Abstract

Visible and infrared satellite images, in combination with detailed landscape information, suggest an appreciable effect of spatial variations in landscape on cumulus cloud formation over relatively flat terrain. These effects are noticeable when forcing from the atmosphere is weak, e.g., when fronts or other disturbances are absent. A case is presented in which clouds are observed to form first over a mesoscale-size area (100 × 300 km) of harvested wheat in Oklahoma, where the ground temperature is warmer than adjoining areas dominated by growing vegetation. In addition, clouds are suppressed over relatively long bands downwind of small man-made lakes and areas characterized by heavy tree cover. The observed variability of cloud relative to landscape type is compared with that simulated with a one-dimensional boundary-layer model. Clouds form earliest over regions characterized by high, sensible heat flux, and are suppressed over regions characterized by high, latent heat flux during relatively dry atmospheric conditions. This observation has significance in gaining understanding of the feedback mechanisms of land modification on climate, as well as understanding relatively short-range weather forecasting.

1. Introduction

Boundary-layer air is heated and moistened in response to the absorption of solar radiation at the earth’s surface. Characteristics of the landscape (vegetation cover, soil moisture, surface roughness, soil type, etc.) control the relative amounts of heat and moisture added to the air in a given location. For many years, humans have pondered the possible effects of changes in the earth’s landscape, both natural and man-made, on climate and weather. The effects of extensive irrigation, reforestation, slashing of forests, and urban heat islands have all been considered. Recently, numerical simulations have suggested a dynamic effect due to differential heating between wet and dry land areas (Anthes 1984; Mahfouf et al. 1987; Segal et al. 1988). These simulations indicate that convergence forms near boundaries between wet and dry regions, which may lead to enhanced cloud development. Aside from this mechanism, convective clouds may simply form earlier over preferred areas because of differences in air-mass modification. The development of convective clouds during summertime daylight hours over land, and development over warm bodies of water during cold-air outbreaks, are both manifestations of this effect. It is interesting to consider whether the mesoscale spatial variation of heat and moisture fluxes over land surfaces alone is significant enough to have an observable effect on the locations of initial convective cloud development.

Previous work has suggested the importance of spatial variability of the landscape. Walsh and Stadler (1983) used a Geographic Information System (GIS) to combine various landscape and moisture characteristics and calculate monthly evapotranspiration over a small watershed in Oklahoma. Their results indicated substantial differences in evapotranspiration between the various landscapes found in the 160-km² study area.

Rabin (1977) used a surface energy-budget model to study the effect of vegetation and soil moisture on the timing of convective storm initiation. Case studies suggested a noticeable earth-surface modulation of convection when synoptic forcing was weak. It was found that manifestation of the effect depends on the nature of the vertical stratification of temperature and moisture in the atmosphere and the characteristics of the landscape. When the lower atmosphere was relatively moist, convective clouds first developed downwind of moist surface areas. On the other hand, when the lower troposphere was relatively dry, development first occurred over the drier, hotter surfaces. The total heat (sensible plus latent) needed to modify initially moist and initially dry atmospheric soundings, such that convective clouds would form, is shown in figure 1. In both cases, the amount of required heat varies with the Bowen ratio (sensible heat/latent heat). The Bowen ratio is a function of surface wetness—small over moist surfaces and large
over dry ground. Less total energy is required to form clouds in regions where the Bowen ratio is smallest during moist atmospheric conditions (8 July 1975) and where the Bowen ratio is largest during dry atmospheric conditions (7 July 1975). Therefore on moist days, clouds should develop earliest over places where the Bowen ratio is smallest, typically over forested zones and regions of antecedent precipitation which release water vapor into the air at rates near potential evapotranspiration. However, on dry days, convection is expected first over places where the Bowen ratio is highest. These would be drier ground areas dominated by shallow-rooted vegetation that has depleted available soil moisture. This hypothesis is tested by examining the development of cumulus clouds from satellite data with respect to spatial patterns of vegetation and antecedent precipitation.

To minimize orographic effects, relatively flat terrain in Oklahoma was chosen for the study. Anomalous wet and dry landscape features must be of sufficient size for different air-mass characteristics to develop locally. For the range of Bowen ratios shown in figure 1, clouds will begin forming over preferred areas after about $200 \times 10^4$ J m$^{-2}$ of sensible and latent heat flux modifies an initially uniform air mass. This implies about 1 h residence time for the air over wet terrain or over dry terrain, assuming typical daytime flux totals of about 500 W m$^{-2}$. Thus, on days with wind speeds less than 5 m s$^{-1}$, one must first identify significant wet and dry anomalies of at least 20-km diameter to observe differential cloud development caused by nonhomogeneous landscapes.

1 The required size of the anomalies is directly proportional to the wind speed.

2. Technique and available data

The relative spatial distribution of the Bowen ratio can be determined from satellite and surface measurements by estimating the amount of active vegetation cover, determining the available moisture for evaporation, and observing the surface temperature. The spatial distribution of evapotranspiration and sensible heat flux over a particular region could also be determined by a numerical model. Unfortunately, there are many uncertainties in the quantitative evaluation of hourly evapotranspiration and heat flux. The following conditions are not readily determined over widespread areas: initial soil moisture, ability of

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**FIG. 1.** Sensible and latent heating of the atmosphere required for initiation of convective clouds vs. Bowen ratio at the ground for two different initial atmospheric profiles of humidity and temperature (from Rabin 1977).
vegetation to access subsurface moisture, and resistance to loss of water to the air through evapotranspiration. These limitations are being addressed by such projects as the First ISLSCP Field Experiment (FIFE) (Sellers et al. 1988). Hence, before invoking a quantitative model, we first tested the hypothesis presented in section 1 by comparing locations of cloud development against areas of relatively extreme Bowen ratio inferred from satellite data.

One of the parameters used to infer the relative Bowen ratio is vegetation cover. In recent studies, the Advanced Very High-Resolution Radiometer (AVHRR) mounted on polar-orbiting NOAA meteorological satellites was used to estimate regional and global vegetation cover. Given cloud-free conditions viewed in daylight, the density of green vegetation is proportional to the normalized differential vegetation index (NDVI) computed by

$$NDVI = \frac{NIR - R}{NIR + R} \quad (1)$$

where NIR is the near-infrared band radiance (0.73–1.1 \(\mu\)m) and \(R\) is the radiance from 0.58 to 0.68 \(\mu\)m. (See Brest and Goward 1987, for details on the spectral dependence of reflectance from vegetation and nonvegetated surfaces). Comparison of the NDVI with results from photosynthesis and transpiration models indicates a direct relationship between NDVI and exchange of water vapor by vegetation canopies, except in water-limited sites dominated by coniferous trees where NDVI is insensitive to water stress and evapotranspiration (Running and Nemani 1988).

Hence, there is some indication that this index may be useful for inferring evapotranspiration. Wetzel and Woodward (1987) used NDVI to help infer surface wetness; Chang and Wetzel (1988) used it as a factor in deducing surface evapotranspiration.

AVHRR data from the NOAA-7 satellite were used to determine NDVI over the area of study on a clear day in early May 1985. An example of the output over Oklahoma is given in figure 2. The brightness values in this figure are proportional to the value of NDVI, and hence to the relative amount of vegetation cover. In general, eastern Oklahoma is dominated by dense vegetation, such as forest areas, which appear white in the figure. Vegetation cover is much more sparse in extreme western Oklahoma, as noted by the darker shading. Lakes and other water bodies are identified as black spots in the figure. There is a relatively bright area (roughly bounded by the four arrows) in western Oklahoma, which is interspersed with small, darker features. Based on an in situ survey and known growing patterns in this area, this bright area is a region of mature winter wheat that is still very green in early May. River valleys are also discernible; they appear to have less vegetation than the surrounding wheat. The very bright zone denoted by "C" is densely covered with hardwood trees. The dark areas marked "A" and "D" are the urban regions of Oklahoma City and Tulsa. Examples of agricultural areas with relatively sparse vegetation are the dark regions east of "B" and that surrounding "E." The former is dominated by irrigated peanut crops, which have sparse canopies at this time of the year. The ground is relatively bare at "E," where cotton is grown later in the spring.

Single-channel visible imagery is routinely available on an hourly basis from geostationary satellites. Hence it is instructive to compare the picture of vegetation cover deduced from NDVI with the albedo (or brightness) pattern from the more familiar single, visible channel. Matthews and Rossow (1987) concluded that the primary factor controlling surface reflectance near 0.6 \(\mu\)m is the density of vegetation cover, although the exact type of vegetation could not be distinguished from reflectance in the visible band alone. Vegetation appears to be generally darker than most soils, since dense coverage of living plants reflects less visible light than bare soil or sparse vegetation. Also plants that have lost their green color when dormant or experiencing water stress should have a larger albedo than otherwise. Brightness data received in the visible channel (0.55–0.75 \(\mu\)m) from a NOAA geostationary satellite (GOES) are shown in figure 3 for the same day as the NDVI image given in figure 2. The data are the same as those used routinely for cloud imagery, except that here the brightness intensity scale has been stretched by approximately a factor of 5 to distinguish relatively small variations in albedo. Displaying the data in this way emphasizes land-surface features that are not seen in the standard visible images used for cloud depiction. Note that the same general pattern can be seen in figures 2 and 3, except that small variations of the NDVI, such as that associated with the belt of winter wheat, are not apparent in the visible data.

**Fig. 2. Normalized Differential Vegetation Index (NDVI) image derived from satellite AVHRR data over Oklahoma on the morning of 3 May 1985. Brightness is proportional to the relative value of NDVI. (Brightest areas are highest NDVI). State and county boundaries are outlined in bold and thin lines, respectively. Areas denoted by letters and arrows are referred to in the text.**
The available moisture for evapotranspiration, a second factor that influences the Bowen ratio, depends both on the type of vegetation cover and soil moisture (Wetzel and Woodward 1987). For example, plants with deep roots have access to more moisture than those limited to a shallow zone. The time history of precipitation is also an important factor. Without employing a detailed hydrological model, precipitation measurements can be used in a qualitative way with vegetation indices to determine the relative magnitude of the Bowen ratio between different areas. For example, relatively large evaporation rates (small Bowen ratio) will occur following rainfall, independent of vegetation type. After a prolonged period of dryness, when soil moisture is depleted in the upper layers, the evapotranspiration rate varies with plant-root depth and other physiological factors.

Several recent studies have shown that the Bowen ratio, the partitioning of surface energy between sensible and latent heat flux, is the principal factor affecting the amplitude of the diurnal temperature variation of surface temperature (e.g., Carlson et al. 1981; Price 1982). Surface temperature at the peak of the diurnal cycle, measured from satellite, can then be used as a simple indicator to confirm the general sense of the Bowen ratio from other landscape attributes. Moreover, the actual temperature may have some bearing on the initiation of clouds. Figure 4 illustrates the spatial variation in equivalent blackbody temperature determined from the GOES infrared window channel (10.5–12.6 μm) close in time to that of figure 3. It is important to note that differences in surface emissivity and absorption of surface radiation by atmospheric constituents could account for some of the variation in this figure. However, several features apparent in the NDVI and visible brightness maps can be identified by local differences in surface temperature. Most notable are the temperature maxima associated with areas “B,” “E,” “A,” and “D” where NDVI is relatively small, and the temperature minima over lakes and surrounding forested areas, such as the one at “C.” The band of winter wheat indicated in figure 2 is mostly cooler than the surrounding areas. The surface temperature anomalies associated with these features are about 5°C.

Spatial patterns of landscape attributes, such as those described here, were compared directly with the locations of initial cloud development as detected with satellite visible imagery. The comparisons were facilitated by using a system designed to store, manip-

Fig. 3. Visible brightness (0.55–0.75 μm) from GOES satellite at 1000 LST 3 May 1985. Background is the same as in figure 2. Generally, brightness is inversely related to vegetation cover. Brightness scale is expanded by a factor of 5 to distinguish surface variations.

Fig. 4. (a) Infrared radiance (10.5–12.6 μm) from GOES satellite at 1000 LST 3 May 1985. Same background as in figure 3. Brightness is inversely proportional to effective blackbody temperature of earth’s surface. Shading intervals are about 2°C. Horizontal arrows indicate locations of clouds where estimation of surface temperature is precluded. (b) Infrared radiance as in (a) but at 1100 LST.
ulate, and display diverse data types within a common geographical reference frame. Specifically, the Man-computer Interactive Data Access System (McIDAS) of the University of Wisconsin–Madison was used (Suomi et al. 1983).

3. Observations

The conditions on 24 June 1988 are ideal for study because they meet several criteria explained in section 1. The time of year was nearly at the summer solstice. Hence, insolation available at the surface for conversion into sensible and latent heat flux to the atmosphere, was near the annual maximum. Strong atmospheric forcing was absent from the region of interest, maximizing the possibility of identifying the effects of spatial variations in landscape on cloud formation. The possibility of strong atmospheric forcing was precluded on the basis of observations of weak wind\(^2\) and pressure-gradient fields (surface and aloft) over Oklahoma and surrounding areas. The sky was free of clouds at sunrise, allowing positive identification of the first cumulus clouds and eliminating possible effects of existing cloud patterns. The air aloft was slightly colder than on previous days, leading to sufficient instability for the development of nonprecipitating cumulus clouds by midday. The lower atmosphere was relatively dry, as evidenced by surface dew points of near 15°C and temperatures near 35°C. No precipitation had been reported from the climatological observation network (approximately 50-km station separation) during the previous 10 days. Initial differences in soil moisture (from spatial differences in rainfall) would diminish after an extended dry period of this length, owing to the depletion of moisture from upper soil layers (e.g., Rabin 1977). Thus, the spatial distribution of antecedent precipitation should not have a major effect on the patterns of evapotranspiration and Bowen ratio on this day.

A map of NDVI for 21 June 1988 is shown in figure 5. The southern half of the image lacks detail, since high-resolution AVHRR data were not archived over this region. Some clouds are present along both the northern and southern edges of the image; they are highlighted in white against a dark background to be distinguished from darker shades of white which represent maximum vegetation cover in the area. As in figure 2, the darkest areas represent the least vegetated landscape. In contrast to the vegetation pattern typical of early May (figure 2), a distinct minimum of vegetation cover now characterizes the wheat belt from north-central through southwest Oklahoma.

The area of minimum vegetation, about 100 km \(\times\) 300 km, is also clearly apparent from surface brightness in the GOES visible channel at 1030 LST 24 June 1988. (The area of highest surface brightness corresponds to the region with yellow tint in the figure on the cover, which was produced by color enhancement of the brightness categories in the GOES images.) Except for the extreme southwest portion, most of the area of minimum vegetation in late June is characterized by relatively high albedo, whereas it was observed to have much lower albedo (figure 3) in early May. The band of high albedo is believed to be the result of wheat stubble (dead plant material) remaining after the harvest of winter wheat, which occurs annually in late May and early June in Oklahoma. (The stubble is light in color; thus it reflects more visible light than active, green vegetation does.) In early May, the wheat is usually in a green, mature stage, and has a lower albedo. On 24 June, the relatively dark area (displayed as green in the figure on the cover) that parallels the yellow band to the northwest is believed to be covered with active plant canopies.

Numerous smaller-scale patterns appear in both the early May and late June imagery. An example is the relatively dark areas surrounding certain lakes. (Lake surfaces are indicated in blue in the cover figure.) One of the most prominent patterns is an area of hardwood forest just east of the Oklahoma City/Norman urban area ("C" in figures 2, 3, and 4), which is marked by the relatively high vegetation index in both figures 2 and 5.

The evolution of cloud development on 24 June...
1988 can be gleaned from the 4-h sequence of visible imagery in the figure on the cover. Clouds were considered to be detected when pixels had a brightness value that exceeded about 99% of all known cloud-free data (from the 1000 LST image). Such pixels were displayed in white to be distinguished from the colored surface areas. (Nevertheless, some unusual surface features, such as an area of salt flats denoted by "F" in figure 3, are always flagged as cloud areas because of their abnormal brightness.) By 1100 LST, the first cumulus clouds begin to form in western Oklahoma, almost exclusively over the yellow band. The areal coverage of cumulus continues to increase in the successive images, and the yellow band is nearly covered with clouds by 1200 LST. Several breaks within the yellow band, where the albedo is lower (enhanced as green), tend to have less cloud cover. Cumulus cloud development also appears to be suppressed over the forested area east of the urban Oklahoma City/Norman area.

Several cloud-free bands downwind of lakes in southern and eastern Oklahoma are visible in the cover figure (surface wind flow was from the southeast), but are most notable when the images are animated or looped. The tendency for relatively small water bodies to remain free of clouds during periods of solar heating and light winds has been reported in other studies. Radar observations from the Thunderstorm Project in Florida showed that radar echoes tended to form over land rather than over small lakes and swamps (Byers and Braham 1949, p. 116). Also, aircraft photographs revealed obvious holes in cumulus cloud fields over lakes during a 1-month observational period in Florida in 1957 (Plank 1965, p. 43).

Every lake of about 1–10-km diameter exerted an appreciable effect on the cloud population early in the day. The minimum lake size which appeared to effect the cloud field is roughly proportional to wind speed. Later in the day, lakes of at least 8–25-km diameter had an effect. The clear bands observed in Oklahoma are from lakes of similar diameters as those cited in Florida. However, the bands observed here extend downwind over areas that are considerably larger than the size of the lakes; the maximum ratio of a clear band to lake size is roughly 10 to 1.

The infrared radiation pattern corresponding to the cloud-free visible image at 1000 LST is given in figure 6. Each shade represents about a 2°C interval in equivalent blackbody temperature. Aside from a few of the same temperature anomalies found in the early
May case (for example, area “C”), a substantial area of locally warmer temperature is located coincident with the yellow band in visible imagery, presumed to be wheat stubble. Despite the fact that less insolation is absorbed there (perhaps 10%–20% less, according to the greater albedos apparent in the satellite imagery), the wheat stubble is warmer than its surroundings because of the lack of plant life to provide evapotranspiration of subsurface moisture. Without substantial evaporation, virtually all the absorbed insolation goes into heating the surface and the overlying air through sensible heat flux. The influence of this effect is also observed in the pattern of daily maximum temperatures observed in the preceding few clear days (figure 7). Highest temperatures were recorded over, or slightly downwind from, the band of maximum albedo. This was not the case in May, before the wheat harvest, when the average daily maximum temperature was quite uniform over western Oklahoma (Duchon et al. 1988).

In contrast to harvested terrain, heavily vegetated areas, such as the forested region at “C” in figure 6, can be characterized by evaporation rates that approach the potential evapotranspiration for a given day. Typically, the potential evapotranspiration accounts for about 70% of the net radiation absorbed at the surface, leaving only about one-third for sensible heat flux (e.g., Sellers 1965; p. 109). Thus, the surface temperature appears considerably lower over such areas. Because of the large heat capacity of water, surface temperatures of lakes and reservoirs are colder than the surrounding land temperature near midday. The sensible heat flux is expected to be smaller over these water surfaces than over vegetation, and perhaps even negative as heated air moves over the colder water surfaces.

4. Comparison with model simulations

Model simulations were performed to further demonstrate the physical basis for the observed effects of landscape on the amount and time of cumulus development. For further details regarding the model and its evapotranspiration parameterization, see Wetzel and Chang (1988). The model utilizes a simple parcel method to predict cloud cover. Heated and moistened surface air is lifted to its equilibrium level while being diluted by a defined amount of mixed-layer air (Wetzel, 1989). Comparisons with observations from the Wangara experiment indicate that an rms error of instantaneous cloud amount of ±10% is possible with this model.

Results from a simulation initialized with the Oklahoma City (OKC) 0600 LST 24 June 1988 sounding are shown in figure 8 for a range of vegetation types and soil conditions. About 30 min must be added to the solar times indicated in figure 8 to correspond with LST used in the satellite images. Clouds form about 2 h earlier over the modeled wheat stubble (simulated albedo: 25%), compared with landscape covered by deciduous trees (simulated albedo: 10%).

The actual time of first cloud development detected by satellite over wheat stubble (1030–1100 LST) is only slightly later (<1 h) than that forecasted. The discrepancy might be explained by observed differences in boundary-layer moisture between the OKC rawinsonde site, used for the model simulation, and the wheat stubble areas farther north and west. At 0600 LST, the surface mixing ratio at Enid, Oklahoma, about 100 km north-northwest of OKC, was 1.8 g kg$^{-1}$ lower than that observed at OKC. Supplemental model runs (not shown) indicate that this difference in moisture accounts for about a 1-h delay in the onset of clouds over wheat stubble.

The cloud development at 1130 LST (cover figure) is remarkably similar to the modeled differences between stubble (80% cloud cover) and trees (clear). In forested areas or in the vicinity of lakes, where the soil may be wet, the model predicts further delay in the time of cumulus onset. Over water surfaces, no clouds form in the model all day. The model fails, however, to account for the clear zones downwind of lakes and forests, since processes like advection and the sinking of air associated with local horizontal circulations are not included.

5. Conclusions

The effects of variations in landscape, observed as perturbations in surface temperature, are seen in the evolution of convective clouds on 24 June 1988. Clouds form earliest over regions characterized by high, sensible heat flux, and are suppressed over regions characterized by high, latent heat flux. This observation supports the hypothesis that clouds form first over areas with highest Bowen ratios during relatively dry atmospheric conditions (figure 1). This result has significance in gaining understanding of the feedback mechanisms of land modification on climate, and in improving relatively short-range weather forecasts.

The increase in albedo of a land surface due to water stress and decreased vegetation cover has been identified as a positive feedback mechanism toward further drying (Charney 1975). The decrease in absorbed incoming solar radiation dominates the radiation budget and leads to a relative heat sink over the area of abnormally high albedo. If the differential
heating pattern associated with the heat sink is of a sufficiently large scale, subsiding air will dominate the area, suppressing precipitation. The observations presented here may, at first glance, appear contradictory to this process. Cloud development is observed to be enhanced rather than suppressed over the vegetation-sparse areas with elevated albedo. However, consideration of the following points is necessary. First, the scale size of the albedo anomaly associated with the harvested wheat is considerably less than that of a major desert region. It is possibly too small to dominate the long-term vertical velocity pattern. Second, the actual albedo of the area characterized by wheat stubble may not be large enough to significantly reduce the net downward radiation flux at the top of the atmosphere (as compared with the albedo of bare, light-colored soil or sand). Third, the clouds observed over the wheat stubble did not bear precipitation and thus would not have ameliorated the dry spell. More importantly, formation of these relatively shallow cumulus clouds tends to substantially increase the effective albedo of the earth, further reducing the net radiation absorbed by the earth-atmosphere system. Thus, the enhanced cloud cover is actually another feedback resulting from decreasing vegetation, which could accelerate the development of a heat sink. Satellite measurements, such as those available from the Earth Radiation Budget Experiment (ERBE) (Ramanathan et al. 1989) could be useful to investigate the importance of this feedback in a large temporal and spatial perspective.

Although the images presented for May and June are from different years, they (and data from other years not presented here) suggest that significant differences in vegetation patterns occur on a time scale of about 1 month, because of agricultural practices such as the wheat harvest. These differences can have a profound effect on the spatial variation of the Bowen ratio, surface-air temperature, and even convective cloud development under certain atmospheric conditions. Undoubtedly, other temporal changes in the landscape occur throughout the growing season that are not unique to the area of this study. One would expect that the locations and patterns of initial cumulus cloud development should vary as landscape conditions change with time. Nevertheless, observations of visible satellite data suggest that cloud-free bands occur downwind of lakes very frequently during the warm season. Noting mankind’s mark on the landscape (nearly every lake in Oklahoma is man-made), the observations presented here can be interpreted as evidence of human effect on weather and climate.

The model results shown in section 4, demonstrate the importance of incorporating landscape information in forecast models if they are to be capable of predicting certain details in temperature and cloud patterns. For the case presented, knowledge of the horizontal variations of the initial atmospheric conditions was not critical, compared with the specification of earth-surface variabilty, in determining the time and location of cloud formation. However, the importance of resulting vegetation patterns to the observable atmospheric structure for a range of conditions is not yet known and warrants further research. Improved methods to measure evapotranspiration and

![Cloud cover forecasted on 24 June 1988 as a function of vegetation type for dry soil.](image)
sensible heat flux through remote means are required before detailed landscape information can be fully incorporated into operational forecasting.

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References


