Relations between Surface Temperature and Air Temperature on a Local Scale during Winter Nights

SHIGETO KAWASHIMA
National Institute of Agro-Environmental Sciences, Tsukuba, Japan

TOMOYUKI ISHIDA
Faculty of Agriculture, Kagawa University, Kagawa, Japan

MITSUO MINOMURA
Center for Environmental Remote Sensing, Chiba University, Chiba, Japan

TETSUHISA MIWA
National Institute of Agro-Environmental Sciences, Tsukuba, Japan

(Manuscript received 2 January 1999, in final form 17 September 1999)

ABSTRACT

The relations between surface temperature and air temperature on clear winter nights were investigated with regard to spatial scale and the vegetation effect at a local meteorological scale. The study was based on nighttime images obtained from the Landsat Thematic Mapper and high-density meteorological data obtained from the Automated Meteorological Data Acquisition System (AMeDAS). The correlation coefficients between the air temperatures and the surface temperatures at the AMeDAS stations were relatively high despite the simple comparison. Surface temperature alone explained 80% of the observed variation in air temperature. The spatial scales of the effect of surface temperature on air temperature and the effect of vegetation density on air temperature were related to the mean lapse rate of the atmospheric boundary layer. Air temperature was more sensitive to vegetation density when the mean lapse rate of the atmospheric boundary layer was smaller. Accuracy in the estimation of air temperature from satellite-derived surface temperature data was improved by multiple regression using the spatially averaged surface temperature and normalized difference vegetation index.

1. Introduction

In the fields of local meteorology, the data obtained from Landsat and National Oceanic and Atmospheric Administration (NOAA) satellites are effective sources of information, because these satellites are loaded with thermal-infrared sensors that provide surface temperature distributions. The ground resolution of the Advanced Very High Resolution Radiometer (AVHRR) sensor on NOAA satellites is coarse, but the cycle of NOAA satellites is short. The ground resolution of the Thematic Mapper (TM) sensor on Landsat satellites is fine, but the cycle of Landsat satellites is long. Thus, the data from NOAA satellites are suitable for dynamical research and the data from Landsat satellites are suitable for research that needs fine resolution.

Much research on surface temperatures has been undertaken using thermal-infrared images derived from aerial multispectral scanner data (Brown 1974; Kawashima 1986; Asrar et al. 1988; Holbo and Luvall 1989), Heat Capacity Mapping Mission satellite data (Carlson et al. 1977; Matson et al. 1978; Price 1984; Kidder and Wu 1987; Balling and Brazel 1988; Roth et al. 1989; Ottle and Vidal-Madjar 1992; Platt and Prata 1993; Johnson et al. 1993), and Landsat TM data (Honjo and Takakura 1987; Kawashima 1991). Knowledge of surface temperatures is very important not only to obtain boundary conditions of the atmosphere but also to understand the environmental conditions necessary for human beings. Estimation of the nighttime thermal environment is very valuable in agriculture to prevent cold damage and to forecast crop yield (Yates et al. 1984; Caselles and Sobrino 1991).
It has been shown from both a theoretical and a practical point of view (Sellers 1985, 1987; Choudhury 1987) that the normalized difference vegetation index (NDVI) derived from satellite data is a good indicator of vegetation density. Vegetation density is one of the most important factors that affect the thermal environment near the ground and can be calculated from the data of channel 3 and channel 4 of the Landsat TM images. The relation between remotely sensed vegetation indices and surface temperature has been examined by a number of authors (Nemani and Running 1989; Smith and Choudhury 1990, 1991; Hope and McDowell 1992; Gallo et al. 1993). Kawashima (1994) examined the effect of vegetation density on the surface temperature in urban and suburban areas on clear winter days, based on daytime and nighttime images obtained from the Landsat TM. He showed that the degree to which vegetation affects surface temperature depends on the difference between the percentage of building area and the percentage of forest area.

In Japan, a dense meteorological observation network comprising 1300 automatic weather stations, the Automated Meteorological Data Acquisition System (AMeDAS), is employed to monitor surface weather conditions on a 24-h basis. In this article, use was made of the fine-resolution images from the Landsat TM and the high-density meteorological data from AMeDAS to investigate the relations between surface temperature and air temperature on clear winter nights with regard to the spatial scale and the vegetation effect at the local meteorological scale.

Much research on interpolation methods has been undertaken to estimate climatic data at unobserved sites using observed data from neighboring sites (e.g., Bergman 1979; Lorenc 1981; Julian and Thiebaux 1975; Tronci et al. 1986; Kawashima and Ishida 1992). Ishida and Kawashima (1993) describe an improved algorithm for interpolating air temperature using spatial characteristics. The standard error, however, is larger than 1.6°C in winter, even using the improved interpolation method. The accuracy of the spatial interpolation method tends to be worse during the nighttime. The accuracy of the remote sensing method was compared with that of the spatial interpolation method for estimating air temperature.

2. Study area and analyzed data

a. Description of the study area

The study area in this article is located in the central part of Japan and covers the main part of the Kanto plain and its surrounding mountainous area (Fig. 1). The size of study area is about 200 km × 200 km. The eastern and southern edges are close to the Pacific Ocean.

The study area includes a wide range of altitudes and climates. The climate of Tokyo is affected greatly by the Pacific Ocean, which brings relatively temperate weather throughout the year. The annual mean temperature of the city is 15.3°C. The mean temperature in the coldest month, January, is 4.7°C. The annual precipitation in Tokyo is 1460 mm, and the precipitation in the winter (December–February) is only about 12% of the annual total precipitation. The climate of Karuizawa, as a representative place in the northwestern mountainous area, is affected by altitude and the Sea of Japan. The annual mean temperature in Karuizawa is 7.7°C. The mean temperature in the coldest month, January, is −3.9°C. The annual precipitation in Karuizawa is 1211 mm, and the precipitation in the winter is only about 8% of the annual total precipitation. Because the probability of fine weather is high in winter, clear satellite images with little cloud or water vapor effects were obtained. The typical winter vegetation in the study area is cedar (Cryptomeria japonica D. Don), cypress (Chamaecyparis obtusa Endl.), pine (Pinus densiflora Sieb. et Zucc.), chinquapin (Shiia sieboldii Makino), and oak (Quercus myrsinaefolia Blume and Quercus crispula Blume).

b. Satellite data

Nighttime and daytime images obtained from the TM on Landsat 5 were analyzed. The nighttime images of the study area (pass 205, row 203) were obtained at approximately 2100 Japan standard time (JST). Because cloudless conditions were required for the study area, four clear images were selected from a large number of winter nighttime images. The analyzed images were obtained on 4 December 1984, 25 February 1986, 26 December 1986, and 27 January 1987. The daytime image (pass 107, row 35), obtained on 23 January 1985 at approximately 1000 JST was used for the land surface classification and estimation of NDVI.

The TM sensor has seven spectral bands. In the visible, near-infrared and midinfrared bands, the pixel size is $30 \text{m} \times 30 \text{m}$; in the thermal-infrared band the pixel size is $120 \text{m} \times 120 \text{m}$. The arrangements of the images are based on the geographical map. To overlay the satellite images on the geographical map, 45 ground control points were selected using conspicuous topographical features.

c. Digital elevation data

The Geographical Survey Institute has collected geographical information in digital form and produced a nationwide digital topographic database from 1:25 000-scale maps (Miyazaki and Tsukahara 1987). The digital elevation data were taken from the database for each 250-m grid over the study area. The range of elevations in the study area is wide, from 0 to over 3500 m.
d. Meteorological data

In Japan, a dense meteorological observation network comprising 1300 automatic weather stations, AMeDAS, is employed to monitor surface weather conditions on a 24-h basis. The mean interval between stations of the network is about 21 km for five-parameter stations, which have instruments for measuring air temperature, wind speed, wind direction, sunshine duration, and precipitation. Air temperature is measured at a height of 1.5 m with a platinum resistance thermometer that reads in 0.1°C increments over the range from −50°C to +50°C. The study area includes 68 five-parameter stations (shown by dots in Fig. 1).

The aerological observatory at Tateno in Tsukuba Science City regularly launches rawinsondes for upper-air observation and obtains profiles of air temperature, wind, air pressure, and water vapor content. Tateno is a representative station for aerological observation in the Kanto district. The aerological observation data were analyzed at 2100 JST, corresponding to the nighttime satellite images.

e. Preprocessing of the data

All pixels were classified into one of six surface types using the supervised maximum likelihood method. Sev-
eral training areas were selected as supervisors for each surface type. The six types of surface condition were named according to each representative feature: 1) freshwater, 2) seawater, 3) buildings (dense area of the city), 4) housing, 5) forests, and 6) soils (arable land, bare ground). Several pixels in each scene were affected by clouds. These pixels were eliminated from the analyzed images.

The digital counts of the visible and near-infrared bands were converted to at-satellite reflectances. These data were corrected for atmospheric effects to obtain the ground values according to Lowtran (low-resolution transmittance model and code) 7 (Kneizys et al. 1988).

The satellite-derived NDVI was used as the index for vegetation density. NDVI was generated from the TM data as

$$\text{NDVI} = (\rho_{\text{NIR}} - \rho_{\text{RED}}) / (\rho_{\text{NIR}} + \rho_{\text{RED}}),$$

where $\rho_{\text{NIR}}$ and $\rho_{\text{RED}}$ are the reflectances in the near-infrared band and red band, respectively. NDVI were calculated in all pixels except for the surface types 1 and 2—that is, freshwater and seawater.

In this analysis, the surface brightness temperature was calculated using the National Aeronautics and Space Administration (NASA) model (NASA 1984) and correcting for atmospheric effects using Lowtran 7 (Kneizys et al. 1988). Surface emissivity information is necessary to estimate the surface temperature from the surface brightness temperature. Representative values of emissivity were used according to surface types: 0.95 for buildings, 0.96 for housing, 0.97 for forests, and 0.95 for soils (Oke 1978; Rees 1990). Comparison was made between calculated sea surface temperature (SST) and observed SST over the same period. The root-mean-square difference was less than 0.4°C.

3. Results

a. Relations between altitude and temperatures

Images of surface temperatures were overlaid on the altitude data of the Geographical Survey Institute. Mean surface temperatures and mean altitudes were calculated at 10-m intervals in altitude. Figure 2 shows the relation between altitude and several kinds of temperature, including surface temperature (solid line), air temperature at screen height by AMeDAS (+), regression line of air temperature (dashed line), and air temperature derived from aerological data at Tateno (■). In the general characteristics of each scene, air temperature of AMeDAS appeared between the surface temperature and the upper-air temperature for the same altitude.

The surface inversion layer generated by radiative cooling appears clearly in the air temperature profile at Tateno for each day except 25 February 1986. The thickness of the inversion layer was approximately 150 m. The variation of surface temperature with altitude shows a pattern similar to that of the air temperature profile at Tateno. Maximum surface temperatures appear at altitudes of 300–500 m.

In Table 1, several general characteristics of the meteorological conditions are listed. Mean air temperatures and mean wind speeds were estimated from AMeDAS observations. Mean surface temperatures were estimated from the data at AMeDAS stations in order to be able to compare them with the mean air temperatures. Mean lapse rates of the atmospheric boundary layer (ABL) were calculated from aerological observations at Tateno.

On 4 December 1984, the mean air temperature by AMeDAS in the study area showed the highest value among those from the analyzed scenes. The mean ABL lapse rate was $-0.398°C (100 m)^{-1}$, the smallest among those from the analyzed scenes. On 25 February 1986, the mean air temperature in the study area showed the lowest value, and the mean ABL lapse rate showed the largest value. On 26 December 1986 and 27 January 1987, the mean air temperatures in the study area and the mean ABL lapse rates showed middle-range values.

b. Relations between air temperature and surface temperature

Surface temperatures at the AMeDAS stations were extracted from surface temperature data. Figure 3 shows the relation between the air temperature obtained from AMeDAS and the surface temperature derived from the single pixel of the thermal image at the AMeDAS station. The regression lines were calculated to represent the relation between the air temperature and the surface temperature for all analyzed scenes.

On 4 December 1984, the mean and standard deviation were $4.7° ± 3.4°C$ for the air temperatures and $-2.9° ± 6.9°C$ for the surface temperatures. The slope of the regression line was the smallest among those from the analyzed scenes, and the range of the surface temperature was wide. The correlation coefficient between the air temperature and the surface temperature was 0.91. The standard error of the regression was 1.40°C.

On 25 February 1986, the mean and standard deviation were $1.9° ± 3.7°C$ for the air temperatures and $-11.0° ± 6.8°C$ for the surface temperatures. The range of the surface temperature was notably lower than those from the other scenes. The correlation coefficient was 0.92, the highest value. The standard error of the regression was 1.42°C.

On 26 December 1986, the mean and standard deviation were $2.4° ± 3.7°C$ for the air temperatures and $-5.5° ± 6.0°C$ for the surface temperatures. The correlation coefficient was 0.87. The standard error of the regression was 1.85°C. On 27 January 1987, the mean and standard deviation were $0.1° ± 3.1°C$ for the air temperatures and $-5.9° ± 3.6°C$ for the surface temperatures. The difference between the air temperature and the surface temperature was relatively small, and
Fig. 2. The relation between altitude and several kinds of temperature, including surface temperature (solid line), air temperature at screen height by AMeDAS (+), regression line of air temperature (dashed line), and air temperature derived from aerological data at Tateno (■), on four different days. The horizontal axis is temperature, and the vertical axis is altitude.

Table 1. General meteorological characteristics in the study area. Mean air temperature and mean wind speed were obtained from AMeDAS observations. Mean surface temperature was estimated from satellite data. Mean lapse rate of ABL and height of surface inversion layer were estimated from the aerological data.

<table>
<thead>
<tr>
<th>Satellite image scene date</th>
<th>Mean air temperature (°C)</th>
<th>Mean surface temperature (°C)</th>
<th>Mean wind speed (m s⁻¹)</th>
<th>Mean lapse rate of ABL °C (100 m)⁻¹</th>
<th>Height of inversion layer (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Dec 1984</td>
<td>4.71</td>
<td>-2.97</td>
<td>1.40</td>
<td>-0.398</td>
<td>148</td>
</tr>
<tr>
<td>25 Feb 1986</td>
<td>-1.93</td>
<td>-11.05</td>
<td>2.47</td>
<td>-0.800</td>
<td>ND</td>
</tr>
<tr>
<td>26 Dec 1986</td>
<td>2.40</td>
<td>-5.64</td>
<td>1.96</td>
<td>-0.498</td>
<td>139</td>
</tr>
<tr>
<td>27 Jan 1987</td>
<td>0.14</td>
<td>-6.03</td>
<td>1.03</td>
<td>-0.696</td>
<td>134</td>
</tr>
</tbody>
</table>
the slope of the regression line shows the largest value among those from the analyzed scenes. The correlation coefficient was 0.87. The standard error of the regression was 1.55°C.

The correlation coefficient between the air temperature and the surface temperature in each scene is relatively high despite the simple comparison between the AMeDAS air temperature and the surface temperature estimated from the single pixel of the thermal image at the AMeDAS station. The range of variation in the surface temperatures in each scene was larger than the range of variation in the air temperatures. Nearly all of the surface temperatures were lower than the corresponding air temperatures. Differences between the air temperatures and the surface temperatures tended to be larger in cases of lower temperatures.

c. **Range of area over which the surface temperature affects the air temperature**

The correlation coefficients between the AMeDAS air temperatures and the satellite-derived surface temperatures at the AMeDAS stations were calculated. The AMeDAS air temperature was related not only to the surface temperature measured at the AMeDAS station itself but also to the surface temperatures in its vicinity. The relationship between surface temperatures in the area around the station and the AMeDAS air temperature was investigated. A series of spatially averaged surface temperatures around each AMeDAS station were calculated; the radius of each circular area was increased by 100-m intervals up to 10 km. Subsequently, the correlation coefficients between the AMeDAS air
temperatures and the spatially averaged surface temperatures were calculated, and then the changes in correlation coefficients were plotted with respect to the radius used for averaging the surface temperature. The horizontal axis is the radius for averaging the surface temperature, and the vertical axis is the correlation coefficients.

Correlations between air temperatures and spatially averaged surface temperatures were higher than the correlations between air temperatures and surface temperatures estimated from the single pixels at the AMeDAS stations. The correlation coefficients showed maximum peaks in the radii of 100–400 m in all scenes. A gently sloping secondary maximum appeared in the radii of 6–8 km except on 4 December 1984.

On 4 December 1984, a maximum peak in the correlation coefficients appeared at the radius of 400 m, the largest radius among those from the analyzed scenes. The correlation coefficients decreased monotonically after the maximum peak, and a secondary maximum could not be observed even at a radius larger than 10 km. On 25 February 1986, the maximum peak appeared at the radius of 100 m, the smallest among those from the analyzed scenes. The secondary maximum had a radius of about 7.5 km and was large as compared with those from other scenes. The effect of cooling on the larger scale is seen clearly on 25 February 1986. On 26 December 1986 and 27 January 1987, maximum peaks appeared at the 300- and 200-m radii, respectively. The secondary maximums appeared at a radius of about 6–7 km.

d. Effects of vegetation on air temperature

Surface temperature was a major predictor variable for air temperature (Fig. 3). At each point, the deviation of the measured air temperature value from the regression line reflects a difference in heat balance conditions at that point. Vegetation density is an important factor influencing the heat balance near the ground that can be estimated from satellite images. The effect of vegetation density on air temperature was examined using multiple regression analysis.

The spatially averaged surface temperature and NDVI for each AMeDAS point were estimated using the radius at which the maximum correlation between air temperature and spatially averaged surface temperature was found. The multiple regression of air temperature on surface temperature and NDVI was investigated. The results are shown in Table 2. Standard errors from the multiple regression using the spatially averaged surface temperatures and NDVI for the four dates in Table 2 were 0.47°C, 1.05°C, 0.86°C, and 0.91°C. The errors were reduced by spatially averaging the surface temperatures and by introducing NDVI as a second predictor variable.

Akaike’s Information Criterion (AIC) (Akaike 1973) values were calculated to check the improvement from introducing NDVI. In the case of simple regression using only the surface temperature, the AIC values were 215.9, 225.4, 253.7, and 230.0 for the four scenes. In the case of multiple regression using the surface temperature and NDVI, the AIC values were 90.3, 191.1, 162.6, and 170.2 for the four scenes. In all scenes, the AIC values showed an improvement from introducing NDVI, but the improvement was clearest on 4 December 1984.

The partial regression coefficient for NDVI represents the rate of change in air temperature as the vegetation density decreases (Fig. 3). The correlation coefficients decreased monotonically after the maximum peak, and a secondary maximum could not be observed even at a radius larger than 10 km. On 25 February 1986, the maximum peak appeared at the radius of 100 m, the smallest among those from the analyzed scenes. The secondary maximum had a radius of about 7.5 km and was large as compared with those from other scenes. The effect of cooling on the larger scale is seen clearly on 25 February 1986. On 26 December 1986 and 27 January 1987, maximum peaks appeared at the 300- and 200-m radii, respectively. The secondary maximums appeared at a radius of about 6–7 km.

Table 2. Results of the multiple regression of air temperature on surface temperature and NDVI. The second column contains the coefficient of determination $R^2$, adjusted by the degrees of freedom. The third column contains the standard error of the multiple regression model for each scene. In the remaining columns, partial regression coefficients ($\beta$) for each predictor variable and constant parameter are listed with standard errors (SE).

<table>
<thead>
<tr>
<th>Satellite image scene date</th>
<th>Adjusted $R^2$</th>
<th>Standard error (°C)</th>
<th>$\beta$ for $T_s$ SE</th>
<th>$\beta$ for NDVI SE</th>
<th>Intercepts SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Dec 1984</td>
<td>0.98</td>
<td>±0.47</td>
<td>0.47 ±0.01</td>
<td>−3.95 ±1.90</td>
<td>5.65 ±0.17</td>
</tr>
<tr>
<td>25 Feb 1986</td>
<td>0.91</td>
<td>±0.86</td>
<td>0.52 ±0.02</td>
<td>−0.51 ±1.37</td>
<td>3.72 ±0.28</td>
</tr>
<tr>
<td>26 Dec 1986</td>
<td>0.94</td>
<td>±0.09</td>
<td>0.57 ±0.02</td>
<td>−0.51 ±1.37</td>
<td>3.72 ±0.28</td>
</tr>
<tr>
<td>27 Jan 1987</td>
<td>0.91</td>
<td>±0.91</td>
<td>0.79 ±0.04</td>
<td>−2.61 ±1.22</td>
<td>4.90 ±0.28</td>
</tr>
</tbody>
</table>
density increases. Thus, the partial regression coefficient for NDVI represents the magnitude of the vegetation density’s effect on air temperature.

The partial regression coefficients for NDVI were negative in all scenes. On 4 December 1984, the absolute value of the partial regression coefficient for NDVI was largest among those from the analyzed scenes, clearly demonstrating the effect of vegetation density on air temperature. On 25 February 1986, the absolute value of the partial regression coefficient for NDVI was smallest among those from the analyzed scenes. In this case, the effect of vegetation density on the air temperature was small.

General meteorological characteristics in the study area (Table 1) were compared with the partial regression coefficients for NDVI. The mean lapse rates of the ABL correlated strongly with the partial regression coefficients for NDVI (Fig. 5). The vertical axis represents the magnitude of the vegetation effect on nighttime air temperature. The coefficient of determination ($R^2$) was 0.957. Air temperature was more sensitive to vegetation density when the mean lapse rate of the ABL was smaller. The effect of vegetation density on air temperature was smaller when the mean lapse rate of the ABL was larger in the absence of the surface inversion layer.

4. Discussion

The cooling process of surface air during winter nights is controlled by two major heat sinks. One sink is the upper cold air mass, which induces the cooling of the surface air layer by means of upward heat transfer. The other sink is the ground surface, which is cooled by radiative cooling. The ground surface induces cooling of the surface air layer by means of downward heat transfer. From this point of view, the analyzed scenes can be classified as follows.

Case 1) The upper-air temperature is very low, cooling by means of upward heat transfer is dominant, and the surface inversion layer is not observed (25 February 1986).

Case 2) The upper-air temperature is low and the surface inversion layer is observed (26 December 1986; 27 January 1987).

Case 3) The upper-air temperature is relatively high, the surface inversion layer is observed, and cooling by means of downward heat transfer is dominant (4 December 1984).

In studies of the ABL, the mean lapse rate is used to represent the thermal condition of the layer. The classification of each scene based on the concept of two major heat sinks corresponds to the mean lapse rate on that date (Table 1). The scenes arranged in order of magnitude of the absolute value of their mean lapse rates are as follows: 4 December 1984 < 26 December 1986 < 27 January 1987 < 25 February 1986. The correlation between air temperature and surface temperature in Fig. 3 was higher on 25 February 1986, when the lapse rate was large, and on 4 December 1984, when the lapse rate was small. When the lapse rates were intermediate (26 December 1986; 27 January 1987), the correlation was smaller. Surface temperature alone explained 80% of the observed variation in air temperature. Standard errors from the simple regression using the single pixel of surface temperature are of the same magnitude as those obtained using the spatial interpolation method.

The correlation coefficients between air temperature and spatially averaged surface temperature were plotted against the radius used for averaging the surface temperature (Fig. 4). The scene from 4 December 1984, when the lapse rate was small, showed only one peak corresponding to a small radius. In contrast, the scene from 25 February 1986, when the lapse rate was large, showed a noticeable secondary maximum when the radius was large. We think that the peak at the small radius corresponds to the scale of cooling induced by the upper cold air mass. In scenes with smaller lapse rates, maximum correlation coefficients were observed at larger radii. The radii at the peaks in Fig. 4 represent the effective ranges where the correlation between surface temperature and air temperature is greatest.

The results suggest that nighttime cooling under a larger lapse rate is accompanied by cooling cells several kilometers in size and that nighttime cooling under a smaller lapse rate is controlled by cooling cells a few hundred meters in size. The effective radius where the peak occurs in Fig. 4 tends to be large when the mean lapse rate is small.
lapse rate of the ABL has decreased. The size of the effective area in which surface temperature affects the air temperature is negatively correlated with the mean lapse rate of the ABL.

After investigating the relation between vegetation density and air temperature, it became clear that the observed variation in air temperature could be explained also to some extent by the vegetation density. The magnitude of the effect of vegetation on air temperature could be related to the mean lapse rate of the ABL. The errors were reduced by multiple regression using the spatially averaged surface temperature and NDVI as independent variables. Thus, estimating the air temperature using satellite images yielded better results than those achieved using the spatial interpolation method.

It is concluded that the spatial scales of the effect of surface temperature on air temperature and the effect of vegetation density on air temperature are related to the vertical thermal structure of the atmospheric boundary layer. Accuracy in the estimation of air temperature from satellite-derived surface temperature data could be improved by using vegetation density data and aerological observation data. The outline of the algorithm for estimating air temperature is as follows.

1) Preparation of the data.
   - $T_a$: Air temperatures observed at several points.
   - $T_s$ and NDVI: Satellite-derived surface temperatures and index of vegetation density.
   - Aerological observation data at a representative point.

2) The averaged surface temperatures and NDVI around the observed points of $T_a$ are calculated using the effective radius, which in turn depends on the lapse rate of the atmospheric boundary layer.

3) The coefficients of the multiple regression model are calculated using $T_a$, averaged $T_s$, and averaged NDVI.

4) Using this model, air temperatures in the study area are estimated.

The algorithm described in this paper is valid in practice if the satellite image is available. Further study must be carried out to examine the diurnal relationship between surface temperature and air temperature.

Acknowledgments. The authors thank Dr. T. Takashima of the Meteorological Research Institute for his helpful guidance on atmospheric correction, Dr. K. Okamoto of the National Institute of Agro-Environmental Sciences for his kind guidance in the image processing, and Ms. I. Utagawa of the National Institute of Agro-Environmental Sciences for help in correcting the manuscript.

REFERENCES


