world. Many ideas found in the study of city climates are talked about in the simplest terms. This will be helpful to my project because it will aid me in clearing up some of the concepts I will be discussing with regard to the climate of cities.

Corburn, Jason. 2009. Cities, climate change, and urban heat island mitigation: localizing global environmental science. Urban Studies 46(2): 413-427.

Corburn gives a detailed account of the problem of Urban Heat Islands within urban areas in addition to policies aimed at the mitigation of the phenomenon. While the study does deal with the localization of mitigation policies more than necessary for my project, it does tie in connections to the great many polices being created to save the planet as a whole. Corburn blatantly states that the problem of climate change is only going to exacerbate the problem facing an ever-growing portion of the world's population. This will be helpful to my project because it will help tie the idea of urban climates to the trendy issue of climate change. It will also be a great source of policies on alleviating some of the adverse effects of the climate in cities.

Hannell, F. G. 1976. Some features of the heat island in an equatorial city. Geografiska Annaler 58(1): 95-109.

Hannell presents an in-depth look at how the Urban Heat Island is a problem not only for cities in the mid-latitudes, but for those near the equator as well. Using the backdrop of Quito, Ecuador, Hannell compares and contrasts the microclimates created in the area's open spaces, older urban centers, and modern urban centers. Hannell specifically points out the reduction of wind speeds moving from the hinterland to the more modern city center. This will be helpful to my project because it will continue to expand my knowledge of the characteristics of city climate and show that some, if not all, are universal between differing latitudes.

Hayden, Bruce P. 1998. Ecosystem feedbacks on climate at the landscape scale. Philosophical Transactions: Biological Sciences 353(1365): 5-18.

Hayden presents an examination of how climate and vegetation interact around cities to influence the climate within the city, while also looking at how the city's climate affects the ecosystem around the urban center. Hayden points to factors such as atmospheric moisture, evapotranspiration, and organic and anthropogenic condensation nuclei to back up his idea that the city and the hinterland are participating in a climatic tug-of-war. Hayden also sums up the main lessons learned in an easy to follow bullet list to assist in complete understanding. This will be helpful to my project because it looks at differing aspects of climate creation outside of the city boundaries, making clear the interconnections between the city and its hinterland.

Landsberg, Helmut E. 1970. Man-made climatic changes. Science 170(3964): 1265-1274.

Landsberg presents an incredibly complete assessment of how mankind has changed the urban environment with all its differing actions. While slightly outdated in some areas, such as the uncertainty that mankind's actions have the ability to change the global climate, the article's points with regard to the climate within cities are still valid with today's knowledge of the environment. Looking at such topics as urban runoff, Landsberg focuses on the fact that cities have less ability to cool themselves with evaporation, as well as cool themselves with transpiration due to the lack of vegetation. This will be helpful to my project because it is an exhaustive compilation of the differing factors creating the climate of cities.

Pease, R. W., Lewis, J. E., and S. I. Outcalt. 1976. Urban terrain climatology and remote sensing. Annals of the Association of American Geographers 66(4): 557-569.

The article presents information on the use of remote sensing to investigate environmental impacts of land use patterns. The authors name properties of cities that control the climate inside, such as urban structure thermal properties, surface roughness, albedo, and distribution of surface moisture. The use of remote sensing data acts as the base for the authors' assessment. This will be helpful to my project because the remote sensing data gives quantifiable information on various aspects of the climate of cities like the aforementioned urban albedo.

Ramachandraiah, C. 1997. Weather and water in urban areas. Economic and Political Weekly 32(43): 2797-2800.

Ramachandraiah presents an extremely detailed account and explanation of the interactions between cities and water. While Ramachandraiah sometimes takes an extreme position on subjects that could be debated, the article is packed with vast information on the Urban Heat Island as well as how water use is related to the phenomenon. Ramachandraiah also makes reference to how a city's reliance upon an aquifer as its source of water can cause damage to the city's infrastructure due to land subsidence and saltwater infiltration near coasts. This article will be helpful to my project because it is incredibly concentrated on urban water, providing much needed information as well as ideas on the current and continuing lack of water for major urban areas.

Tuller, Stanton E. 1973. Microclimate variations in a downtown urban environment. Geografiska Annaler 55(3): 123-135.

Tuller presents a look at the vast array of differing microclimates within the general climate of cities. Tuller specifically looks at the different microclimates created on the North, South, East and West exposures of the city, looking at differences in solar radiation to help explain the differences between each area. While the information is presented in reference to the city's microclimates it is also important when extrapolated to the city as a whole. This will be helpful to my project because it looks at discrete factors involved in the creation of a city's climate, allowing for a better understanding of what factors contribute to the overall conditions.

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Introduction

The world is an ever-changing place. The geographical boundaries separating populations are becoming obsolete, as technology has enabled the spread of information at speeds never witnessed before. This spread of information has in turn changed how we understand the natural systems of the Earth. Human populations are becoming increasingly aware of how these natural systems are being altered, especially the climate. Some of the most notable alterations of climate are found in and around urban areas. These alterations all lead to the conditions creating the climate of cities.

The impact of cities has become the focus of many environmental studies. These studies have led to discoveries of the elements contributing to the climate in urban areas. The elements altering urban climate are also found to affect global climate, aiding in the understanding of how each system works with the other. The interconnections between urban climate elements show how a small change in one can force a drastic change in another. These studies have also revealed other things cities affect, such as human health.

The climate of cities refers to the overall trend of conditions within the urban area. This is not to be confused with day-to-day changes in the meteorological conditions, which we usually refer to as weather. The weather in urban areas can change minute to minute while the climate of the same urban area takes a longer time to establish. Some of the factors that shape the climate can even have an immediate impact on the local weather.

The impact of urban climate can also be experienced in the area surrounding the city, referred to as the hinterland. Conditions within an urban area affect not only the surrounding hinterland but also natural landscapes and other urban centers downwind. Smog, increased ozone levels, and heat, all of which are byproducts of increasing urbanization, can be spread from the source city. The spread of these byproducts can damage the outlying regions to the point that they cannot recover naturally or with human intervention.

The change in urban environments brings about the need to mitigate the climatic influence of these built-up areas. Many mitigation techniques have been in use in particular areas of the world for some time while others are only in the theoretical stage. Some of the climate improvement practices can even create new economic opportunities and jobs. These suggestions are changing some negative impacts of the climate of cities and turning them into, at the very least, milder ones.

In this report I plan to map out how the climate of cities is created and how it is manifested. I will discuss the most important factors governing the local climate as well as point out the connections between the parts. The effects on the hinterland will also be an important aspect while not forgetting the impacts on human health. Finally, future implications for urban areas and ideas for negative impact mitigation will finish up the discussion.

Contributing factors

Albedo

The climate is driven by incoming solar radiation that interacts with various parts of the Earth in different ways. This incoming radiation has the ability to make plants grow, heat surfaces, and ignite chemical reactions. Not all of the radiation reaches ground level; however, as surfaces suspended in air or on the ground reflect differing amounts of the shortwave radiation. This reflectance is often known as albedo.

According to Christopherson, albedo is more precisely defined as the reflective quality of a surface, expressed as the percentage of reflected insolation to incoming insolation (Christopherson 2006: 92). The amount of radiation that is reflected by a surface greatly depends on surface color, angle of impact, and the texture of the surface. Surfaces that are lighter in color such as snow reflect more insolation than darker surfaces such as asphalt. The angle of the sun above the ground also influences the albedo of a surface, as greater angles allow for more of a glancing impact therefore increasing the amount of radiation that will not be absorbed by the surface. Smoother, flatter surfaces such as a flat open field reflect more insolation than their rougher counterparts such as a stand of trees.

In the natural environment albedo plays a great role in the energy balance. In a balanced climate the same amount of shortwave radiation would be entering the Earth's atmosphere as shortwave and longwave radiation leaving the Earth. With an unequal energy equation the climate of the Earth would heat up or cool down depending on which side of the equation was the greatest. Too much shortwave radiation and the Earth would fry while a deficiency would cause it to freeze.

Nature does a good job balancing the two sides. The amounts of clouds in the atmosphere, ice and snow at the poles and high altitudes, and barren landscapes use their high albedos to help reflect the incoming shortwave radiation back out into space. On the other side of that coin, the amount of oceans, lakes, stands of dark green forests, and differing soil coloration work to absorb the incoming radiation and prevent its loss.

Albedo shifts its role from helping to equalize the energy equation to favoring the absorption of the incoming solar radiation within the context of urban areas. Urban areas contain more features composed of differing materials and with darker colors allowing for more absorption of incoming radiation. These features include such things as asphalt covered parking lots and streets, dark colored roofs, and different coloring on an increased number of structures. Even increased amounts of glass in urban areas disturb albedo since glass allows shortwave radiation to pass through but does not allow longwave radiation to pass back out.

The changes in surface roughness and the angles of structures work together to alter the overall surface albedo. The smooth flat surfaces of buildings allow for more incoming solar radiation to be reflected while the vertical heights of the buildings change the direction of the reflected radiation so that it bounces into other buildings. This allows more chances for the reflected radiation to be absorbed by other structures nearby.

Along with the different albedo levels, the changes in surface material change the thermal conductivity. According to Landsberg, when we change a rural area to an urban one, we convert an essentially spongy surface of low heat conductivity into an impermeable layer with high capacity for absorbing and conducting heat (Landsberg 1970). This means that while natural surfaces will heat up, they do not retain that heat and therefore cool off quickly. Man-made surfaces, however, retain that heat they absorbed during the day while natural surfaces around them cool down. This contributes to the creation of urban heat islands.

Heat islands

I have alluded to the temperature in a city being higher than in its hinterland. The term urban heat island has been created to refer to an urban microclimate that is warmer on the average than areas in the surrounding countryside (Christopherson 2006: 107). On average in these urban heat islands both maximum and minimum temperatures are higher than nearby rural settings (Christopherson 2006: 107). The annual mean of urban temperatures is found to be 0.9 – 5.4 F^{O} higher than the surrounding landscape (Landsberg 1981). This means that the heat outside of the city is no match for the heat inside the city. The reason for the name urban heat island is due to the fact that whether you are looking at an infrared image of a city and rural countryside, a map of isotherms, or a hand drawn cross section of temperatures, a noticeable island will begin to form near the hottest areas of the city.

This can be seen naturally by looking for areas in nature with differentials in heat. Large areas with a mixture of grassland, barren soils, stands of trees, and sources of water will all have slightly different temperatures. These slight differences of temperature will cause some areas of a temperature map to stand out from the rest and although the differences may be slight, even slight changes in temperature can be cause for concern. Overlooking the serious implications of urban heat islands can spell trouble for those living inside of the urban area.

In urban areas many things contribute to the urban heat island. As mentioned previously many of the materials used to build cities hold on to shortwave radiation and re-radiate heat back into the city. This is due to the fact that these materials store heat to a greater depth because of more rapid conductivity than soil (Ramachandraiah 1997). With less vegetation available to intercept and use the incoming shortwave radiation, more is available to be absorbed by the manmade environment. (Ramachandraiah 1997).

Precipitation

The next factor in the creation of the climate of cities that is important to discuss is precipitation. As Christopherson puts it, precipitation is the moisture supply to Earth's surface (Christopherson 2006: 249). He continues in saying that it arrives as rain, sleet [freezing rain, or liquid rain that freezes during descent for clouds], snow, hail [formed when raindrops are continually circulated in a cloud allowing moisture to continually freeze], dew, frost, or fog [a cloud in contact with the ground] (Christopherson 2006: 249). Many times when we hear the word precipitation we automatically think about rain but it is important to recognize these other forms to avoid confusion in addition to the fact that they may be more prevalent in different climates across Earth. For example, according to Chandler, visibility in London is notoriously bad and the city is widely associated with mists, and with fogs (Chandler 1962).

In the natural systems, precipitation recharges the fresh water supply on landmasses. While the other forms of precipitation can add to the fresh water reserves their contributions are greatly overshadowed by the immense amount provided by rain and snow. This recharge may be immediate in the form of rain or more gradual in the form of snow. The benefits of the immediate recharge is that the fresh water can immediately be used by vegetation in the areas where precipitation falls but lasts a shorter amount of time due to runoff. This quick gain and loss does not allow for the freshwater to infiltrate and recharge aquifers so dams are often used to store freshwater for later use.

Melt water from a snow pack takes longer to be available to vegetation but because it has to melt completely before it is gone, this fresh water supply lasts longer overall. In addition to lasting into the later months the slow melt of snow allows for more infiltration into aquifers, recharging what has been drained by use of that aquifer. However, the downside of snow packs is that they must melt before the stored water may be used by civilizations.

In urban areas the characteristics of precipitation are roughly the same while the frequency of events, the types of precipitation released, the composition of the precipitation, and the factors involved in the initial release of the moisture are altered. In natural systems precipitation begins in clouds where the water vapor attached to condensation nuclei is cooled down to the point of freezing, causing it to fall from the sky. The freezing of the water vapor is due to the lifting of an air mass by four different lifting mechanisms: convergent, convectional, orographic, and frontal.

According to Christopherson, air flowing from different directions into the same low-pressure area is converging, displacing air upward in convergent lifting

(Christopherson 2006: 211). The rising of heated air allowing for cool air to fill the void and in turn be heated is convectional lifting (Christopherson 2006: 212). Clouds can also be forced to rise in altitude by running into and passing over mountains in orographic lifting, resulting in increased rainfall on the windward side of the mountain and a rain shadow [lack of rainfall] on the leeward side of said mountain. Frontal lifting occurs when a warm air mass is forced above or gently slides over a cold air mass.

In urban areas convectional and orographic lifting are the most common in producing precipitation. Conventional lifting is due to the increased temperature of urban air, causing cloud formation and subsequent precipitation as moisture rich air from outside of the city is heated and lifted away from the hot manmade surfaces in the urban area. Orographic lifting is also increased due to the change in the roughness of the natural landscape. When a city, full of skyscrapers and industrial centers, is built up on an area where a naturally smooth flat surface would be, the air masses will be forced to rise above the large buildings instead of being free to flow along unchanged.

It is obvious from this point that with this increase in lifting mechanisms in urban areas the frequency of precipitation also increases. As Landsberg points out, the updraft leads, together with the large amount of water vapor released by combustion processes and steam power, to the increased rainfall reported from cities (Landsberg 1970). Landsberg quantifies the overall precipitation increase as 5% - 15% more, with snowfall within the city decreasing 5% - 10%, while snowfall downwind of the city increases 10% (Landsberg 1981). Harman and Elton report something similar about LaPorte, Indiana; that increasing addition of heat and nuclei to the atmosphere by [cities] enhance convective precipitation (Harman and Elton 1971). While LaPorte is slightly different due to the nearby lake effect, in which air masses pass over warmer lakes gaining moisture and uplift, the results are still the same.

Urban areas also have an effect on governing the dominant form of precipitation that falls. This is due again to the fact that urban areas are typically hotter than surrounding areas and their surface materials hold in heat much longer than natural surfaces. In storm systems where one would encounter temperatures conducive to sleet formation, urban air is warm enough to not allow the refreezing of rain as it falls from the sky. The same is true of snow except that snow still falls within cities but cities do not see as many snow days as more rural areas do. As Chandler points out, within cities, fallen snow will melt more quickly in central parks than in suburban gardens. The fallen snow in suburban gardens will also disappear several days before the snow covering the farmlands around London (Chandler 1962). Therefore, rates of snow melt increase as one moves closer to urban centers. Brazel and Marcus summarize, the ablation-season snow-and-ice budget should be altered by sidewall thermal radiation and rates of snowmelt may noticeably increase (Brazel and Marcus 1982).

Precipitation composition is an important factor to consider when discussing urban precipitation. Cities, due to many different human activities, release immense amounts of pollution into the atmosphere. This pollution has a tendency to make its way into clouds and come down most commonly in the form of acid precipitation but acid fogs have been known to be a problem as well. This acidic precipitation causes the advanced decay of many stone structures and art as well as paint on resident's vehicles and homes. Acid precipitation is also a problem because it travels with storm systems downwind and affects land and communities not responsible for the pollution in the first place.

Surface roughness

Surface roughness is another contributing factor in the creation of city climate. Surface roughness refers to objects on the surface of the landscape that hinder the free flow of air as it moves across a surface. Many things can affect surface roughness from small things such as hedges to large things such as mountain ranges. No matter the size of the occluding object wind must still move through, around, or above in order to continue on its path.

In natural systems surface roughness range widely. Winds sweeping over flat open expanses have nothing to divert their path and therefore those areas are considered to have a low surface roughness. Fields, plains, even areas of ice all have lower surface roughness and do little to slow down prevailing winds. But even nature has areas of high surface roughness such as stands of forests that slow and deflect wind.

In a city, man made structures act like the natural stands of forest in slowing and diverting the path of wind. The biggest difference between a forested area and a city is that cities tend to sprout up in areas where fields once dominated. This means that humans are changing an area of low surface roughness into an area of potentially extreme roughness. This often-dramatic change in roughness can have differing consequences.

Winds coming in contact with cities can be forced around the outskirts. Landsberg found that annual mean wind speed in urban environments was 20% - 30%

less than the mean wind speed in rural areas (Landsberg 1981). This has the potential to create a dead zone in the urban center, which will not allow for summer heat to be pushed down wind. Instead the city continues to bake without any way to cool itself off other than allowing the heated air to rise out from the city center. Winds can also be funneled through the streets and alleyways between buildings. This funneling increases the speed of the winds much like a barely open doorway in a home. It also can create eddies of wind flow in the city similar to eddies formed in a fast flowing river. These eddies alter the heat differentials between different areas in the city. The final direction winds can move around the city is to climb over it. The rising wind over cities is orographic lifting that causes increased precipitation over cities. This is a major effect that cities cause because it foreshadows the impact the different factors involved in creating the climate of cities have upon each other.

Runoff

The loss of fresh water due to runoff is another important aspect to consider when discussing the climate of cities. Runoff refers to the loss of fresh water due to both overland and groundwater flow. This means that it can be lost on the surface of land like a river or stream draining into the ocean or below the surface near the water table. The availability of runoff for use by humans and vegetation is based largely on rate and location of flow. Slower flowing sources can be harnessed more than faster flowing ones.

Nature takes steps to reducing the amount of fresh water lost. The speed at which the water flows in overland flow is reduced in part to the roughness of the surface upon which it is flowing. Water flowing over soils and grasses can pick up less momentum when it is constantly coming into contact with objects that slow its progress. This is the reason behind the erosive force streams and rivers can have once their energy increases. But steps are taken before the water even reaches ground level to help diminish the amount of water lost. Trees have the natural ability to slow the fall of water due in large part to the number of branches, leaves, and needles that slows the fall before it makes impact with Earth's crust.

The natural safeguards in place to reduce the amount of runoff lost are ruined as cities are built and expanded. Asphalt of roadways and concrete of sidewalks replaces the grasses and bushes of nature. Cities not only have less vegetation to soak up the precipitation but their non-porous surfaces cause water to runoff at an even faster rate. As Christopherson points out, the effects of urbanization are quite dramatic, both increasing and hastening peak flow (Christopherson 2006: 464); peak flow being the highest amount of runoff following the peak of a storm. He continues by saying that the sealed surfaces of the city drastically reduce infiltration [penetration of fresh water into soil] (Christopherson 2006: 465).

Even the protection of trees is lost due to urbanization. The impermeable building materials used to build homes, offices, and skyscrapers aid in the loss of precipitation. While moisture may be caught before its impact with the ground, the smooth sides of buildings and their efficient drainage systems do nothing to hamper the quickness at which runoff flows. The sewer systems of cities also diminish the availability of water for vegetation by collecting it in impermeable systems away from plants that need it.

Another problem with runoff from cities is the increased pollution concentrations in the water. Bennett, et. al. attribute this to the fact that:

> "precipitation cleanses a variety of objects in the environment, including buildings, cars, streets, shopping centers, and so on, it is [therefore] not surprising that storm waters contain substantial amounts of pollution" (Bennett et al 1981).

As storms drop water onto the smooth flat surfaces of urban areas and the runoff begins to pick up speed, the water's ability to transport oils and metals from vehicles and industries is greatly increased. And pollution in runoff is not just a problem found in rain. The team continues by saying that snowmelt runoff is similar to rainfall runoff in that the most highly developed areas produce the largest pollutant masses (Bennett et al 1981).

Interconnectivity of factors

Effects of one factor on another

Now, having taken a look at the factors contributing to the creation of the climate of cities it is important to look at the interconnections found between the factors. First and foremost is how each of the factors affects the other factors involved in creating the climate in urban areas. For example, the lowering of surface albedo does not just affect albedo. The lowering of the albedo in turn leads to increasing temperatures of the surfaces that shortwave radiation come in contact with. This increased temperature causes the air around the surfaces to heat up which in turn causes the newly heated air to rise. As pointed out earlier, rising air is one of the causes of cloud formation and ultimately the start of precipitation. The lower the albedo of surfaces in cities not only reduces the amount of shortwave radiation that is reflected back out to space but it also changes precipitation patterns in these urban areas.

Even with the increased likelihood of precipitation due to the decrease in surface albedo, it does not stop there. Due to the increase temperatures in urban areas, fallen snow will have increased rates of melting. This means higher runoff rates, a problem exacerbated by the changes in surface roughness. Increasing runoff rates can cause serious problems for the inhabitants of cities by overloading water treatment facilities in the situations when the extra runoff is actually sent to a treatment center.

The lowering of surface albedo as cities expand also has an effect on the urban heat islands of urban areas. Less natural vegetation reduce a city's transpiration and evaporative cooling that helps to lower urban temperatures. This loss of cooling can either create more intense heat islands in the cityscape or it can enlarge existing heat islands.

Precipitation obviously has an impact on runoff rates. Increasing the amount of precipitation in a city also increases the amount of fresh water that is lost due to urban runoff. It also increases the problem of pollution found in the urban runoff. This also affects the urban heat islands because since increased precipitation will lead to increased speed of runoff due to changes in the surface roughness of city materials, incoming solar radiation does not work as much on evaporating the fallen moisture as it would in a natural setting. That means that while precipitation would normally help to regulate temperature in a natural setting, the urban heat islands do not benefit as much from this effect.

In some ways precipitation may even increase temperatures in the city and therefore increase the size of urban heat islands. With increasing days of cloudiness and storms more people living and working in the city may combat changes in sensible heat by increasing the usage of heaters to heat structures and vehicles, therefore increasing temperatures. Increased number of days with precipitation can also affect the number of people who utilize vehicles to travel through the city rather than using human power by walking. This increased usage of vehicles can also lead to increased heat islands due to exhaust as well as increased heat from engines.

Surface roughness also affects the other factors involved in creating the climate of cities, the most obvious of which is increasing runoff. The smoother impermeable surfaces quickly shed unwanted water off their surfaces so that humans are not inconvenienced by nature. As mentioned earlier, smoother surfaces along with the funneling of precipitation increases runoff because water is forced to accumulate faster than it naturally would.

The change in surface roughness also has implications for the albedo of surfaces within urban areas. This is due to the fact that albedo not only relies on the color of surfaces but also to the texture of the surface. Smoother flatter surfaces have a tendency to increase albedo, therefore reflecting more incoming solar radiation. The only problem with that is that, as mentioned previously, incoming insolation is caught in mazelike reflection and radiation canyons, allowing for the urban surfaces to absorb more radiation than a natural landscape would (Christopherson 2006: 107). While smoother surfaces may boost albedo the changing of surface roughness only aids the absorption of an increasing amount of shortwave radiation therefore escalating temperatures and eventually leading to amplified amounts of precipitation due to increased rising air.

The reradiating of shortwave radiation around the urban surfaces also has an impact upon urban heat islands. With more chances for the incoming solar radiation to be absorbed by the highly absorptive and conductive surface materials within cities, urban heat islands will only become more drastic. Areas with sufficient sunlight can heat to higher temperatures than before urbanization.

Increased runoff rates in cities have a tremendous impact upon urban heat islands. In natural environments when precipitation has saturated the top layers of soil, water begins to accumulate on the soil surface. While some of this water is lost due to runoff some of it also finds itself in areas where it does not drain for some periods of time. This accumulation eventually has a cooling effect due in large part to incoming shortwave radiation being used to evaporate the water as opposed to heating the landscape. In urban areas where build up of water is frowned upon and therefore steps are taken to shed the landscape of excess water as fast as possible, the incoming solar radiation is no longer being used to evaporate standing water but instead continues to heat the surrounding surfaces.

Runoff in cities can also change the apparent degree of urban heat islands. Drainages from cities can shift the location of water accumulation as opposed to actually getting rid of it all together. This can cause areas surrounding mild heat islands to drop in temperature, causing the heat islands to seem even more drastic than they normally would.

Effects on other parts of the climate

The factors involved in creating the climate of cities not only affect each other but also can have a significant impact upon other parts of the climate system. The heat generated in cities causes air to rise and can lead to increased incidents of super-cell storm systems. According to Landsberg, the occurrence of thunderstorms, a great predictor of tornadoes, increase by 10% - 15% in urban areas (Landsberg 1981). In areas of the country and the world already affected by tornadoes and cyclones, the increased number of super-cell storms can spell disaster as numbers of tornadoes as well as their strength increases. When adding this to the alterations that human induced climate change is creating, the increase of severe weather events becomes more of a reality.

In some areas, however, cities may actually reduce the amount of precipitation that falls while the amount of water vapor in the air increases. This is due to the fact that there are many times more condensation nuclei over land as there are over oceans and largely because of the particulate emissions of cities there are more condensation nuclei over cities as the natural landscapes (Hayden 1998). Condensation nuclei originating in cities can be found downwind just as condensation nuclei of continental origin are found in the marine air far from land (Hayden 1998). Saturating the air with these city-born condensation nuclei can actually spread out the water vapor so much that there is not sufficient amounts on one nucleus to initiate rainfall. Adding more water vapor to the nuclei as air masses travel over the landscape can also alter the precipitation patterns lee of cities, as Landsberg confirmed with 10% more snowfall downwind of cities (Landsberg 1981).

Effects on the hinterland

The areas outside of the cities are also affected by the changes within cities. As mentioned previously the increased temperatures in cities can create more precipitation in some areas and restrict precipitation in others. The increased heat coming out of cities also affects the hinterland because of the alteration of the range of tolerance of plants and animals, making it more difficult for them to survive near urban areas. Just as scientists predict that increased global temperatures as a result of climate change will affect plants and animals on a worldwide scale, the same is true of those plants and animals surrounding the city. Their ability to cope with and survive during extreme heat events will be reduced, as they are made even hotter by the city. This can lead to the death and possible extinction of many plant and animal species, an unfortunate cost of urban growth.

In other areas of the world where permafrost is a part the environment, the increasing numbers of cities could spell disaster. Cities of any size produce increased temperatures. These increased temperatures in the climate of cities increase melting of ice and snow (Loaiciga 2003). In many places these cities or areas surrounding the cities are built on top of the permafrost using it as a stable foundation. However, as the permafrost begins to melt that foundation becomes compromised, leading to serious problems such as the sinking of buildings, the breakdown of infrastructure and public works, and the beginnings of erosion of the soil that had been kept in place by the frozen water inside.

Implications for the future

As the world's population continues to increase more and more people are moving to cities. In order to accommodate the increasing numbers of inhabitants, cities must expand their boundaries further and faster than previously experienced. Because pressures to accommodate extra people in cities are greatest in the Third World these areas will see the greatest change (Meier 1976). This global urbanization could potentially spell disaster for regional climates. What is worse, the expanding size of cities could begin to create problems so large that they begin to affect climate on a global scale. It then becomes possible for the problems created to become too large to solve.

Air pollution

The most obvious future forecast for the cities of the future is increased air pollution. As more citizens around the world begin flocking toward the urban centers to use air conditioners, cars, lights, etc., more and more carbon dioxide and pollutants will be pumped into the air. As heat is added to cities, gaseous contaminants such as ozone will increase in concentration 5-25 times that of rural environments (Christopherson 2006: 79). Because ozone damages biological tissues, this increase will wreak havoc on children, with one in four in U.S. cities at risk of developing health problems from ozone pollution (Christopherson 2006: 79).

The increasing ozone levels will also lead to increased photochemical smog. This smog will begin to dominate the skies as one city blends into the next and the megalopolis dominates the ground. This will lead to increased deaths of the elderly and infirm, which, as mentioned previously, are already in an impaired position to cope with the added stress to their bodies. Pollution will also not be equal over space within the cities because the pollutants created in one area of the city can also be transported to another since pollutants are dispersed in accordance with the local wind field (Pease et al 1976).

Urban heat islands

Air pollution will not be the only problem as more and more cities sprout up and grow around the world. The urban heat islands that are in place now will continue to get hotter and larger while new heat islands will be created as the natural landscape is altered. Just like the increased air pollution, the increased temperatures affect the elderly, infirm, and the urban poor more than other urban inhabitants. The increased temperatures will have an even greater impact than it currently does on the vegetation around the urban boundaries as more heat resistant plants will need to be used as those incapable of handling the heat die off.

Human health

While increasing temperatures due to urban heat islands have the ability to affect the vegetation currently growing in the city, their greatest impacts are on the inhabitants of the city. Extreme heat events tend to impact disproportionately the urban poor, elderly, and infirm (Corburn 2009). This means that when urban temperatures begin to climb, those most affected will be the ones unable to defend themselves. The urban poor will not have the means to cool down while the elderly and infirm will be less able to tolerate the higher temperatures. In addition to this, as more air conditioning units are turned on to counteract the sweltering temperatures more heat is pumped into the air, leading to higher temperatures and increases in air pollution greenhouse gas emissions. The air in cities almost appears to reflect the tragedy of the commons, in which the common resource is exploited for every individual's personal gain.

Fresh water

The availability of fresh water will also be impacted by increased urbanization throughout the world. With more people aggregated in one area, nearby water will be under more pressure. This increased pressure will create a need to transport water into the city from farther away. As more people use the limited fresh water there will be an increase in various pollutants running back into the water supply from the increasing use of water-consuming domestic appliances such as washing machines and dishwashers

(Ramachandraiah 1997). The cities located near the coasts are also facing the common threat of salt-water intrusion into aquifers (Ramachandraiah 1997).

Mitigation ideas

Having looked at future implications as urbanization increases globally it is important to discuss possibilities of reducing the impact cities make upon local and regional climatic systems. Unfortunately it will take more than just a single idea to help alleviate the problems since some of the suggestions are not perfectly suited for every climate while others are simply not yet practical. However, if humanity can band together in order to help fight this escalating issue and understand it is in their long term best interests, even small changes spread over large enough areas can lead to dramatic improvements.

Green roofs

The first idea for mitigating the repercussions of the climate of cities is by creating green roofs. Green roofs attempt to mimic natural landscapes by covering the tops of buildings with grass or other types of vegetation. While it not only alters the rooftops to be more appealing to the eyes, it also helps to offset the climate of urban areas. Rather than allowing sunlight to directly heat up the rooftops of buildings the shortwave radiation is used by the plants for photosynthesis. This conversion also helps to cool the surrounding air by transpiration as the vegetation releases water vapor as a byproduct of photosynthesis.

The changing of color of rooftops from a typically black color to that of green also increases the albedo of the rooftop surfaces. This slight increase in albedo helps to reflect more incoming solar radiation in addition to using the shortwave radiation for photosynthesis instead of conversion into longwave radiation. Green roofs can also help slow the rate at which precipitation runs off the urban surfaces (Taylor 2007). Since vegetation must grow in soil and needs moisture to stay alive the rain and snow falling on green roofs will first recharge soil moisture available to the vegetation before proceeding into the drainage systems of cities.

White roofs

The second mitigation idea specifically targets the changes in albedo that a city creates. White roofs are beginning to be used by large industrial buildings as a way to reflect more incoming solar radiation and therefore decrease the need for cooling the building. White roofs involve paints being applied to the tar or shingles that typically cover rooftops of large buildings and residential areas. With more shortwave radiation being reflected back into space instead of being absorbed into the rooftop materials the air temperature will decrease. A decrease in air temperature will lead to a decrease in the amount of convective lifting taking place and reduce the amount of precipitation falling on the city. Less precipitation in cities will ultimately lead to a reduction in the total amount of fresh water lost to runoff

Solar panels

A great mitigation idea for places with above normal days of sunshine is the use of solar panels. While the use of solar panels is increasing in popularity throughout the world, their high costs make them unrealistic for use on a large-scale. Ideas for their use, however, are still noteworthy for the days when the price of the panels decreases. Using solar panels on the roofs of residential buildings does more than just produce electricity for the house and the electrical grid. Much like the green roofs mentioned previously, as shortwave radiation comes in contact with the cells in the solar panels 18.8% - 50% of it is being used up instead of being absorbed by rooftops themselves (Christopherson 2006: 106). This causes a reduction in temperature of the home in addition to the electrical output. The use of solar panels does not stop there however.

With many parking lots in urban areas covered in black asphalt the temperatures of these lots can skyrocket at peak hours of sunshine. By using simple carports to cover the asphalt parking spaces the temperatures of these areas can be greatly reduced. However, the metal of the carports will eventually heat up as well. By placing solar panels on top of the carports like the rooftops of residential buildings, the incoming shortwave radiation will be converted into electricity instead of just being absorbed and reradiated in the form of longwave radiation. This electricity could be used to power the many shopping buildings that typically reside adjacent to these lots.

Urban forestry

Possibly the greatest mitigation idea to reduce the impact of cities upon the climate is urban forestry. According to Oke, 'forest' is defined as at least 10% of the land is stocked with trees (Oke 1989). Oke continues by saying some urban trees are remnant or at least derived from the pre-urban vegetation, others are planted or transplanted native or exotic species (Oke 1989). Planting trees within the urban environment, or simply leaving some from the natural landscape, tackles a great number of problems. The trees provide shade for the citizens and black streets throughout the city. Trees also allow for cooling in the areas around them as the incoming shortwave radiation is used for photosynthesis and transpiration rather than absorption, conversion, and re-emission as longwave radiation. The increase in vegetation is also an added bonus as a visual stimulant.

An important thing to consider when developing an urban forestry management plan is the selection of local tree varieties over imports. The diversity of local tree species can be adequately maintained within the city without the use of non-natives. Using the correct tree species in the correct places is another important thing to consider. The use of trees that spread above ground or near surface ground roots would be better used in city parks where they have the room to expand rather than near sidewalks and roads where the roots would cause the cracking of both. The implementation of an urban forest can also create new jobs due to the need for tree maintenance and various other factors related to upkeep. Keeping these ideas in mind can lead to a very successful management plan to partially offset the climatic changes that cities create.

Conclusion

The climate created within urban areas is an interesting topic when considering the modern lifestyle many have become accustomed to. Changing the natural landscape in the smallest amount ultimately alters the local climate in possibly unintended ways. Urban changes range from increased heat in and around the center of the urban area, to increased precipitation and ultimately increased runoff. Other changes in built up urban environments include decreased surface albedo, increased surface roughness, as well as increased vertical air movement.

As more individuals around the world begin flocking to urban areas we can only begin to speculate about how the environment will react. As cities begin to grow and merge into one giant urban landscape in places, the climatic alteration potential of cities can become so intense that the global climate may be altered. It will take continued monitoring and mitigation in order to keep the overall impact of cities from severely and permanently adding to global climate change.

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