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Soil Temperature Response in Korea to a Changing Climate Using a Land Surface Model

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Abstract: The land surface processes play an important role in weather and climate systems through its regulation of radiation, heat, water and momentum fluxes. Soil temperature (ST) is one of the most important parameters in the land surface processes; however, there are few extensive measurements of ST with a long time series in the world. According to the CLImatology of Parameters at the Surface (CLIPS) methodology, the output of a trusted Soil-Vegetation-Atmosphere Transfer (SVAT) scheme can be utilized instead of observations to investigate the regional climate of interest. In this study, ST in South Korea is estimated in a view of future climate using the output from a trusted SVAT scheme — the University of TOrino model of land Process Interaction with Atmosphere (UTOPIA), which is driven by a regional climate model. Here characteristic changes in ST are analyzed under the IPCC A2 future climate for 2046-2055 and 2091-2100, and are compared with those under the reference climate for 1996-2005. The UTOPIA results were validated using the observed ST in the reference climate, and the model proved to produce reasonable ST in South Korea. The UTOPIA simulations indicate that ST increases due to environmental change, especially in air temperature (AT), in the future climate. The increment of ST is proportional to that of AT except for winter. In wintertime, the ST variations are different from region to region mainly due to variations in snow cover, which keeps ST from significant changes by the climate change.

Key words: Land surface process, soil temperature, climate change, soil-vegetation-atmosphere transfer (SVAT) scheme, University of TOrino model of land Process Interaction with Atmosphere (UTOPIA)

1. Introduction

For decades, the importance of land surface processes in the numerical simulations of weather and climate has been well known. The land has a significant impact on weather and climate through its regulation of radiation, heat, water and momentum fluxes across the land-atmosphere interface (Pielke et al., 1998; Nicholson, 2000; Kanae et al., 2006; Myoung et al., 2012).

Soil temperature (ST) is one of the most important parameters in the land surface processes. Most studies on the land surface parameters thus far have focused on soil moisture (e.g., Meng and Quiring, 2008; Seneviratne et al., 2010; Jaeger and Seneviratne, 2011; Peng et al., 2017), with less attention to ST; however, ST plays as important roles as soil moisture in weather, climate and environment. It serves as a lower boundary condition for predicting air temperature and moisture, convection, and clouds. Ground heat flux and the long wave radiation is a function of ST; thus the land energy budget can be determined by ST. Besides, understanding and predicting variation of land-related values such as crop production, agricultural planning, and soil nitrification or contamination depend on the knowledge of ST (e.g., Arai-Sanoh et al., 2010; Davenport et al., 2012). Fan (2009) found that incorporating the observed ST resulted in a persistent soil heating condition favorable to convective development in a regional model, leading to changes in locations and intensities of precipitating systems. Xue et al. (2012) demonstrated impact of the ST anomaly in the western US on summer precipitation over the southeastern US. Gómez et al. (2016) showed a marked improvement in simulating extreme heat events by incorporating ST into a regional model. Zhang et al. (2016) reported that, using a 50-yr temperature data of 1962-2011 in China, surface ST increased 31% more than air temperature, potentially leading to more carbon release to the atmosphere than predicted; thus inducing more warming through positive feedback.

Despite this importance, compared to measurement of soil moisture (e.g., Robock et al., 2000; Fan and van den Dool, 2004; Dorigo et al., 2011), there are significantly fewer extensive experimental measurements of ST in the world (e.g., Seyfried et al., 2001); thus prohibiting the correct estimation of the land energy budget on a wide area and for a sufficiently long time. Therefore, estimating land surface parameters by a modeling approach could alleviate this kind of problems, especially for ST. The model-based ST products often serve as alternatives for observations (e.g., Zhu and Liang, 2005; Pleim

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and Gilliam, 2009; Xia et al., 2013): the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS; Pitman et al., 1993) is one of the well-known examples. Recently, efforts to obtain higher-quality land surface parameters have been made via optimization (e.g., Hong et al., 2014, 2015) and/or improvement (e.g., Park and Park, 2016) of physical parameterization schemes in the model.

In this study, the energy budgets of the land surface were evaluated in view of the climate change, especially focusing on ST. Using a land surface model (LSM), the energy budgets under both the past and future climate conditions were simulated for the whole South Korea. To diagnose the future climate conditions, climate scenarios extracted from a regional climate model were applied. Several attempts to predict future climate effects using the future climate scenario can be found in the literature (e.g., Li et al., 2006; Krepalani et al., 2007; Mote and Salathé, 2010; Lee et al., 2015; Peng et al., 2017). South Korea has some future projections based on climate scenarios as well (e.g., Boo et al., 2004; Koo et al., 2009; Oh et al., 2016; Suh et al., 2016); however, they mostly focus on the meteorological variables like air temperature and precipitation. Furthermore, there have been few secondary researches using those projections, especially focusing on soil parameters like ST. The major goals of this study are: 1) to compare the past and future climate in South Korea under a fixed/given climate scenario; 2) to evaluate and analyze the effects of the climate change on ST; and 3) to obtain the long-term ST and other land-related values. Although ST can be affected by many factors, including vegetation fractions and types, soil moisture, air and skin temperatures, etc., we do not aim to examine the sensitivity of ST with respect to individual factors in this study.

Section 2 contains the description of models. A detailed description of experimental design including the climate scenarios is presented in Section 3. Section 4 shows the results of model simulations based on the climate scenarios, and Section 5 offers conclusions and a summary of the major findings.

2. Model description

The future projections are obtained from the fifth-generation NCAR/Penn State Mesoscale Model (Grell et al., 1994; hereafter referred to as MM5) for two different periods and are used to assess the regional climate change in South Korea. For the LSM, we employ the University of TOrino model of land Process Interaction with Atmosphere (UTOPIA; Cassardo, 2015), previously known as the Land Surface Process Model (LSPM; Cassardo, 2006), to simulate the effects of climate change on the energy components and to predict the future ST. Although the MM5 regional projections also produce ST, we prefer to run an offline external land surface scheme, i.e., UTOPIA, for evaluating all the soil parameters at the soil surface and in the soil layers, in order to have them well harmonized between each other; otherwise, we should take some parameters from one model (e.g., UTOPIA) and other parameters from another model (e.g., MM5), which would lead to dissonance or imbalance among the soil parameters.

a. Regional climate model: MM5

In the present study, we adopted climate scenarios which were extracted from a regional climate model, i.e., MM5 — a limited-area, nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulation. It has been widely used for numerical weather prediction, air quality studies, and hydrological studies (e.g., Mass and Kuo, 1998; Hogrefe et al., 2004).

The regional climate scenarios for Korea are produced by downscaling outputs from the Community Climate System Model version 3 (CCSM3; Collins et al., 2006), using MM5 — the same version and configuration used by Lee et al. (2015). The CCSM3 simulations were made for the periods of 1870-2000 (for 20C) and 2001-2100 (for 21C), using the Eulerian spectral core with 26 vertical layers and a spatial resolution of T85: the outputs are used as the initial and time-dependent boundary conditions for regional downscaling (Choi et al., 2011; Lee et al., 2015). The downscaled MM5 simulations are performed by nudging the CCSM3 outputs with a 6-hr interval. The MM5 configuration for climate simulations in this study include the followings: Reisner mixed-phase (Reisner et al., 1998) for micro-physics, Kain-Fritsch (Kain and Fritsch, 1993) for cumulus scheme, Medium-Range Forecast (MRF; Hong and Pan, 1996) for the planetary boundary layer, Rapid Radiative Transfer Model (Mlawer et al., 1997) for radiation, and Noah LSM (Chen and Dudhia, 2001) for land surface processes.

Although MM5 was developed for the study and prediction of mesoscale atmospheric phenomena, it has also been used for numerous regional climate studies around the world: for assessing model performance or impact (e.g., Fernández et al., 2007; Trusilova et al., 2008; Solman and Pessacg, 2012; Kum et al., 2014) as well as for producing regional climate scenarios (e.g., Tadross et al., 2006; Trusilova et al., 2008; Solman and Pessacg, 2012; Cabré et al., 2016). In addition, many regional climate studies over Korea have been performed using MM5 (e.g., Boo et al., 2004; Koo et al., 2009; Kum et al., 2014), and demonstrated reliability and capability of MM5 in evaluating future climate scenarios over Korea.

b. Land surface model: UTOPIA

The UTOPIA is a one-dimensional diagnostic model and was formerly named LSPM (Cassardo et al., 1995, 1998; Cassardo, 2006). It is a typical Soil-Vegetation-Atmosphere Transfer (SVAT) scheme (e.g., Boone et al., 2000; Arora, 2002), including three main zones for a schematic spatial structure — the soil, the vegetation and the atmospheric layers. It can quantify energy, momentum and water exchanges between the atmosphere and land surface.

The land surface processes in UTOPIA are described in terms of physical fluxes and hydrologic state of the land. The former includes radiation fluxes, momentum fluxes, sensible and latent energy fluxes and heat transfer in multi-layer soil, whereas the latter includes snow accumulation and melt, rainfall, interception, infiltration, runoff, and soil hydrology. In particular, snow is characterized by several physical properties — density, albedo, water equivalent, depth, water content, etc. — evaluated at every time step. In addition, depending on its height, the model evaluates at every time step the fractional coverage, different for vegetation and bare soil. The surface energy budget is evaluated considering all (radiative, conductive and convective) fluxes from vegetation, bare soil and snow, in which the weights are determined by the respective fractional covers.

Initial conditions of soil parameters in UTOPIA are required for soil type, ST and soil moisture at each soil layer. For this study, initial values of ST and soil moisture have been set following Cassardo (2015) — we did not use any soil data from MM5 for UTOPIA. For the ST initialization, an analytical solution of the Fourier heat equation is adopted; for the soil moisture initialization, a function obtained via an exponential adjustment of soil moisture with field capacity at increasing depths is employed.

The ST is calculated using multi-layer schemes whose parameters include thermal conductivity, dry volumetric heat capacity, soil surface albedo and emissivity. The UTOPIA can have as many soil layers as a user specifies; however, a sufficient number of layers is required for numerical stability. Note that numerical stability is strictly related to the integration time step — better stability with smaller time step. However, even with a sufficiently small time step, numerical instability may occur due to another factor, especially in solving soil moisture equation. If the same depth of soil is simulated using few soil layers, some numerical schemes that are used to discretize and solve soil water budget equation can become unstable in the presence of strong moisture gradients; thus leading to errors in the representation of soil moisture profiles. Meng and Quiring (2008) found that the multiple soil layers can represent well the vertical heterogeneity in soil properties.

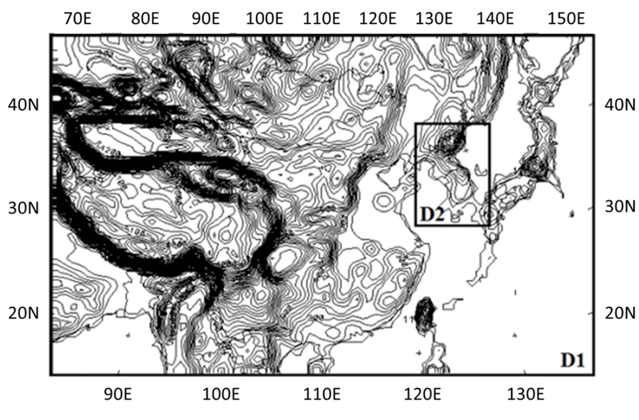


Fig. 1. Model domain and topography for East Asia (D1; 54 km resolution) and for the Korean Peninsula (D2; 18 km resolution) simulations through one-way nesting. From Choi et al. (2011).

In this study, the soil layer number is fixed to be 11. A detailed description of UTOPIA is referred to Cassardo (2015).

The UTOPIA has been tested in field experiments and with measured data, or coupled with an atmospheric model. Very detailed studies have been carried out not only for the Po Valley and Piemont, Italy (Cassardo et al., 1998, 2002, 2006) but also for regions out of Europe such as Sahel (Qian et al., 2001), the Gobi desert (Feng et al., 1997) and Korea (Cassardo et al., 2009). A recent application included the coupling of UTOPIA with the Weather Research and Forecast (WRF) model — the coupled WRF-UTOPIA had been applied to study a flash flood caused by a typhoon landfall (Zhang et al., 2011).

3. Experiment and case description

a. Domain and period

The MM5 simulations are performed at a 54-km horizontal resolution over East Asia with 23 vertical sigma levels, and at an 18 km spacing over Korea through one-way nesting (see Fig. 1). Over South Korea, we have the surface climate data at 268 grids. The MM5 has two soil layers with depths of 0-10 cm and 10-200 cm, respectively.

The domain for UTOPIA is South Korea bordered by the meridians 125°E and 130°E and the parallels 33°N and 38°N. It contains 268 grid points, spaced by about 18 km (Fig. 2). The boundary conditions are obtained from MM5. The UTOPIA has a total of 11 soil layers whose bottom-level depths are represented as: 5, 15, 35, 75, 155, 315, 635, 1275, 2555, 5115, and 10235 cm, from layer 1 (top) to 11 (bottom), respectively. With this deep soil layer (i.e., larger than 100 m), we can prevent non-null fluxes of heat and moisture from the bottom: those spurious fluxes can enter the model domain during long-term simulations, especially when the soil depth is shallow. Furthermore, it is demonstrated that the performance of LSMs is better with a soil layer having several levels than just 2-3 levels (Ruti et al., 1997). With regard to the spin-up time of UTOPIA, it was demonstrated that a period of 3-5 months is generally sufficient, in standard climatic conditions (see Cassardo et al., 1999); however, given the long time span (10 years) of climatic analysis, we did not eliminate the spin-up months as they would have little influence on the final averaged results.

Note that the depth of two bottom soil layers, i.e., the 10th and 11th layers, are 2,560 cm and 5,120 cm, respectively — occupying more than half of the total soil layer depth. These deepest layers are not intended to represent simulation results (i.e., future ST and soil moisture); they were rather used as boundary relaxation zones. In an experiment with 10 soil layers (i.e., by eliminating the 11th layer, hence the total depth of 5,115 cm), using the same spin-up time, we found that the solutions at the top layer were not affected at all. This implies that the spin-up process introduced no spurious errors, for different choice of the soil layer depth, and is adequately set in our simulations.

For the reference climate (RC), the 10-year climate of 1996-

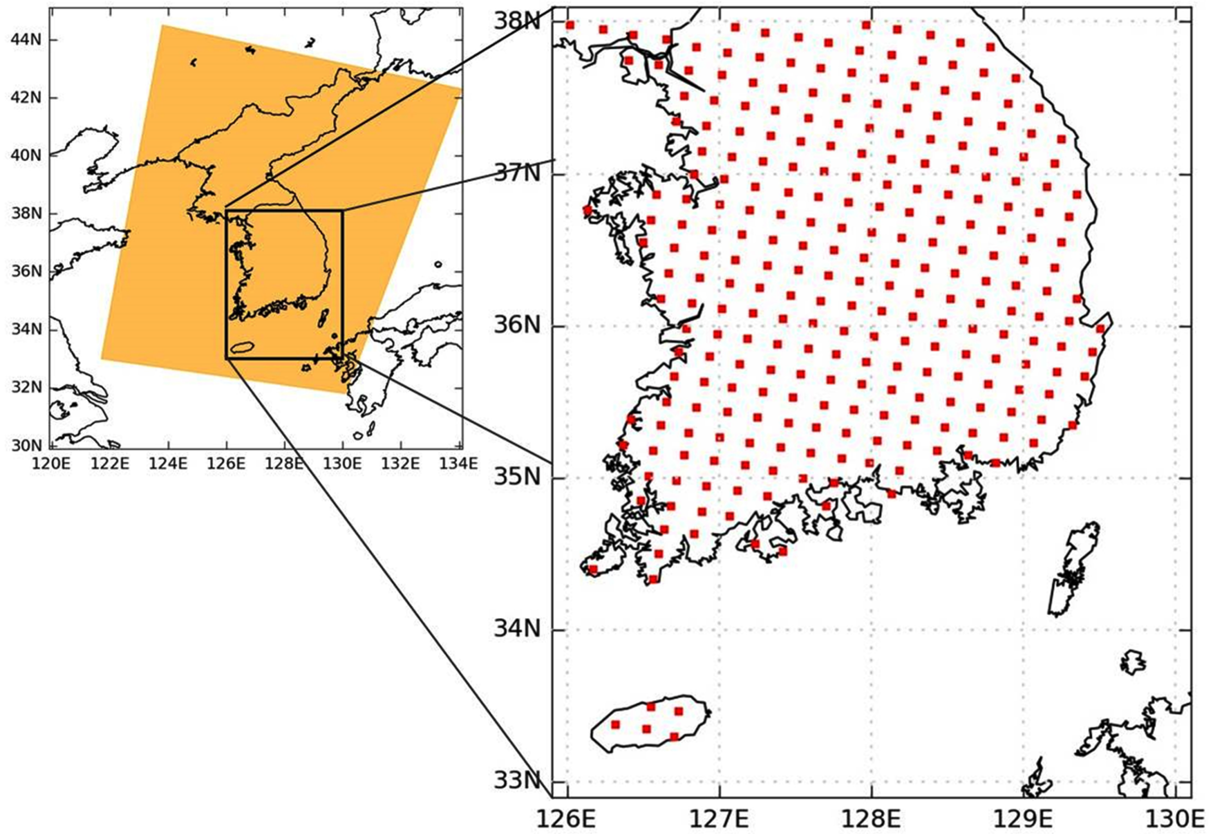


Fig. 2. Domain of climate scenarios (left), with the MM5 domain color-shaded, and the extracted grids for UTOPIA (right; red-dotted). The number of the UTOPIA grids is 268.

2005 is used. With respect to RC, two periods of the future climate (FC) are considered: 2046-2055 and 2091-2100. These future climate periods are hereafter referenced to as FC_{2046} and FC_{2091} according to the start year of each period. It is desirable to have a long-term data set, e.g., ~30 years, for a comprehensive climatic analysis; however, our climate projections were made in slices of ten-year periods (see, e.g., Wisser et al., 2011; Lee et al., 2015), and climatic analyses using ST was often made in a period less than 10 years (e.g., Hashimoto and Suzuki, 2004; Li et al., 2013).

b. Climate simulations

Some variables in the atmospheric layer were needed as boundary conditions (BCs), including air temperature, humidity, pressure, wind velocity, long- and short-wave incoming radiation, and precipitation rate. Usually, these variables are measured, but in this study to diagnose the effects of climate change, outputs of future climate from the MM5 simulations have been used.

The climate simulations of FC_{2046} and FC_{2091} were run based on the IPCC A2 emissions scenario (IPCC, 2000). The A2 scenario assumes the higher emission at the end of the 21st century, and describes an increasing global population with economic growth slower than in the other scenarios. This scenario is comparable to the Representative Concentration Pathway (RCP) 8.5 (Riahi et al., 2011) that provides an updated and revised future emission storyline. Cabré et al. (2016) indicated that A2 has similarities to RCP 8.5 in terms of radiative forcing, future trajectories (~8 W m^{-2} by 2100), and changes in global mean temperature (2.0-5.9°C for 2090-2099 compared to 1980-1999 for A2; 2.6-4.8°C for 2081-2100 compared to 1986-2005 for RCP 8.5). The non-mitigation scenarios, including A2, are described in the IPCC Special Report on Emissions Scenarios (IPCC, 2000); an overview of RCP scenarios is provided in van Vuuren et al. (2011).

The IPCC A2 scenario is a marker scenario and has been adopted to study future climate by itself (e.g., Bell et al., 2007; Graham et al., 2013) or through intercomparisons with other IPCC scenarios (e.g., Fischer et al., 2005; Déqué et al., 2007). It has also been applied to assess the impact of climate change on various fields, e.g., water resources (Arnell, 2004; Akhtar et al., 2008), food production (Parry et al., 2004), agriculture (Fischer et al., 2005), health problem (Bell et al., 2007), biodiversity (Williams et al., 2007), and regional climate and environment (Giorgi and Lionello, 2008; Lenihan et al., 2008; Chen et al., 2011; Graham et al., 2013).

Although a study with more scenarios would increase the spread of ST simulations, we decided to select a scenario at the higher end (A2) due to the limited resources. With this choice, we expect that the results would show the largest differences with respect to the RC; thus bringing about the highest impact to the global/regional environment and society. In the viewpoint of adaptation, we are more concerned about adaptation to a larger climate change because we can adapt relatively easily to the smaller climate changes by the lower end scenarios. On the other hand, we would like to underline that the major aim of this study is to focus on the possibility and reliability of using the simulated ST as a surrogate database for dealing with the lack of observations, rather than studying the impact of different climate conditions on ST.

All meteorological variables have been extracted from the climate scenarios with a time interval of 1 hr. One of the advantages using the climate simulation results instead of real observation data is that there are no missing values for the whole simulation period. However, to keep the stability of the UTOPIA, all variables for the UTOPIA BCs were interpolated to 30 mins by a cubic natural spline method, except precipitation data, for which the rate was kept constant in the consecutive time steps (30 min). By this assumption, the total precipitation amount is conserved through a smoothing of the highest peaks.

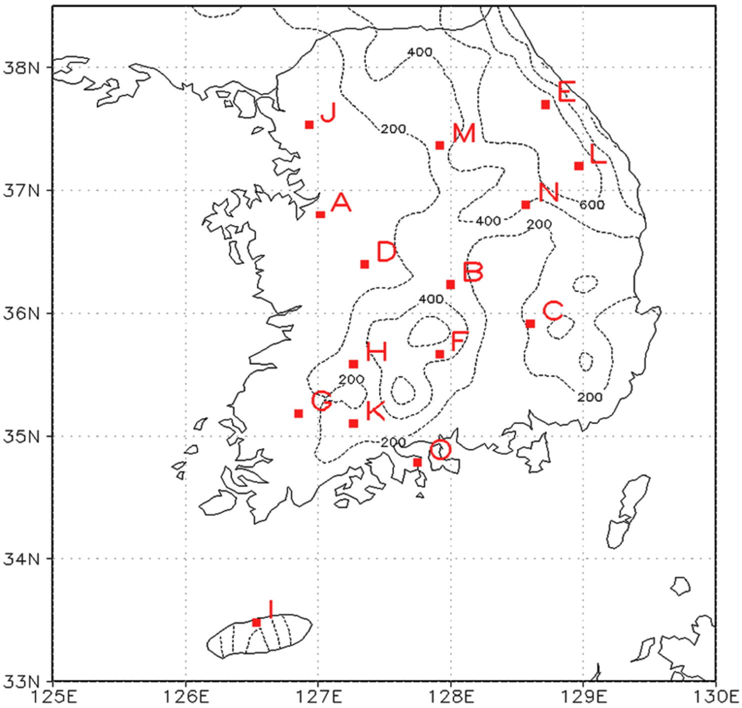
4. Results and discussion

a. Reference climate simulation and observations

The variables in RC, used as input data for UTOPIA, were compared with the corresponding observations. Air temperature (AT) is usually a criterion for estimating the climate change because of its huge impact on the energy budgets, and consequently on the land surface parameters.

The AT is strongly related to ST and can be a good parameter to estimate ST, especially for the land with less soil moisture. Jin and Mullens (2014) showed that, at the monthly annual cycle scale, surface AT had a higher correlation with upper ST than skin temperature, due to the lag of heat transport from the skin level to the surface air and to underground, respectively. Ahmad and Rasul (2008) derived correlations between AT and ST, both of the seasonal and daily mean, and found generally high correlations but with seasonal variations. Islam et al. (2015) also showed a strong positive correlation between AT and ST up to 20 cm depth of soil. Chudinova et al. (2006) found coincident oscillations in the annual time series of surface AT and ST in most Siberian areas. Zheng et al. (1993) showed that ST under snow or a vegetation cover had a reduced warming rate. Francone et al. (2010) reported the decrease of ST following the variation of AT during a cold spell. It is obvious that ST depends on surface AT, which serves as the boundary condition acting on the soil surface.

We first have compared seasonal ATs of RC with those from observed data. Among 76 weather stations operated by the Korean Meteorological Administration (KMA), we have selected 15 stations in consideration of spatial distribution, altitude, and data availability (see Fig. 3). These stations are sporadically distributed over a space to represent the meteor-



Station Index	Station Name	Latitude (°N)	Longitude (°E)
A	Cheonan	36.47	127.00
B	Chupungryung	36.13	128.00
C	Daegu	35.53	128.37
D	Daejon	36.22	127.22
E	Daegwanryung	37.41	128.46
F	Gochang	35.40	127.55
G	Gwangju	35.10	126.53
H	Imshil	35.37	127.17
I	Jeju	33.31	126.32
J	Seoul	37.34	126.80
K	Suncheon	35.04	127.14
L	Taeback	37.10	128.59
M	Wonju	37.20	127.57
N	Yeongju	36.52	128.31
O	Yeosu	34.44	127.44

Fig. 3. Fifteen weather stations for a comparison of RC and observations, represented on a map with station index (left). Dotted isolines represent the topographic height above sea level (in m). In the table (right), name and location, in terms of latitude and longitude, are shown for the corresponding station.

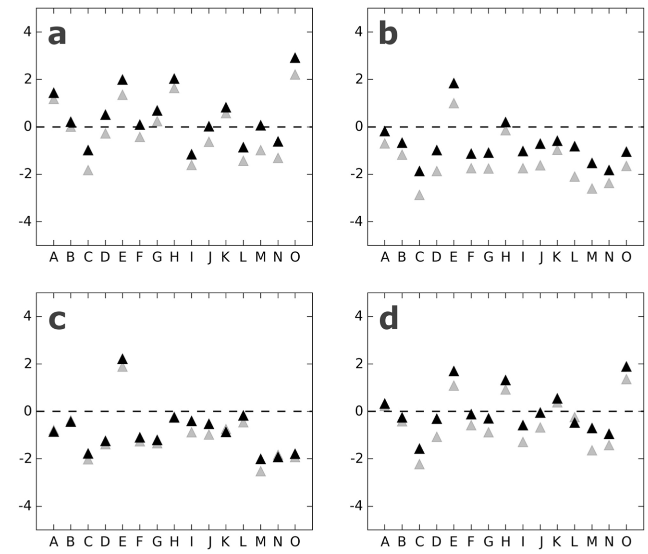


Fig. 4. Differences of air temperatures (the ordinate in °C) between the reference climate (RC) and observed data for the same period (i.e., 1996-2005; O_{RC}) and those of the past 30 years (i.e., 1971-2000; O_{NC}), respectively, for the 15 stations (indices in the abscissa). The grey triangles represent "RC – O_{RC}" and the black ones "RC – O_{NC}", averaged for the months of a) December, January and February (DJF), b) March, April and May (MAM), c) June, July and August (JJA), and d) September, October and November (SON).

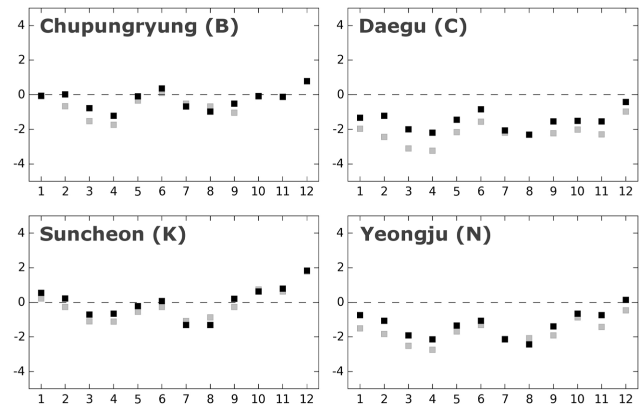


Fig. 5. Differences in air temperatures (the ordinate in °C) for different months (the abscissa): "RC – O_{RC}" (grey squares) and "RC – O_{NC}" (black squares) for Chupungryung (B), Daegu (C), Suncheon (K), and Yeongju (N), respectively.

ological characteristics of the broad region covering South Korea and are sufficient for validation purpose. The observed datasets are downloaded from the official website of the KMA (http://www.kma.go.kr/weather/climate/past_cal.jsp).

Figure 4 shows differences of surface ATs between RC and the observed data for each season, i.e., winter (December-January-February; DJF), spring (March-April-May; MMA), summer (June-July-August; JJA) and autumn (September-October-November; SON). For the observed data, two observation periods are selected — one for the same period with RC (1996-2005; hereafter "O_{RC}") and the other for the period of 1971-2000 representing the past climate with the 30-year mean (i.e., normal) values (hereafter "O_{NC}").

In Fig. 4, two AT differences (i.e., "RC – O_{RC}" vs. "RC – O_{NC}") show quite similar values, with absolute values less than 1°C. This implies that RC can be considered to be representative of the past climate conditions. It is noteworthy that O_{RC} shows higher AT than O_{NC} in most situations and seasons, except in summer (JJA; Fig. 4c). Such discrepancy may be partly justified considering the observational periods (1996-2005 for O_{RC} vs. 1971-2000 for O_{NC}). It is not surprising because the most recent 10 years (i.e., RC) showed an increasing trend of recorded temperature. Our results show that RC represents well the observed characteristics of AT at each station, with errors in the range of ± 2°C. The ATs of RC mostly have negative (cold) biases, except in winter (DJF; Fig. 4a). It is noteworthy that Yeosu (O), a coastal site, shows large positive biases in winter (Fig. 4a) and autumn (Fig. 4d); Daegwanryung (E), a high-mountain site, also depicts large positive biases in all seasons, distinctively in spring (Fig. 4b) and summer (Fig. 4c). This may be attributed to the deficiency of model to represent the local features that affect long-term AT, such as topography, radiation, local circulations, etc., in the region where the stations are located.

To examine RC in detail, monthly values were compared for selected stations. Figure 5 depicts the comparison between RC and observation in terms of the monthly average AT at Chupungryung (B), Daegu (C), Suncheon (K) and Yeongju (N). In most cases, the ATs of RC are lower than observations as stations C and N (i.e., cold bias or underestimation). However, some stations (e.g., stations B and K) show higher AT of RC in winter compared to the observations (i.e., warm bias or overestimation). There is an exceptional case such as station E (Daegwanryung; not shown), which displays warm biases throughout the year as shown in Fig. 4.

b. Reference and future climate scenarios

In this section, the differences of AT between the RC and FCs are described briefly. Figure 6 depicts the AT changes in the FCs with respect to the RC. In the FCs, South Korea undergoes a substantial warming. The ATs in FC_{2091} (red dots) are the largest, exceeding those in FC_{2046} (blue dots) at all stations. Especially, both FC_{2046} and FC_{2091} periods show the largest increment in winter (DJF; Fig. 6a) in most stations. Differences of the AT increment between FC_{2046} and FC_{2091} in the same locations are also the largest in winter.

In FC_{2046}, station O (Yeosu) is the only one that shows negative increments in AT (i.e., becomes colder than RC) during winter and autumn (see Figs. 6a and 6d). In FC_{2091}, it shows positive increments but much lower than the other stations. Given that the RC has strong positive AT biases in Yeosu during these two seasons (see Figs. 4a and 4d), it is reasonable to assume that the same biases are remained in the FCs as well. This implies that Yeosu will apparently have a

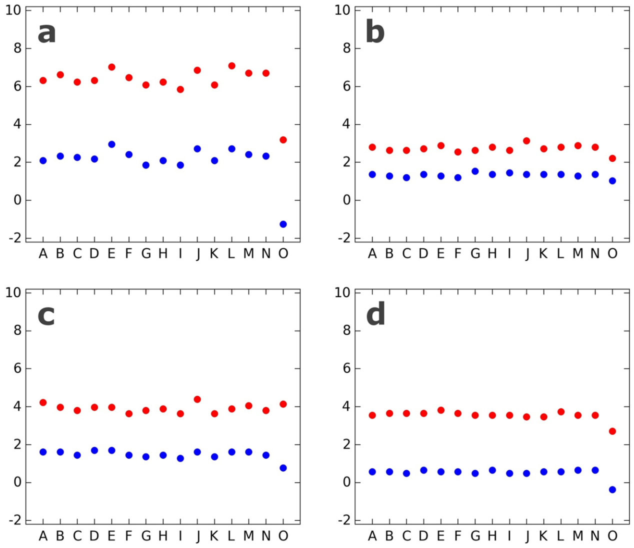


Fig. 6. Same as in Fig. 4 but for the air temperature differences between FCs and RC. The FCs include the period of 2046-2055 (FC_{2046}) and 2091-2100 (FC_{2091}). The blue dots represent "FC_{2046} – RC", and the red dots "FC_{2091} – RC": the former is always lower than the latter.

much lower AT in the future than the other stations during winter and autumn. In order to investigate this exceptional behavior, we need to do detailed analyses on various synoptic/climatic factors and local atmospheric circulations using high-resolution data, which is not feasible with the model data of current (coarse) resolution.

c. Soil temperature

To verify whether UTOPIA is able to reproduce the land surface parameters using RC, the simulated ST in the first layer, 5 cm, was compared with the observed ST at the same depth. This layer is considered to be the more representative than all the other soil layers because: i) the 5 cm depth is commonly defined as the top soil layer in many studies; ii) it is easier to validate the simulated ST with the measured ST — KMA provides measurement data at the depths of 5, 10, 20, and 30 cm only. Furthermore, the top soil layer shows the largest effects, due to various interactions of the soil parameters with the atmosphere.

The observed and simulated STs for 15 stations are shown in Fig. 7. The solid line indicates the monthly averages of the simulated ST, while the dashed line represents the monthly observed ST. Because there are no continuous ST observations for 10 years, the climate values from 1970 to 2000 were used instead of 10-year observations. Regarding STs from UTOPIA, four nearest simulated grid points were selected for each weather station. Then, STs at the four points were interpolated by the bi-linear interpolation, except station I (Jeju) and O (Yeosu) due to the impossible choice of four land neighboring points evenly by their geographical locations (i.e., coastal areas).

In general, compared to the observed values, the simulated ones are mostly underestimated, mainly in summer, as shown in Fig. 7. This tendency is also detected when ATs of RC was compared with those of observations (see section 4a and Fig. 4). For example, the simulated STs are lower until November at stations B and K, then become higher than observations in December as the annual cycle of AT (see Fig. 4). In another case, only station E shows overestimated ST throughout the year in accordance with overestimated AT in the RC. Station O shows a warm bias in ST during autumn and winter following the tendency in AT (see Figs. 4a and 4d). Our results indicate that ST has a reasonable monthly cycle in accordance with AT.

When we consider the AT differences between the RC and observations, AT in the RC is mostly lower in spring and summer compared to observations (see Figs. 4b and 4c). Similar to the simulated ATs of RC, the simulated STs of RC show cold biases in the spring and summer in most stations, except E and L (see Fig. 7). In stations E and L, located over the mountainous regions, the simulated STs of RC show warm biases in most months.

In the present study, no soil freezing scheme was applied in UTOPIA. The exclusion of soil freezing leads to the lower STs during winter time because of the lack of latent heat released from the frozen soil (Boone et al., 2000; Luo et al., 2003). Although the cold bias can be attributed to some other factors, e.g., a wrong estimate of cloudiness or solar radiation or both, the absence of freezing scheme can be one of the reasons why the simulated ST is lower than the observed ST in the middle of winter (January) for every station except station O (Yeosu).

As a result, even if the simulated winter ST is lower than the observed ST, UTOPIA provides reasonable and realistic seasonal cycle of ST in the RC, so it can be considered as a reference and is able to give credible output for the future climate conditions. However, as already mentioned, the uncertainties of the FC scenario can affect directly to the simulation results of UTOPIA.

d. Soil temperature and snow

Snow cover plays a vital role in energy budget through high albedo and low thermal conductivity, especially over the alpine areas; thus affecting the wintertime ST significantly (see Zheng et al., 1993; Gustafsson et al., 2001; Zhang, 2005; Yu et al., 2010). In terms of soil parameter prediction, adequate parameterization of the snow-covered albedo has been an important subject of land surface process modeling (e.g., Zhang et al., 2008; Park and Park, 2016). In this section, we show the 2-dimensional maps of ST by interpolating 268 grid points in South Korea and discuss the potential relationship between ST and snow cover in FCs.

Figure 8 shows STs of the RC in winter (Fig. 8a) and summer (Fig. 8b), when the largest changes are found. As inferred from the northeastern part of South Korea (i.e., the region of the highest elevation), STs become lower as the latitude and elevation are higher, especially in winter. The STs

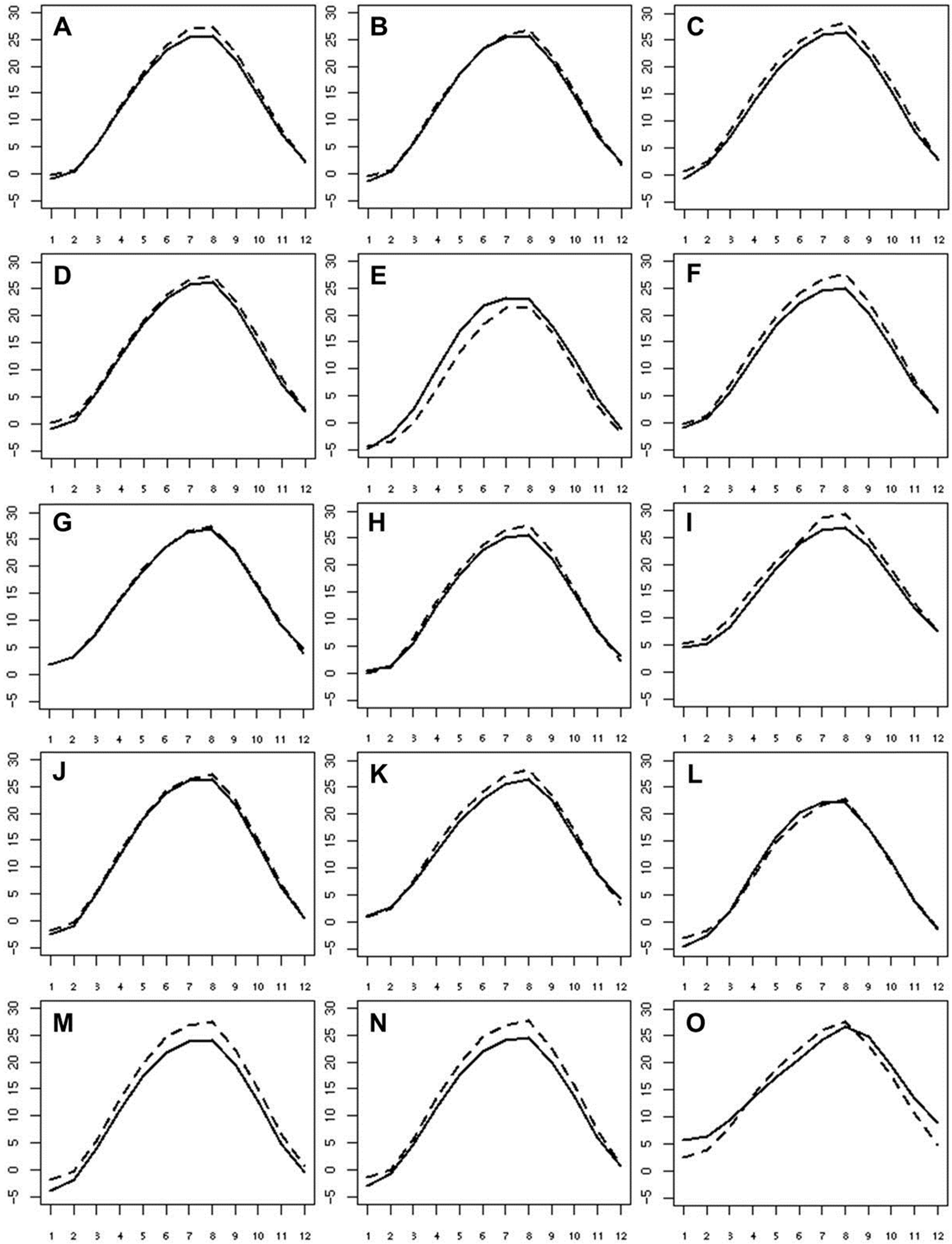


Fig. 7. Comparison of soil temperatures (the ordinate in °C) of the reference climate for the model simulation (solid) and the observational data (dashed), for 15 stations from A to O, for different months (the abscissa).

are relatively high in the narrow region of the northeastern part that includes the coastal areas with steep mountain slopes in both winter and summer.

In Fig. 9, the ST differences between the FC and RC (i.e., FC – RC) are shown for the summer (JJA; Figs. 9a and 9b) and the winter (DJF; Figs. 9c and 9d). In summer, the entire regions show an increase of STs. In general, the high latitudes show evident increases of STs, and the plains show larger

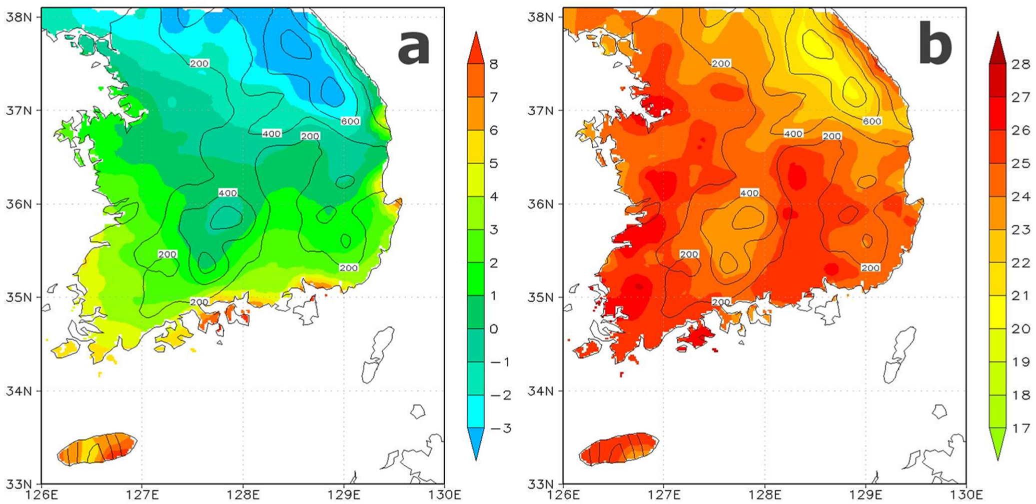


Fig. 8. The simulated soil temperature (color; in °C) of the reference climate for a) winter (DJF) and b) summer (JJA). Solid isolines represent the topographic height above sea level (in m).

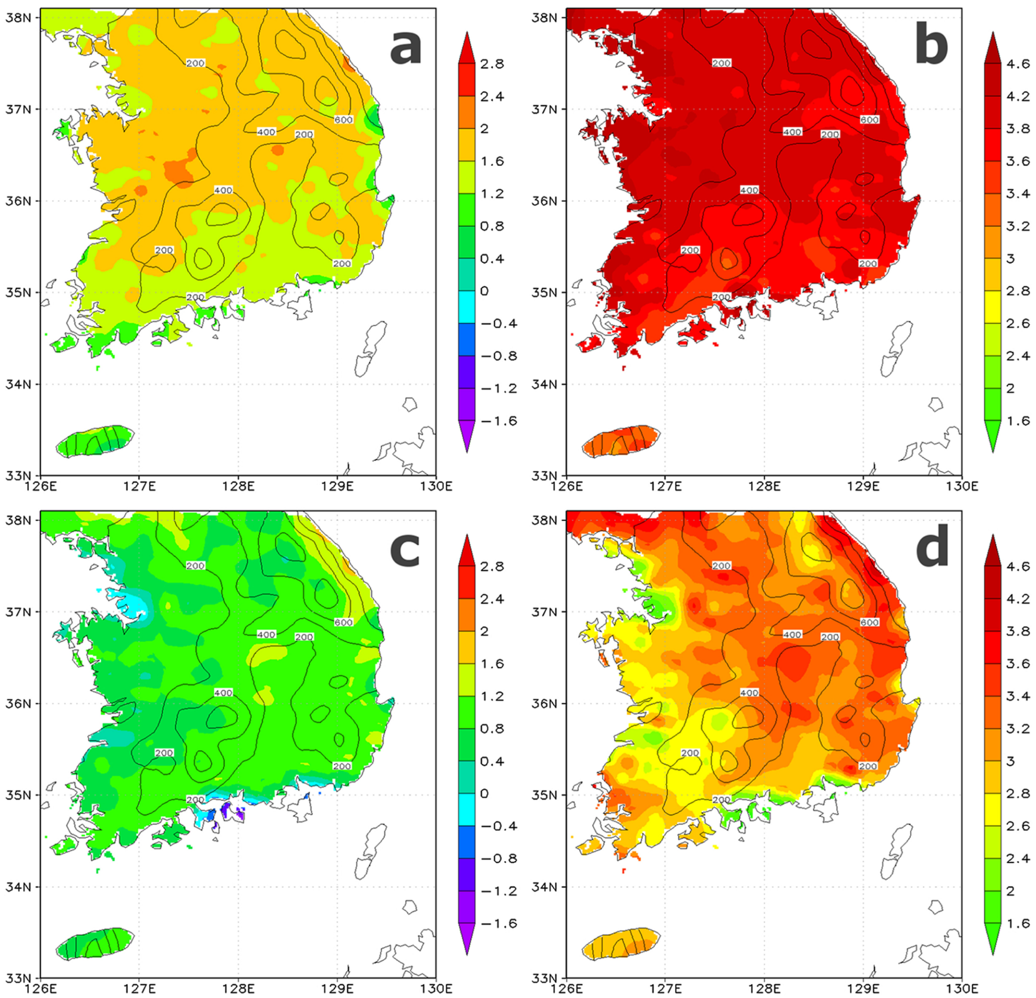


Fig. 9. Difference of soil temperature (color; in °C): a) and c) "$FC_{2046} - RC$", and b) and d) "$FC_{2091} - RC$", averaged for the summer months (JJA; upper panels) and for the winter months (DJF; lower panels). Solid isolines represent the topographic height above sea level (in m).

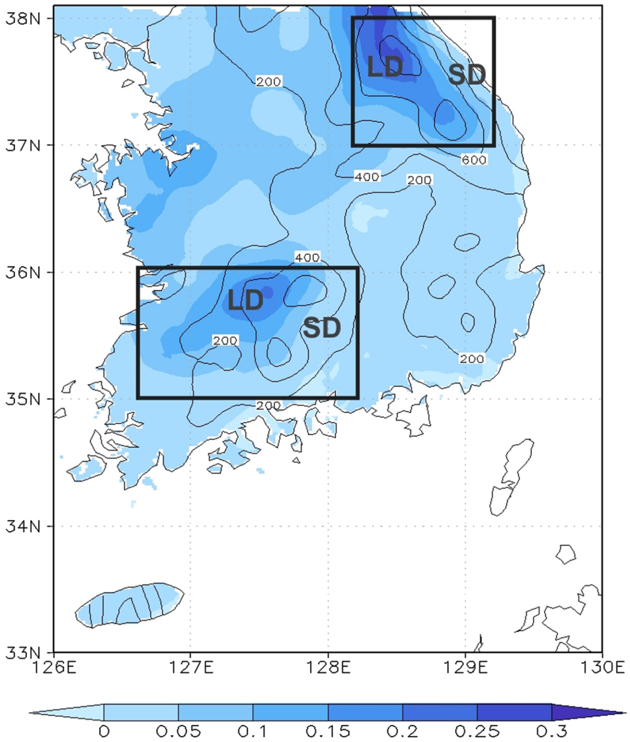


Fig. 10. The simulated snow depths (color; in m) of the reference climate averaged for the winter months (DJF). Regions of black boxes show high correlations between the decrease of snow depth and the increase of soil temperature in the future climates. Regions of SD (LD) represent the small (large) decrease in snow amount in the future climates. Solid isolines represent the topographic height above sea level (in m).

increases over the latitudinal regions higher than 36°N. This large increase of ST in the plains in summer occurs where the higher ST in the RC is observed (see Fig. 8b). In summer, the increase of ST (and AT) could be a consequence of an increase of the net radiation, and thus of sensible heat flux: this effect has been demonstrated in some plain stations of northwestern Italy during summer (see Cassardo et al., 2007). Meanwhile, the decrease in the winter ST in the region where station O (Yeosu) is located (Fig. 9c) is in good agreement with the cold increment in AT (see Fig. 6a). Generally, STs show a much larger increase in summer than winter in both FC_{2046} and FC_{2091}.

It is noteworthy that STs show a remarkable increase in the northeastern coastal and slant areas in both winter and summer under the future climate condition (Fig. 9). On the other hand, the nearby mountain summits show a relatively smaller increase of STs. Cassardo et al. (2009) showed that, during a summer monsoon in Korea, the dependency of ST to elevation (i.e., lower ST with higher elevation) was evident only for mountains higher than 1 km above sea level. In winter, the difference in the increase of ST may be related to the snow cover change. Zheng et al. (1993) showed that changes of ST under snow cover were smaller than those without snow cover. As seen in Fig. 10, the mountain top areas have a larger amount of snow than the coastal and slant areas. With the presence of snow, which is a poor conductor, STs are kept stable and no conspicuous change is detected (Gustafsson et al., 2001).

To confirm the existing relationship between ST and snow as a signal of changing climate, the point-to-point correlations are calculated between the increase of ST and the decrease of snow in FCs, using the 10-yr averaged values from each point. Significantly high correlations are found in the boxed areas in Fig. 10, where a relatively larger amount of snow is accumulated in the RC simulation. The average correlation coefficients for FC_{2046} and FC_{2091}, respectively, are 0.838 and 0.731 for the region of 35°-36°N, 126.7°-128.2°E, and 0.731 and 0.819 for region of 37°-38°N, 128.2°-129.2°E. Note that higher snow depths are observed around the mountainous areas, both in the northeastern and southwestern parts of South Korea. In the northeastern part, higher snow depths are observed over the mountain summits, whereas in the southwestern part they occur at the windward slope with prevailing northwesterly in winter.

In fact, the positive correlation between the decrease of snow depth and the increase of ST can be interpreted as a signal of climate change, or at least as an increase of AT: the ST increase can change the snowpack behavior — later formation, earlier ablation, and decreased height — due to a greater incidence of winter rainfalls instead of snowfalls. On the contrary, if the decrease of snow depth would be due only to the precipitation decrease (i.e., AT would not change or even decrease), ST would not vary or even decrease due to the decrease of insulating effect by the shallower (or null) snow layer.

Figure 11 shows that, in the northeastern part of South Korea, the snow amount will decrease at a higher rate over the mountain summit areas than the coastal and slant areas in the future (see "LD" and "SD", respectively, in Fig. 10). Although the decrease of the snow amount over the mountain summits is quite substantial (e.g., about ~0.14 m) in the FCs, the snow amount there in the RC is very high (e.g., about 0.3 m); thus snow still exists over the mountain summits in the FCs. On the contrary, at the northeastern coast and slant areas, say with height 200-400 m, shows a small decrease of snow (e.g., −0.04 ~0 m) in the FC_{2091}; however, snow depth there in the RC is 0~0.05 m, implying a strong reduction or disappearance of snow in the FC_{2091}. Thus, STs in the northeastern slants rise more and the inter-regional ST variation becomes bigger in the FC_{2091} as shown in Fig. 9d.

In conclusion, the future change in ST is strongly related to the change in AT. In summer, ATs increase about 2°C and 4°C, respectively, for FC_{2046} and FC_{2091}. The simulated STs show increases similar to ATs in summer. In winter, for FC_{2046} and FC_{2091}, respectively, AT increases about 2°C and 6°C (see Sect. 4.2), while ST rises by only 1.4°C and 4°C (see Fig. 9). The effects of snow presence and regional variations are more noticeable in winter, especially in FC_{2046}. In FC_{2091}, with an increase of ST by 4°C, snow will be less frequent in space and time, being limited only to the highest peaks and perhaps not

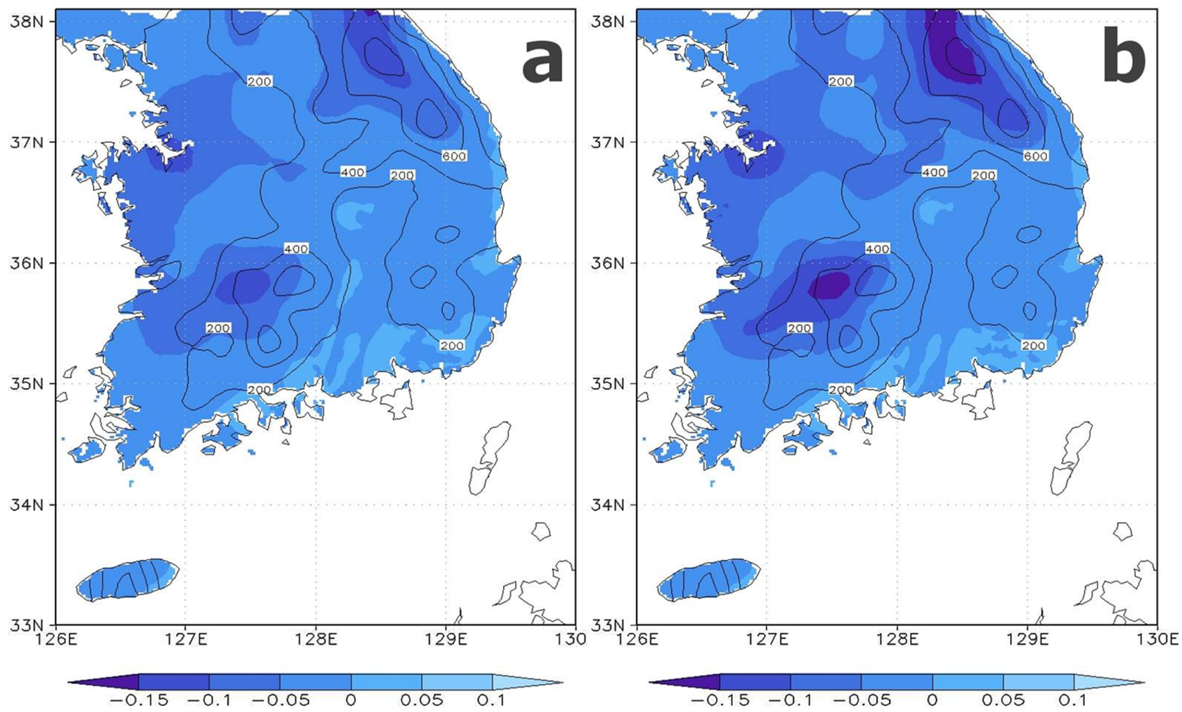


Fig. 11. Difference of snow depths (color; in m): a) "FC_{2046} – RC" and b) "FC_{2091} – RC". Solid isolines represent the topographic height above sea level (in m).

for the whole winter. The changes in STs during spring and autumn are less pronounced than during winter and summer. Temporally, the simulated warming is most pronounced in the FC_{2091} and during summer, with values of 3.3 -4.3°C, and the increasing rate is faster in the far future (i.e., FC_{2091}).

5. Conclusions

In this study, the land energy budgets are calculated over South Korea under the IPCC A2 emission scenario for the future periods of 2046-2055 (FC_{2046}) and 2091-2100 (FC_{2091}) with respect to the reference period 1996-2005 (RC). The simulations were performed with a land surface model, called the UTOPIA, using the MM5-derived atmospheric parameters as its boundary conditions, which are downscaled from the CCM3 global climate model. We focused on soil temperature (ST) due to a lack of their measurements despite their importance in many fields including meteorology and climatology.

Before carrying out the simulations, we confirmed the possibility of using RC as a reference climate conditions through the comparison of air temperature (AT) between RC and observations. The ATs of RC show reasonable and typical climate trends of South Korea.

We compared the land energy budgets between the RC and FCs for four seasons; however, in this study, we analyzed STs only in summer and winter, when their changes are the most significant. The increase in STs in the FCs strongly depends on the increase in the corresponding ATs. However, in winter, STs show lower increases compared to ATs, due to the snow effect. Snow keeps STs less variable and more stable with respect to the ambient warming, leading to variability in STs between the snow-covered and snowless regions. This variability becomes bigger in FC_{2091} since there are regions without snow even in winter.

Our results indicate that STs will increase due to the global warming in the future. The increases in STs are predominant in summer, but are also evident in winter when the snow disappears. In the RC, the increase in ST shows a good agreement with the increase in AT. According to the FC scenarios, the largest AT increase will occur in winter; thus, there will be a substantial increase in ST especially when the snow melts totally.

This study also provides a dataset of STs in South Korea for the RC and FCs. It can be used in many research fields, including meteorology, climatology, agriculture, etc., especially in intercomparing various climate scenario and model studies. In fact, Europe has carried out a project called the Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects (PRUDENCE), using an array of climate models and impact models in order to quantify their confidence and uncertainties in predictions of future climate and its impacts. So this dataset can be considered as the very first contribution, in terms of ST, of a sort of PRUDENCE project for South Korea. Note that our simulations did not consider the potential change of vegetation or land cover in the FCs. The setting of the vegetation and land cover was exactly the same for both the RC and FCs as in the MM5 simulations. Therefore, the increase in ST can be alleviated or intensified depending on the vegetation and land cover types in the future.

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