The Urban Moisture Climate

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ABSTRACT.—Data collected on 26 July 1974 as a part of project METROMEX in St. Louis show the three-dimensional structure of the urban moisture field. Mesoscale dry regions at the urban surface, corresponding to large residential and light industrial land-use characterization, were responsible for a reduction in specific humidity in the urban mixing layer. Anthropogenic sources and sinks of water vapor were estimated and found to be insignificant for summer daytime mesoscale influences on the atmospheric water balance of the urban area. The effects of reduced moisture in the urban area are directly related to the urban heat island, visibility, fog, precipitation, and human comfort in our cities.

HUMAN LIFE PATTERNS have changed radically in the last century with the increasing migration from rural to urban areas. The increased magnitude of climatic anomalies accompanying urban-industrial expansion are well documented by the urban heat island and are further evident in the effects on visibility, fog, moisture, and precipitation. These factors are important to human comfort, land-use planning, and engineering considerations.

The moisture budget appears to be a key contributor to urban climate anomalies. Seasonal surface-moisture anomalies have been noted in large urban areas. The greatest urban-rural humidity differences are during summer afternoons when the urban dry island is greatest in magnitude. Summer nighttime differences in urban-rural absolute humidity patterns suggest that the city is drier when the nocturnal heat island is strongest. Wintertime studies, however, show that the urban area is more moist than its rural counterpart. Intensification of the urban heat island has been directly related to less absolute moisture *(Wood 1971)* and reduced evaporation *(Myrup 1969)*. A reduction in urban moisture, with a corresponding reduction in latent heat energy, may also account for anomalous precipitation patterns *(Terjung et al. 1971; Boatman 1974)*. On the local scale uncertainty has been expressed whether the overall water contribution from the city is reduced compared to rural areas since much water vapor is released by combustion, industry, and cooling operations.

Project METROMEX (*METRO*politan *M*eteorological *EX*periment) was initiated in 1971 to statistically and physically evaluate the possible modification of weather and climate by an urban-industrial complex. Recent studies by the University of Wyoming in Project METROMEX focused on the problem of urban moisture *(Sisterson 1975)*. Data were acquired from the instrumented Wyoming research aircraft and instrumented meteorological weather mobiles, along with surface networks operated by cooperating groups (Illinois State Water Survey, St. Louis City and County Air Pollution Agencies).

Three aspects of urban moisture were investigated: (1) relative magnitudes of anthropogenic sources and sinks, (2) the three-dimensional structure of the moisture field, and (3) evaluation of the moisture budget components.

SOURCES AND SINKS OF MOISTURE

Estimates of automobile and industrial sources of water vapor were compared to potential evaporation calculations. The industries chosen in this study warranted investigation because of their size and location in the St. Louis area. The results of water vapor production rates (gm hr^{-1}) for anthropogenic sources and potential evaporation for the urban area are shown in table 1. Even if only a fraction of the radiation energy is used for evaporation, it is apparent that potential evaporation (for a 30-km by 30-km surface area) is several orders of magnitude greater than anthropogenic moisture sources. However, industrial sources are essentially point sources of water vapor. If the potential evaporation is considerd for an area only 3 km by 3 km, the rate of water vapor production approaches that of the major industrial sources. Thus, during the daylight hours, anthropogenic sources do not appear to be of consequence except on the local scale. At nighttime, when potential evaporation is greatly reduced and mixing is limited, anthropogenic sources are indeed a relevant factor in the urban water balance, so that the urban atmosphere at night may be more moist than the rural atmosphere.

Hygroscopic aerosols, photochemical reactions, and precipitation are major moisture sinks for an urban atmosphere. In this study, cases were chosen on non-precipitation days, so the precipitation component was neglected. Particulate mass concentrations of 100μgm m^{-3} (0.5μm size) have been reported for a highly polluted day in Los Angeles, California. In the extreme case, all particles are assumed to be hygroscopic salt particles at a relative humidity of 90 percent. For this case, the maximum change in specific humidity in the urban area (30 km by 30 km by 1.5 km) would be only 2.75×10^{-4} gm kgm^{-1}. This amount is insignificant and cannot be detected by moisture measurement.

Investigation of photochemical reactions in the urban atmosphere was limited to the formation of sulfuric acid, the most common and prolific photochemical pollutant. In the extreme case, all sulfur dioxide was assumed to react with water vapor to form sulfuric acid. In all cases, the water vapor necessary to convert all the SO_2 to H_2SO_4 was at least one order of magnitude less than the water vapor emissions from the industry.

Sulfuric acid is also deliquescent at high concentrations. The excess water vapor between industrial source and reaction requirements was used to dilute sulfuric acid concentrations in the industrial plumes. The Labadie power plant plume showed the greatest potential concentrations of sulfuric acid. Only if the environmental relative humidity is greater than 94 percent could sulfuric acid from the Labadie plant absorb ambient water vapor—again assuming

Table 1.—Urban area sources of water vapor

Classification	Source	Water vapor (gm hr^{-1})
Auto	Automobile	2.3×10^8
Refineries	Amoco	1.2×10^8
	Shell	3.0×10^8
Power Plants	Meramec	2.0×10^7
	Portage des Sioux	1.9×10^7
	Labadie	5.8×10^7
Cement	Alfa	2.9×10^7
	Missouri Portland	7.6×10^7
Steel	Granite City	1.8×10^8
Nature	Potential Evaporation	6.7×10^{11}

all SO_2 converted to H_2SO_4. The photochemical reaction of sulfuric dioxide and water vapor is therefore clearly not a significant factor in the extraction of water vapor from the urban atmosphere on the mesoscale, and in general, the deliquescense of sulfuric acid is insignificant.

ST. LOUIS CASE STUDY— 26 JULY 1974

Atmospheric moisture patterns are influenced by advection, turbulent mixing, and local sources and sinks of moisture. In the METROMEX field studies, aircraft transects were chosen so that unique air columns were successively intercepted at two flight levels as they passed over the urban area. The flight pattern thus minimized advection. Horizontal turbulent mixing was found to be insignificant and downward entrainment of dry air into the mixing layer was initially assumed insignificant with the presence of a subsidence inversion.

Because surface data were acquired from fixed stations, the time rate of change of surface moisture measurements included advection. Calculations showed that surface moisture advection on the mesoscale was insignificant. Local advection, however, was not assessable and may be important.

Temperature and moisture comparison between corrected weather mobiles, hygrothermographs, and telemetry stations at locations where data from all three uniquely different sources could be compared, showed consistent results. A similar consistence was observed between aircraft and radiosonde measurements in the free atmosphere. It is important to recognize that the characteristic of the moisture anomalies described in this section were consistent among four independent types of instruments.

Data from 26 July 1974 for 1530 to 1630 CDT are presented to illustrate moisture patterns that have been observed on a number of fair summer days. Low-level winds on this day were northerly with speeds less than 5 m sec^{-1}. Specific humidity and potential temperature patterns are shown for the surface at 1600 CDT (fig. 1). Dry regions exist along the northern, southern, and western edges of St. Louis, corresponding to major residential and light industrial land-use characterizations (fig. 2). Heat islands are apparent north of the city and along the southern edge. Because these analyses are based upon individual stations, local effects influence station readings, and small regions of low moisture and high temperatures are apparent *(Chandler 1967, Kopec 1973)*. Weather mobile data also show as much as 2 gm kgm^{-1} and a 1C variation in moisture and temperature, respectively, over distances of 1 km.

Patterns of specific humidity and potential temperature are shown for 450 m MSL (300 m AGL) in figure 3. A single widespread dry region exists along the southern edge of St. Louis, with tongues of dry air extending along the eastern and western edges of the metropolitan area. A single heat island is also apparent and corresponds to the dry region. Both humidity and temperature patterns are reasonably well correlated with those on the surface. The patterns of specific humidity and potential temperature patterns at 900 m MSL (fig. 4) correlate well with those at 450 m MSL. Both dry regions and heat fields are more widespread at the upper level.

From data acquired at the three levels between 1530 and 1630 CDT, three-dimensional analyses of the moisture fields in the mixing layer were constructed. Isopleth analysis of the specific humidity is shown for 10.2 gm kgm^{-1} (fig. 5) and 11.8 gm kgm^{-1} (fig. 6). A plume-like structure with an hourglass configuration is evident. The drier surface air is apparently mixed vertically through the mixing layer. Measurements of the wind field convergence also

Figure 1.—Specific humidity (gm kgm^{-1}) and potential temperature (°K) patterns for the surface at 1600 CDT. Heavy dashed lines show weather mobile transects. The shaded region defines urban and suburban areas.

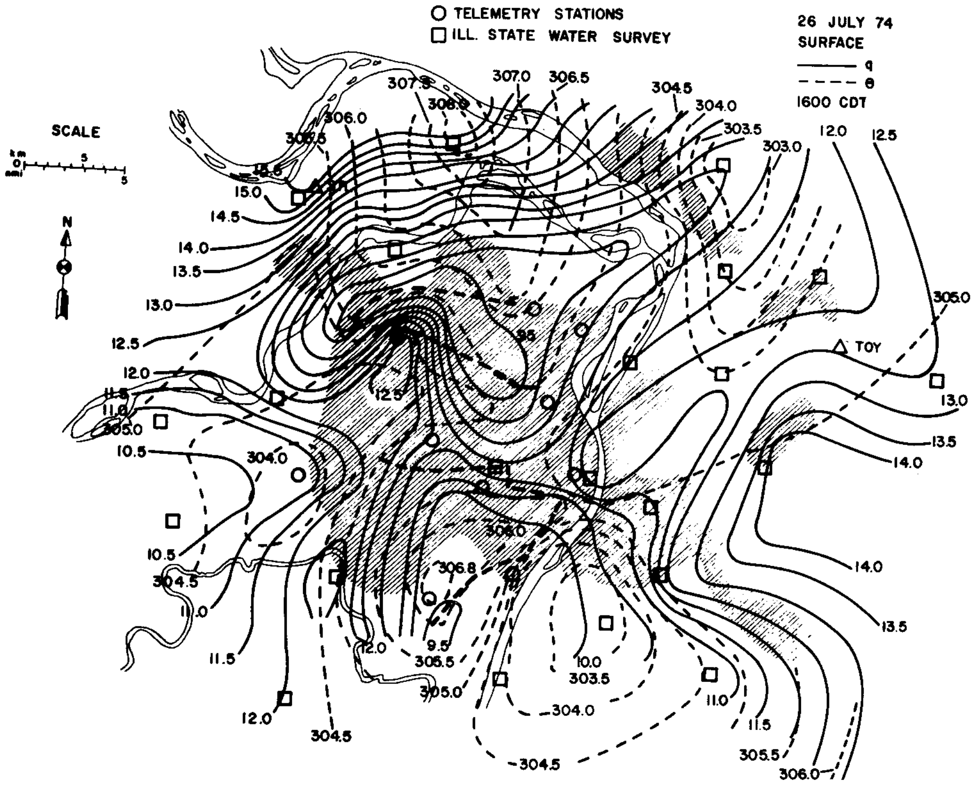


Figure 2.—St. Louis and surrounding area land use characteristics. Roadways and their corresponding route numbers are shown. The solid triangles represent the St. Louis and Troy navigational vortacs.

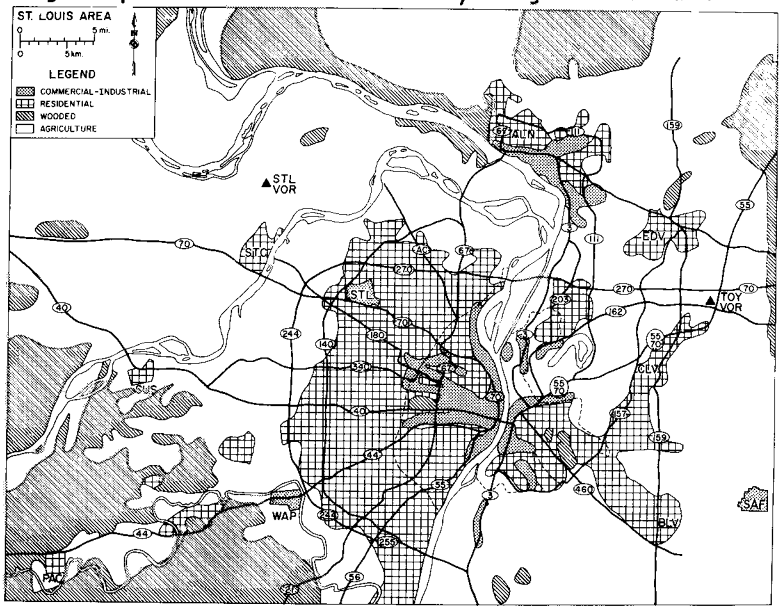


Figure 3.—Specific humidity (gm kgm⁻¹) and potential temperature (°K) patterns at 0.45 km MSL (1530-1630 CDT).

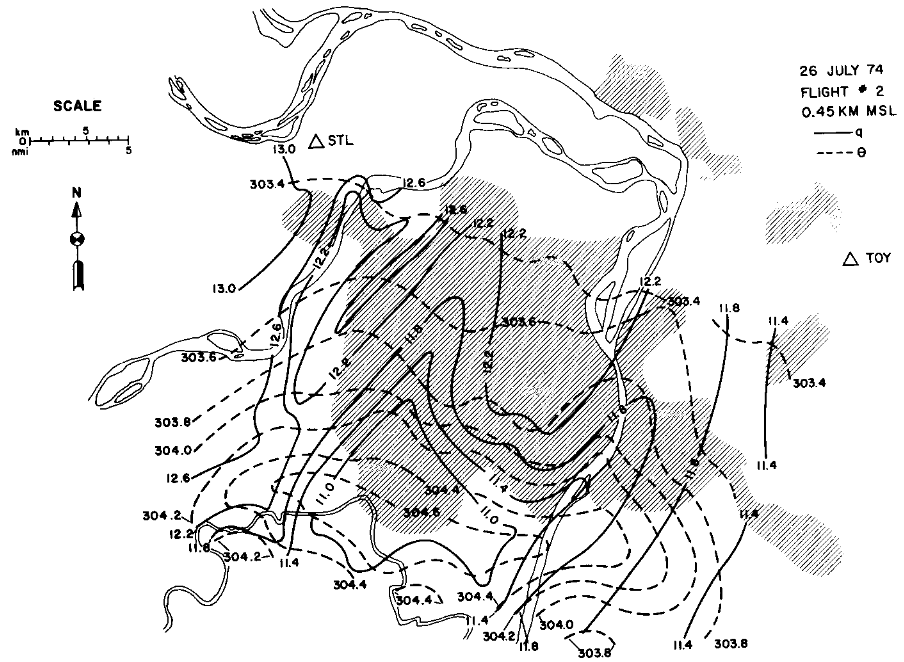


Figure 4.—Specific humidity (gm kgm⁻¹) and potential temperature (°K) patterns at 0.9 km MSL (1530-1630 CDT).

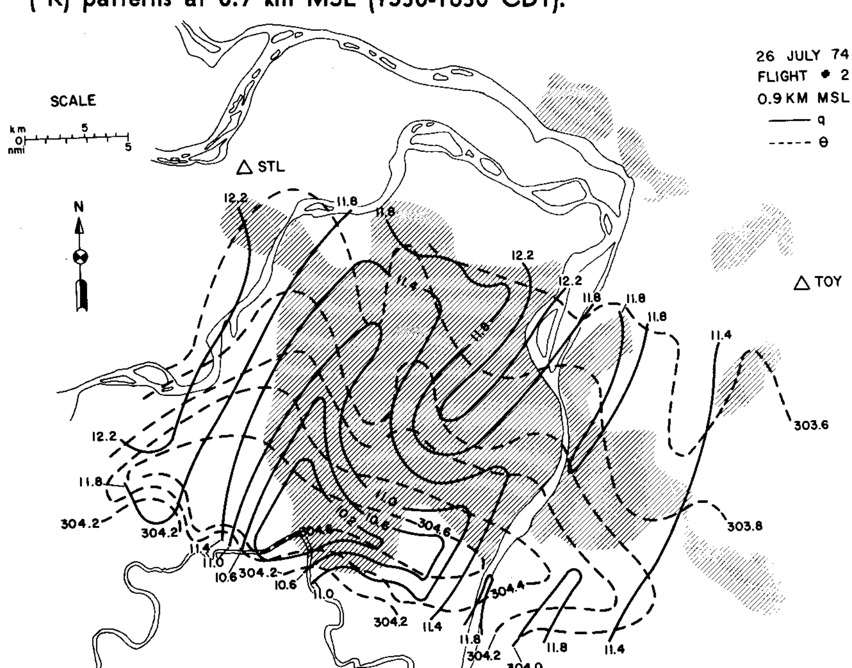


Figure 5.—Three dimensional analysis of the 10.2 gm kgm-1 isohume (1530-1630 CDT) for 26 July 1974.

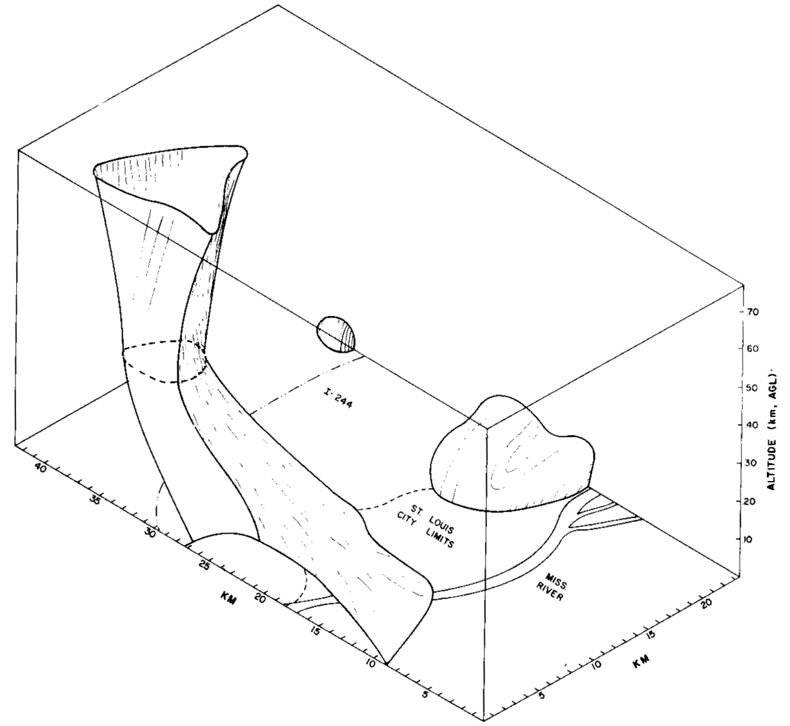


Figure 6.—Three dimensional analysis of the 11.8 gm kgm-1 isohume (1530-1630 CDT) for 26 July 1974.

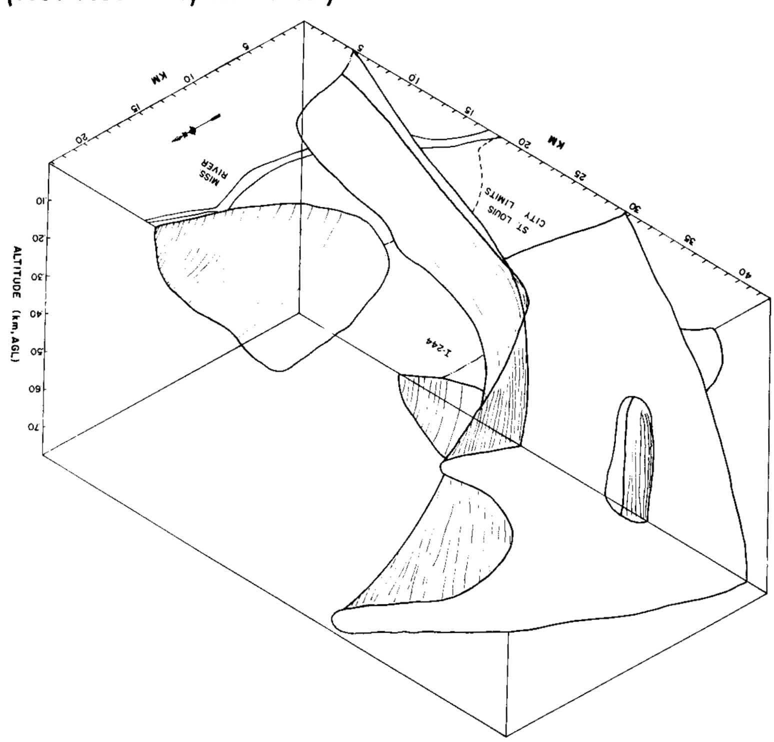


Figure 7.—Upwind aircraft sounding at 1533 CDT.

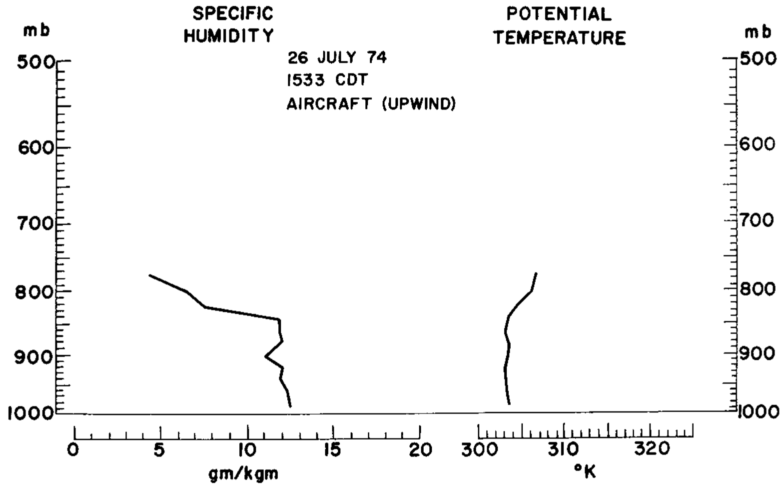


Figure 8.—Tower Grove Park radiosonde sounding at 1500 CDT.

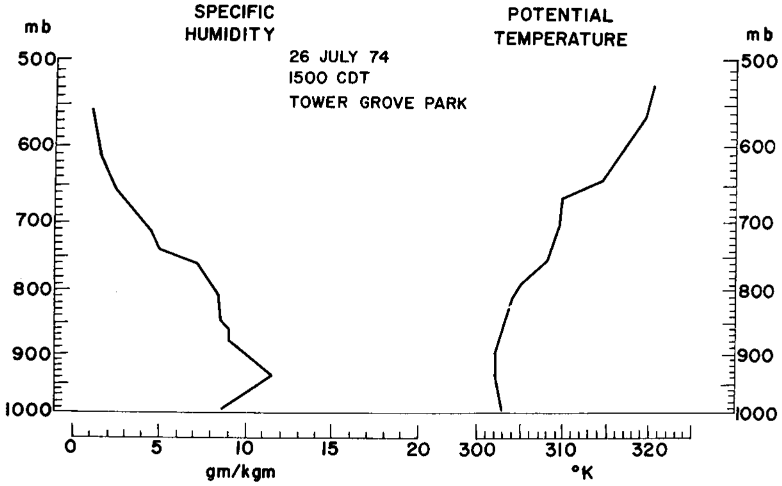
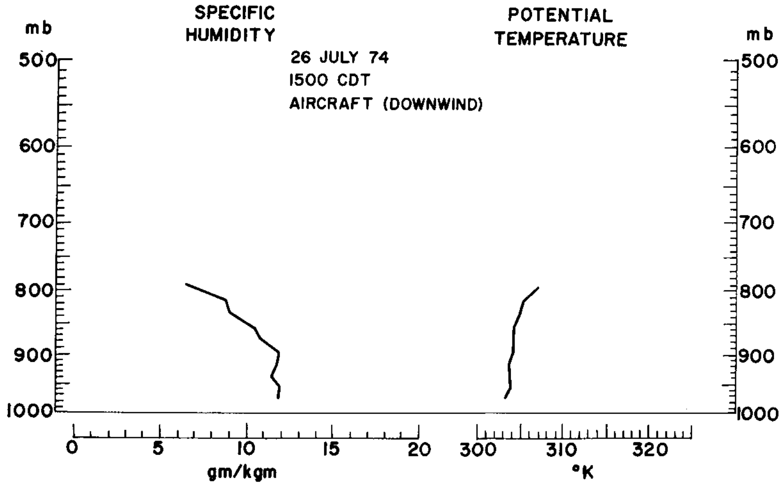


Figure 9.—Downwind aircraft sounding at 1500 CDT.



support the concept of convergence and ascent in the dry regions.

Aircraft and radiosonde soundings were also analyzed for the effects of urban modification on vertical moisture profiles. Aircraft soundings were extrapolated to the surface, using local surface values of humidity and temperature. Likewise, values from an aspirated psychrometer established the surface temperature and humidity for radiosondes. Three soundings (upwind, over, and downwind to St. Louis), taken within a period of 30 minutes, are shown in figures 7 to 9. Particular attention is focused on the lowest 50 mb moisture profile of each sounding. The upwind sounding shows a slight decrease in specific humidity with height. The sounding at Tower Grove Park, (5 km southwest of downtown St. Louis), taken near a large concrete area, shows a large increase of specific humidity with height. The downwind sounding shows only a slight increase of humidity with height. These soundings show that within the lowest 50 mb the urban surface is drier than the air above 950 mb on this day. These features are characteristic of a number of case study days. Hence, as air columns pass over the urban area from a region of high surface humidity (upwind) to a region of lower surface humidity, the mixing of dry air into the columns reverses the low-level humidity gradient and decreases the average specific humidity of the columns.

These soundings also show that the inversion is elevated over the urban area by 600 m. The sharp moisture discontinuity at the base of the inversion of the upwind sounding is not present over the city. There is an apparent eroding of the air beneath the inversion, probably attributable to nonuniform downward entrainment of dry air. This violates the previous assumption of negligible entrainment into the mixing layer. This entrainment term could not be assessed, but it is apparent that downward mixing across the inversion will also dry out the columns.

Overall, the urban-influenced atmosphere is drier than the surrounding rural area. Because there is less moisture potential at the city surface (vegetation, porous soils, etc.), less energy is used for evapotranspiration purposes. The excess energy is then utilized between sensible heat energy and ground stored energy, which generally causes the urban atmosphere to be hotter.

In summary of the 26 July 1974 study, dry regions are found within the St. Louis urban area. These regions of low specific humidity correlate well with impervious surfaces found in the densely populated residential areas and light industrial areas. Although the moisture content of air columns passing over the city may decrease from downward entrainment of dry air from above the mixing layer, reduced evapotranspiration at the surface clearly contributes to a reduction in average specific humidity of the columns. It can be inferred that up to 50 percent of the St. Louis area *(Marotz and Coiner 1973)* is represented by modified surfaces. Thus the urban surface environment is drier due to reduced evapotranspiration from widespread impervious surfaces.

RELEVANCE TO URBAN-DWELLERS

From energy budget considerations, nearly equal amounts of radiation are available at both urban and rural surfaces *(Maisel 1971, Rouse et al. 1973)*; however, less radiation is used as latent heat energy, so that sensible heat energy and ground stored energy must be greater in the urban area. Loose soil and plant material characteristically are very poor heat conductors and have a low heat capacity. Hence all heat transactions take place in a thin surface layer in most rural areas. In contrast, urban areas have massive surfaces of stone, brick, concrete and asphalt. These have better heat conductivity than soils and therefore may be warmed to appreciable depth by incoming solar radiation. Nocturnally the stored heat is gradually released, which keeps the city surfaces warmer than surrounding grassland or trees. In addition, the heated vertical surfaces of buildings radiate toward each other and do not lose heat by radiation toward the sky as a horizontal surface in the open country would *(Landsberg and Maisel 1972)*.

The increase in sensible heat energy (the heat island) is a well-documented phenomenon in urban areas. High environmental temperatures affect health. Prolonged exposure to high temperatures associated with summer heat waves can result in death either as a primary cause or as a contributing factor in heart disease, strokes, and pulmonary disorders. There is evidence to suggest that a large percentage of heat-related deaths may be of man's own design by climate modification through urbanization. Clarke and Bach *(1971)* showed a relationship between average daily temperature and deaths attributed primarily to heat during the July 1966 St. Louis heat wave, in which 500 deaths occurred in East St. Louis, Illinois. Although no heat deaths occurred at an average temperature of 31.7C, deaths increased markedly with every one-degree increase in temperature above 32.2C (assumed the critical level). A rise of the average daily temperature of only 0.6C above 32.2C resulted in 11 heat deaths. Seventy-three heat deaths occurred when the average daily temperature was 35C. This 2.8C increment of average daily temperature is about the same as the average temperature difference between the urban and suburban environments, based on the afternoon and evening temperatures obtained in Clarke and Bach's study.

Other effects of the urban moisture climate may also contribute to man's discomfort in his atmospheric environment. The reduced moisture content of urban-influenced air may locally deprive storms of latent heat energy, so that the intensity of thunderstorms could be expected to decrease over the urban area, as observed by Boatman *(1974)*. This may further result in precipitation anomalies observed downwind of large urban areas. The small amounts of water vapor absorbed by hygroscopic aerosols generated from industrial effluents create haze particles that severely reduce visibility in the urban area. The effect of increased moisture from industry at night when mixing is only within a shallow layer would be expected to increase urban humidity, such that the city may be more moist than surrounding country air. This may also explain the greater tendency for fog in urban areas.

Finally, now that evidence for an urban area as a potential weather modifier on the basis of its physical presence is realized, some recommendations may be offered that would help to make the city a more comfortable place in which to work and live. From energy and moisture budget considerations, green belts or vegetated areas are necessary within our cities. Green belts would not only help to embellish the downtown image, but also moderate the cities temperature. Large asphalt parking lots should be transected with trees and shrubs to reduce overheating. Fountains and small parks should be constructed within the heart of the city where the greatest percentage of concrete and impervious surfaces exist. Gardens and vegetation could be planted on rooftops. All of these modifications of the urban moisture budget would contribute to a moderation of the daytime temperature excess of the urban heat island.

CONCLUSIONS

The lack of available moisture from the urban surface leads to increased sensible heat energy and ground stored energy. Properly spaced green areas are perhaps the most important means of controlling the urban temperature excess. The urban heat island effect could also be reduced in torrid latitudes by using building materials that have lower heat conductivity and capacity. Building with different materials and colors, through changes in albedo and heat absorption, would cause differentials in heating and encourage mixing and ventilation. On the other hand, cities in high latitudes may be purposefully constructed to strengthen the heat-island effect. If the effects of urban development on the local climate are considered in the urban planning process, climate modification can be purposely controlled toward man's comfort rather than allowed to inadvertently develop to man's distress.

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