

Article

Possible Impacts of Snow Darkening Effects on the Hydrological Cycle over Western Eurasia and East Asia

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Abstract: In this paper, we investigated the possible impact of snow darkening effect (SDE) by light-absorbing aerosols on the regional changes of the hydrological cycle over Eurasia using the NASA GEOS-5 Model with aerosol tracers and a state-of-the-art snow darkening module, the Goddard SnoW Impurity Module (GOSWIM) for the land surface. Two sets of ten-member ensemble experiments for 10 years were carried out forced by prescribed sea surface temperature (2002–2011) with different atmospheric initial conditions, with and without SDE, respectively. Results show that SDE can exert a significant regional influence in partitioning the contributions of evaporative and advective processes on the hydrological cycle, during spring and summer season. Over western Eurasia, SDE-induced rainfall increase during early spring can be largely explained by the increased evaporation from snowmelt. Rainfall, however, decreases in early summer due to the reduced evaporation as well as moisture divergence and atmospheric subsidence associated with the development of an anomalous mid- to upper-tropospheric anticyclonic circulation. On the other hand, in the East Asian monsoon region, moisture advection from the adjacent ocean is a main contributor to rainfall increase in the melting season. A warmer land-surface caused by earlier snowmelt and subsequent drying further increases moisture transport and convergence significantly enhancing rainfall over the region. Our findings suggest that the SDE may play an important role in leading to hotter and drier summers over western Eurasia, through coupled land-atmosphere interaction, while enhancing East Asian summer monsoonal precipitation via enhanced land-ocean thermal contrast and moisture transport due to the SDE-induced warmer Eurasian continent.

Keywords: snow darkening effect; soil moisture; hydrological cycle; precipitation recycling; land-atmosphere interaction

1. Introduction

Light absorbing aerosols (LAAs, e.g., dust, Black Carbon, and Organic Carbon) can affect the energy budgets and hydrological cycle of the atmosphere and land in a variety of ways. As presented in previous studies, LAAs absorb and scatter solar radiation in the atmosphere, altering the climate system [1–8]. In addition, LAAs deposited on snow reduce snow albedo by snow darkening effect (hereafter SDE) and accelerate snowmelt during spring in mid-latitudes [9–19]. As well known, snow in Eurasia continent also plays an important role in regional and global climate system change. Snowfall and snow cover are closely linked to local changes in air temperature and atmospheric circulation [20,21]. The snowpack over Eurasia has an inverse relation with subsequent Asian summer monsoon precipitation. Heavy snowfall and widespread snow cover in the winter and spring will cool



and delay the heating over Eurasia in summer due to the high albedo of snow and consumption of heat for snow melting. As a result, summer monsoon in Asia is weakening and the start of monsoon is delayed [16,22–25]. These effects are closely related to changes of surface energy and water budgets. Changes in snowmelt affect the infiltration and outflow processes, resulting in changes of soil moisture content [26].

Soil moisture can affect not only the local climate, but also other regions through land-atmosphere coupling and teleconnection. Changes in soil moisture induce variations in latent heat and the sensible heat fluxes, thereby changing the temperature near the surface. Studies have shown that positive soil moisture anomalies enhance evaporation, affecting heat and moisture exchange between near surface and atmosphere [27,28]. Thus, the feedback between land and atmosphere plays an important role not only in energy balance but also in the water balance of the hydrologic cycle [29–31]. Previous studies have demonstrated that this feedback affects regional climate change in various regions such as United States [32,33], Europe [34–37], and East Asia [38–40]. Several studies have analyzed land-atmosphere interactions using precipitation recycling ratio [41–46]. The water vapor of total precipitation consists of local evaporation and externally moisture transportation. The recycling ratio is defined as the fraction of precipitation over a specified area that originated as surface evapotranspiration from same area [47]. The water recycling ratio is different depending on regional and seasonal characteristics of the land surface. Notably, Dominguez and Kumar [26] and Li et al. [29] demonstrated that water recycling is a key component in total precipitation over arid regions which are far from ocean. Trenberth et al. [48] and Zhang et al. [49] suggested that precipitation recycling ratio is a good indicator to measure interactions between land surface and atmosphere.

This study aims to explore impacts of SDE by LAAs on hydrological cycle focused on possible connection between Western Eurasia (WE) and East Asia (EA), and to analyze the precipitation recycling compare features in two regions to understand precipitation change properties. In particular, the land-atmosphere system of the selected two regions responded very differently to SDE. One of the regions became drier and the other region got wetter [13]. For this reason, the local responses of hydrological cycle by SDE were analyzed by comparing changes in WE and EA region. Previous work have found atmospheric circulation pattern linking Europe to Asia during the boreal warm season [50,51]. However, the connection mechanism induced by SDE is still not well understood. Therefore, this study investigated the changes in atmospheric circulation patterns by SDE and the changes in hydrological cycle. This paper is organized as follows. Section 2 presents the data and methods used in this study. In Section 3.1, describes the forcing and responses by SDE. Sections 3.2 and 3.3 provide description of precipitation and SDE-induced changes over western Eurasia and East Asian, respectively. The results of the land-atmosphere interactions are discussed in Section 3.4 with conclusions in Section 4.

2. Materials and Methods

We use the NASA Goddard Earth Observing System Model Version 5 (GEOS-5) [52] to carry out ensemble experiments to obtain the SDE impacts on the hydrological cycle over Eurasia, with prescribed sea surface temperatures (SSTs) and sea ice. The land surface model in this GCM is the catchment model [53,54]. The GEOS-5 uses the GOddard SnoW Impurity Module (GOSWIM) which includes radiative transfer calculations of snow albedo and tracks through the snow the mass distributions of deposited constituent aerosols of dust, BC, and OC [12,19]. The emission, transport and radiative processes of aerosols are provided by the Goddard Chemistry Aerosol Radiation and Transport (GOCART) module [55]. The version of GEOS-5 used in this study does not consider aerosol indirect effects [56].

In this study, two sets of 10-member ensemble experiments were carried out. All the experiments are integrated for 10 years (from 2002 to 2011). In these experiments, the horizontal resolution of GEOS-5 is set at $2^{\circ} \times 2.5^{\circ}$ in latitude and longitude, with 72 vertical layers [13]. The process of land surface and snow interactions (GOSWIM) is turned on in the control experiment (SDE). The second

set of experiments is identical to the SDE except for No-SDE (NSDE) by disabling of the GOSWIM radiative transfer calculations in snow. Both SDE and NSDE included atmospheric heating by LAAs. The bias and evaluation of the experiments were provided by Lau et al. [15] and Yasunari et al. [13]. The SDE is defined as the difference between two sets of ensemble experiments (SDE minus NSDE). The statistical significance of the results was evaluated using the Welch's t-test. To quantify solar absorption by light-absorbing impurities, such as dust, BC, and OC, in snow, we used a total Snow Impurity Absorption Coefficient (total SIAC) as defined in Lau et al. [15]. The SIAC is the product of the impurity mass concentration and the mass absorption coefficients (MACs) in snow. The MAC values of each aerosol are based on the result of Yasunari et al. [12]. Total SIAC is expressed as the sum of the SIAC for each type of impurity.

We have applied the approach of Brubaker et al. [47] to compute a precipitation recycling ratio. Considering a domain traversed by a length scale L, average horizontal moisture flux F, average precipitation P, and average evapotranspiration E, the total precipitation P is the sum of an advective (P_a) and a local evaporative (P_l) components of water vapor, i.e.,

$$P = P_a + P_l$$

If $F = \frac{1}{2}(F_{in} + F_{out})$, where F_{in} is the flux of moisture into the region and F_{out} is the out flux, then, the horizontal flux of advected moisture over the region is

$$Q_a = F_{in} - \frac{P_a L}{2}$$

and the horizontal flux of evaporated moisture is

$$Q_l = \frac{(E - P_l)L}{2}$$

Assuming that the atmosphere is well mixed, the ratio of precipitation from advection vs. evaporation is equal to the ratio of average advected to evaporated moisture in the air. Thus,

$$\frac{P_a}{P_l} = \frac{Q_a}{Q_l} = \frac{F_{in} - \frac{P_aL}{2}}{\frac{(E-P_l)L}{2}}$$

so that the fraction of precipitation due to evaporative origin can be written

$$\beta_1 \equiv \frac{P_1}{P} = \frac{EL}{EL + 2F_{in}}$$

and the fraction of precipitation due to advective origin is

$$\beta_2 \equiv \frac{P_a}{P} = \frac{2F_{in}}{EL + 2F_{in}}$$

In this study, the above equations were used to analyze the regional precipitation changes. A more detailed description of the recycling model can be found in Brubaker et al. [47].

3. Results and Discussion

3.1. Forcing and Responses by SDE

The spatial distributions of total SIAC during April–May (AM) and June–July (JJ) are shown in Figure 1. The large values of AM mean total SIAC are found over the north of Caspian by mineral dusts from adjacent deserts. The strong signals of light-absorbing by BC deposited on the snow are over Western Europe and East Asia, near highly industrialized cities. On the other hand, in all regions,

the contribution of OC to total SIAC is generally less than 20% [13,15]. As a result, of SDE, increased shortwave radiation over the snow induces rapid snowmelt and surface warming. The most distinctive warming is found over Western Eurasia, East Asia, and Tibetan plateau where the total SIAC is stronger than other place, which means that the SDE is important at these regions. The onset of snowmelt was earlier due to the increased in incoming energy on the surface by SDE. Changes in snowmelt are related to increase in short wave radiation and surface temperature. During April to May, snowmelt increases in the north region of maximum change of shortwave radiation and decreases in the south region resulting from earlier and rapid snowmelt in March (Figure 1a, Figure 2a,c). The spatial distribution of precipitation during April to May shows that the precipitation is increased by the SDE over most of Eurasian continent, except for around 40 °N. The precipitation anomaly is the largest over China inland and the rainfall increases in India, Japan, and the western part of Eurasia continent (e.g., Europe and Russia) are also significant. On the other hand, precipitation decreased in some areas, particularly in the Southeast Asia and the Korean Peninsula (Figure 3c). Increase in soil moisture is evident in regions of increased precipitation and snowmelt. However, spatial distribution of soil moisture is more complicated than that of precipitation and snowmelt because it relates to evaporation and runoff as well as precipitation and snowmelt variation (Figure 3e).

In JJ, the strong signal of total SIAC does not appear below 40 °N, except for the Himalayas-Tibetan plateau because snow line moves northward with season (Figure 1b). The strong response of shortwave radiation over the Himalayas-Tibetan plateau and polar region is directly linked to changes in the snow cover and surface albedo. The decreased snow cover by SDE leads to a reduced surface albedo, which cause land surface warming over that region, with the amplitude of greater than 3 °C. At the same time, the surface warming in the mid-latitude regions persists, but weaker than in AM (Figure 2b). The reductions in snowmelt were noticeable in western Russia and the eastern part of the Tibetan plateau. These regions coincide with the areas where snowmelt increased significantly during April and May (Figure 2d). The changes in daily precipitation by SDE show that there is a large difference depending on the region. As a result of increased moisture transport, precipitation is remarkably increased from the Bay of Bengal to East Asia, including China and Korea. On the other hand, the reduction in precipitation is prominent in Western Eurasia and west part of India subcontinent and Arabian Sea. Correspondingly, the soil moisture changes in eastern and western Eurasia have shown opposite sign (Figure 3d,f).



Figure 1. Spatial distribution of total Snow Impurities Absorption Coefficient (total SIAC) in (**a**) April–May and (**b**) June–July. Colors of dots indicate dominant component (more than 50% contribution). Two boxes in (**a**) indicate Western Eurasia (20–60 °E, 40–60 °N) and the East Asia (110–135 °E, 24–56 °N) domain, respectively.





Figure 2. Spatial distributions of SDE-induced anomalies of (**a**) surface skin temperature(shaded) and shortwave radiation(contour), and (**c**) snowmelt during April–May. (**b**,**d**) are same as (**a**,**c**), except for June–July. Dots represent statistical significance at 99%.

In particular, in Western Eurasia (WE, 20–60 °E, 40–60 °N) and East Asia (EA, 110–135°E, 24–56 °N), the increase in temperature and rainfall are noticeable during AM, but the change in precipitation is quite different during JJ. This is the reason we choose the two regions. The differences between the WE and EA will be discussed in more detail in Sections 3.2 and 3.3.

3.2. Changes in Western Eurasia ($40 \sim 60^{\circ}N, 20 \sim 60^{\circ}E$)

To further examine the changes in precipitation over the WE, we analyzed the regional-average daily variation. The total precipitation increased gradually from April, with the maximum value 2.3 mm/day in July and then steadily decreasing until the early October (Figure 4a). As mentioned earlier, total precipitation is the sum of advective and evaporative precipitation. Based on this, we separated into the two types of precipitation by source and examined their contribution. The advective precipitation in this region is 1.2mm/day of annual mean, accounting for more than 76.8% of total amount however its seasonal variability is not large. In contrast, there is a distinct seasonality in the contribution of advective precipitation (β_1) to total amount is less than 10%, while it is increasing up to 40.6% in summer, suggesting that summer precipitation in WE is more sensitive to soil moisture than in wintertime, even though moisture transport is the dominant component for both winter and summer (Figure 4b). These results are consistent with the findings of Schär et al. [36] that European precipitation in summer is sensitive to the soil moisture using the regional climate model. Furthermore, in Bisselink and Dolman [57], the results of precipitation recycling ratio for central Europe presented using ERA-40 data are agreement with the results of this study.



Figure 3. Spatial distributions of (**a**) mean precipitation (shaded, mm/day) with 850 hPa moisture transport (vector, $gkg^{-1}ms^{-1}$), SDE induced anomalies of (**c**) precipitation and 850 hPa moisture transports, and (**e**) soil wetness (%) during April–May. (**b**,**d**,**f**) are the same as (**a**,**c**,**e**), respectively, except for June–July. Dots represent statistical significance at 95%.

The SDE-induced change in total precipitation increases from April to May but decreases during peak period (Figure 4a). Noteworthy is that 92.7% of the increase in precipitation is attributable to the P₁ (Table 1) due to evaporative moisture change over the region, which corresponds well with the upward motion in the same period (Figure 4c). Notably, during April and May, the anomalous rising motions are found most pronounced in the troposphere. In addition, the surface warming due to SDE during AM can induce earlier and more snowmelt, and the snow-melted water lead to more soil wetting [15]. These changes provide favorable conditions for evaporation from surface to atmosphere. Hence the precipitation change due to SDE is closely related to the soil moisture change, which means that the interaction between land and atmosphere is important. The change in water content on a daily scale is described in Lau et al. [15] in more detail. During June and July, the reduction in precipitation is also found consistent with the enhanced descent movement (Figure 4c). At the same period, the low-level moisture flux at 850 hPa is divergence horizontally in associated with increased subsidence and the development of large-scale, mid- to upper-level anomalous anticyclonic circulation (see discussion in Section 3.4). Overall, for western Eurasia, the contributions of advection and evaporation to total

precipitation changes are 47.2% and 52.8%, respectively (Table 1). The above results show that the reduction in precipitation is found to be similarly affected by two factors, evaporation and advection, in early summer.



Figure 4. Seasonal variations of daily changes in (**a**) precipitation (mm/day), (**b**) β_1 , and (**c**) pressure velocity $(-100 \times Pas^{-1})$ for WE. Black, purple, and green lines in (**a**) are P₁ (local-induced precipitation), Pa (advection-induced precipitation), and P (total precipitation), respectively. Red (blue) shadings represent increased (reduced) anomalies by SDE. Positive (negative) values in (**c**) indicate rising (sinking) motion. See text for definition of β_1 .

Table 1. Changes in components of precipitation during AM and JJ for WE. (a) Local-induced precipitation (mm/day), (b) advection-induced precipitation (mm/day), (c) total precipitation (mm/day), (d) the fraction of Local-induced precipitation (%), and (e) the fraction of advection-induced precipitation (%). **, and * in (c) represent statistical significance at 99%, 95% and 90%, respectively.

	(a) ΔP_1	(b) ΔP_a	(c) Δ <i>P</i>	(d) $\Delta\beta_1$	(e) $\Delta\beta_2$
AM	0.089	0.007	0.096 **	92.7	7.3
JJ	-0.034	-0.038	-0.072 *	47.2	52.8

3.3. Changes in East Asia (24 ~ 56°N, 110 ~ 135°E)

East Asia is well-known as a representative seasonal monsoon region. Over the East Asian domain annual mean precipitation is about 3.1mm/day, the lowest in winter and the highest in summer, with the summer precipitation accounting for more than 46.2% of annual total precipitation amount. The total

precipitation increases rapidly following the onset of the summer monsoon, and peaks in June-July in this region due almost entirely to moisture advection. In other words, advective precipitation (P_a) is far more dominant than evaporative precipitation, with maximum contribution of 83.1% in May. On the other hand, recycled precipitation (P_1) is minimal, from 0.36 mm/day to 1.6 mm/day. The ratio of P_1 to total precipitation (β_1 , not shown) decreases from January to April. This ratio (β_1) does not exceed 25% in June and July. In wintertime, the local evaporative precipitation is relatively more important than the other seasons (up to 40%). However, because of scarce wintertime precipitation, the absolute amount of precipitation from local evaporative process is small (Figure 5a,b).



Figure 5. Seasonal variations of daily changes in (**a**) precipitation (mm/day), (**b**) β_1 , and (**c**) pressure velocity $(-100 \times Pas^{-1})$ for EA. Black, purple, and green lines in (**a**) are P₁ (local-induced precipitation), Pa (advection-induced precipitation), and P (total precipitation), respectively. Red (blue) shadings represent increased (reduced) anomalies by SDE. Positive (negative) values in (**c**) indicate rising (sinking) motion. See text for definition of β_2 .

During April and May, the change in precipitation is 0.274 mm/day, which is statistically significant within 1%. P₁ and P_a contributed 20.4% and 79.6% to this change, respectively. During June and July, increase in precipitation is less than that of AM period, but the contribution of change in precipitation by moisture advection increases to 97.2% (Table 2). These results are due to increased large-scale thermal contrast associated with a warmer land over northern Eurasia and the Himalayas-Tibetan region caused by the SDE (cf., Figure 2b, and Lau and Kim 2018). SDE-induced vertical motion is strongest in April–June and lasts through July–August in conjunction with the increased rainfall (Figure 5c).

Table 2. Changes in components of precipitation during AM and JJ for EA. (a) Local-induced precipitation (mm/day), (b) advection-induced precipitation (mm/day), (c) total precipitation, (d) the fraction of Local-induced precipitation (%), and (e) the fraction of advection-induced precipitation (%). *** and * in (c) represent statistical significance at 99%, 95% and 90%, respectively.

	(a) ΔP_1	(b) ΔP_a	(c) Δ <i>P</i>	(d) $\Delta\beta_1$	(e) $\Delta\beta_2$
AM	0.056	0.218	0.274 ***	20.4	79.6
IJ	0.006	0.208	0.214 *	2.8	97.2

3.4. Changes in Atmospheric Circulations

In this section, we examine changes in atmospheric conditions during spring and summer, associated with changes in precipitation in the two regions by SDE. For WE region, during April and May, the land surface is warmed by increased incoming solar energy due to LAAs deposited on snow. The soil moisture is increased by accelerated snowmelt. In conjunction with air temperature, moisture is increased in the lower troposphere. These changes are in agreements with the increased in evaporative precipitation over the WE. Because, increases in energy and water at the surface, and atmospheric heating near the surface can lead to more evaporation. As mentioned in Section 3.2, the role of local recycled precipitation becomes important, from spring to summer, for total precipitation in WE. For this reason, increasing water content on the surface increases precipitation, but as the surface dries, precipitation decreases. As a result, precipitation from evaporation and locally recycled moisture is statistically significantly reduced after the surface has dried due to reduced snowmelt. This mechanism, Wet-First-Dry-Later (WFDL), was demonstrated by Lau et al. [10] as a key component of atmosphere-land-snow-aerosol interaction in the WE.

The atmospheric warming is accompanied by an anomalous anticyclone in the upper troposphere, centered over Middle East and southern Europe, with increased upper level easterlies over tropical African/Middle-East/Asian monsoon domain, and enhanced westerlies over WE (Figure 6a). The high-pressure anomalies are associated with large-scale downward motion, leading to reduced relative humidity and clouds in troposphere. The enhanced subsidence in the atmosphere not only warms the atmosphere adiabatically, but also dries the atmosphere by bringing drier air from above, reducing cloudiness, allowing more solar radiation absorption by the land surface (Figure 6). Therefore, atmospheric conditions in the low-level are changed favorable for increased evaporation, and drying and warming of the land surface, and the atmosphere. Consequentially, most of precipitation changes in WE during April and May are dominated by changes in locally recycled precipitation. These atmospheric conditions continue until the summer and are further strengthened with dry land surface.



Figure 6. The changes in (**a**) streamlines of horizontal wind at 200hPa and total cloud fraction (%), (**b**) the meridional-averaged (10–140 °E) vertical profiles of relative humidity (shaded, %) and streamlines of east-west circulation (streamlines) by SDE in Jun. Green and red rectangular box in (**a**,**b**) indicate Western Eurasia (20–60 °E, 40–60 °N) and the East Asia (110–135 °E, 24–56 °N) domain, respectively.

On the other hand, over EA, precipitation continues to increase from early spring to summer. As a result, the Asian summer monsoon rainy season occurs earlier, and is strengthened due to SDE. The surface warming of continental scale by SDE can lead to an increase in land-sea contrast, resulting in increase of moisture transport from adjacent ocean to inland. As a result, increased moistening of the lower and mid-troposphere by anomalous low-level southerlies and south-westerlies and strengthened rising motions over the EA. The moisture flux associated with these circulation features have been argued as being essential for sustaining the large-scale monsoon [58]. In addition, warming of the Himalayas and Tibetan Plateau (HTP) can play an important role in changing precipitation over EA. During JJ, the strongest warming is located in the HTP. Unlike other areas of similar latitude, the SDE in these regions is still prominent due to impact of the high terrain effects [16]. The atmospheric warming also occurred in the middle and upper levels over the HTP region. The anomalous east-wind at upper level are showed from the Sea of Okhotsk to East Asia region. This result is related to the weakening of subtropical East Asian jet. Lau and Kim [16] showed that these changes are related to the formation of the Rossby wave train, which alternates between anti-cyclone and cyclone in northern Eurasia, with an enhanced anomalous Tibetan plateau anticyclone. Due to changes in temperature and jet stream induced by SDE, the precipitation zone is shifted northward and resulting in a significant increase in precipitation in East Asia and a decrease in precipitation in Indochina Peninsula and southern China.

Moreover, the aforementioned changes are accompanied by a downward motion in the western part of Eurasia (0–40 °E) and upward motion in the eastern part (70–140 °E), with the strongest motion over the HTP. Figure 6b shows SDE-induced changes in relative humidity and anomalous anti-clockwise circulation in the zonal and vertical directions. This result indicates that precipitation can be suppressed by drier land surface conditions and anomalous subsidence in the Western Eurasia region where local evaporative precipitation is important. Over EA, moisture flux transport is a principal factor for the

change in precipitation. The result of strengthening in moisture flux transport and upward motion lead to more humid atmospheric conditions in the most of vertical layers. Consequently, the changes in precipitation caused by SDE is distinct, depending on regional characteristics, dry Western Eurasia become drier and wet East Asia become wetter, due to surface and atmospheric changes associated with SDE.

4. Conclusions

Based on the global climate model simulation using the NASA GEOS-5, we have examined the possible impact of snow darkening effect (SDE) by light-absorbing aerosols (LAAs) on the regional dependency of the hydrological cycle over Eurasia. In particular, this study analyzed the characteristics of precipitation and its changes in two regions (west of Eurasia and East Asia) during spring and summer. The recycling ratio was used to determine the characteristics of precipitation by region. This method was described in previous studies as a good indicator of the interaction between the surface and the atmosphere.

Over Western Eurasia, the local origin precipitation becomes increasingly important as the transition from spring to summer progresses, with the maximum ratio of 40.6%. This regional precipitation characteristic implies that the role of evaporation from the soil moisture to the precipitation is important, i.e., the interaction of the land and the atmosphere is closely related to changes in regional precipitation. In spring, snow contaminated by absorbing aerosols has lower surface albedo and thereby absorbs more SW radiation. As a result, the excessive energy over the surface induces surface warming and early snowmelt, increasing soil moisture. As mentioned earlier, increased soil moisture and warmer temperature during the period facilitate more evaporation, and more water vapor is supplied from the surface to the atmosphere, resulting in increased precipitation. The local-origin precipitation accounts for about 92.7% of total precipitation changes during April and May. On the other hand, the decrease in summer total precipitation was affected the changes in evaporative ($\Delta\beta_1$) and advective ($\Delta\beta_2$) precipitation by 47.2% and 52.8%, respectively. In other word, the changes in total precipitation during summer are related to the reduction of soil moisture due to early snowmelt as well as the moisture divergence associated with the development of anticyclonic circulation from the lower to the upper atmosphere.

East Asia is well-known as a representative seasonal monsoon region. Therefore, the precipitation in this region is influenced by the monsoon flow, and its characteristics are apparent. In particular, the total amount of precipitation in the region is concentrated in the summer. This result is caused by the transport of large amounts of water from the oceans adjacent to this area in the same period. Namely, since East Asia is located on the eastern coast of Eurasia continent, changes in precipitation are highly affected by the surrounding ocean. During April and May, P₁ and P_a contributed 20.4% ($\Delta\beta_1$) and 79.6% ($\Delta\beta_a$) to the total precipitation change (+0.27 mm/day) respectively. Although increase in precipitation (+0.21mm/day) is less than that of AM period, the contribution of change in precipitation by moisture advection increases to 97.2% (Table 2). Warmer land-surface over northern Eurasia and the Himalayas-Tibetan region due to SDE further increases moisture convergence and significantly increases precipitation over the East Asia region.

In summary, the atmospheric warming and drying accompanied by anomalous anticyclone in the upper troposphere, centered over Middle East and southern Europe is strongly coupled with moisture advection from adjacent ocean and moistening in the East Asian monsoon region with an enhanced anomalous Tibetan plateau anticyclone, resulting in anomalous anti-clockwise circulation in the zonal-vertical direction over Eurasian continent. This finding suggests that the SDE may play an important role in advancing and strengthening monsoonal circulation in East Asia, while it may lead to dry and hot summers by intensifying and maintaining anomalous anticyclone over the mid-western Eurasia. Author Contributions: Conceptualization, J.S., M.-K.K.; formal analysis, J.S.; investigation, J.S., M.-K.K., W.K.M.L., and K.-M.K.; writing—original draft preparation, J.S.; writing—review and editing, W.K.M.L., K.-M.K., and M.-K.K.; visualization, J.S.

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