REVIEW
Practical Utilization of High-Resolution Air Temperature Data as Geographical Information for Local Agriculture

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Abstract

Mesh data of air temperature in a geographical information system are useful for the precise management of farmland with unique meteorology, especially in hilly and mountainous areas. However, there have been few cases in which the application of mesh data has increased agricultural productivity because the mesh data have been too incomplete to be handled as practical data for agriculture. Thus, a practical method of developing mesh data of air temperature is reviewed; this paper is a review of author studies. Air temperature data are estimated from the variation in air temperature between an estimation site and an existing observation site. There are two factors behind the differences in air temperature: the radiative cooling intensity at the estimation site and the radiative cooling intensity at the existing observation site. Furthermore, a method of compiling high-resolution mesh data from coupled general circulation model data to make quantitative assessments of the effects of climate change is presented. A correction model of downscaling data employing a regional climate model was developed through stepwise multiple regression analysis using the variation in monthly mean air temperatures between the observation and regional climate model output as a dependent variable and geographical factors as independent variables.

Discipline: Agro-meteorology
Additional key words: air temperature, climate change, geographical information system, precision agriculture

Introduction

Researchers in the field of agricultural meteorology have proposed consideration of unique meteorological conditions resulting from various terrains to facilitate the precise management of local agriculture. Mesh data of air temperature in a geographical information system (GIS) can be used to evaluate the meteorological conditions for individual farmland sites. The Japan Meteorological Agency (JMA) has published mesh climatic data at one-kilometer mesh resolution (30" latitude × 45" longitude) for Japan. Public agricultural research centers in each prefecture of Japan have developed air temperature mesh data for local agriculture. However, despite the availability of these mesh data, they have hardly been used to increase agricultural productivity in Japan. There are two main reasons: (1) geographical information tech-

nology has been mainly used by research specialists and (2) meteorological mesh data are too incomplete to be handled as practical data for the management of individual farmland sites, with data having a coarse resolution or being recorded with different equipment over a specific period.

Geographical information technology is familiar to the public. A field management system using GIS has been developed (Yoshida 2009), a technology which allows even farmers unfamiliar with GIS to manage farmland. This system has reached the practical application stage, hence practical techniques and the development of mesh data of air temperature are reviewed in this paper. Furthermore, this paper also reviews a method of compiling high-resolution mesh data to quantitatively assess the effects of climate change for the appropriate management of farmland, since these are of critical concern globally.

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Techniques of developing practical mesh data of air temperature for a GIS in agricultural management

1. Practical mesh size of air temperature data

The utilization of meteorological mesh data by GIS is an effective means of assessing areal air temperature conditions. Various resolutions of mesh data are available, depending on the intended use. Data with a mesh resolution of a few kilometers may be suitable to determine the outlines of agricultural productions, growing stages or other agricultural indicators in administrative agencies, institutes and similar. However practical mesh sizes should have a resolution not exceeding a few hundred meters for precise management in agriculture. Higher resolution information of the surface terrain in the analysis of air temperature should improve the precision of the estimated air temperature, because the surface air temperature is strongly affected by surface topography. Mesh data of air temperature of potential economic value in agriculture are rare in Japan. However, mesh data with economic value for many extensive fields have been used in Hokkaido, Japan; e.g. a map of these data has been used to predict the growth of wheat and operate harvesters efficiently (Okuno, 2007). The mesh resolution is 250 m (7.5" latitude × 11.25" longitude), even though farmland in Hokkaido is more expansive than elsewhere in Japan (Sameshima et al., 2008). Farmland in hilly and mountainous areas, which occupy about 70% of Japan, may require higher resolution mesh data because many of these areas vary by more than 300 m in elevation within a single one-kilometer mesh (Ueyama, 2004). To address this problem, mesh data of air temperature with a 50 m mesh resolution (1.5" latitude × 2.25" longitude) were developed, since a 50 m mesh digital elevation model of Japan is provided at low cost by the Geospatial Information Authority of Japan (GSI). Now elevation data with a 10m resolution around Japan is provided free in a website of GSI, whereupon the Aster Global Digital elevation Model (GDEM), with 30m resolution and using global ASTER data, is provided by Earth Remote Sensing Data Analysis (ERSDAC), Japan.

2. Method of compiling 50 m mesh data of air temperature

There are two main methods of estimating air temperature in mesh cells: numerical methods based on a physical model and interpolating methods taking data from a meteorological observation network. Numerical analysis based on the laws of physics to determine air temperature becomes extremely cumbersome at fine scales, and the data inevitably include model bias error. In practice therefore, it is useful to interpolate data from a meteorological observation network when compiling high-resolution mesh data. There are several methods allowing the spatial interpolation of site-based meteorological data, including inverse-distance weighting, kriging and multiple regression. Spatial autocorrelation must be strong for inverse-distance weighting and kriging, and the air temperature at each site is independently affected by the unique local geographical terrain. Regression models are preferred for spatial interpolation of air temperature in meshes of a few tens of meters, especially in hilly or mountainous areas.

In Japan, 50 m mesh data of air temperature were firstly compiled by Ohara (1999). The 50 m mesh data were compiled using estimation models through stepwise multiple regression analysis of observation data recorded by handmade equipment. The observation data were considered the dependent variable and the geographical factors, developed using a 50 m mesh digital elevation model, were considered independent variables. Numerous handmade equipment was deployed across geographically complex terrain. In addition, researchers (e.g. Blennow and Person, 1998; Lookingbil and Urban, 2003; Ueyama, 2004) deployed considerable handmade equipment for measuring air temperature to compile air temperature mesh data at a resolution of meters.

This chapter presents the method of Ueyama (2004) used to develop 50 m mesh data of air temperature. Two new factors are added to the geographical factors used: the rate of water mesh and the mesh number of the maximum gradient passing frequency, both of which affect the minimum air temperature, meaning the accuracy of the estimation model should improve. The geographical factors used are given in Table 1. The general statistics software SAS is used in developing estimation equations through stepwise multiple regression analysis. Estimation models determined by stepwise multiple regression analysis may be less realistic since independent variables are selected automatically and solely on the basis of statistical standards. A realistic multiple regression equation for estimating air temperature was then developed as follows. In stepwise multiple regression analysis, a statistical standard, the Type 1 error in SAS, was modified when the same independent variables with different R values (50m mesh extension numbers) were selected and their plus or minus signs differed. The regression analysis was halted when the equation was found to be meteorologically consistent; i.e. a regression model was developed with unique variables.

Practical method of estimating air temperature from existing observations

Mesh data developed from observation data recorded by handmade equipment are not generally available in real agriculture because any such mesh data existing represents only meteorological conditions over a specific period. In addition, the unique nature of the equipment used in the above studies makes it difficult to compare results with those of other areal air temperature studies. A method is therefore needed to obtain universal air temperature data for an optional period from observations made at existing observation sites. A new method proposed by Ueyama (2008) is thus presented in this chapter. This method continuously estimates air temperature from

Table 1. Explanatory variables for the multiple regression model. Explanatory variables are calculated for 50m-mesh-extension numbers R = 1 to R = 60, except for elevation, line mesh number and row mesh number

Independent variables
Elevation
Line mesh number
Row mesh number
Mean elevation
Difference of elevation
Exposure*
Mean slope degree
Rate of water mesh**
Mesh number of maximum gradient passing frequency***

* Exposure is determined as the fraction of grids within R grids of the central grid having Δh lower elevation than the central grid; Δh varies from -30 to 30m at 10m intervals; namely, there are seven exposure settings.
** Rate of water mesh is the ratio of the area of water within the cell.
*** The maximum gradient passing frequency is determined by the following method (Matsumura et al., 1988).
1. The grid with the maximum gradient among the eight grids adjacent to that selected is found. 2. The maximum gradient track is determined by continuously determining the maximum gradient grids by changing the selected grid until no further increase in the gradient is found. 3. The process is repeated starting with each grid as the initial target grid in turn. 4. The number of grids crossed by a maximum gradient track until reaching the target grid is defined as the maximum gradient passing frequency.

existing observation data, such as that recorded by meteorological observatories and weather stations.

1. Estimation technique

As a starting point, air temperature is converted to potential temperature because the influence of topographical factors (except altitude) is probably underestimated in the stepwise multiple regression model. The potential temperature is used to estimate the difference in potential temperature between an estimation site and an adjacent permanent observation site. There are different air temperature variations between an estimation site and a permanent observation site in complex terrain, even under identical weather conditions. Therefore, the difference in the potential temperature ($\Delta\theta$) is partitioned into two components: the "estimation site component" (T_{ESC}) and observation site component, or "standard site component" (T_{SSC}):

$$\Delta\theta = T_{ESC} + T_{SSC},$$

T_{ESC} is calculated using

$$T_{ESC} = \frac{1}{DAYS} \sum_{d=1}^{d=DAYS} \left(\Delta\theta_d - \overline{\Delta\theta_d} \right)$$

where DAYS is the number of days in the estimation period, d is an individual day in the period of interest, $\Delta\theta_d$ is the difference in the potential temperature between the estimation and observation sites, and $\overline{\Delta\theta_d}$ is the average value of $\Delta\theta_d$ for all estimation sites.

The models used to estimate T_{ESC} and T_{SSC} are formulated using a variable that represents radiative cooling intensity. A new meteorological scale — the radiative cooling scale (RCS) — is proposed as a variable to represent radiative cooling intensity in the estimation area. This scale is defined as the difference in potential temperature between an upper air pressure surface and the grand surface, as there is higher cooling radiative intensity at a lower air temperature on a ground surface:

$$RCS = \theta - \theta_G$$

where θ is the potential temperature at the upper level on the observation site and θ_G is the potential temperature at the latter.

The RCS does not indicate the cooling radiative intensity directly since it is not a numerical indicator but a scale indicating the upper meteorological condition over the whole estimation area; i.e. higher or weaker radiative cooling intensity. To complete the analysis, the RCS is

required for areas without rawinsonde observation data. An estimation model of the RCS is then formulated using existing observation data since the RCS is simply a scale for the upper meteorological condition. The equation is a multiple regression with three meteorological variables: the percentage of possible sunshine, daily temperature range, and average nocturnal wind speed from UTC 1000 to 1200. These variables were selected assuming they are strongly related to the radiative cooling intensity.

There is a linear correlation between RCS and T_{ESC}, the sites for which negative slopes exist become significantly colder at night, such as those on valley floors or within topographic basins, while those for which there are positive slopes have mild overnight temperatures, e.g. those on hilltops or the upper parts of hill slopes. There is also a linear correlation between RCS and T_{SSC}. A multiple regression equation as an estimation model of T_{SSC} is proposed, although it would be valid to assume a linear correlation between RCS and T_{SSC} to develop the simplest model. This is because it would be inappropriate to use the RCS as a variable, despite recording meteorological data at the observation site for T_{SSC} since the RCS is a statistical estimate and would offer less precision.

Figure 1 presents 50 m mesh data of the mean air temperature as climate data, averaging data from 1971 to 2000, with the data for each year estimated from observations made at the Automated Meteorological Data Acquisition System (AMeDAS) station employing the method of Ueyama (2008); AMeDAS has numerous nationwide meteorological observation stations, with approximately 800 observation sites for air temperature, wind speed, wind direction, and sunshine duration, 1300 observation sites for precipitation, and 200 observation sites for snowfall respectively. This area is located in the north of Hiroshima prefecture, Japan; ranging in elevation from approximately 160 to 1010 m. The estimation model for mesh data was developed taking the difference in air temperature between the AMeDAS station and the estimation site for a half year as dependent variables. The accuracy of stepwise regression analysis using the air temperature difference as a dependent variable exceeds that of estimation models developed using only air temperature observations. The method of Ueyama (2008) for estimating the air temperature difference would be a useful technique in developing an estimation model for compiling mesh data.

There are various mean periods of air temperature available, depending on the intended use of the data. Daily data should be more valuable for precise management in agriculture, although there are only reports for data on a monthly and ten day mean basis. Accordingly, a method is developing to estimate daily data using Ueyama's idea.

Compilation technique for practical mesh data of climate change effects

1. Correction method of downscaling data of coupled general circulation models

Dynamical downscaling (DDS) using regional climate models (RCMs) of coupled general circulation models (CGCMs) should be appropriate for the downscaling of principal climate factors in agricultural assessments, especially in areas of complex topography such as Japan. Correction methods for climate data downscaled using an RCM were developed for local assessments of climate change effects, since climate data downscaled through DDS include model bias error from the RCM. However, the grid intervals used in past studies are probably insufficient when making practical assessments for local agriculture in areas of complex topography. Furthermore, the analysis of errors in downscaled surface air temperature data is expected to be difficult because the quantitative correlation between observation data obtained in field studies for assessments and data from an RCM is unclear. Therefore, data that are more specific, standardized and of higher resolution are required in quantitative assessments for local agriculture and a method to compile 250 m mesh data, as proposed by Ueyama et al. (2010), is presented in this chapter. Ueyama et al. (2010) compiled 1 km mesh data from 250 m mesh data for the Kyushu region of Japan, one for which grid data had been developed over a wide area.

The DDS technique known as the pseudo global warming (PGW) method (Sato et al., 2007) is used in this method. The PGW data given by the sum of 6-hourly re-
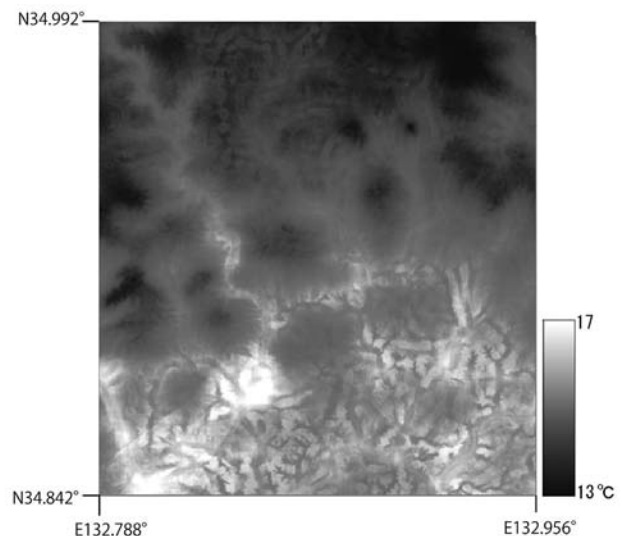

Fig. 1. 50 m mesh data of the 10-day mean air temperature for a hilly area, Hiroshima, Japan

analysis data and climate change components, namely the averaged monthly differences between current and future climate as projected by the GCM, are used as initial and boundary conditions for downscaling by the RCM. The PGW data include temperature, wind velocity, geopotential height, relative humidity and sea surface temperature. The advantages of the PGW method are that (1) it reduces CGCM bias and saves computing resources since it swiftly estimates the difference between current and future climates without an set of simulations and (2) assessments of future climate made using a correction model for the RCM bias developed for the current climate are more reliable.

The correction model for RCM bias is developed from the relationship between the RCM bias and factors characterizing a site with the same. The correction model for the RCM bias is developed as follows: A high-resolution monthly mean air temperature distribution for the current climate is computed by the RCM, whereupon a correction model for the RCM bias was developed by stepwise multiple regression analysis; taking the difference between the observed and computed monthly mean air temperatures as a dependent variable and the geographical factors listed in Table 2 as independent variables. Independent variables were developed using a 250 m mesh digital elevation model.

Figure 2 is a 250 m mesh map compiled for the month of August in the 2040s (2040–2049); the correction model was developed using data recorded at 49 AMeDAS sites shown in Fig. 2. The method corrected the RCM bias from 1.69 to 0.63°C for the month of August in the 1990s (1990–1999); accuracy was verified using the root-mean-square error calculated at five observatories shown in Fig. 2. Mesh data developed employing the method are useful for the quantitative assessment of real farmland because the mesh size is practical and the data is standardized using existing observation data.

Conclusion

Two methods to develop digital mesh data of air temperature for the precise management of farmland using a GIS are reviewed: (1) estimating 50 m mesh data from existing observations and (2) compiling 250 m mesh data of air temperature corrected with existing observations from CGCMs. The vitality of rural districts, especially areas where farms are small and spread over hilly and mountainous areas, should be maintained through the precise management of agriculture and based on the unique meteorology of local areas. Furthermore, a technique to develop precise digital meteorological data is required for specific and quantitative assessments of the effects of climate change on agriculture, since concerns regarding climate change and requests for quantitative

Table 2. Independent variables for multiple regression analysis. Each variable is computed for a 250-m-mesh-extension number R = 1 to R = 40, except for elevation, line mesh number, row mesh number and shortest distance from the coastline

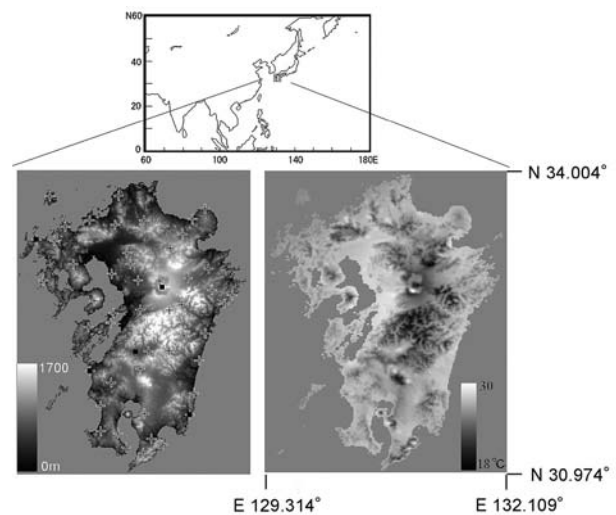| Independent Variables |
| --- |
| Elevation |
| Line mesh number from south to north |
| Row mesh number from west to east |
| Shortest distance from the coastline |
| Mean elevation |
| Difference of elevation |
| Exposure ratio |
| Mean slope degree |
| Rate of sea mesh |
| Mesh number of maximum gradient passing frequency |

Fig. 2. Map of the 250 m resolution compilation domain for the Kyushu region, Japan
The bottom left image is a 250 m mesh elevation map showing 49 AMeDAS stations (circles) and five observatories (crosses). The bottom right image shows the 250 m mesh data of the monthly mean air temperature in the months of August in the 2040s (2040–2049).

assessments of its effects on real farmland have increased.

Rural districts are not only important in terms of food production but are also where civilization, culture and spirit originated in Japan, hence playing a key role in the development of Japan toward an advanced nation. Therefore, maintaining their vitality is not only important for food production but also for the growth of the nation. This concept is not unique to Japan but also applies to other nations, including those industrializing e.g. ASEAN, India, Korea and others.

Acknowledgments

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