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THE RELATIONSHIP BETWEEN REGIONAL AVERAGES OF LATENT AND SENSIBLE HEAT FLUXES AND PATCH SCALE

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SYNOPSIS

The relationship between regional averages of latent/sensible heat flux and patch scale is discussed. When numerical simulation using the Local Circulation Model is performed, the circulation in the sub-grid region, namely, the area that is between each grid point, is often ignored. Accordingly, wind speed in the sub-grid is assumed to be much slower than background wind speed. On the other hand, the regional average latent/sensible heat flux from the complex land use surface, which includes several patches, is often estimated using the 'weighted average method'. Some researchers have pointed out that this method is available for patches with a scale of less than 10km due to 'scale issues'.

In this study, some numerical simulations were performed under the condition where the circulation of heat is easily triggered in the sub-grid region, and then the effect of patch scale was considered. The main results are as follows; consideration of 'scale issues' is unnecessary within the error margin of 20% in the application of the weighted average method under limited conditions where bare land is selected as the target, and is compared against a baseline 10 km patch scale; even with an allowance of 10% error, this conclusion does not change if the patch scale is limited to below 100 km.

INTRODUCTION

Precisely quantifying the rate of evapotranspiration from vegetation-covered land such as forests as well as from bare land is an important goal, since evapotranspiration is a major loss term in hydrology and water resources engineering. For this reason, numerous observations, experiments and numerical simulations have been carried out with the aim of achieving accurate estimations of the rate and amount of evapotranspiration under different geographical conditions. When measuring evapotranspiration volumes from a single land-use surface, it is not necessary to consider the scale issues mentioned below that are the subject of this study. This principle does not however, hold true in cases where areas of differently covered ground (defined as 'patches' when each piece is regarded as being homogeneous) are dotted, mosaic-like, over a wide area. In this case, calculation of the regional average of evapotranspiration rates over the complex land-use surface requires the evapotranspiration rates of all patches to be known together with the method of aggregating the evapotranspiration rate over each of the respective patches. The modeling scale is often much larger or much smaller than the observation scale in hydrology. To bridge that gap, 'scaling', namely, aggregation or disaggregation is necessary (2). In this study, we discuss the problems related to this aggregation method, or upsacaling, as one of the scale issues in hydrology. With the setting up of numerical simulations, in particular, this issue must be taken into account. The authors have carried out simulation studies (7) on Local Circulation Models (hereafter called LCMs) in the Lake Biwa basin, and have similarly investigated issues of scale (6)(8) in LCMs.

In LCMs, grid points, which are positioned directly above the ground surface (generally regarded as the upper end of the boundary layer facing the ground), are arranged two-dimensionally at intervals of 1 ~ 100 km. Assuming a 10-km interval between horizontal grid points along the X- and Y- axes, an LCM, or an atmospheric model requires three flux values (momentum, sensible heat, and latent heat) as its lower boundary conditions at the lowest layer which consists of the lowest grid points of the atmospheric model (hereafter called the Lowest Layer Grid Point). These fluxes are obtained from the physical quantities at Lowest Layer Grid Points and the corresponding physical quantities on the ground surface, which means an area of 10 km×10 km below a grid point, and these fluxes are 'regional average fluxes'. Since the ordinary ground surface consists of a complex variety of land use surfaces, ideas must be devised to allow the calculation of three types of fluxes. In one example, a 100 km^2 surface corresponding to a Lowest Layer Grid Point is regarded as a homogeneous land-use surface. In this case, the surface is not divided into several 'homogeneous patches'. On the other hand, the weighted average method has also been proposed as a method of identifying regional average fluxes, by calculating the weighted average fluxes according to the size of each patch (4). This is applied in the approach utilized for cases where each piece of ground surface corresponding to a Lowest Layer Grid Point in an LCM is composed of a multiplicity of different patches. In this method, we first observe flux values for each patch and Lowest Layer Grid Point, and then carry out average calculation weighted by the area size of each patch, and finally obtain the regional average fluxes that denote the lower boundary condition for the Lowest Layer Grid Points.

Let us suppose that Patch A of a certain type of ground cover is intermixed with Patch B of a different type of ground cover over a ground area of 100 km^2. Case 1 presupposes that Patches A and B share half of the space respectively, meaning that only two patches are included. On the other hand, Case 2 assumes a mosaic distribution of multiple numbers of A-type patches and B-type patches, each accounting for 50% of the total area. According to the weighted average method, the regional average flux is assumed to be the same for Case 1 and Case 2. In a real situation, however, this does not always hold true. This becomes one of the scale problems in LCM simulation.

The aim of this study is to investigate the influence of patch scale on the value of regional average flux when using the weighted average method.

METHOD OF INVESTIGATION

This study employed numerical simulation using the LCM for the investigation. The adopted model is a two-dimensional one initially developed by Kimura et al. (3), and modified by us for this study. It is a dry model presupposing the Boussinesq approximation and conditions of hydrostatic equilibrium, and has been extensively used in research by Kimura and his coworkers. The equations in our model are similar to those used by them, and are thus omitted for simplicity (see Reference 3). Major variables for the calculation are horizontal wind velocity (two-dimensional), vertical wind velocity, potential temperature, and specific humidity. The temperature of the ground surface was estimated using the Force Restore Method (FRM) (1). The so-called β method (5) was employed for the calculation of the latent heat flux between the ground surface and Lowest Layer Grid Point. In other words, the wettability was expressed by the

Table 1 Major calculation assumptions

Common Conditions
β :1.0 (wet land) 0.0 (dry land) sublayer Stanton no.:0.6
roughness length (momentum) :0.5(m) calculation time :48(hour)
Condition for respective cases
Case a L: 400 km interval of grid points: 1 km
Patch Scale: 5(a1), 10(a2), 50(a3), 100(a4), 200(a5)Km
Case b L: 4000 km interval of grid points: 10 km
Patch Scale: 100(b1), 200(b2), 500(b3), 1000(b4), 2000(b5)Km
Case c L:20000 km interval of grid points: 50 km
Patch Scale: 1000(c1), 2500(c2), 5000(c3), 10000(c4) Km
Case w L: 4000km interval of grid points: 1 km
Patch Scale: 10(w1), 50(w2), 100(w3), 500(w3), 1000(w4), 2000(w5) km

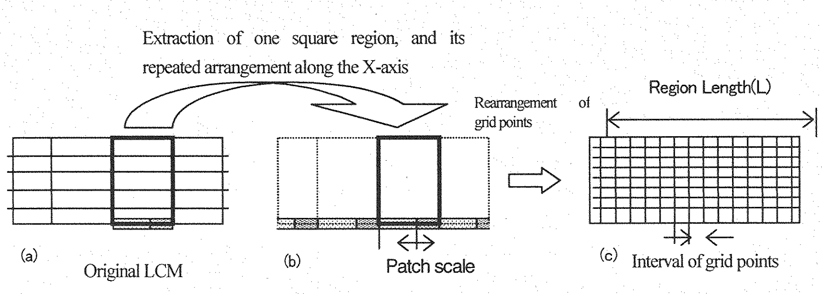


Fig.1 Basic Concept of Model

evaporation efficiency β, and the latent heat flux was estimated from the specific humidity at the Lowest Layer Grid Point and specific humidity of saturation at the ground surface. The calculation was conducted over a period of 48 hours, assuming a constant value of β throughout the period. Other premises are shown in Table 1.

The basic approach adopted in this study is illustrated in Fig. 1, assuming a two-dimensional model. The arrangement of grid points in LCM enables the calculation of physical quantities at each grid point. Phenomena between adjacent two grid points (or in the sub-grid region, namely, the area, which is between each grid point,) cannot be expressed unless a specific parameterization is employed. Heat circulation within a sub-grid scale is often ignored in this type of numerical simulation using LCM.

We extracted a square region on the surface corresponding to the Lowest Layer Grid Point of the original LCM, deliberately creating conditions where the circulation of heat is easily triggered, and proceeded with our examination of the extent of influence of patch scale on the regional average flux mentioned in the above described weighted average method. The expression 'to extract a square region' mentioned above means to remove one square region from the large-scale model (namely, original LCM; cf. Fig. 1(a)) and to allocate the region repeatedly along the X-axis as is shown in Fig. 1 (b). In reality, we iterated this area along the X-axis (Fig. 1 (b)) so that the assumption of hydrostatic equilibrium for the model is satisfied, and set up a new calculation area (Fig. 1(c)) in which the grid points were rearranged. Subsequently, calculations using the LCM, for which the calculation area was this new calculation area (Fig. 1(c)), were performed, and the periodic boundary conditions were adopted as lateral boundary conditions.

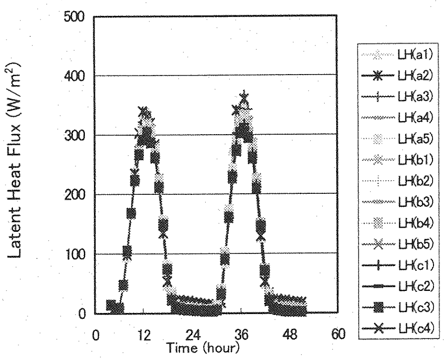
More specifically, we performed the following calculations. First, we fixed the calculation area of length L in the X-direction (called L hereafter), set up wet ground (β = 1) on a ground of area L/2 (totaling them in the X-direction), and dry land (β = 0) on the remaining area of L/2. The total areas of wet land and dry land in the region (more precisely, the total of the lengths, since the model is two-dimensional) are precisely equal. Under these conditions, we applied various arrangements of patches (whose length is referred to as l hereafter) in our survey of the influence of patch scale on the regional average of latent/sensible heat flux values.

In Case a1, we arranged alternating areas of wet land and dry land of l = 5 km. Likewise in Case a2, Case a3, and Case a4, the same arrangement with l = 10 km, 50 km, and 100 km, respectively were assigned. In Case a5 in particular, the whole area of L = 400 km is simply divided into a wet area and a dry area of l = 200 km. Conditions for Case b, Case c, and Case w are summarized in Table 1. Concerning the influence of wind velocities, three calculations (at initial wind velocities of 1, 5, and 10 m/s) were conducted for each experiment. As mentioned above, the periodic boundary condition was adopted. Assumption of patch scales greater than 1,000 km is likely to be impractical, but this size was included in our study (see Table 1) to assist evaluation of the overall trend, and for the future application of the result in models on a far larger scale, such as GCMs. The reason for classification into Cases a, b, and c by the regional length L are as follows:

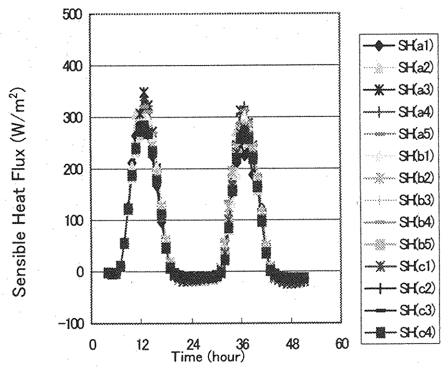
1) In the calculation of an experiment with a patch scale of 10 km comprising only one dry area and one wet area, a minimum L of 20 km is sufficient. However, the premise of hydrostatic equilibrium requires a much greater length. Therefore, the regional length was set at 400 km for Case a.

2) In this study, the length of the patch scale was extended to 10,000 km, so the regional length was set at 20,000 km for Case c.

3) Execution of all calculations under the condition selected for Case c (constant regional length of L = 20,000 km) will clearly lead to waste of computational resources when only calculations with small patch scale are required.

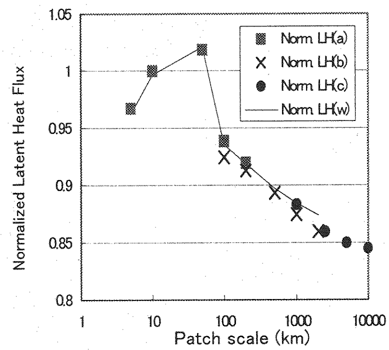


(a) Latent heat flux

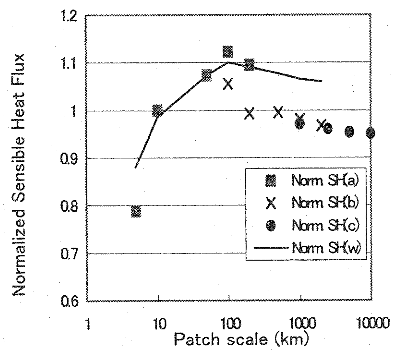


(b) Sensible heat flux

Fig.2 Changes in Latent/Seisible Fluxes with Time



(a) Latent heat flux



(b) Sensible heat flux

Fig.3 Relationship between Patch Scale and Normalized Flux Values at Initial Wind Velocity of 1 m/s

We have added inspections on the validity of dividing calculations into three cases of a, b, and c in a later section.

CALCULATION RESULTS AND DISCUSSION

(1) Effect of patch scale

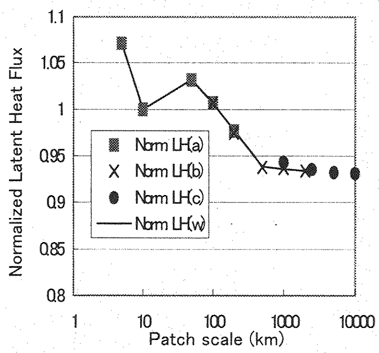
Figs. 2(a) and 2(b) plot the changes in latent/sensible heat fluxes over time (up to 48 hours after the start of calculation) at an initial wind velocity of 1 m/s. The X-axis is graduated in local standard time (hours). The counting rule for hours exceeding 24 is based on simple addition (e.g. on the second day, 13:00 is counted as 13 + 24 = 37). In these figures, calculations in 15 cases with patch scales varying from 5 km to 10,000 km are plotted simultaneously. Although it is very difficult to distinguish the curves for each of the 15 cases in these figures, the authors intend to show how closely the curves overlap except at around 12:00. These figures suggest the following facts:

(a) Both the latent heat flux and the sensible heat flux are strongly influenced by the difference in patch scale at around 12:00 (and 36:00 on the second day). At other times, the effect of patch scale on the heat flux is not conspicuous.

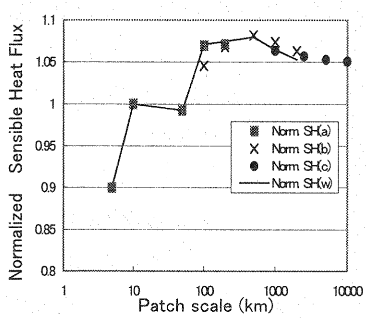
(b) The value of flux varies slightly at night depending on the scale, but can be negated.

The results shown are for cases with an initial wind velocity of 1 m/s. Similar results have been obtained in other cases at initial wind velocities of 5 and 10 m/s, but are omitted here owing to limited space.

Having obtained a result as described in (a) above, we moved to a comparison of regional average values at 13:00 (LST) on the second day. In Figs. 3, 4, and 5, the Y axis denotes regional average flux at 13:00 (LST) plotted against the X axis of patch scale (km) plotted on a logarithmic scale. These flux values are normalized against the standard value for patch scale of 10 km for Case a(2). Cases with patch scale of 5 km are also included in the figure, but there is room for discussion regarding these cases. Due to the assumption of hydrostatic equilibrium for LCM, the interval of grid points in

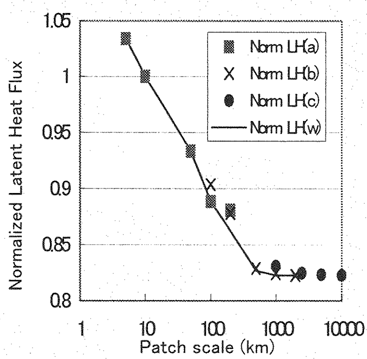


(a) Latent heat flux

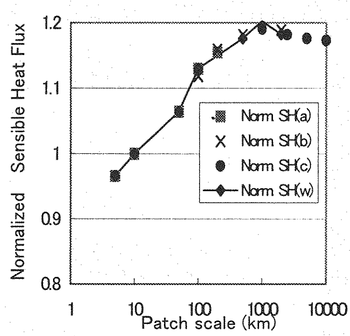


(b) Sensible heat flux

Fig. 4 Same figure as Fig.3, but wind velocity is 5 m/s



(a) Latent heat flux



(b) Sensible heat flux

Fig. 5 Same figure as Fig.3, but wind velocity is 10 m/s

these case is set to 1km. Accordingly, the interval between points in 1km corresponds to 5 grids. Since one patch is usually expressed by more than five grid points, the curves for patch scale of 5 km in these figures should simply be regarded as a reference.

Fig. 3(a) illustrates changes in the latent heat flux. The symbol ■ denotes the results of Case a, namely of 400 km regional length and 1 km interval of grid points, with × corresponding to Case b (4,000 km regional length and 10 km interval), and ● corresponding to Case c (20,000 km and 50 km). With respect to patch scales of 100 km and 200 km, the calculation was performed both for Case a and Case b. Fig. 3(b) shows our results for sensible heat flux similar to Fig. 3(a). Figs. 4 and 5 illustrate data at an initial wind velocity of 5 and 10 m/s, and can also be interpreted in a similar manner to Fig. 3. Prior to the following discussions, we selected the results for a patch scale of 10 km as the control, and defined the discrepancy of other results with different patch scale values from the control as the margin of error. The authors intend to clarify the effect of the patch scale on the regional average fluxes, therefore, let us consider the relationship between a margin of error and the patch scale. First, we assume a permissible error to be 20%. From Figs.3, 4, and 5, the following conclusions can be deduced.

(c) Allowing a margin of error of 20%, the latent/sensible flux values remain within the limit of the margin even when the patch scale is extended to 10,000 km. Considering the following premises, we may deduce that the effect of the patch scale can be negated in the simulation below.

1) The calculation was performed under conditions where thermal circulation is deliberately evoked (under mixed presence of patches $\beta = 0$ and $\beta = 1$).

2) Based on the previous result of (a), the comparison was conducted at the least advantageous hour of 13:00 (LST).

3) The actual calculation is not expected to be performed under the conditions of 10,000 km patch.

(d) Even when the permissible limit of error is more strictly reduced to 10%, the effects arising from heat circulation are generally small at a patch scale length of 100 km or less, so the influence of patch scale is regarded as being negligible.

(e) If we use a region where the patch scale exceeds 100 km, the normalized latent heat flux decreases with patch scale. The cause of this is the oasis effect, and the normalized sensible heat increases with patch scale because of the decrease in latent heat flux, except in the case of 1m/s. Concerning the case of 1m/s, other effects are relatively stronger

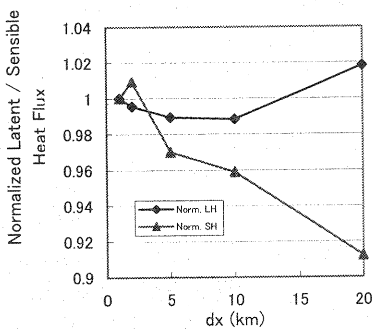


Fig. 6 Relationship between Grid Point Interval (dx) and Normalized Flux Values

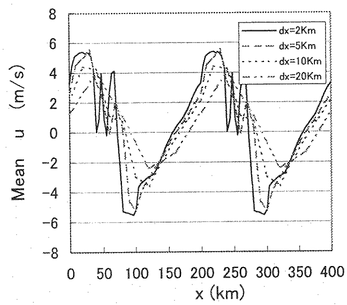


Fig. 7 Distribution of Horizontal Wind Velocities

than the oasis effect, since the wind speed is slow. Moreover, the reason why the margin of error is largest for a patch scale of 100 km when wind speed is slow is related to the scale of local circulation over the homogeneous patch.

Limited to Fig. 3(b), the calculation results for the three cases did not overlap well with each other. For Cases b and c they are slightly and continuously overlapped, but there is a discontinuity between the results for Cases a and b. For this reason, we have supplemented calculations for Case w in all cases. The calculations are based on the assumption of a regional length of 4,000 km and grid points at intervals of 1 km as shown in Table 1. The solid lines in Figs. 3, 4, and 5 illustrate the result. In Fig. 3, the calculation result for Case w does not correspond well with the other results plotted by × and ●, but corresponds well in Figs. 4 and 5. This leads to the following conclusion:

(f) Differences due to varying intervals between grid points become more evident at small initial wind velocities. When larger values are assigned to the initial wind velocity (for example 5 m/s or 10 m/s), the above effect becomes negligible even when the interval is increased to 1 ~ 50 km according to the extended regional length.

In cases of large regional length, large interval values are usually selected to save computational resources. In Case b and Case c, we have followed this general rule in our calculations. Therefore, the results of Case w do not contradict the above-mentioned results of (c) and (d). They only assert that the error margin increased (although remaining within 10%) under conditions where the interval between the grid points decreased (as in Figure 3(b)) for a patch scale exceeding 100 km. The result of (f), however, poses a new problem concerning 'Calculation error in the latent/sensible heat flux and the interval of grid points', which will be discussed in detail in the next section.

(2) Influence of grid interval

As mentioned in the previous section, results of Cases a (interval of 1 km), b (10 km), and c (50 km) in Figs. 3(a) and 3(b) did not overlap well with each other, and did not fit well onto the curve for Case w (intervals of 1 km), particularly for sensible heat flux. We have assumed that this arises from differences in the interval (dx) between grid points for respective cases, and thus proceeded with new calculations as shown below.

1) Five values were assigned to dx, namely 1 km, 2 km, 5 km, 10 km, and 20 km with all other conditions remaining unchanged.

2) As seen from Figure 3(b), the error increases at positions around a patch scale of 100 km, so the subsequent calculations were conducted assuming a patch scale of 100 km.

Subsequently, we describe Fig.6 in which the relationship between dx and the margin of latent/sensible heat fluxes are shown. Here, we selected the hour 13:00 (LST) on the second day within the time period of 48 hours, and the latent/sensible heat fluxes were normalized against the case of dx = 1 km (along the Y-axis). The X-axis is assigned to dx (interval). From this figure, the following conclusions were deduced.

(g) The sensible heat fluxes in Fig. 3 did not clearly overlap with each other to a greater extent than the latent heat flux, and did not correspond with the result of Case w. In Fig. 6 the effect of dx on the latent heat flux is not significant.

(h) With respect to the sensible heat flux, the effect of varied dx becomes evident. This suggests that the dx values should be specifically determined when the initial wind velocity is set up with small values, though the error margin remains within 10% in such cases.

In this section, the calculations were conducted for a patch scale of 100 km. We selected an area of 400 km (in length) from the whole region, which contained two units of dry land and wet land respectively, and plotted the distribution of horizontal wind velocities at an altitude of 10 m in Fig. 7. Our results indicate that the wind velocity distribution varies slightly depending on the difference in dx even when the patch scale is set at a constant 100 km.

CONCLUSIONS AND FUTURE SUBJECTS FOR RESEARCH

We have investigated the relationship between the patch scale and the regional average flux in the application of the weighted average method. The Local Circulation Model (LCM) often presupposes that the wind velocity in the sub-grid region is much smaller than the background wind. It is clear, however, that the loss of precision in LCM simulations is partly caused by the circulation of heat within each sub-grid. Therefore, we launched simulations under conditions where the circulation of heat is deliberately set at a high value, that is, wet land ($\beta = 1$) and dry land ($\beta = 0$) are positioned alternately. This condition leads to a climate where both land and sea breezes are blowing. Our results indicate that consideration of scale issues is unnecessary within the error margin of 20% in the application of the weighted average method under limited conditions where bare land is selected as the target, and is compared against a baseline 10 km patch scale. Even with an allowance of 10% error, the conclusion does not change if the patch scale is limited to below 100 km.

Our intentions for future research projects are as follows:

1) It necessary to extend our study of LCM to vegetation models in addition to soil (or ground surface) models in order to obtain more comprehensive results.

2) The literature (4) employs an assumption in the application of the weighted average method that the atmosphere represented by a Lowest Layer Grid Point is blended satisfactorily at a constant altitude, yielding the same physical quantities.

In this research, the above assumption was not employed, since a grid square with a denser distribution of grid points was extracted for the present study. We are not certain whether it becomes necessary to take patch scale into account when this assumption is used, so it will be necessary to examine this issue. We intend to continue these investigations while developing new schemes.

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