Correlation of Land Use and Cover with Meteorological Anomalies

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ABSTRACT

Aerial reconnaissance of the greater St. Louis area has led to the identification and classification of land use types. The land use classification provides as much compatibility as possible with other classification systems, yet offers the inclusion of percentage vegetative cover as an innovative characteristic of the land use description. The observed meteorological (thermodynamic, kinematic and radiative) anomalies in the vicinity of the metropolitan area are shown to be affiliated with "meteorologically significant" land cover characteristics.

It is suggested that the specific details of population, areal extent and type of metropolitan land cover must be considered in estimating the potential for inadvertent weather modification.

1. Introduction

It has been established in numerous empirical studies that city mesoclimates are markedly different from those over surrounding, more natural areas; i.e., city environments are usually warmer, drier, less wind, cloudier and have a larger particulate burden than their rural counterparts. The most extensive study of urban meteorology has been conducted under the auspices of Project METROMEX (Changnon et al., 1971). The contrasting atmospheric properties seem to be the direct result of differential urban-rural energy disposition brought about by significant physical differences between cities and their surroundings; namely, the contrasting character of surface material (e.g., vegetation versus concrete), landscape shape and structure, heat sources and retention, and evapotranspiration.

While meteorologists for several decades have published information on urban climates, there is now a need to correlate these meteorological anomalies with more specific land use identification and description than are now used (such as "downtown, center of the city, residential, commercial," etc.). The purpose of this article is to identify some certain features of the land use in St. Louis that are unique and may be "meteorologically significant" in explaining some thermodynamic, kinematic and radiative anomalies associated with the overriding atmosphere of the metropolitan St. Louis area.

2. Procedure

Low-level airborne mapping and photography were used to establish our "meteorological" land use mosaic for Metropolitan St. Louis. As a standard procedure in its research activities, the University of Wyoming operated a Queen Air aircraft in the airspace over St. Louis. Aside from the computer-directed collection and recording of the meteorological and aircraft operational parameters, the data acquisition system is also equipped with an event marker. Event information, which is a discrete signal used to indicate up to 30 selected events such as specific land uses or photography, can be received from the pilot, copilot (scientist) and technician positions. In this manner, a designated event marker corresponding to a unique land use could be activated during the entire flight of that land use. Among the aircraft operational parameters recorded are heading, VOR azimuth and DME position which allow plotting the aircraft flight path to within ±1° and 0.2 km, respectively. Thus, flight paths, time and corresponding event markers were plotted yielding a land use mosaic. Only those flights or portions thereof at 150–300 m AGL (above ground level) were used to collect land use information to minimize downward line of sight errors. Scores of photographs were also taken to identify what was meant by a particular land use type as well as to aid in establishing the areal extent of the land use type. Voice recorders were utilized by crew members for complementary information regarding use of event markers and photography. Since the research flight paths were many and varied across the entire metropolitan area, an adequate density of land use data was acquired. No major modification in land use in the metropolitan area was noted in the observational period 1973–76.

There is no one ideal classification of land use and land cover, and it is unlikely that one could ever be developed. In developing our classification system, every effort has been made to provide as much compatibility as possible with other classification systems.
currently being used by the various Federal agencies involved in land use inventory and mapping (e.g., Anderson et al., 1976). Our system satisfies the three major attributes of the classification process as outlined by Grigg (1965): 1) it gives names to categories by simply using accepted terminology; 2) it enables the classification scheme to be transferable; and 3) it allows inductive generalizations to be made. The classification system is capable of further refinement on the basis of more extended and varied use.

The approach to land use and land cover classification embodied in our system described herein is “meteorologically oriented,” in contrast, for example, with the “people orientation” of Land Use Coding developed by the U. S. Urban Renewal Administration and the Bureau of Public Roads (1965).

3. Results

The analysis of the land use determination is shown in Fig. 1. The land use types in this classification assigned to the St. Louis Metropolitan area are listed in Table 1 along with a brief description of each. The types of land use and land cover categorization developed in this classification system can be related to other systems which classify the potential for any particular activity or land value. The classification is general enough to find utility in describing any metropolitan area land use as well as specific enough for association with relevant metropolitan anomalies.

For our use, the term “Metropolitan St. Louis area” has been assigned to that area encompassed by the outlying boundary of the normal residential (R1) land use. The Alton-Wood River, Ill., area (extreme northeast) has not been included in this metropolitan area, since it will be addressed separately. According to 1970 Census Bureau statistics, the City of St. Louis has a population of 622,236 (ranks 18) with a population density 3938 people per square kilometer (ranks 7). Census Bureau figures show a population of 2,363,017

Fig. 1. Land use mosaic for the Metropolitan St. Louis area. Circled numbers with arrows show the location, viewing direction and figure number of accompanying photographs depicting examples of land use classification.
### Table 1. Identification and classification of land use types found in Metropolitan St. Louis

<table>
<thead>
<tr>
<th>Type</th>
<th>Use and structures</th>
<th>Description</th>
<th>Vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1</td>
<td>Heavy industrial</td>
<td>Grass and tree growth extremely rare; &lt;5% vegetation</td>
<td></td>
</tr>
<tr>
<td>I2</td>
<td>Light-moderate industrial</td>
<td>Very limited grass, trees almost total absent; &lt;5% vegetation</td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>Commercial</td>
<td>Office and apartment buildings, hotels; &gt;10 story heights, flat roofs</td>
<td>Limited grass and trees; &lt;15% vegetation</td>
</tr>
<tr>
<td>R1</td>
<td>Common residential</td>
<td>Single family dwelling with normal easements; generally one story, pitched roof structures; frequent driveways</td>
<td>Abundant grass lawns and light-moderately wooded; &gt;70% vegetation</td>
</tr>
<tr>
<td>R2</td>
<td>Compact residential</td>
<td>Single, some multiple, family dwelling with close spacing; generally &lt;2 story, pitched roof structures; garages (via alley), no driveways</td>
<td>Limited lawn sizes and shade trees; &lt;30% vegetation</td>
</tr>
<tr>
<td>R3</td>
<td>Compact residential</td>
<td>Old multi-family dwellings with close (&lt;2 m) lateral separation; generally 2 story, flat roof structures; garages (via alley) and ashpits, no driveways</td>
<td>Limited lawn sizes, old established shade trees; &lt;35% vegetation</td>
</tr>
<tr>
<td>R4</td>
<td>Estate residential</td>
<td>Expansive family dwelling on multi-acre tracts</td>
<td>Abundant grass lawns and lightly wooded; &gt;80% vegetation</td>
</tr>
<tr>
<td>A1</td>
<td>Metropolitan natural</td>
<td>Major municipal, state, or federal parks, golf courses, cemeteries, campuses; occasional single story structures</td>
<td>Nearly total grass and lightly wooded; &gt;95% vegetation</td>
</tr>
<tr>
<td>A2</td>
<td>Agricultural rural</td>
<td>Local crops (e.g., corn, soybean); &gt;95% vegetation</td>
<td>Mostly wild grasses and weeds, lightly wooded; &gt;90% vegetation</td>
</tr>
<tr>
<td>A3</td>
<td>Undeveloped</td>
<td>Uncultivated; wasteland</td>
<td>Heavily wooded; &gt;95% vegetation</td>
</tr>
<tr>
<td>A4</td>
<td>Undeveloped rural</td>
<td>Rivers, lakes</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>Water surfaces</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

for a Metropolitan St. Louis. An inspection of Fig. 1 collaborates the population density statistics since land use type R3 is seen to comprise approximately 40% of the area within the city limits.

Fig. 1 also shows the packing of land use types I1, I2, C1, R2 and R3 in the center of the metropolitan area. Since these land uses are comprised of only 5–30% vegetation and contain an abundance of man-made structures, a probable influence on meteorological anomalies is anticipated more than from a more “industrial” or “residential” classification.

Figs. 2–6 show representative views of some land use types shown in Fig. 1 and described in Table 1. An unabridged listing of land use photographs may also be found in Auer (1975b).

In particular, Figs. 4 and 5 highlight type R3. Since these residential structures seem to be coincident with most of the surface meteorological anomalies reviewed later, some additional description may be worthwhile. These multi-family dwellings (mostly two-family flats) were built circa 1915. Two features stand out clearly in Figs. 4 and 5: 1) nearly all dwellings are two-story and have flat, tarred roofs; and 2) the spacing between the buildings is very narrow (<2 m) with symmetry block after block. On-site estimates of the vegetative cover are less than 35%.

Table 2 gives a summary of the areal contributions according to land use types found in Metropolitan St. Louis. The contribution of streets, sidewalks and alleys to the total land use has not been included in Table 2. However, from input gleaned from aerial photographs,
detailed road maps and Abell (1975), area estimates of street and sidewalk thoroughfares for St. Louis city and the metropolitan area can be made, and as a first approximation, may be assumed proportionately distributed through land use types I-C-R. Within the city limits, 21.6 km² of street pavement and 6.5 km² of sidewalk are estimated, corresponding to 13.6% and 4.1%, respectively, of the total city area. Suburban estimates are placed at 147.1 km² (14.9%) and 46.8 km² (4.7%), respectively.

It should also be pointed out that the areal coverage of metropolitan natural (A1) land use is dominated by the contributions of a few large recreational parks and cemeteries throughout the metropolitan area (e.g., Forest Park, Calvary-Bellefontaine Cemetery). While there are numerous (over 175) examples of A1 land use, the vast majority are small in size and their effect is obscured by surrounding anthropogenic alterations.

Within the city limits of St. Louis, the integrated vegetative cover is estimated at approximately 45%. However, 70% (109 km²) of the city area consists of I1-I2-C1-R2-R3 land use, adjacent to the center of the city. These land uses collectively account for only a 25% vegetative surface. For the St. Louis Metropolitan area, the integrated vegetative cover is estimated at 65%.

At the extreme northeastern edge of the metropolitan area is the Alton-Wood River industrial complex. The principal industries in this area consist of steel smelting and several petroleum refining complexes, dominated by the Shell Oil Refinery (see Fig. 6) at Wood River which ranks nationally among the top 12 refineries in terms of petroleum products output. The Alton-Wood River complex is addressed separately here because it has been demonstrated to be associated with some unusual and substantial increases in rainfall statistics (Schickedanz, 1974a) and clouds (Auer, 1976), although it is not large in areal extent and somewhat displaced from the other I1-I2-C1 land uses. The land use consists of types I1 and I2 with areas of 6.2 and 15.3 km², respectively; the associated domicile use is generally R1, covering about 50 km². While the land use may not seem impressive and conducive to weather anomalies, it should be noted that the refinery complex ranks as one of the strongest localized sources of heat ($7 \times 10^{11}$ cal h⁻¹) and water vapor ($3 \times 10^8$ g h⁻¹) output in the St. Louis region.

Table 2. Summary of areal coverages (km²) of specific land uses for Metropolitan St. Louis, excluding waterways, thoroughfares and the Alton-Wood River industrial complex. Numbers in parentheses are percents.

<table>
<thead>
<tr>
<th>Land use type</th>
<th>City of St. Louis</th>
<th>Missouri</th>
<th>Illinois</th>
<th>Metropolitan area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I1</td>
<td>5.4 (3)</td>
<td>4.2 (&lt;1)</td>
<td>6.7 (&lt;3)</td>
<td>16.3 (1)</td>
</tr>
<tr>
<td>I2</td>
<td>21.4 (14)</td>
<td>14.6 (2)</td>
<td>33.9 (13)</td>
<td>69.9 (6)</td>
</tr>
<tr>
<td>C1</td>
<td>5.9 (4)</td>
<td>1.1 (&lt;1)</td>
<td>0.2 (&lt;1)</td>
<td>7.2 (&lt;1)</td>
</tr>
<tr>
<td>R1</td>
<td>29.2 (18)</td>
<td>629.4 (87)</td>
<td>198.2 (75)</td>
<td>856.8 (73)</td>
</tr>
<tr>
<td>R2</td>
<td>13.3 (9)</td>
<td>2.2 (&lt;1)</td>
<td>—</td>
<td>15.5 (1)</td>
</tr>
<tr>
<td>R3</td>
<td>63.4 (40)</td>
<td>1.8 (&lt;1)</td>
<td>—</td>
<td>65.2 (6)</td>
</tr>
<tr>
<td>R4</td>
<td>—</td>
<td>53.3 (7)</td>
<td>—</td>
<td>53.3 (5)</td>
</tr>
<tr>
<td>A1</td>
<td>19.8 (12)</td>
<td>20.4 (3)</td>
<td>24.4 (9)</td>
<td>64.6 (6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>158.4 (100)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>727.0 (100)</td>
<td>263.4 (100)</td>
<td>1148.8 (100)</td>
</tr>
<tr>
<td>Total area</td>
<td>990.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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2 Abell, W., 1975: Personal communication. Administrative Assistant to the Director of Streets, Room 322, City Hall, St. Louis, Mo. 63103.
4. Implications

Certain types of land use, when adjacently located, can effectively alter surface characteristics, landscape structure, heat source and retention, and evapotranspiration, thereby increasing the dimensions of what has been termed "the urban area" in the literature on urban meteorology.

Like most large cities, St. Louis has a marked surface heat island (±1.5 to ±3.0°C) and a coincident (in space and time) identifiable minimum specific humidity (−0.5 to −1.5 g kg⁻¹) evident in the summer afternoon climatology (Jones, 1973; Jones and Schickedanz, 1974) as well as in summertime case studies (Dirks, 1974a,b; Sisterson, 1975). Temperature increases (+1°C) and specific humidity deficits (−1 g kg⁻¹) often extend a kilometer or more above the city and through the mixing layer to cloud bases (Auer and Changnon, 1977). An example of the thermodynamic anomalies in Fig. 7 is reproduced from Dirks (1974b) and clearly shows the
the metropolitan area, observable as a specific humidity deficit.

Thermal perturbations, along with the effect of increased surface friction, may alter the airflow across a metropolitan area. The low-level airflow under light and moderate wind conditions has been found to be markedly perturbed by the city and often results in distinct convergence in or just downwind of the city center (Ackerman, 1974a,b, 1977; Auer, 1975a; Sisterson, 1975; Kropfli and Kohn, 1977; Wong and Dirks, 1978).

The thermodynamic anomalies in the mixing layer over the city are reflected in the preferred areas in and downwind of the urban area for the initiation of cumulus clouds, seasonally (Schickendanz, 1974b) and by case study (Auer, 1974, 1976). Convective cloud bases are generally higher by 200–600 m over and slightly downwind of the city (Ackerman and Appleman, 1974; Boatman and Auer, 1974; Semonin and Changnon, 1974; Changnon et al., 1976; Shea and Auer, 1978).

Anomalies in radiation parameters have also been documented in St. Louis. A nighttime infrared surface heat island has been shown to stand out clearly over the downtown St. Louis area (Braham, 1974). Reduced albedo values of 11–13% have been found for commercial-industrial-old residential sites contrasted with albedo values of 16–22% for surrounding rural areas (Dabberdt and Davis, 1974; White et al., 1978). Variations in albedo and emitted terrestrial radiation, related to mesoscale changes in land use and cover, have been found responsible for differences in net radiation accumulated within the St. Louis metropolitan and surrounding rural areas (White et al., 1978).
It is recognized that no single land use type may, by itself, be responsible for a particular thermodynamic, kinematic or radiative anomaly. There may indeed be interactive and feedback processes between land use types and anomalies which are not yet clearly understood. However, evidence from METROMEX nourishes the premise that there is a direct interaction between land use type and anomaly since certain land use types are coincident with some observed surface anomaly locations.

Schickedanz (1974a) has documented anomalous characteristics of summertime convective rainfall across the Metropolitan St. Louis area. Grosh and Semonin (1973), Boatman and Auer (1974), Changnon and Semonin (1975) and Changnon et al. (1976) have observed thunderstorm occurrence of the type studied by Schickedanz and concluded that temperature and specific humidity anomalies associated with the urban surface and overriding mixing layer can alter storm behavior and possibly explain the 20–30% precipitation increases (Huff and Vogel, 1977) in the localized area within 40 km of the city center.

In his review of urban climatic rainfall patterns, Changnon (1976) concluded that a critical size of metropolitan population (>1,000,000) must be attained before a metropolitan area affects rainfall downwind. Furthermore, since sizeable rainfall increases were found in non-industrial cities, as well as in industrial cities with widely varying industrial bases, the rainfall anomalies seem associated with thermodynamic and/or kinematic characteristics of the land cover.

Thus, it appears that some specific details of population, size and type of natural landscape alteration must be considered in estimating the potential of inadvertent precipitation modification. Land use types of I1-I2-C1-R2-R3, which cover as little as 100 km² in the case of St. Louis, should be suspect for mesoscale thermodynamic anomalies sufficient to cause inadvertent precipitation modification.

If meteorological land use types, as listed in Table 1, and areas of coverage, as shown in Table 2, can be identified for other urban studies, better comparisons and transfer of analyses can be made through stratification by land use. Eventually it is hoped that the recognition of the meteorological land use types proposed herein will find their place in the format of defining and describing the anomaly, identifying responsible initial processes, linking these processes to anthropogenic...

Fig. 7. Analysis of urban temperature (°C, solid) and specific humidity (g kg⁻¹, dashed) anomalies with respect to upwind values at 305 m AGL for 1145–1500 CDT 23 August 71 (after Dirks, 1974b). The land use analysis is repeated from Fig. 1.
activities, and ultimately relating these findings to the translation and prediction of anomalies in other metropolitan areas.

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REFERENCES