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Vegetation change in the regional surface climate over East Asia due to global warming using BIOME4

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Summary. — This study investigates the possible changes in the regional surface climate due to global warming from a MM5 downscaling simulation for the period of 1971-2100. The main focus of this study is to observe the changes in vegetation types over East Asia. BIOME4, an equilibrium terrestrial biosphere model, is utilized to simulate vegetation patterns. Regional projections of this study show the increase of surface air temperature by 5°C and precipitation by 6% over East Asia in the end of the 21st century. The present study also noticed that the increasing trend of temperature is associated with the increasing trends of the minimum temperature of the coldest month. Therefore, the region of favorable temperature conditions for vegetation growth in lower latitudes seems to extend toward the higher latitude. It leads to a northward shift of vegetation distribution in the lower latitudes besides the area extension. For instance, the trend in which the warm mixed forest and temperate deciduous forest shift northward may be distinguished. At the same time, the area of temperate deciduous forest pervades the area and replaces temperate grassland regions. Of interest, the tropical evergreen forest is expected to appear over southern China in the end of the 21st century. The possible vegetation changes are mainly affected by a temperature increase rather than a precipitation increase.

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PACS `93.30.Db` – Asia.

1. – Introduction

It has been reported that a wide area over the world has experienced the effects of global warming [1]. Such long-term changes in climate in recent centuries are identified as being human-induced, and have received much attention internationally, stimulating comprehensive research on the effect of global warming. Generally, to produce the information as a guide for long-term climate change evaluation, a projection approach is applied by the climate model. Projections that carried out based on the future emissions scenarios of greenhouse gases and aerosols must be carefully monitored to explain the results [1-3]. However, the results can give useful insights for possible consequences due to climate change.

Generally, global warming is associated with climate changes such as temperature and precipitation. Since ecosystem distributions are mostly dependent on the climate condition, changes in the climate impose a significant influence on the growth condition of the vegetation. The authors in [4] and [5] demonstrated the redistribution of vegetation due to climate change. In [6, 7] the poleward shift of several biomes such as the temperate deciduous forest in China is shown. In addition, in [7] the feasibility of downscaled projections is suggested, since precipitation anomalies in regional scale may induce different responses in vegetation.

The downscaled projection is important in evaluating the surface climate change for complex mountainous terrain regions such as the Korean peninsula [8]. The Korean peninsula is covered by the forest over 70% of the total area; henceforth the impact of the climate change on the vegetation distribution is expected to be severe. Therefore, many studies were carried out to estimate the climate change effect on the vegetation distribution over Korea [8].

Based on the previous studies, we have investigated possible changes of vegetation responses to the climate change in East Asia surrounding the Korean peninsula. To simulate the vegetation distribution, we have used BIOME4 [5].

2. – Data and methodology

Future projections in this study are the monthly precipitation and 2 m height air temperature simulated by the Pennsylvania State University-National Center for Atmospheric Research (PSU-NCAR) nonhydrostatic mesoscale model version 5 (MM5). Those are in a 27 km horizontal resolution and 18 layers of σ-coordinate in vertical covering the period of 1971-2100. The domain is centered at 38°N and 125°E, and covers an area of $3348 \times 2808\ \mathrm{km}^2$ (125×105 grid points), encompassing the whole Korean peninsula and East Asia. The initial and boundary conditions of MM5 are provided from large-scale fields by ECMWF Hamburg Atmosphere Model Version 4 coupled with the Hamburg Ocean Primitive Equation-Global (ECHAM4/HOPE-G) model of Max Planck Institute for Meteorology (MPI). MM5 is nested with linear orography blending method similar to [9] and integration is carried out by one month interval. The planetary boundary layer is parameterized by the medium-range forecast scheme [10]. Also, in MM5, Grell cumulus parameterization scheme [11] and the Reisner mixed-phase microphysics are employed. The ECHAM4/HOPE-G model is described by [12] and [13]. More details for climate data downscaling are described in [14].

The simulations of the ECHAM4/HOPE-G are based on the greenhouse gas scenario of the SRES (Special Report on Emission Scenarios) A2 developed by the IPCC. SRES A2 is one of anthropogenic forcing scenarios derived from different assumptions of future social and technological development [15]. It is known as the scenario with more rapid increase of greenhouse gases concentration compared to B2 [16]. Based on the A2 and B2 scenarios, future projections over East Asia demonstrated the temperature increase of 4.1°C and 3.2°C and precipitation increase of 5.0% and 4.0% around the end of the 21st century, respectively [17]. Similar results of warmer and wetter climate in the 21st century over East Asia between both scenarios are shown in [14]. In [15] it is also shown that the simulated changes for the A2 scenario show a high level of coherency with those for the B2 scenario. Based on the previous results, we used the A2 scenario and analyzed a possibility of potential surface vegetation change related to the future climate change.

Also this study used the Climate Research Unit (CRU) data which is known as a high-resolution data set of surface climate over global land areas and primarily developed in the International Water Management Institute's World Water and Climate Atlas. We used monthly precipitation and temperature gridded at 0.5 degree horizontal resolution for the period of 1901-2000 [18]. Sunshine duration has a $10'$ latitude/longitude grid resolution for the period of 1961-1990 [19].

For the vegetation responses to prescribed climatic changes, we used an equilibrium terrestrial biosphere model, BIOME4 [5]. BIOME4 was developed from the BIOME3 of [20], which is a coupled carbon and water flux model that simulate global steady-state vegetation distribution. The model can be applied to the assessment of changes in potential vegetation patterns in response to different climate in an equilibrium state while it does not simulate the time-dependent dynamics of vegetation [21]. The model is driven by monthly mean temperature, sunshine and precipitation. BIOME4 is based on 13 plant functional types (PFTs). Each type is described by a set of limiting climatic conditions that determine whether net primary productivity (NPP) is calculated for a given location [21]. A coupled carbon and water flux scheme determines the seasonal maximum leaf area index (LAI) that maximizes NPP for each PFT [5]. The PFTs with the highest NPP are chosen and ranked for a given grid cell. The resultant ranked combination of PFTs allow for an assignment to one of biomes.

To validate our model simulation, PMIP2 (Paleoclimate Modelling Intercomparison Project) vegetation data for the present time (0 K year) are used from `http://www-lsce.cea.fr/pmip2` [22-25].

3. – Results

3˙1. *Change in temperature and precipitation.*

– The monthly mean temperature and precipitation in this study are derived from MM5 simulation during the period of 1971-2000 (fig. 1a). The distributions are similar to those of CRU as shown in fig. 2.

Regional projections of this study show the increase of surface air temperature by 5°C over East Asia in the end of the 21st century. The increment is larger in the higher latitudes than in the lower latitudes, which implies that vegetation in the higher latitudes is more significantly affected compared to that in the lower latitudes, as will be shown in more detail in the next section.

The temperature is a critical factor for vegetation survival, since it affects the metabolism of the vegetation and concurrently determines its growth rate [8]. The amount of precipitation is also important. The mean increase of precipitation during the period of 2071-2100, compared to the period of 1971-2000, is about 6%, as the increase appears almost over the entire domain (fig. 1b). The results show that, in the period 1971-2000, the rate of precipitation increases with the temperature, which seems to contribute to a favorable condition for vegetation growth. The details of the process need further study.

3˙2. *Change in the biome.*

– To estimate the impact of climate change and vegetation distribution in East Asia, three experiments have been performed (table I). The CO_2 concentration is derived from the SRES A2. MM5-PRESENT, in fig. 3a, represents the distribution of vegetation derived by BIOME4 during the period 1971-2000.

In MM5-PRESENT, the dominant biomes are warm mixed forest, temperate deciduous forest and temperate grassland, which cover the largest portion of the total grid cells. The vegetation distribution is similar with that in CRU-PRESENT (fig. 3b). In

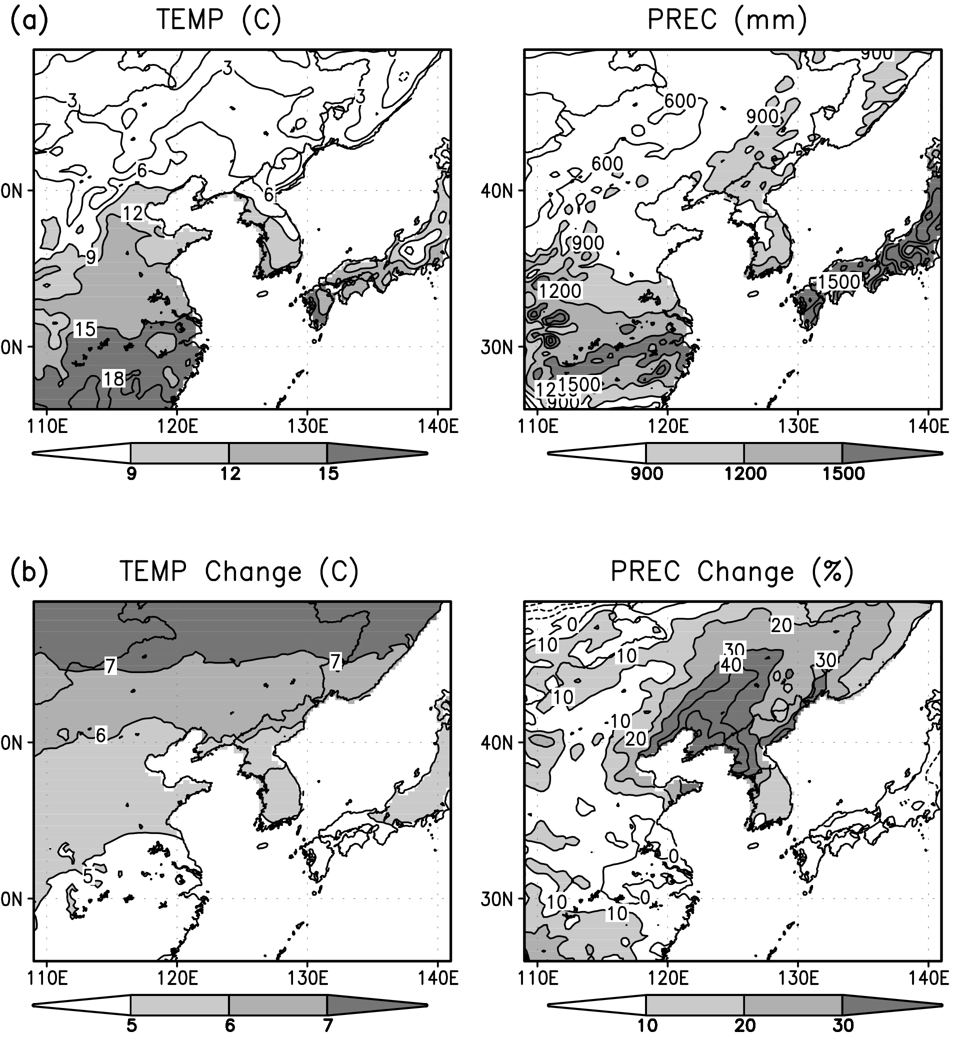

Fig. 1. – a) Composite maps of annual mean temperature (°C) and annual precipitation (mm) of MM5 over East Asian region for the period of 1971-2000. b) Difference of temperature and precipitation of MM5 for the period 2071-2100 with respect to the period 1971-2000.

Table I. – *Design of numerical experiments (assumptions for the impacts assessments).*

	Period for temp. and prec.	CO_2(p.p.m.)
CRU-PRESENT	1971-2000	340
MM5-PRESENT	1971-2000	340
MM5-FUTURE	2071-2100	680

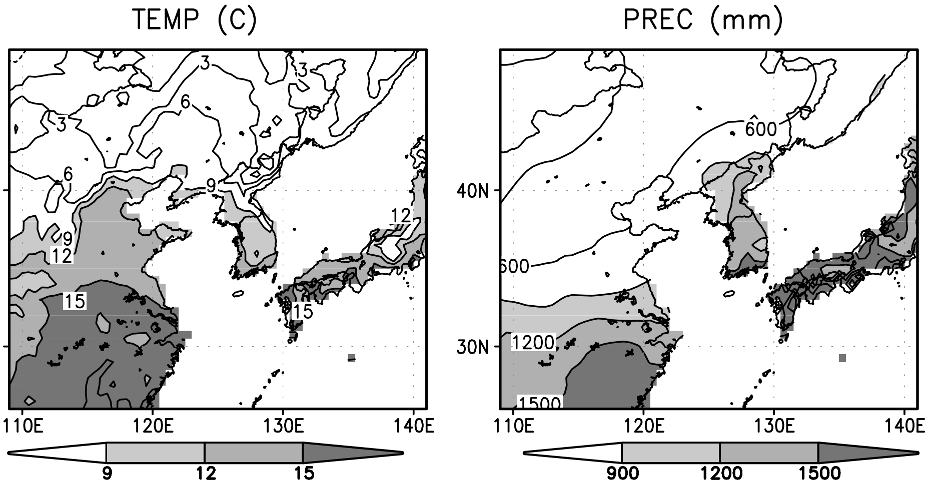

Fig. 2. – Composite maps of annual mean temperature (°C) and annual precipitation (mm) of CRU TS2.0 over East Asian region for the period of 1971-2000.

this study we mainly focus on the three dominant biomes as well as tropical evergreen forest.

The simulated vegetation maps in MM5-PRESENT and CRU-PRESENT are compared with the PMIP2 observation for the present time (0 K year) (fig. 4). The observation data is too sparse to be quantitatively compared with the simulations, but they show a qualitative consistence with the simulation over South and Far East China. Several species of the simulated biomes agree with the observations such as warm mixed forests over southern China, and temperate deciduous forests near 40°N, and temperate grassland north of 40°N. Whereas biomes distribution between 35°N and 40°N does not coincide with the observations, the difference seems to be that observations are based on the station report and their period of 0 K year does not coincide with those of the MM5 projection over the 30-year period.

Figure 5 shows potential vegetation changes based on the projections between 1971-2000 and 2071-2100, when the global warming continues at the rate indicated by SRES A2. In contrast to MM5-PRESENT, there are noticeable changes in the distribution of vegetation. The simulated area of warm mixed forest apparently shifts northward by about 4° in MM5-FUTURE without significant change of the occupied area. Tropical evergreen forest appears over southern China, south of 35°N. The temperate deciduous forest area also shifts northward and replaces the temperate grassland, mainly found north of about 45°N, where its area expands by 19.2% compared to that of MM5-PRESENT. [7] explained the northward expansion of the temperate deciduous forest, replacing grassland as due to the warmer and wetter climate.

The remarkable changes of vegetation distribution in MM5-FUTURE with respect to MM5-PRESENT seem to be affected by the temperature increase.

Figure 6 presents the increment of minimum temperature of the coldest month (T_{c}) associated with the temperature increment: this last, due to global warming, is associated with the T_{c} increment. The T_{c} increase also reflects the trend of the T_{c} value moving northward. As a consequence, the T_{c} increase could allow specific biomes to occupy regions in the higher latitude, since biomes have T_{c}, a threshold value of climate rule for

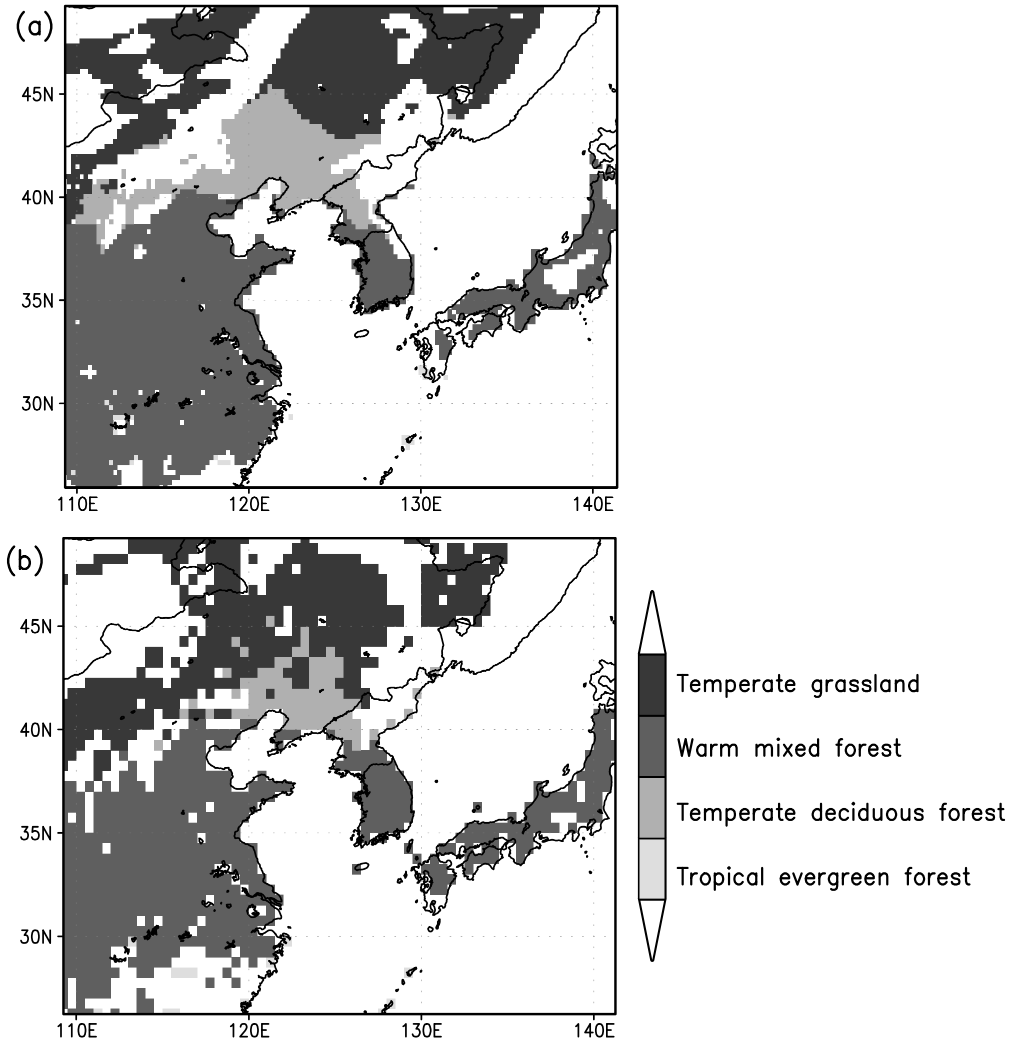

Fig. 3. – Vegetation distributions simulated by BIOME4 driven by the MM5 simulation (a) and CRU data (b) for the period 1971-2000.

growth and survival. Even though the T_c value does not exactly coincide with the biome area, the area shift of biomes apparently seems to be related with the T_c value.

According to [20], the tropical evergreen forest consists of tropical broad-leaved evergreen PFT. The tropical broad-leaved evergreen PFT has a T_c of 0°C for climate rule. Based on their definition, the northward shift of 0°C by about 5 degrees of latitude in fig. 6 reflects the tropical broad-leaved evergreen PFT occupying a higher latitude in the period 2071-2100 compared to the period 1971-2000. As a result, the tropical broad-leaved evergreen PFT is able to acquire large values in LAI and NPP, and is selected as dominant plant type at each grid. As a result, the tropical broad-leaved evergreen PFT becomes high in rank, and the tropical evergreen forest is assigned. Apparently there is an area expansion or shift to the north of the tropical evergreen forest.

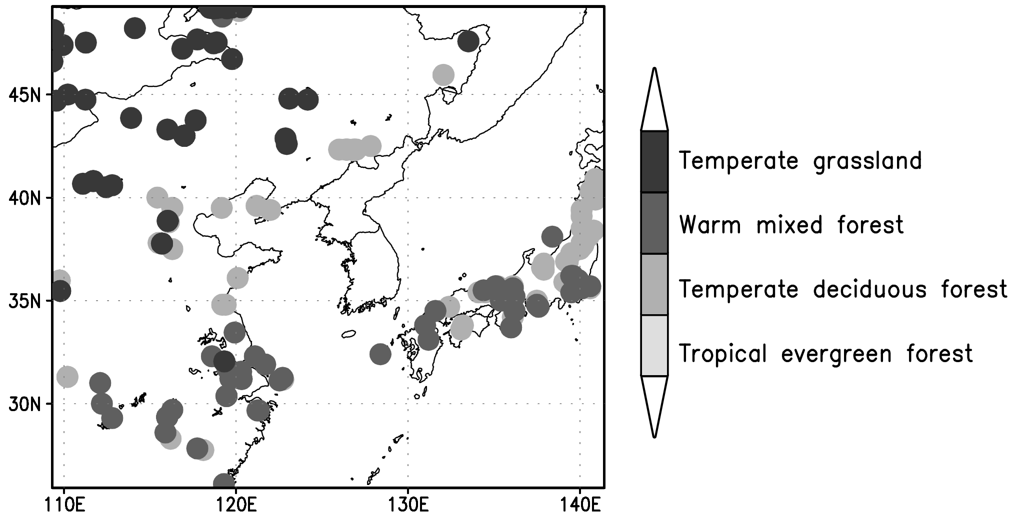

Fig. 4. – Observed vegetation distributions for 0 Ka year.

In an analogous way, the northward extension of the warm mixed forest, as well as the temperate deciduous forest, is explained in MM5-FUTURE compared to MM5-PRESENT. Area expansion trends also appear in the temperate deciduous forest with 19.2%. The warm mixed forest is related to the temperate broad-leaved evergreen PFT [20] that is defined with T_c from $-10°C$ to $0°C$. As shown in fig. 6, the corresponding T_c shifts northward to around 5 degrees. The authors in [7] also demonstrated

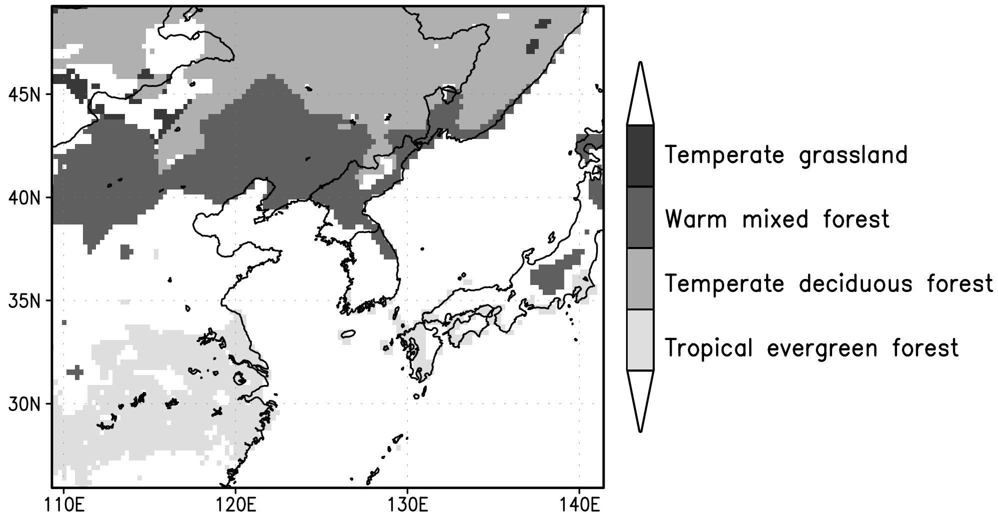

Fig. 5. – Change of vegetation distribution simulated by BIOME4 driven by the MM5 simulation which is calculated over the period of 2100-2070 minus 1971-2000. In this figure, white area represents absence of vegetation changes, while other light-to-dark grey areas represent new vegetation types.

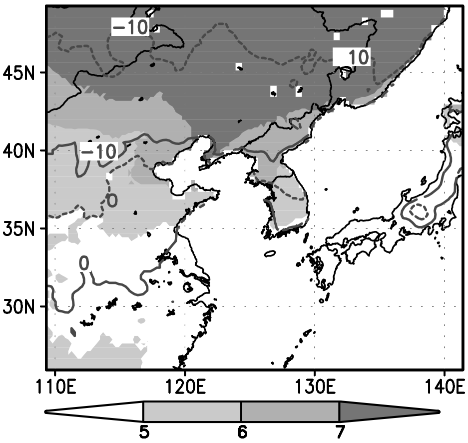

Fig. 6. – Change of minimum temperature(°C, shading) in the coldest month for the period of 2071-2100 with respect to 1971-2000 based on the MM5 simulation. 0°C and −10°C lines during the period of 1971-2000 and 2071-2100 are represented by solid line and dotted line, respectively.

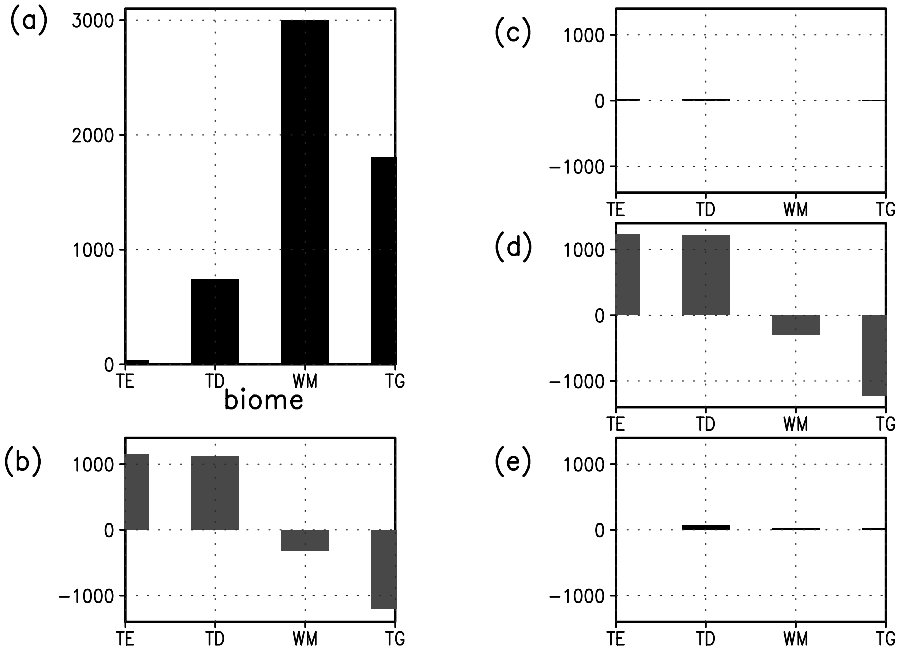

Fig. 7. – a) The number of grid cell of vegetation types of biome by MM5 during the period of 1971-2000 in fig. 3a. b) Change in number of grid cell of the vegetation types associated with the temperature increase from the 2071-2100 period with respect to the 1971-2000 period. c) Same as in b), but for precipitation. d) Same as in b), but for precipitation and temperature. e) Change in the number of grid cell of the vegetation types with CO_2 concentration increase. TE, TD, WM, and TG represent tropical evergreen forest, temperate deciduous forest, warm mixed forest, and temperate grassland, respectively.

the same result with the northward extension of a warm mixed forest associated with global warming, explaining that the vegetation change is a response to a warmer and wetter climate.

For the domain above 45°N, in northeastern China, the temperate grassland shrinks in MM5-FUTURE in contrast to MM5-PRESENT. According to [8], in wet conditions the woody-type PFT will dominate the growth of grasses. Accordingly, in wet condition such as those shown in fig. 1, grass is lower in rank, and its area shrinks in the process of competition.

In addition to T_c, other studies of [26, 27] reflect the GDD5 (Growing-degree days above 5°C) for climate rule for vegetation distribution. GDD5 is the sum of the daily temperature above 5°C. Also, the GDD5 does not directly determine the biome, but it may reflect the vegetation growth area change. Consistent with T_c, GDD5 has also considerably increased over the entire domain (figure not shown).

3·3. *Response to warmer and wetter climate change.* – Sensitivity experiments investigate the response of vegetation type which responds to the temperature and precipitation anomalies (fig. 7). Anomalies of temperature and precipitation are calculated from the temperature and precipitation during the periods of 2071-2100 with respect to those of the period 1971-2000. As shown in fig. 1, the anomalies of both quantities are positive over the entire domain. Figure 7a represents the number of grid cells of four biomes in fig. 3a. As shown in fig. 3a, the warm mixed forest has the largest area of the total grid cell. For temperature anomalies, fig. 7b shows a considerable area change of the biomes. As mentioned in comparison between MM5-PRESENT and MM5-FUTURE (figs. 3 and 5), there are area of expansion of tropical evergreen forest and temperate deciduous forest and area shrink of temperate grass land. The warm mixed forest does not show an area change due to the temperature increase, but the latitude of the distribution exhibits a large shift toward the north (fig. 5).

In contrast to the temperature change, the vegetation response to precipitation anomalies show neither noticeable area change (fig. 7c) nor area shift (figure not shown). Therefore vegetation response to anomalies of the temperature and precipitation in fig. 7d is mostly affected by temperature change.

Additionally, we examine the effect of only doubled CO_2 concentration under a fixed climate condition for the period of 1971-2000 (fig. 7e). Results show that the effect on vegetation growth is smaller than the effect of temperature change, implying that the CO_2 concentration effect on vegetation production is significantly affected by the climate condition rather than the CO_2 concentration itself. Possible responses of vegetation distribution to the climate change appear, rather than only to the atmospheric CO_2 concentration increase with a fixed climate condition.

4. – Conclusions

This study investigates the potential changes of vegetation distribution in the regional surface climate change due to global warming for the period of 1971-2100. Using a MM5 projection due to the SRES A2 scenario, the temperature over East Asia is expected to increase by 5°C, and the annual precipitation amount by 6% at the end of the 21st century. The increasing trend of temperature is associated with increasing trends of the minimum coldest-month temperature. The warming trend in addition to precipitation increase seems to contribute toward a favorable warmer condition in the higher latitudes, and to allow vegetation in the lower latitudes to shift northward. Therefore, tropical evergreen forests may appear over southern China at the expense of the warm mixed forest in the end of the 21st century. The warm mixed forests shift northward by about 5°. The area in which the temperate deciduous forest is found would shift northward, replacing the temperate grassland, and accompanying the area extension at the same time.

The area change of vegetation is primarily affected by the temperature change. In contrast, the vegetation response of precipitation change is negligible except in the desert region. The possible vegetation changes are affected by the temperature increase rather than the precipitation increase. As a result, vegetation distributions are expected to change severely over the entire domain in East Asia associated with global warming.

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