

**Annual Report**

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**A Study of the Role of Clouds in the Relationship Between  
Land Use/Land Cover and the Climate and Air Quality  
of the Atlanta Area**

Stanley Q. Kidder, Principal Investigator  
and  
Jan Hafner, Co-Investigator

*Cooperative Institute for Research in the Atmosphere (CIRA)  
Colorado State University  
Fort Collins, CO 80523-1375*

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## **Abstract**

The goal of Project ATLANTA is to derive a better scientific understanding of how land cover changes associated with urbanization affect local and regional climate and air quality. Clouds play a significant role in this relationship. Using GOES images, we found that in a 63-day period (5 July–5 September 1996) there were zero days which were clear for the entire daylight period. Days which are cloud-free in the morning become partly cloudy with small cumulus clouds in the afternoon in response to solar heating. This result casts doubt on the applicability of California-style air quality models which run in perpetual clear skies. Days which are clear in the morning have higher ozone than those which are cloudy in the morning. Using the RAMS model, we found that urbanization increases the skin surface temperature by about 1.0–1.5°C on average under cloudy conditions, with an extreme of +3.5°C. Clouds cool the surface due to their shading effect by 1.5–2.0°C on average, with an extreme of 5.0°C. RAMS simulates well the building stage of the cumulus cloud field, but does poorly in the decaying phase. Next year's work: doing a detailed cloud climatology and developing improved RAMS cloud simulations.

## **1. Introduction**

The key goal of Project ATLANTA is “to derive a better scientific understanding of how land cover changes associated with urbanization, principally in transforming forest lands to urban land covers through time, has, and will, effect local and regional climate, surface energy flux, and air quality characteristics.” Clouds are significant intermediaries in this land cover–climate connection. Changes in land cover will change the cloud cover—particularly of the small clouds—which will change the solar insolation, the outgoing infrared radiation, and thus the climate and the air quality. CIRA is performing three tasks aimed at improving our understanding of the role of clouds in the land cover–climate connection:

1. Use GOES 8 data to construct a cloud climatology over Atlanta for the summer of 1996. This will serve as a basis for the mesoscale modeling study of clouds described in Task 3.
2. Use GOES 8 data to understand the diurnal variability of albedo, soil moisture availability, thermal inertia, and surface roughness needed to initialize the mesoscale models.
3. Run the RAMS model to simulate the cloud field which is prevalent around Atlanta in the summer. Compare the clouds produced in the model with the clouds deduced from GOES 8 data. Determine what effects changes in land use/land cover would have on the modeled cloud field.

## **2. First-Year Accomplishments and Results**

The work on this project can be divided into two parts: satellite observations of clouds and mesoscale modeling of clouds. The accomplishments and results of these two parts are presented in the next two sections.

### **2.1 Satellite Observations of Clouds**

Clouds are one of the key factors in the climate system because of their radiative properties. They reflect incoming shortwave radiation, decreasing the surface temperature; on the other hand, clouds contribute to downward infrared radiation reducing the cooling rate at the surface. Yet there is surprisingly little good data on clouds or their effects. One of the key goals of this project is to collect reliable cloud observations for the Atlanta area.

#### **Satellite Data Collection**

The first step in this process is to collect high resolution GOES 8 data. The two-month period 5 July 1996 through 5 September 1996 was chosen for study in part because the Atlanta Olympics offered the opportunity to acquire many special weather observations. More than 25,000 GOES 8 images were acquired from the CSU Earthstation and archived on Exabyte tape. The 1 km visible data were transferred to two CD-ROMs for further processing. A third CD-ROM containing the 11  $\mu\text{m}$  (channel 4) data was also made.

In addition, GOES 8 data were collected in May 1997 and in August 1997 at the same time as aircraft observations of Atlanta. Also, GOES data were collected in July and August 1997 to support air quality modeling being done by Haider Taha.

## **Cloud Climatology**

A major goal of the CIRA part of Project ATLANTA is the production of a climatology of clouds in the Atlanta area, particularly during the summer. Significant progress toward this goal was made in the first year of the project.

### *Video Tape*

Using the 1996 GOES data, a video tape of the daytime clouds for the entire 63-day period was made. It shows that there were no days in this period which were entirely cloud free. The clearest days had extensive small cumulus coverage which peaked in the early afternoon near the time of peak solar heating. Figure 1 shows a typical day with this type of cumulus cover.

### *Cloud Classification*

The video tape showed that Atlanta experiences many types of clouds in the summer: thunderstorms, frontal clouds, fog, and small cumulus. A second step toward the cloud climatology was in using the visible imagery to classify each day of the 63-day period into various cloud categories. The most important classification is whether it was clear in the morning or cloudy in the morning. In the afternoon, days which are clear in the morning look like Figure 1, that is, they are dominated by small cumulus clouds, which shade the surface, thus cooling it and possibly reducing the production of photochemical smog. Sixteen days of the 63-day period (about 25%) fell into this category.

### *Cloud Cover Algorithm*

A final step taken this year toward constructing a cloud climatology was in formulating an experimental cloud cover algorithm for two days, 21 and 23 August 1996. These days were both clear in the morning and cloudy in the afternoon. Both were chosen for numerical simulation (see Section 2.2). First, the GOES visible channel measurements were converted into isotropic albedo by dividing the reflectances (calibrated according to Weinreb et al., 1997) by the cosine of the solar zenith angle. Next, a histogram of the albedos in the study around Atlanta (see Section 2.2) was constructed each hour. Binning the data in 1% albedo bins, the spread of the clear spots was estimated as the distance from the peak of the distribution to the darkest pixel. It was assumed that the distribution for clear pixels would extend as far on the bright side of the distribution as on the dark side. Any pixels brighter than the assumed clear-sky maximum brightness were classified as cloudy. This scheme worked well for the morning and late afternoon images which appeared to be clear. It also gave reasonable cloud fractions during the cloudy part of the day. (Figure 2).

## **Comparison with Ozone**

To investigate what is important in the relationship between clouds and air quality, ozone concentration was selected as a variable to represent air quality. Hourly ozone concentrations, measured at the six air monitoring stations in the Atlanta area were acquired from the Georgia Department of Natural Resources for the 63-day period for which GOES data were collected. Ozone concentration was compared with cloud data in two ways.

### *Ozone and cloud type classification*

Figure 3 shows the maximum hourly ozone concentration from the six Atlanta monitoring stations for each of the 63 days. The days which were clear in the morning are white, shaded bars indicate days which were cloudy in the morning. Clear mornings tend to be higher ozone days.

### *Ozone, Cloud, Solar Insolation Phasing*

Ozone is produced by photochemical processes, but is destroyed by other processes. Figure 4 shows that the rise of ozone concentrations is in phase with solar insolation and also with cumulus cloud formation, but ozone persists after the insolation and the clouds decay.

### **Preliminary Conclusions**

Atlanta, in the summer, is a very cloudy place. In our 63-day period (5 July–5 September 1996) there were zero days which were clear for the entire daylight period. Days which are cloud-free in the morning become partly cloud in the afternoon in response to solar heating. This result casts doubt on the applicability of California-style air quality models which run in perpetual clear skies.

Cloud cover can be relatively easily retrieved from GOES data. Days which are clear in the morning have higher ozone than those which are cloudy in the morning, although this is not the only determinant of ozone concentration.

### **Future Work**

Several things will be done in next year's work. First, a more detailed cloud climatology will be constructed for each day of the 63-day period. Also properties of the clouds will be investigated. Finally, a more detailed look at the relationship between ozone and cloud cover will be undertaken.

## **2.2 Mesoscale Modeling of Clouds**

The effect of urbanization on local climate and weather has been known since 1833 when Howard (1833) published his observations of temperature contrast between London and nearby rural areas. Probably the best known urban effect is the urban heat island which is a temperature excess in a city as compared to its surroundings. Most of the studies on the urban heat island effect were conducted for clear-sky conditions, which are favorable for the urban heat island development. The effect of clouds on a small scale is probably better known qualitatively than quantitatively, and the magnitude of the cloud effect is not well understood. Clouds tend to reduce the diurnal temperature range and, thus, the urban heat island magnitude mainly at night (Kidder and Essenwanger, 1995). Land use alteration can induce changes in cloud development. Warmer and moister surfaces increase the upward moisture flux, resulting in more or larger clouds. The other significant factor in cloud formation is concentration of cloud condensation nuclei (CNN), which is usually higher over urban or industrialized areas (Landsberg, 1981). Thus, urbanization will affect the clouds, which will have an impact on other variables.

The understanding of the role of clouds over a small area like a city has implications in air quality modeling, since these models do not consider clouds. In some cases (like southern

California) this is not a deficiency. However, it is a major drawback in humid and cloudy areas such as the Southeast in summer. The magnitude of the cloud effect can provide an estimate of errors in the air quality model.

### **Numerical modeling**

RAMS (Regional Atmospheric Modeling System, Pielke et al., 1992) is a numerical model designed for atmospheric applications providing a large degree of flexibility, including hydrostatic or nonhydrostatic options, full microphysics, nested grid capability or 4-D data assimilation. The possible applications can range from hemispheric simulations to modeling of individual storm cells or even to flow over buildings (Nicholls et al., 1995). The major advantage of RAMS relevant to this study is that it explicitly resolves clouds.

The modeling domain was selected to be  $370 \times 320$  km ( $37 \times 32$  grid mesh), which coincides with the area of Atlanta's air quality model. To resolve individual fair weather cumuli the grid spacing should be about 1 km or even less. Thus, three nested grids were employed with decreasing grid spacing of 10 km, 3.3 km, and 1.1 km. The coarse grid is dimensioned  $37 \times 32$  grid points, the second grid has  $32 \times 32$  grid mesh. The finest grid, dimensioned  $38 \times 38$ , encompasses almost all of downtown Atlanta. All three grids have 26 grid points in the vertical and 8 levels in the soil model. Vertical resolution increases with height from 200 m to the top of the domain at 10,500 m. The soil levels are: 25, 21, 17, 13, 9, 6, 3 cm and the surface ( $z=0$ ). The model's top boundary condition was set as a rigid lid (or wall on top). The Klemp–Wilhelmson radiative condition (Klemp, Wilhelmson 1978a, b) was applied as the lateral boundary condition, in which the normal velocity components are advected from the inside of the domain. For the rest of variables the zero gradient condition was prescribed. The bottom boundary condition is supplied by the soil/vegetation model which prognoses the surface temperature and the surface moisture.

Land use/cover classification is based on BATS (Biosphere Atmosphere Transfer Scheme) (Dickinson et al., 1986), which recognizes 18 land use/cover classes. Since there is no urban class in the BATS scheme, a substitute had to be constructed. Desert and semidesert were selected as a base for the urban classification. However, some adjustments were necessary; the surface roughness was increased to 1.0 m, the albedo decreased to 0.15, and the emissivity changed to 0.9. USGS (US Geological Survey) land use/cover data set with horizontal resolution of 200 m was used to create an urban mask which would overwrite the default BATS land use/cover class. An example of "urban" and "nonurban" land use/cover parameters is in Figures 5a and 5b. Figures 5c and 5d show the land use categorization for urban simulation for grids 2 and 3, respectively.

The net effect of land use/cover is determined as a difference between two numerical simulations: urban and control ("nonurban"). The urban run includes the city in all relevant parameterizations: albedo, surface roughness, soil textural class, vegetation type and cover. The control simulation is achieved by replacing the city in the model by the natural land use/cover characteristics of the city's surroundings. In other words, the control run simulates an environment undisturbed by urbanization. In Figure 5 the urban areas marked by red are replaced by natural land use/cover, which, in the case of Atlanta, happened to be crop/mixed farming.

The effect of clouds on surface variables is estimated as a difference between the urban run with explicit microphysics and the corresponding “dry” run without clouds at all (microphysics “turned off”). The difference would correspond to the net surface effect of clouds.

## Results

Dates 21 and 23 August 1996 were selected for numerical simulations. The reason for this selection is the clear sky conditions in the morning on both days with small fair weather Cu development later in the day. In addition, 21 August exhibited relatively low concentrations of ozone whereas 23 August showed high values of ozone, which may be a good case for the air quality comparison. Soundings taken at Peachtree City at 1200 UTC (0700 LST) about 50 km southwest of Atlanta were used for model initialization.

### *The case of 21 August 1996*

On 21 August 1996 the synoptic situation can be described as a high pressure area stretching over the whole Southeast, which is favorable setting for small clouds development. The clear-sky condition is an advantage for the RAMS’ initialization since the cloud field does not need to be initialized at the beginning of the model run. After initialization, the model was run for 8 hours beginning at 0700 LST (1200 UTC) for each three simulations: urban, nonurban, and dry “no clouds” case.

The difference between the urban and nonurban runs is taken as the net urban effect on various parameters. Our focus is on the finest grid covering downtown Atlanta since it can resolve small clouds. The urban effect on skin surface temperature is shown in Figure 6, which correspond to the time of the maximum urban heat island intensity at 1300 LST.

The urban heat island does not show uniform structure; there are warmer and cooler spots. The warmest point is about  $+3.5^{\circ}\text{C}$  on the eastern side of the city. Some “cool” islands are in the middle of the city, exhibiting about  $-1.7^{\circ}\text{C}$  perturbations. This inhomogeneity is largely the effect of clouds, as they would develop differently in an urban and corresponding natural environment. The temporal evolution of the urban heat island at the point of maximum magnitude (red cross in Figure 6) is shown in Figure 7. The oscillating nature of the urban heat island is due to clouds as they pass over this particular point. This shading effect is clearly demonstrated in Figure 8, which shows the surface energy components for the urban simulation. The incoming radiation (shortwave and longwave combined) shows oscillation through the day as the result of cloud shading.

The net effect of clouds on the skin surface temperature is depicted in Figure 9, which shows predominately negative values; however, there are some areas with positive magnitude. The negative skin surface temperature is the result of the cloud shading. The maximum cloud cooling effect is about  $-5.0^{\circ}\text{C}$  located close to the eastern boundary. The areas with positive values are small and their magnitude is less than  $+0.5^{\circ}\text{C}$  ( $+0.44^{\circ}\text{C}$  max.). They probably occur in areas which are not cloud shaded and, thus, represent the urban heat island effect unmodified by clouds. The temporal evolution of the cooling effect on the skin surface temperature at the point of its maximum (red cross in Figure 9) is in Figure 10. Unlike the urban effect the cloud effect does not oscillate, but it gradually drops down to about  $-5.0^{\circ}\text{C}$  (1300 LST) and then it slowly increases.

However, due to the still unpredictable nature of convection and convective clouds, it is not possible to determine the exact location of warm or cool spots; rather, modeling results give overall information in a statistical sense. In other words, those are the maxima and minima that can be expected somewhere in the area. To estimate the overall effect of either urbanization or clouds, averages of the skin surface temperatures over the finest grid 3 were calculated, and the results are shown in Figure 11. The urban effect is positive, implying a heat island, then it slowly decreases its magnitude in time. The cloud effect starts at zero, and after the time of cloud onset it begins to drop gradually up to  $-2.5^{\circ}\text{C}$ . From this follows that the urban warming effect takes place at any time, but it is in less magnitude than the cloud effect. The cloud effect gets stronger with time as more clouds develop, reaching a magnitude of  $-2.5^{\circ}\text{C}$  later in the afternoon.

The effect of urbanization on clouds is presented in Figure 12, which is the comparison of fractional cloud cover for the urban and nonurban simulations. The threshold for “cloudiness” was set at a mixing ratio of  $0.3\text{ g/kg}$  of total condensate. It is seen that the onset of convective clouds is at the same time for both urban and natural land types. In the morning more clouds tend to develop over the urban area as compare to natural land. In the afternoon it is the opposite; natural land use/cover type of environment would experience more clouds than corresponding urban landscape. Possible explanations will be discussed in the next section.

The GOES 8 visible data were utilized to compare and verify the modeled cloud fields. Since grid to grid comparison of individual clouds would not yield any significant correlation due to somewhat random nature of convective activity, the average fractional cloud coverage for the finest grid 3 was calculated. The comparison of modeled and observed cloud coverage is in Figure 13. RAMS tends to start convective clouds earlier by about 20–30 minutes than the observed onset of convective Cu. In the morning hours, the difference between modeled and observed cloud coverage is within 10% and both patterns are very similar. However, in the afternoon RAMS continues to produce clouds as opposed to GOES 8-observed clouds, which decrease in time. The possible reasons for the overestimation of clouds in RAMS model will be discussed in the next section.

#### *The case of 23 August 1996*

The synoptic situation for 23 August was similar to that two days prior (21. August). The high pressure system that developed over Southeast was slowly weakening.

The urban effect on the skin surface temperature at the time of the maximum intensity (1300 LST) is in Figure 14. As in the previous case there are warmer and cool spots within the smallest grid 3. The coolest areas show the “cool” island of about  $-1.5^{\circ}\text{C}$  or less; the maximum of the heat island in the city is about  $3.0^{\circ}\text{C}$  (denoted by the red cross in Figure 14). There is another maximum at the northeast city’s boundary exhibiting  $+3.5^{\circ}\text{C}$  heat island (the maximum value underlined in Figure 14). The temporal evolution of the urban heat island at the point of its maximum is given in Figure 15. The magnitude of the urban heat island shows oscillations as in the first case, which is the effect of cloud shading. The amplitude of these oscillations is smaller compared to the first case, which may be due to fewer clouds in this case. The time when the first convective clouds appeared is about 1015 LST in this case, which is about the same time as in the first case. However, the overall cloud cover is less through the day on 23 August than that on 21. August (c.f. Figures 13 and 21). Figure 16 shows the surface energy components in time

at the point of the maximum urban heat island. It shows much less fluctuation of all components, including the incoming radiation, than in the first case (c.f. Figure 8).

The cloud effect on the skin surface temperature is given in Figure 17, corresponding to the time of the maximum intensity (1300 LST). The majority of the urban area exhibits negative values, which indicates the cooling effect of clouds. There are a few small spots with positive magnitudes. The maximum is about  $+0.77^{\circ}\text{C}$  on the west side of the city (maximum value underlined in Figure 17). The minimum, or the largest cooling, occurred on the east side of the city (denoted by the red cross in Figure 17) with a magnitude of  $-3.8^{\circ}\text{C}$ . The temporal evolution of the cloud cooling effect at the point of its maximum (grid 33,21) is presented in Figure 18. During the first two hours, there are no clouds; thus, no effect can take place. Later on as more clouds developed the cooling effect became stronger. The maximum cloud cooling peaked at 1300 LST and weakened afterwards. The averaged urban and cloud effects over the smallest grid 3 are given in Figure 19. As on 21 August, the urban effect shows positive values, implying a heat island. The effect of clouds is cooling. The magnitude of the urban effect shows little oscillation through the day. The cooling cloud effect increases with time as a response to more cloud shading.

The effect of urbanization on clouds is presented in Figure 20 which shows the comparison of urban and corresponding nonurban modeled clouds. The basic difference between this case and the first one is that fewer clouds developed over the urban area than over the corresponding natural land use/cover. In the first case the urban area tended to increase cloudiness in the morning and decrease it in the afternoon. In this case there is a constant increase of cloudiness over the natural environment.

The comparison of observed and modeled clouds in terms of fractional cloud coverage is given in Figure 21. As in the first case, RAMS overestimated the cloud coverage, especially early in the day and later in the afternoon. In the morning RAMS biased cloud cover by 25%. The closest match of RAMS and observed clouds is around noon when the difference is about 10% or less. The possible reasons for RAMS overestimation of clouds are discussed in the next section.

## **Discussion and Conclusions**

Mesoscale models, and RAMS in particular, can provide information on the effects of urbanization and clouds on various surface variables. The major benefit of modeling is that it provides more information than in situ or remote sensing observations and, in addition, the physics is resolved at each grid point. RAMS can simulate small convective clouds in promising agreement with GOES 8 observations.

The results show the effect of land use on surface temperature and cloud fields. Urbanization increases the skin surface temperature by about  $1.0\text{--}1.5^{\circ}\text{C}$  on average under cloudy conditions. The extreme values of the urban heat island can be up to  $+3.5^{\circ}\text{C}$ . Clouds cool the surface due to their shading effect. The average cooling is about  $1.5\text{--}2.0^{\circ}\text{C}$  and increases with time as more clouds develop. The extreme value can be up to  $-5.0^{\circ}\text{C}$ . Though larger in magnitude than the urban heat island effect, the cloud cooling effect that takes place only when there are clouds. In this case the time of the maximum intensity of the cloud effect corresponds to the peak of convective activity, which is usually in the early afternoon.

The effect of Atlanta on small Cu clouds is a slight increase (~10%) in the morning hours and a reduction in the afternoon (<10%) in the case of 21 August. The possible reasons for the morning increase of cloudiness over the urban area may be the urban heat island itself. A warmer surface will enhance vertical upward motion resulting in more clouds. The afternoon reduction may be the blocking effect of a rough city that would reduce the advection of already developed small Cu clouds into the city from the outside (Bornstein and LeRoy, 1990). However, RAMS does not model this blocking effect well. Thus, the afternoon reduction is more likely the result of decreased moisture in the city as compared to natural surroundings. The moister natural land would slow convection in the morning due to lower skin surface temperature, but it would provide more moisture for the afternoon clouds. In the second case (23 August) there is a significant reduction of cloudiness by the urban type of land use/cover (Figure 20). This enhancement by the natural cover can be over 10% (see Figure 20 at 1100 LST). The slight reduction of natural land type cloud cover in the afternoon does not seem to be significant. The vertical profiles of relative humidity, which are given in Figure 22, may help to explain less "urban" clouds in the second case. The sounding for 21 August is relatively more humid than that for the second case up to about 3500 m. The only exception is a layer between 900 and 1100 m. At present it is uncertain whether the initial profile of relative humidity is the main cause of the different behavior of the modeled clouds over urban and natural land cover as seen in Figures 12 and 20. It seems that if the initial moisture is sufficient, natural land cover would enhance cloudiness as opposed to the less moist initial vertical profile (the case 21 August).

The comparison of modeled and observed cloud cover reveals that RAMS tends to overestimate the cloud especially in the afternoons, which makes the afternoon results somewhat uncertain. The possible reasons for RAMS's cloud overestimation could be the numerically overpredicted advection of clouds from the coarser grid 2 into the grid 3. Since the coarser grid 2 has grid spacing of 3.3 km, it cannot effectively resolve small cumuli and tends to overestimate the cloud amount and water content (M. E. Nicholls 1997, personal comm.).

The other reason could be the surface parameterization. The RAMS is rather sensitive to the surface parameters especially vegetation and the leaf area index (LAI) (P. L. Vidale, 1997, personal comm.). The values of albedo, soil textural class parameters, soil moisture, vegetation fractional coverage and LAI as prescribed in the model may not be representative for a given grid point. Larger values of LAI increase the transpiration of water from the vegetation, which means more moisture is available to form more clouds than in a dry air. The same applies in the case of larger vegetation fractional coverage.

## **Future Work**

Next year's work will focus on improving RAMS performance as to cloud modeling. This will include investigation of the possible effect of erroneous cloud advection from the coarser grid 2 into the finest grid 3, and a check of the surface parameters. Right now it is not known what is the main source of errors in cloud modeling—surface parameters or the overestimated cloud advection from grid 2.

It may be useful to use remote sensing data to infer some surface parameters, e.g., albedo, LAI, vegetation fractional coverage. Landsat data are available for the Atlanta area and ATLAS (Advanced Thermal and Land Applications Sensor) data were collected for Atlanta in August 1997. Visible GOES 8 data were collected for the summer 1996 over most of Georgia and

adjacent region, and can be used to retrieve albedo or possibly other relevant surface parameters (soil moisture).

A switch to a new version of RAMS (just developed) may improve the cloud modeling results since a new surface/soil/vegetation scheme (Surface-Atmosphere Vegetation Transfer Scheme – SVATS) has been implemented. The major benefit is that it allows multiple patches of different vegetative cover and soil textural class within a single grid box. The current version of RAMS (RAMS 3b) recognizes only one type of vegetation/soil type in a grid box, which cannot account for subgrid variability.

In addition to GOES 8 imagery, data from mesonet stations will be used to verify the model results if available.

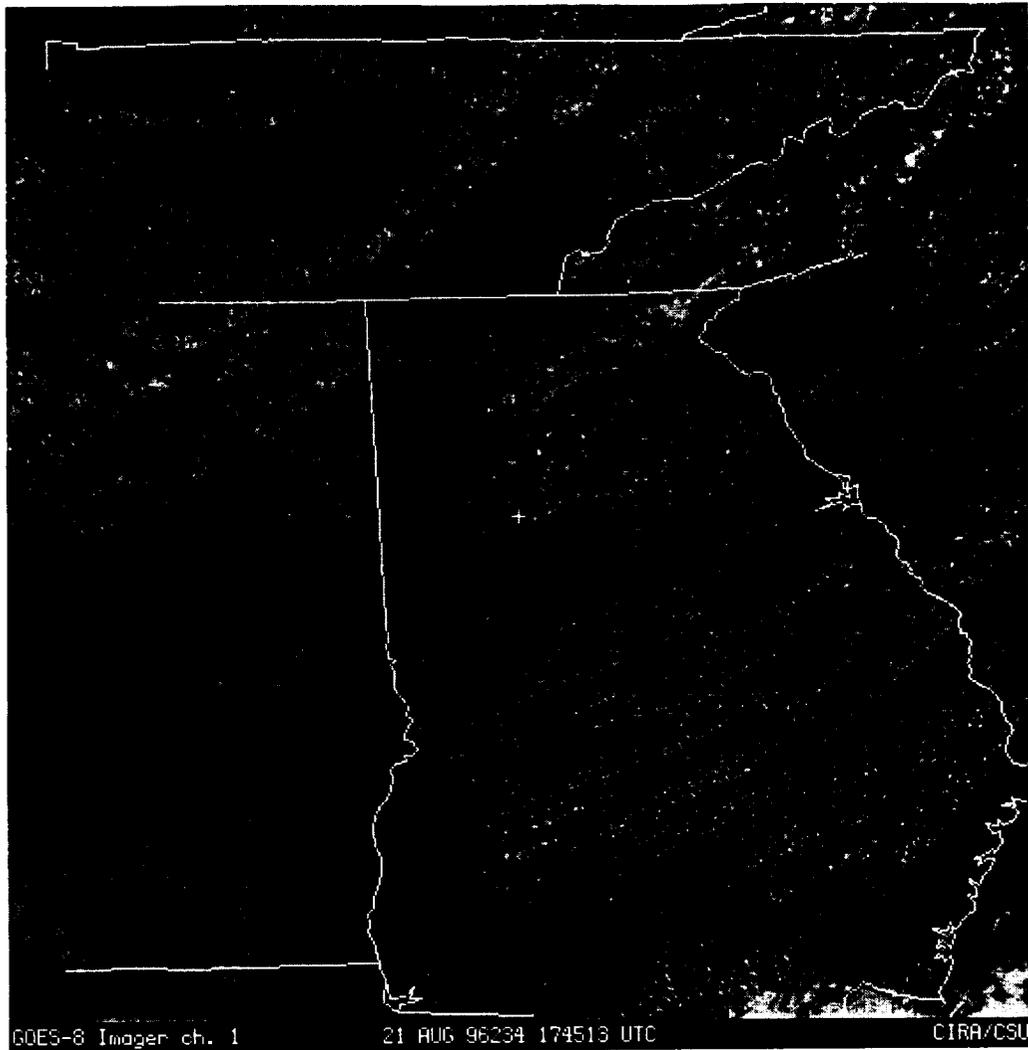
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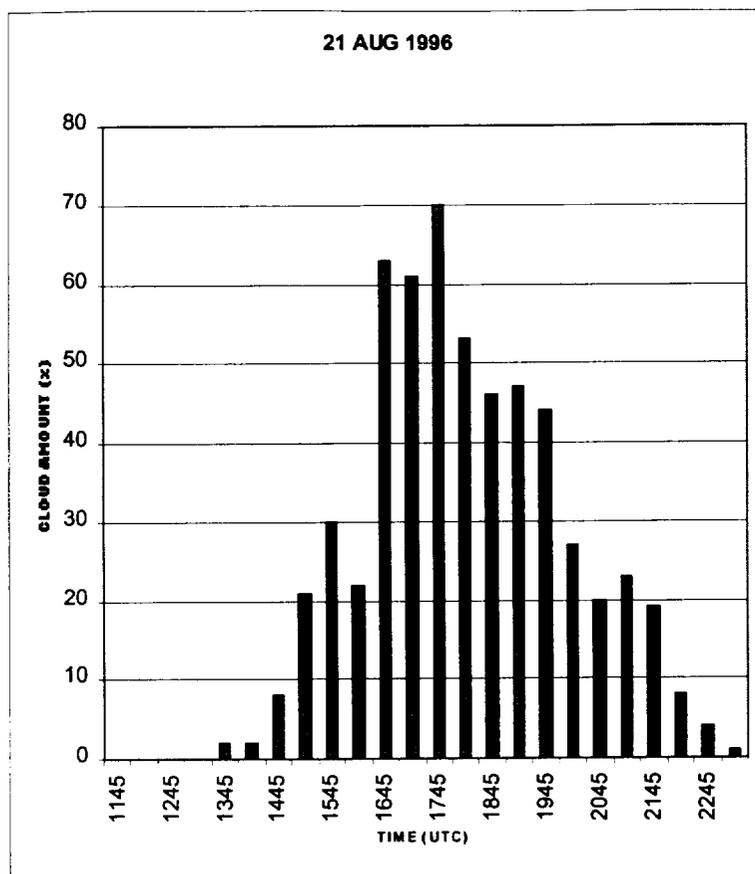
### **3. Publications**

One paper was submitted for publication this year: Hafner, J., and S. Q. Kidder, "Modeling and Urban Heat Island with the Aid of Satellite Data," *Journal of Applied Meteorology*. We expect the paper to be published during the second year of the grant, and a reprint will appear in next year's annual report.

## 4. Figures

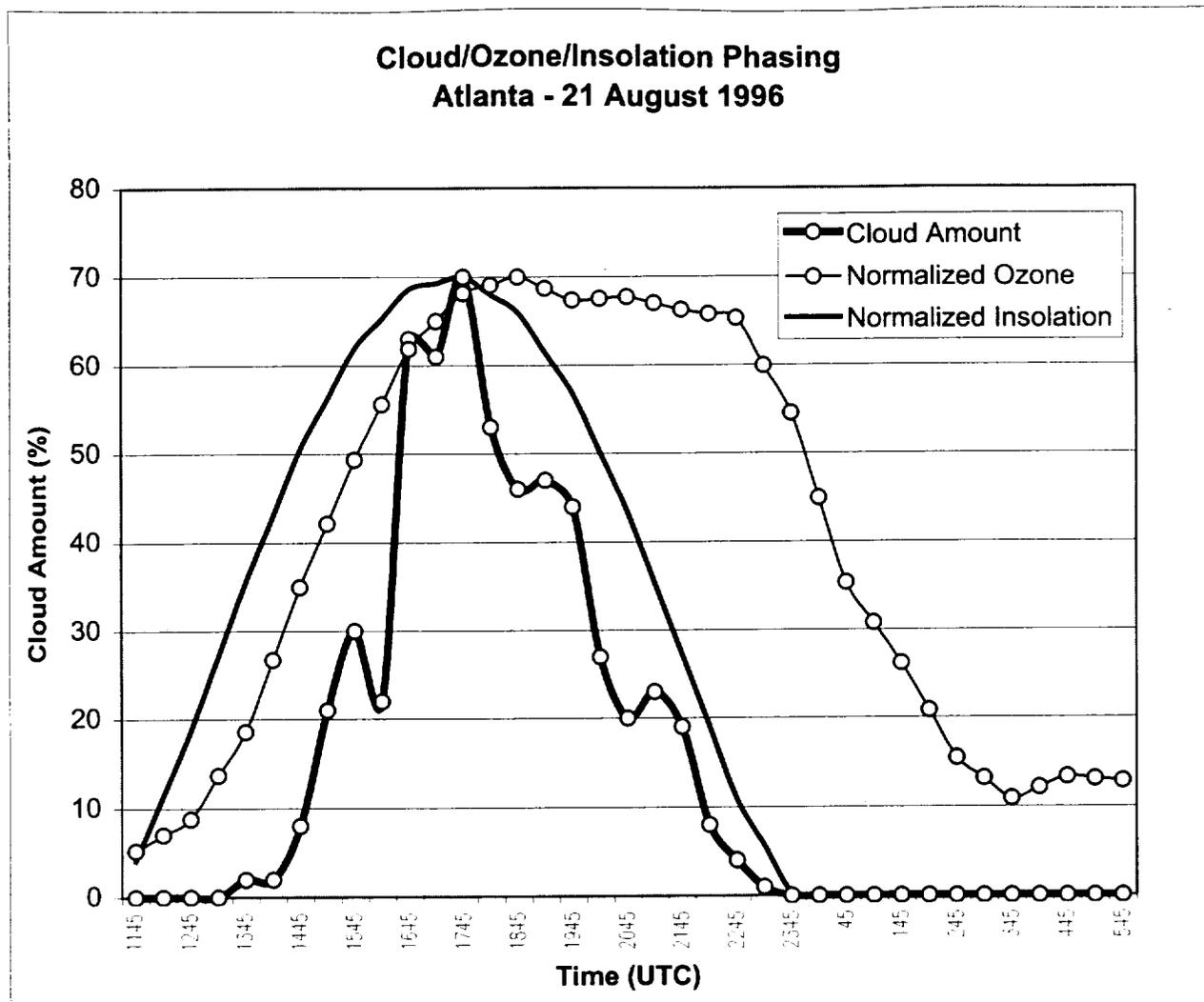


**Figure 1.** GOES 8 visible image of the Atlanta area. This is typical of otherwise clear days in the Southeast in the summer. Small clouds always break out in response to solar heating of a humid environment.

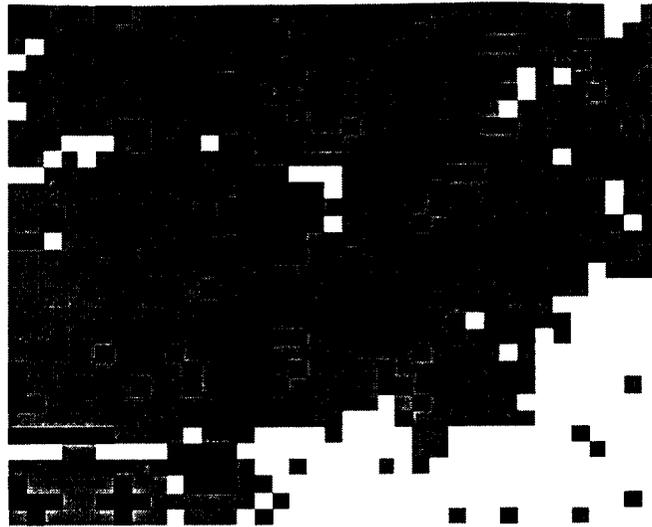


**Figure 2.** After correcting the GOES-measured radiance for the solar zenith angle, a histogram technique can be applied to determine the fraction of the area around Atlanta which are covered with clouds. The cloud cover rises and falls with solar insolation. This technique is preliminary, so that the calculated cloud amount cannot be considered final or exact, but at the peak of the afternoon cloudiness, over 50% of the area is cloud covered, which reflects sunlight back to space, cools the area, and possibly decreases the production of ozone and other photochemical species.



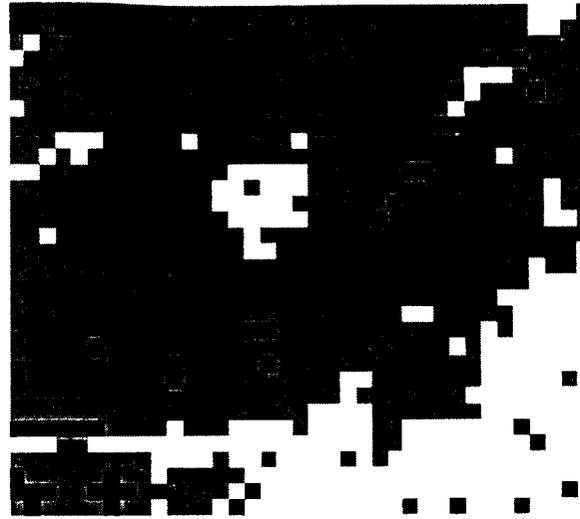


**Figure 4.** The relative phasing of clouds, ozone, and solar insolation for one day in Atlanta. Clouds and solar insolation are nearly in phase. The rise of ozone is in phase with solar insolation, but its destruction is not.



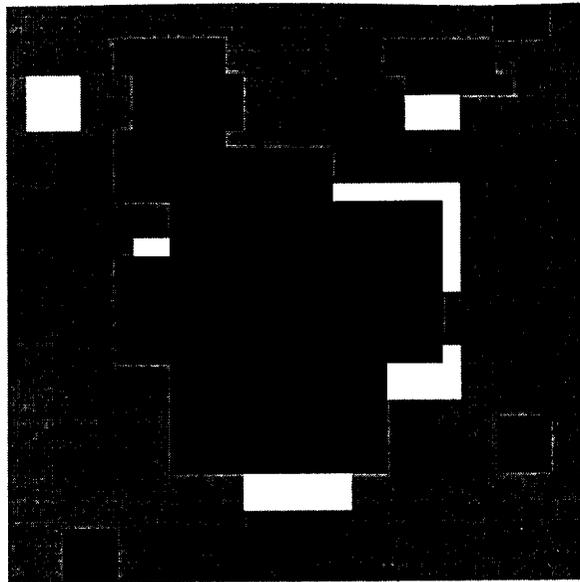
- urban
- mixed woodland
- deciduous broadleaf tree
- evergreen needleleaf tree
- crop/mixed farming

**Figure 5a.** Land use cover categorization for the grid 1 – urban simulation , 37 x 32 grids (370 x 320 km) with 10 km grid spacing.



- urban
- mixed woodland
- deciduous broadleaf tree
- evergreen needleleaf tree
- crop/mixed farming

**Figure 5b.** Land use/cover categorization for nonurban simulation grid 1. The urban land type is being replaced by natural land cover.



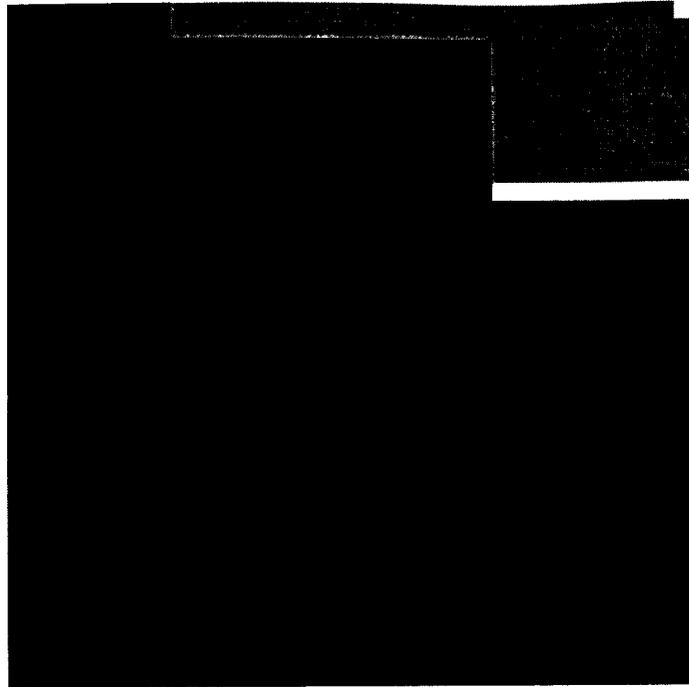
urban

crop/mixed farming



mixed woodland

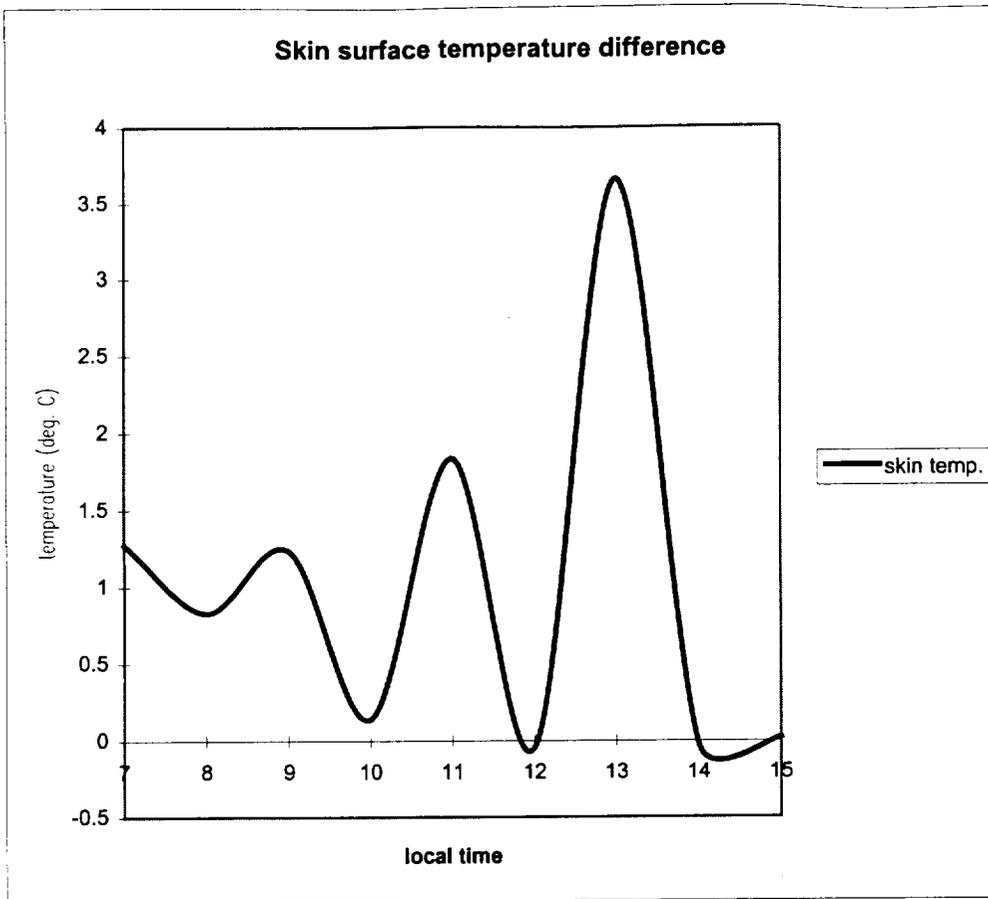
**Figure 5c.** Land use cover categorization for the grid 2. 32 x 32 grids (105 x 105 km) grid spacing 3.3 km (urban simulation).



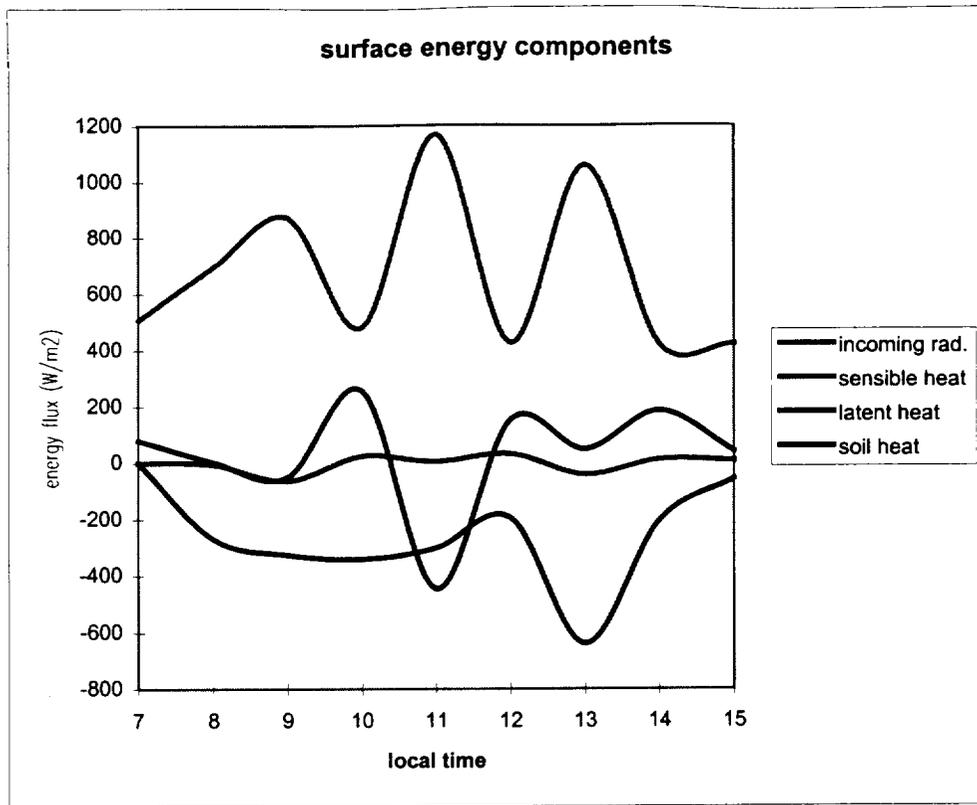
- urban
- crop/mixed farming
- mixed woodland

**Figure 5d.** Land use cover for the grid 3, 38 x 38 grids (42 x 42 km), grid spacing 1.1 km (urban simulation).



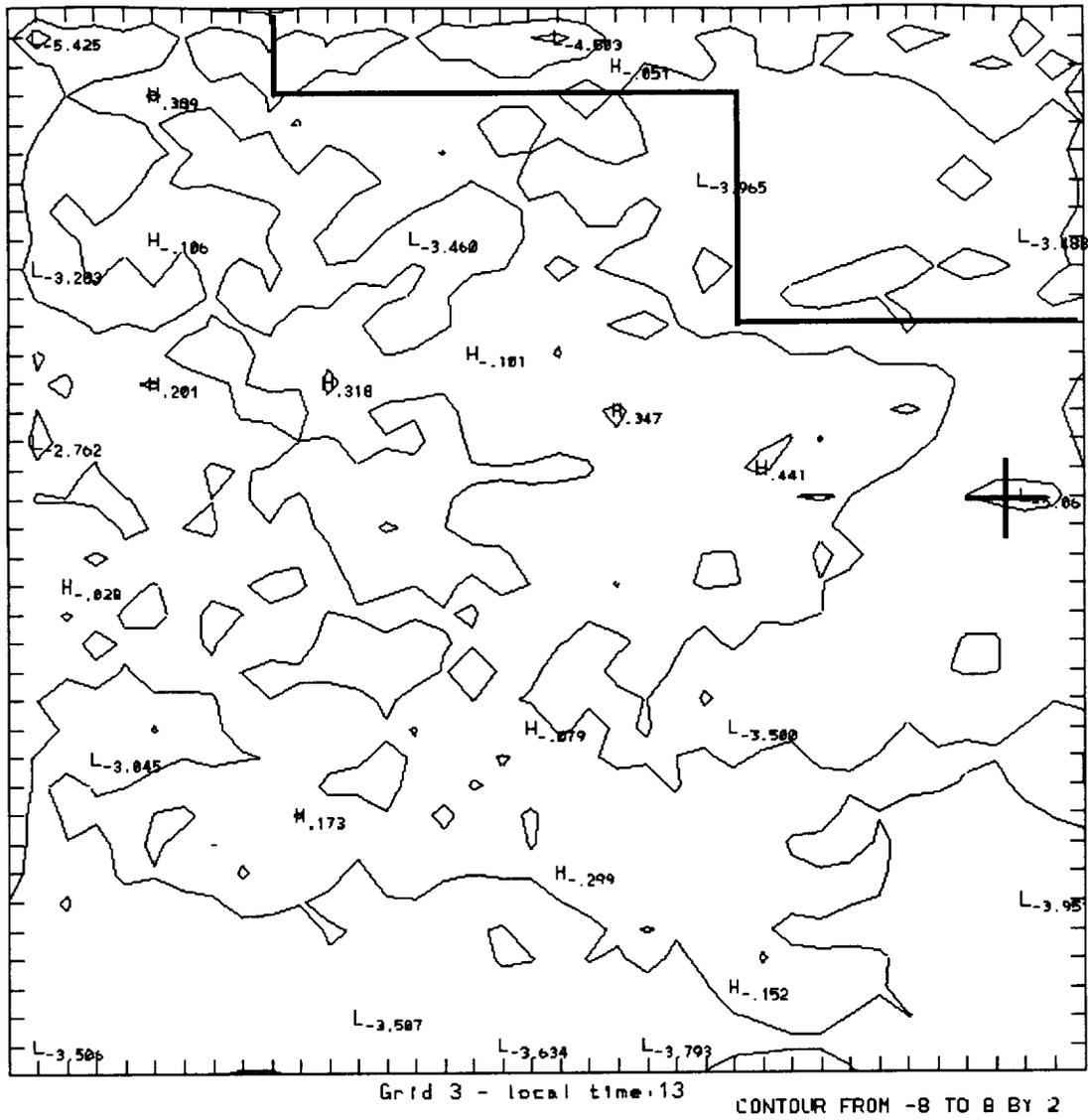


**Figure 7.** Temporal evolution of the urban heat island ( $^{\circ}\text{C}$  skin surface temperature) at the point of its maximum (red cross in Figure 2).

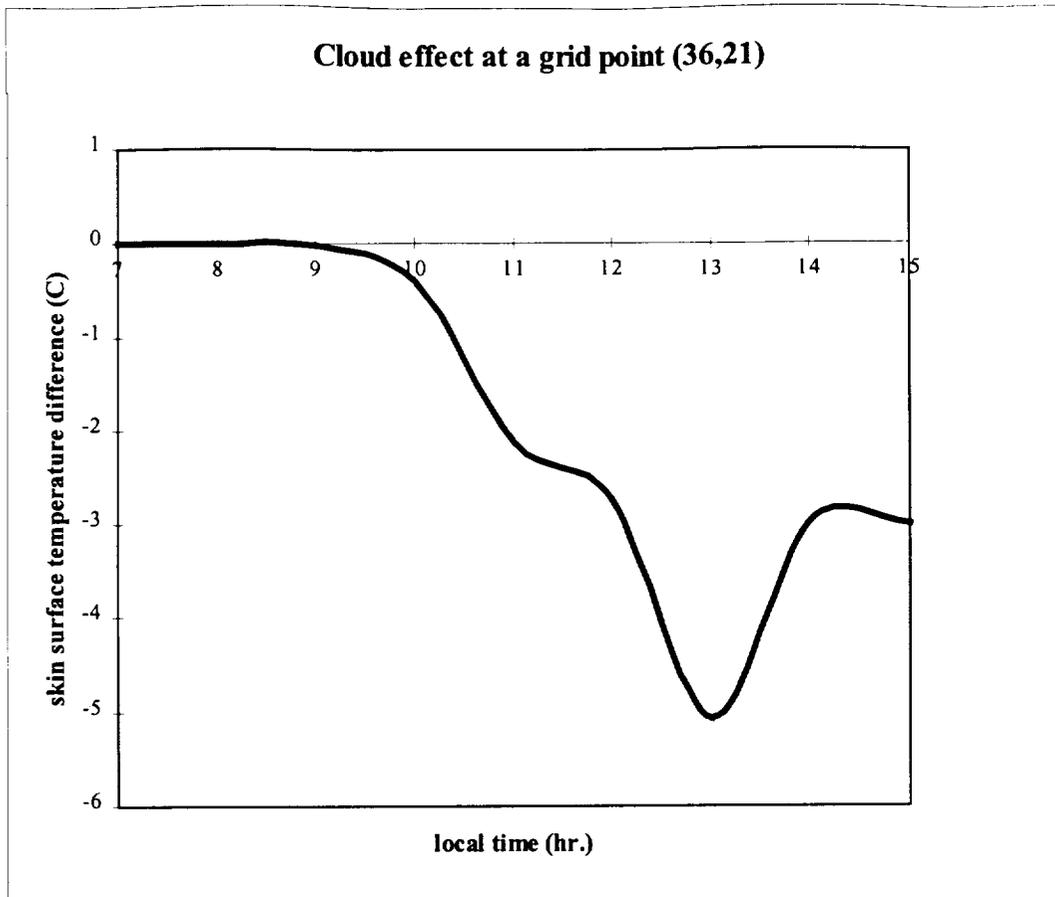


**Figure 8.** The surface energy components at the point of the maximum magnitude of the urban heat island (red cross in Figure 2).

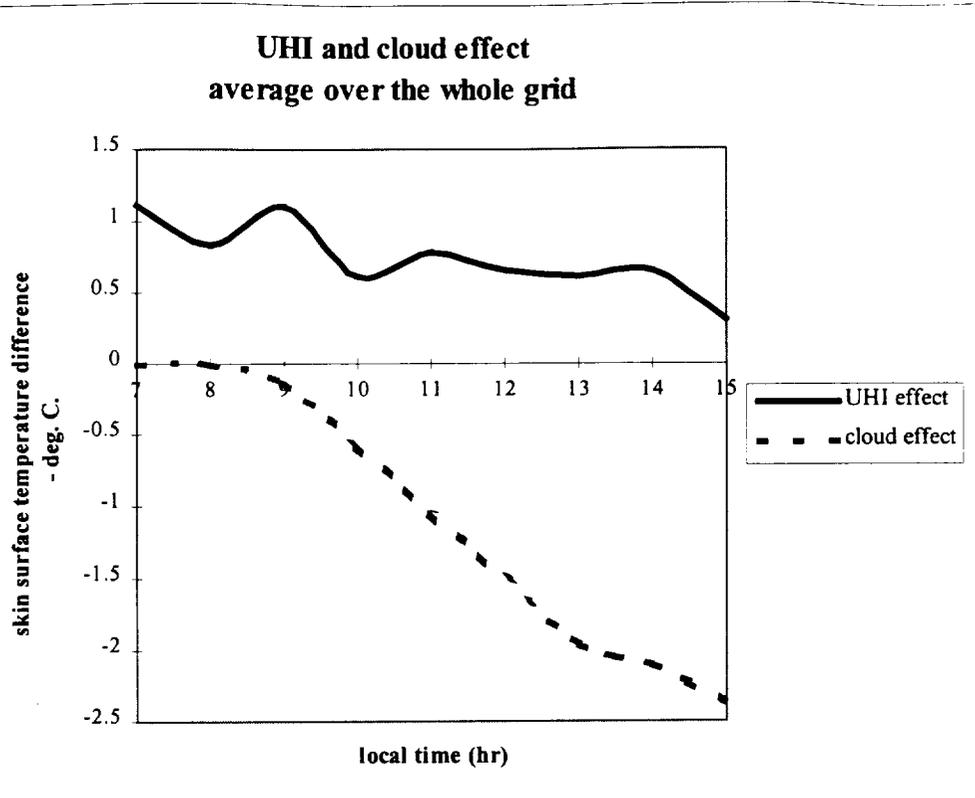
Skin surface temp. diff. (K)



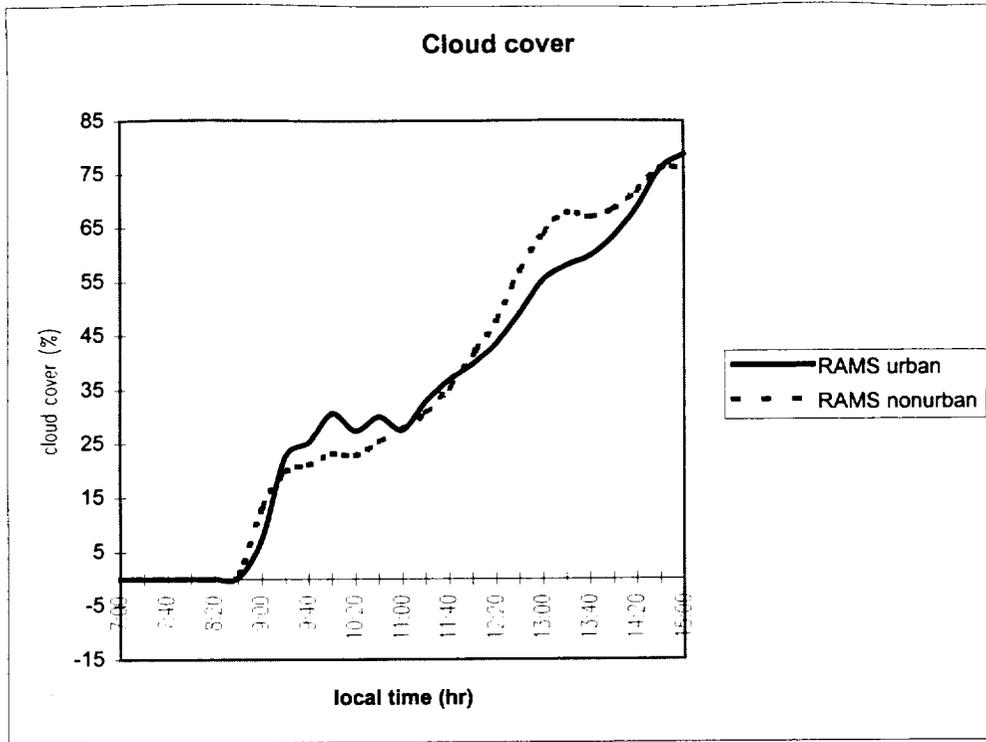
**Figure 9.** The cloud effect (K) on the skin surface temperature (grid 3). The thick line marks Atlanta's boundary.



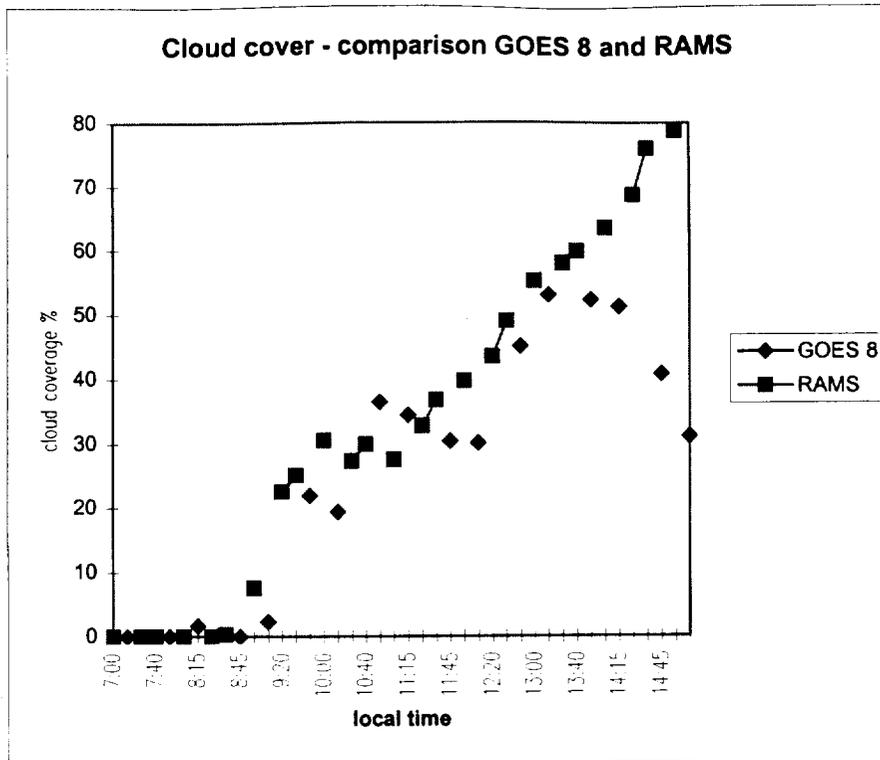
**Figure 10.** The cloud effect (°C) on the skin surface temperature at the point of its largest magnitude (denoted by the red cross in Figure 5), grid 3.



**Figure 11.** The averaged values of the urban heat island effect and the cloud effect (all °C) on the skin surface temperature, for grid 3.

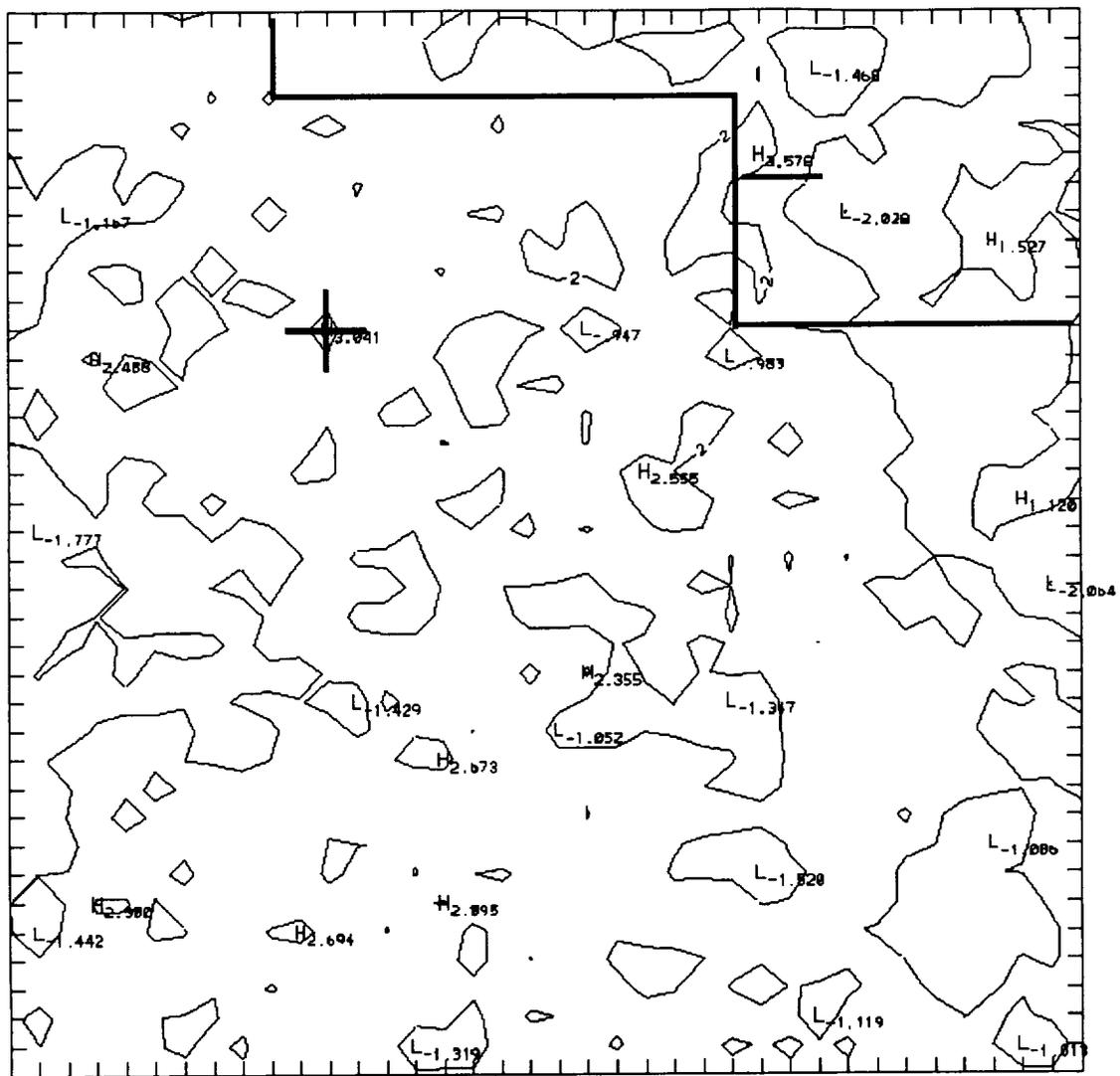


**Figure 12.** The effect of land use on cloud cover. Comparison of urban and nonurban modeled cloud cover (%) for grid 3.



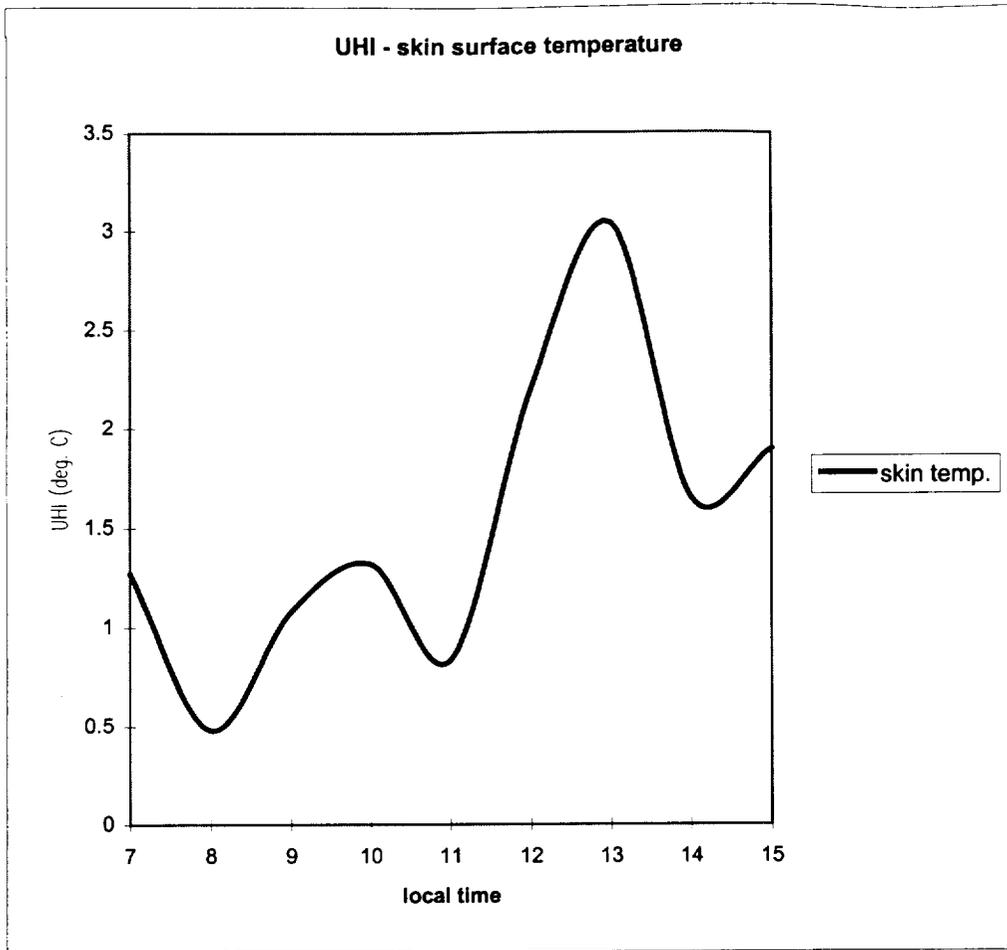
**Figure 13.** Modeled and observed clouds expressed as cloud coverage (%) for the finest grid 3. [Note that the GOES 8 cloud amounts in this figure were derived by a slightly different algorithm than those in Figure 2 and thus they do not exactly match. Both techniques are experimental and are meant to indicate the relative cloud amount, not its exact value..]

Skin surface temp. diff. (K)

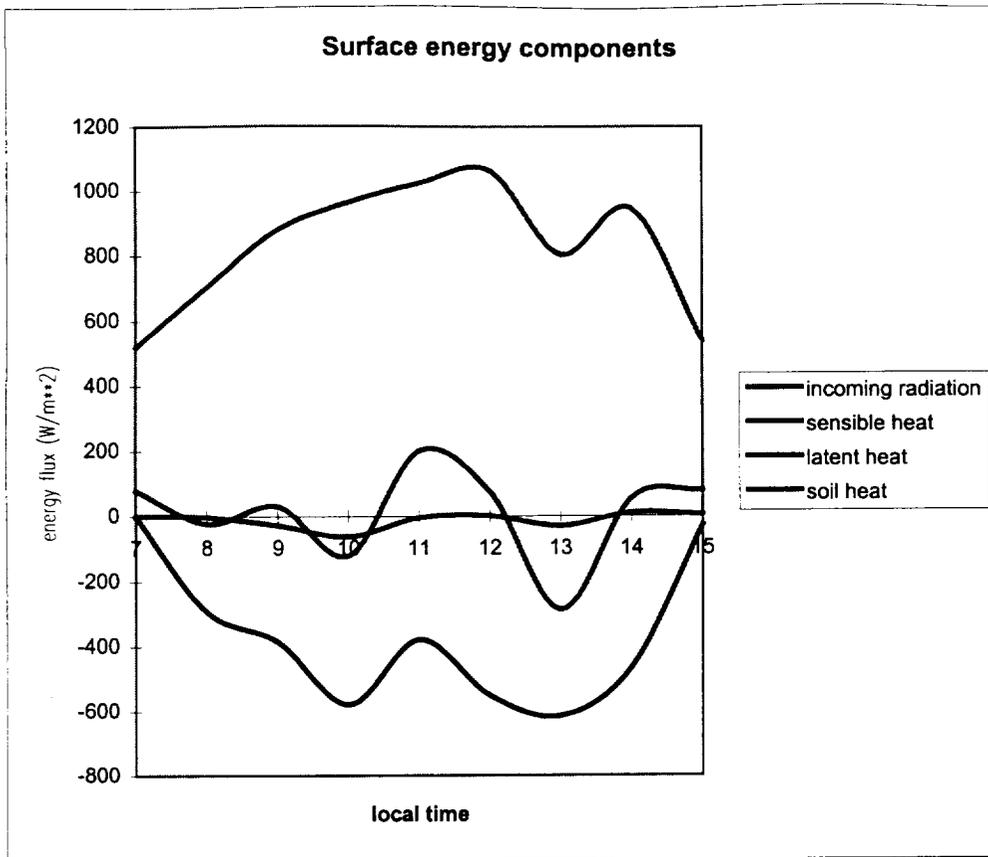


Grid 3 - local time: 1300 CONTOUR FROM -8 TO 8 BY 2

**Figure 14** Urban heat island (K) in terms of skin surface temperature at the finest grid 3 at 1300 LST. The thick line marks Atlanta's boundary.



**Figure 15.** Temporal evolution of the urban heat island ( $^{\circ}\text{C}$  skin surface temperature) at the point of its maximum (red cross in Figure 10).



**Figure 16.** The surface energy components at the point of the maximum magnitude of the urban heat island (red cross in Figure 11).

Skin surface temp. diff. (K)

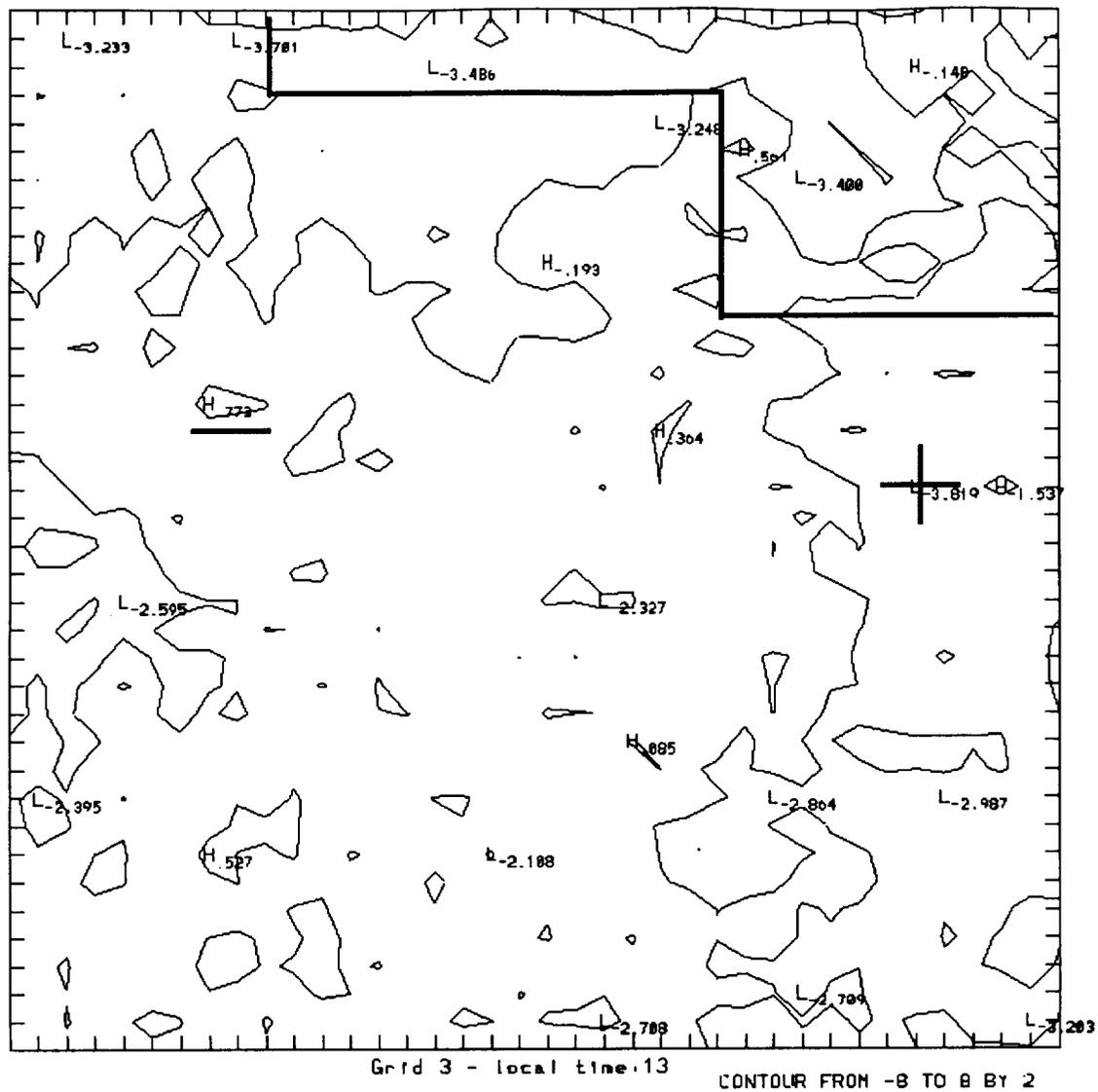
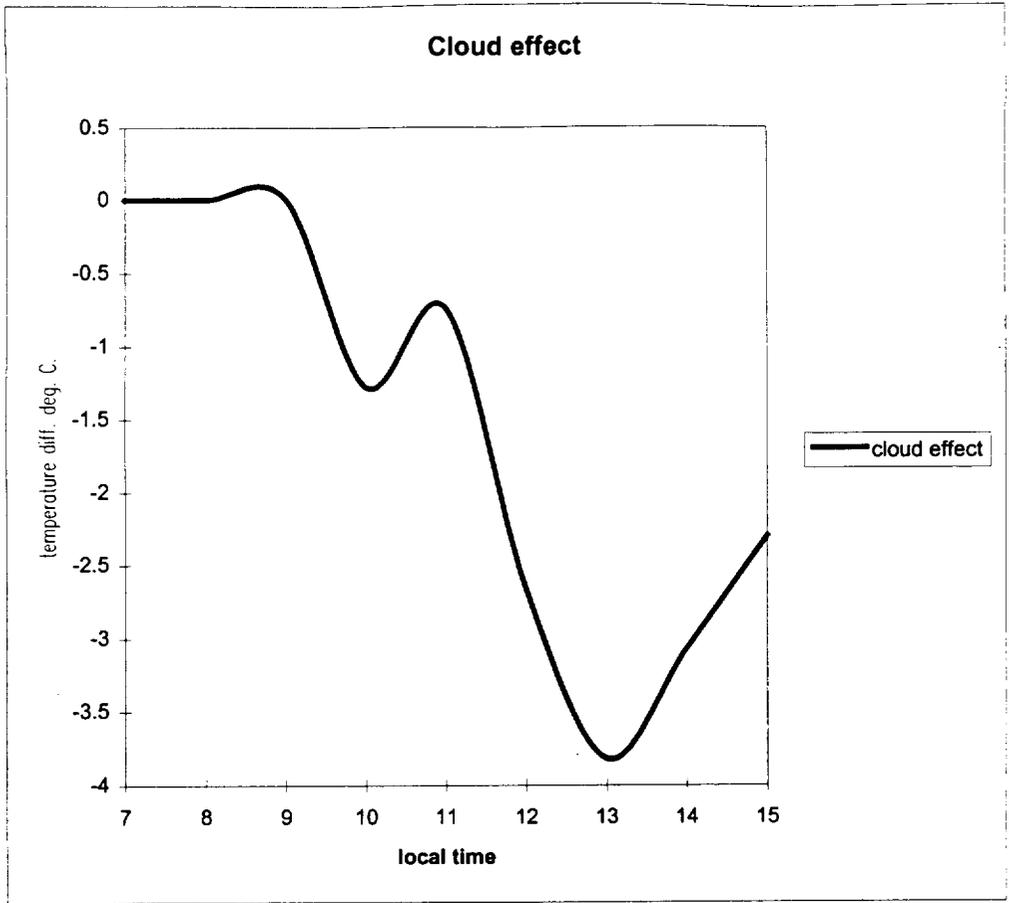
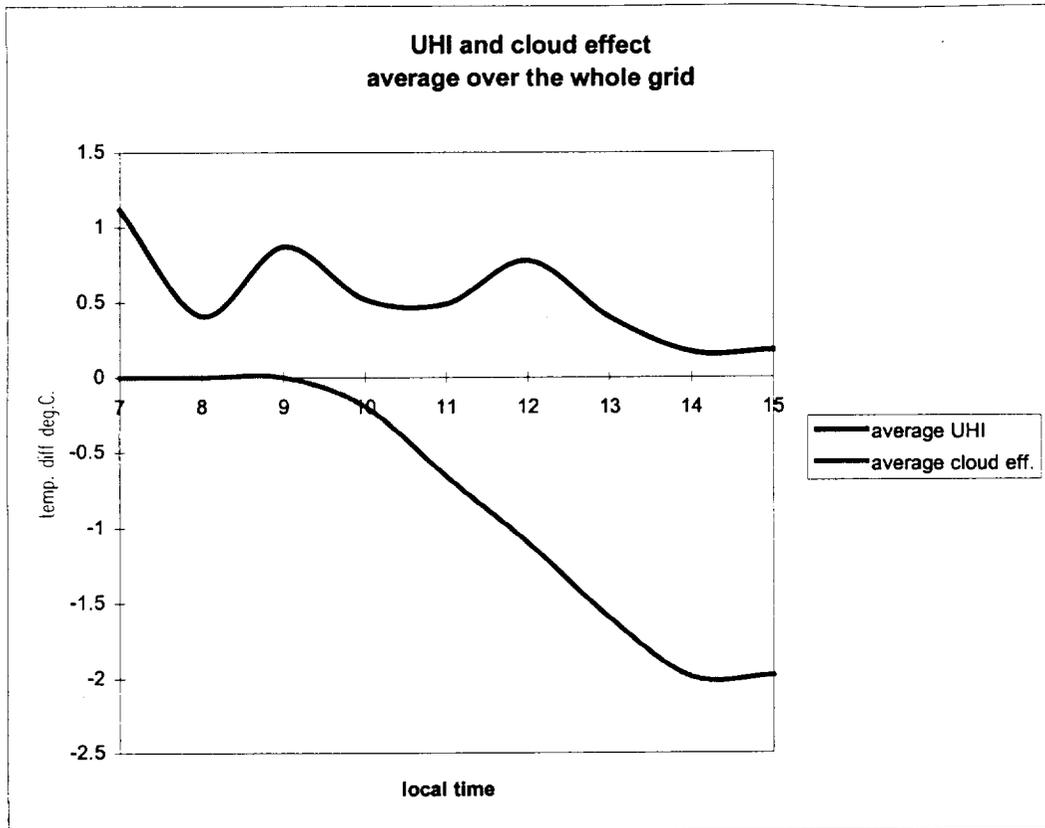


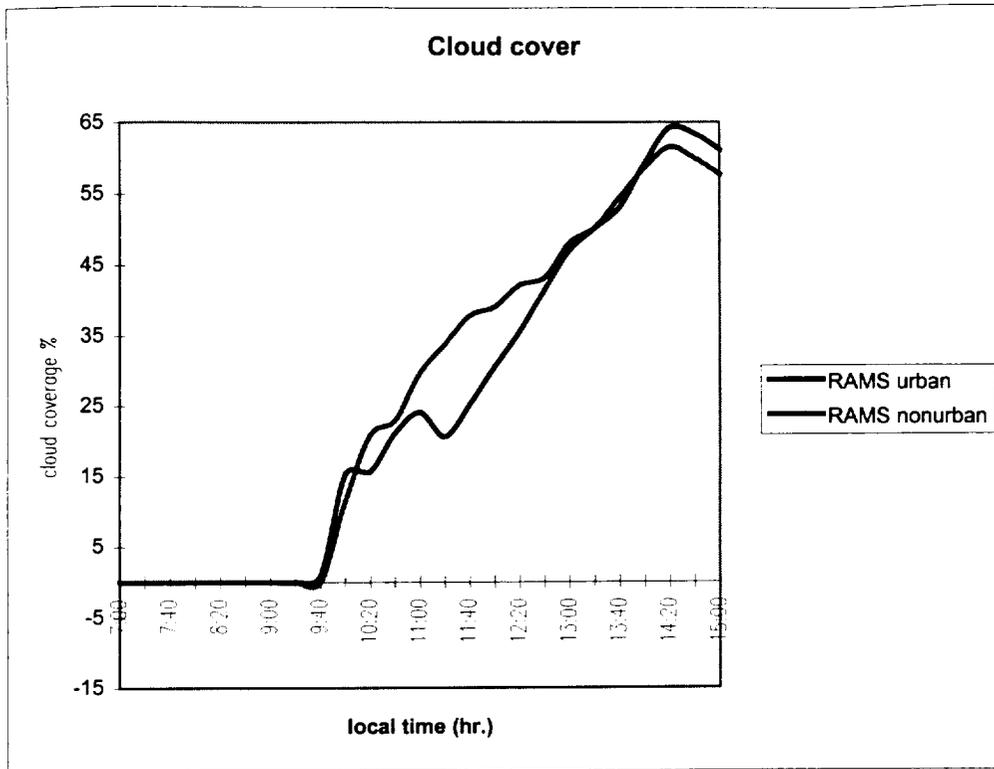
Figure 17. The cloud effect (K) on the skin surface temperature (grid 3). The thick line marks Atlanta's boundary.



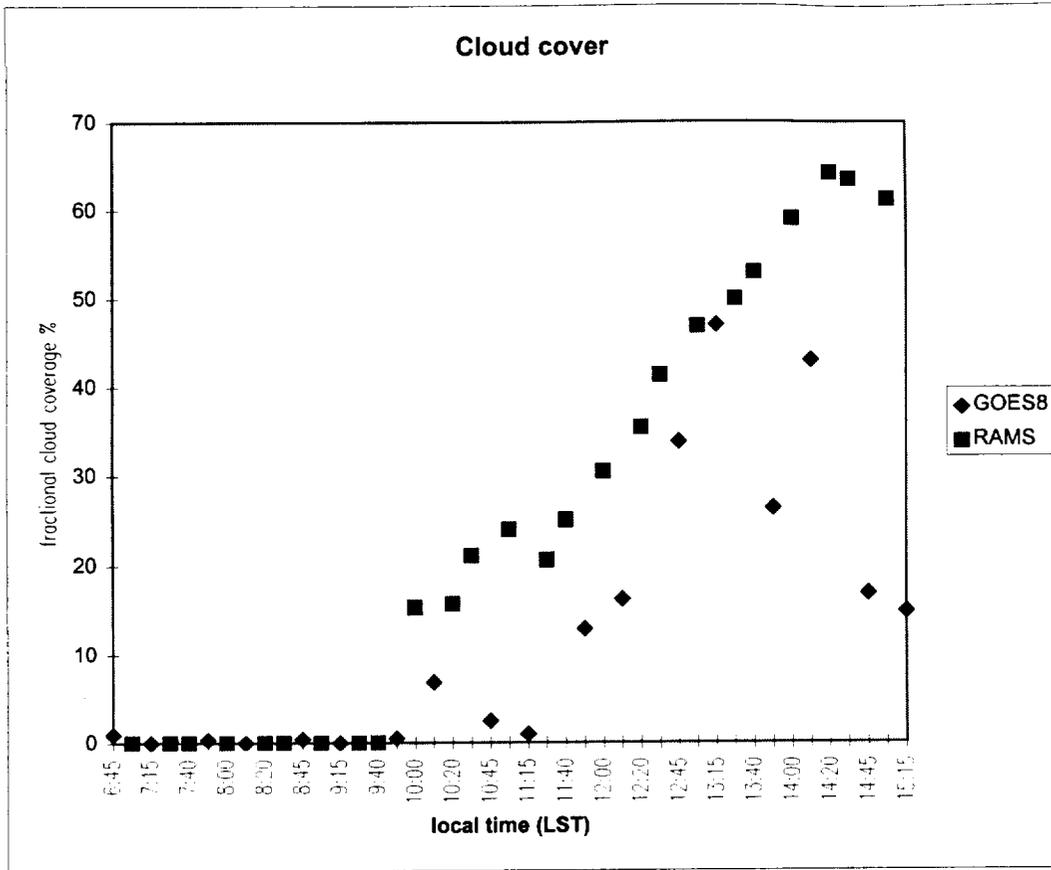
**Figure 18.** The cloud effect ( $^{\circ}\text{C}$ ) on the skin surface temperature at the point of its largest magnitude (denoted by the red cross in Figure 13).



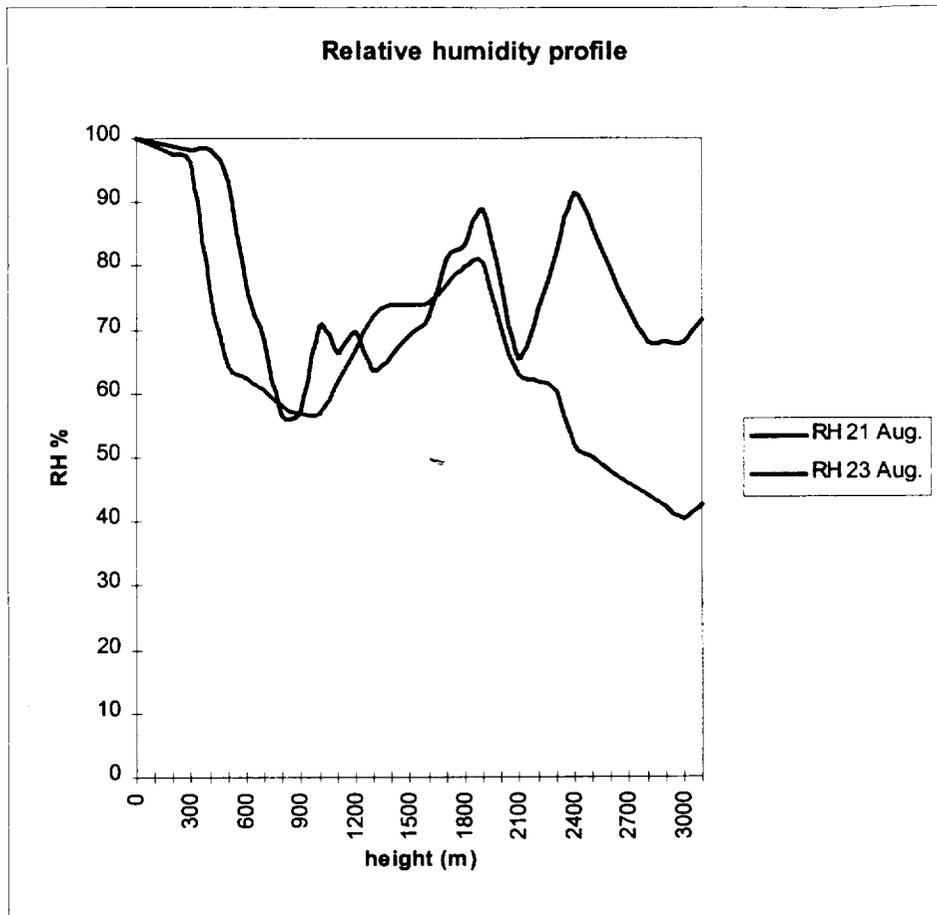
**Figure 19.** The averaged values of the urban heat island effect and the cloud effect (all °C) on the skin surface temperature, grid 3.



**Figure 20.** The effect of land use on cloud cover. Comparison of urban and nonurban modeled cloud cover (%) on grid 3.



**Figure 21.** Modeled and observed clouds expressed as the fractional cloud coverage (%) for the finest grid 3.



**Figure 22.** Profiles of relative humidity (%) for 21 and 23 August 1996 12 UTC at Peachtree City.

# REPORT DOCUMENTATION PAGE

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