The role of snow-darkening effect in the Asian monsoon region

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Background

What’s snow-darkening effect?

Picture source: https://svs.gsfc.nasa.gov/vis/a010000/a011800/a011899/ThomasPainter_Colorado.jpeg
Dust, Black carbon, and organic carbon transports

What is snow darkening effect (SDE)?

Light Absorbing Aerosols (LAA) absorb solar radiation especially in visible wavelengths and can accelerate snow melting.

Warren and Wiscombe (1980, JAS)
Snow darkening effect and its feedbacks can not be ignored on the climate discussion in the cryosphere.

- Snow darkening by LAA depositions on snow
- Snow albedo reduction (visible)
- More solar radiation absorption on snow
- Acceleration of snow melting and aging
- Growth of snow grain size
- Snow albedo reduction (near infrared)

Suggested snow albedo feedbacks by the snow darkening effect (Translated and adapted from Figure 2 in Japanese of Aoki and Tanaka, 2008, *Tenki*)
Recent updates on the BC RF on snow:

+0.046 (+0.015 to +0.094) W m$^{-2}$

summarized by Bond et al. (2013, JGR);

+0.04 (+0.02 to +0.09) W m$^{-2}$

adapted by IPCC AR5 (Boucher et al., 2013).
What has the NASA team done so far?
Build-up aerosols over the Indo-Gangetic Plain (IGP) in pre-monsoon (spring) season would change atmospheric temperature distributions and circulation patterns (e.g., Lau et al., 2006).

A global modeling study

Contour: Temperature

Solid & dashed lines:
Dust & BC AOT

Adapted from Lau et al. (2006, Clim. Dyn.)

Satellite data analysis:
AOD climatology based on the daily Aqua MODIS aerosol product (Level 2)

Gautam et al. (2010, J. Geophys. Res.)
EHP postulates:

a) Warming and moistening of the upper troposphere over the Tibetan Plateau
b) An advance of the rainy season in northern India/Napal, Himalayas foothills in May-June
c) The increased convection spreads from the foothills of the Himalayas to central India, resulting in an intensification of the Indian monsoon in June-July
d) Subsequent reduction of monsoon rain in central India in July-August

e) Enhanced snowmelt and rapid retreat of Himalayan glacier
Lau (2016) mentioned that aerosols now have an important role in assessing the monsoon climate system.
The GOddard SnoW Impurity Module (GOSWIM) for the NASA GEOS-5 Earth System Model: Preliminary Comparisons with Observations in Sapporo, Japan

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Snow darkening simulations of seasonal snowpack by NASA GEOS-5 over the land region

Yasunari et al., 2015, J. Geophys. Res. Atmos.

High-resolution global atmospheric modeling on aerosols by NASA GEOS-5: http://www.nasa.gov/multimedia/imagegallery/image_feature_2393.html

Simulated dust, BC, and OC mass concentrations in spring (MAM) in the top of snow layer by NASA GEOS-5 model (10-year ensemble mean climatology)
With and without the snow darkening effect (SDE) in the GEOS-5 experiments

Yasunari et al., 2015, J. Geophys. Res. Atmos.

Start dates with initial conditions

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Dust+BC+OC SDE

- For each Exp, experiments with and without SDE were carried out.
- Ensemble mean climatology: Averaging the 10-set of exps. by 10 years (i.e., 100 samples)
- Welch’s t-test assuming unequal variances
GEOS-5 settings on the experiments

• Horizontally 2°x2.5°; vertically 72 layers
• Dust, BC, and OC depositions from GOCART (e.g., Ginoux et al., 2000, JGR; Chin et al., 2000, JGR; 2002, JAS; Colarco et al., 2010, JGR, 2014, JGR)
• GOSWIM (Yasunari et al., SOLA, 2014) is coupled in the Catchment land surface model, excluding the land ice (i.e., glaciers and the ice sheets) and sea ice parts
• Prescribed observed SST (Reynolds et al., 2002, J. Clim.)
• Biofuel and fossil fuel emissions until 2006 based on the emission dataset (A2-MAP-v1; Diehl et al., 2012, ACPD; data in 2006 used after 2006). Biomass burning emissions based on the Quick Fire Emission Data set (QFED; Petrenko et al., 2012, JGR, and Darmenov and da Silva, 2015, NASA Tech. Rep. Ser. GMDA)
• Monthly mean outputs are used for analyses

Yasunari et al., 2015, J. Geophys. Res. Atmos.
The Quick Fire Emissions Dataset (QFED) uses satellite observations of fire radiative power to estimate emissions of aerosols and trace gases from fires. Global mesoscale model simulations with high-resolution QFED emissions in GEOS-5 capture individual fire plumes and large-scale features over Africa and the Americas in September 2005, shown in this snapshot of aerosol optical thickness.

Diagnosed relative percentage of dust, BC, or OC (mass of OM was used) visible absorption coefficients in the total absorption of them in the top snow layer (The SDE case; the calculations were based on the calculated visible absorption coefficients for these snow impurities from the spring ensemble mean climatologies) Adapted from Yasunari et al., 2015, *J. Geophys. Res. Atmos.*
Reduction of SWE
Increase of surface net solar radiation flux
3 - 6 K increases of surface skin temperature near the snow line at the mid-latitudes

10% Snow cover fraction line by MODIS (Magenta)

GOSWIM-module coupled NASA GEOS-5 simulations for the northern hemisphere spring Snow-Darkening Effect (SDE)

Water balance in spring in each domain
- SDE intensified the water cycle in East Asia (EA)
- SDE strengthens the dryness over the area spanning Europe to Central Asia (EUCA)

Positive value: To the ground
- ●□: Confidence limit of ≥ 99%

Adapted from Yasunari et al., 2015, J. Geophys. Res. Atmos.
The existence of snow-darkening effect (SDE) significantly increased advection from the ocean (i.e., implying atmospheric water vapor increase), and precipitation over the area spanning from the Himalayas to East Asia.

Precipitation climatology in spring without SDE (The control case)

Changes of precipitation and wind fields at 850 hPa with SDE
(Dots & vectors in red denote confidence limits on precipitation & either horizontal or meridional wind component of ≥ 99%, respectively)

Difference of standard deviations on precipitation between the cases with and without SDE (Only the grid points where the confidence limits were ≥ 99% in Panel (b))

Yasunari et al., 2015, J. Geophys. Res. Atmos.
The existence of SDE further increased precipitation over the areas spanning the areas from the Himalayas to East Asia, compared to that of spring.

Precipitation climatology in summer without SDE (The control case)

Changes of precipitation and wind fields at 850 hPa with SDE
(Dots & vectors in red denote confidence limits on precipitation & either horizontal or meridional wind component of $\geq 99\%$, respectively)

Difference of standard deviations on precipitation between the cases with and without SDE
(Only the grid points where the confidence limits were $\geq 99\%$ in Panel (b))

SDE over the Eurasia can induce the Wet-First-Dry-Later (WFDL) feedbacks, which is suggested by Lau et al. (in preparation).

Changes of zonal mean latitude-time cross-sections of the seasonal cycle anomaly of the surface skin temperature, with net surface short wave radiation, and soil wetness with snowmelt rate the Eurasia (10-140°E, 20-80°N).

A wet-first-dry-later (WFDL) land-atmosphere feedback induced by aerosol snow-darkening effect (SDE)

No SDE

- Frozen soil
- Warmed
- Subsidence
- Heat waves

SDE

- Aerosol deposition
- Wetter soil
- Warmer drier soil
- Increased subsidence
- More heat waves

Spring  Summer  Fall
The changes of heatwave frequency over Eurasia due to SDE showed a boomerang shape in which two stronger regions were seen in Central Asia and China. The peak seasons of higher heatwave frequency at 40-60°N and 60-80°N were in spring and early summer, respectively.
What’s the current issue on SDE modeling for GCM?
Uncertainty on modeled BC mass concentration in snow is large!

Simulated BC mass concentrations in the top snow layer in MAM 2008 by three global models (GEOS-5, Oslo-CTM2, and CAM5).

GEOS-5 Simulation (using MERRA atmospheric fields by Rienecker et al., 2011, J. Clim.)

CAM5 Simulation (High flushing case; Qian et al., 2014, ERL)

Oslo-CTM2 simulation (data from Figure 6 of Forsström et al., 2013, JGR)

CAM5 Simulation (Low flushing case; Qian et al., 2014, ERL)

The uncertainty on the BC mass concentration difference (i.e., one order difference) has potential to change the visible broadband albedos of greater than 10%.

Similar and more discussions are available in Japanese (Yasunari et al., 2016, Saihyou (細氷)).
We have been updating the GOddard SnoW Impurity Module (GOSWIM) to the latest version of GEOS-5 (from Fortuna 2.5 version to Heracles version), so that the snow-darkening calculations can be available in GEOS-5 over glaciers and the ice sheets.
Now, our understanding on Asian monsoon study is that atmospheric LAA (e.g., Lau et al., 2006; Lau and Kim, 2006) and LAA in snow as the snow-darkening effect (Yasunari et al., 2015; Lau et al., in preparation) are both essential to further understand the Asian monsoon region on its climate system.

Feedbacks caused by SDE in spring increased water cycle in East Asia and intensified dryness over the areas spanning Europe to Central Asia (Yasunari et al., 2015). SDE over the Eurasia can induce the Wet-First-Dry-Later (WFDL) feedbacks (Lau et al., in preparation).
Take-home message 2

Simulated BC mass concentrations in snow among global models has large uncertainty (e.g., Qian et al., 2015), likely inducing one order magnitude differences which likely contribute to $\geq 10\%$ broadband albedo change (e.g., Yasunari et al., 2016)

The NASA GEOS-5 will be able to simulate SDE over not only the seasonal snowpack but also snow over the land ice region (i.e., glaciers and the ice sheets)

Thanks for your attention, and I will take a couple of questions!