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LETTERS

Snow–Albedo Feedback and Seasonal Climate Variability over North America

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ABSTRACT

Interannual variations in the tropical Pacific sea surface temperatures related to El Niño–Southern Oscillation (ENSO) are known to influence wintertime surface climate anomalies over North America. However, the role of local land surface processes in this phenomenon is not well understood. Here, using a suite of atmospheric general circulation model simulations, it is demonstrated that the North American surface climate anomalies related to ENSO are greatly enhanced by a local snow–albedo feedback. Implications of this feedback mechanism on seasonal climate predictions and greenhouse gas–induced climate changes are discussed.

1. Introduction

During boreal winter, large surface temperature climate anomalies over North America are associated with extreme phases of the El Niño–Southern Oscillation (ENSO) phenomenon (Ropelewski and Halpert 1986; Kiladis and Diaz 1989). In the warm phase of ENSO, while surface air temperatures over central and northwestern North America are above normal, below-normal temperatures occur over the southeastern United States. Reverse conditions tend to occur in the extreme cold phase of ENSO. These temperature anomalies are linked to the changes in the large-scale atmospheric circulation patterns forced by anomalous tropical convection, which, in turn, is due to the interannual variations in the tropical Pacific SSTs (Horel and Wallace 1981; Hoskins and Karoly 1981). In this paper, we investigate to what extent the surface temperature climate anomalies over North America are a direct consequence of changes in the large-scale circulation patterns linked to ENSO and to what extent feedbacks from local land surface processes also contribute.

2. Modeling experiments and observed data

For the season of concern, that is, boreal winter, a likely candidate among different land surface processes that can influence surface temperature climate anomalies is the snow depth and its effect on surface albedo. Using a suite of atmospheric general circulation model (AGCM) experiments, we investigate the role of snow–albedo feedback on modulating the direct response of North American surface temperature climate to the interannual variations in tropical Pacific SSTs. The direct response is estimated from a set of AGCM simulations in which interannual variations in the snow depth are not included. The surface temperature response in this set of simulations is then compared with the response in another set of AGCM simulations in which the snow depth is allowed to vary. The difference in response between these two sets of simulations provides an estimate of the modulation of the direct response by the feedback associated with the changes in snow amount.

The AGCM used in this study is the National Centers for Environmental Prediction (NCEP) seasonal forecast model (Kanamitsu 1989). This AGCM has a spectral triangular truncation at horizontal wavenumber 42 (T42) and has 28 levels in the vertical direction. The horizontal grid spacing is approximately 3° in latitude and longitude. Two sets of three-member ensemble AGCM sim-

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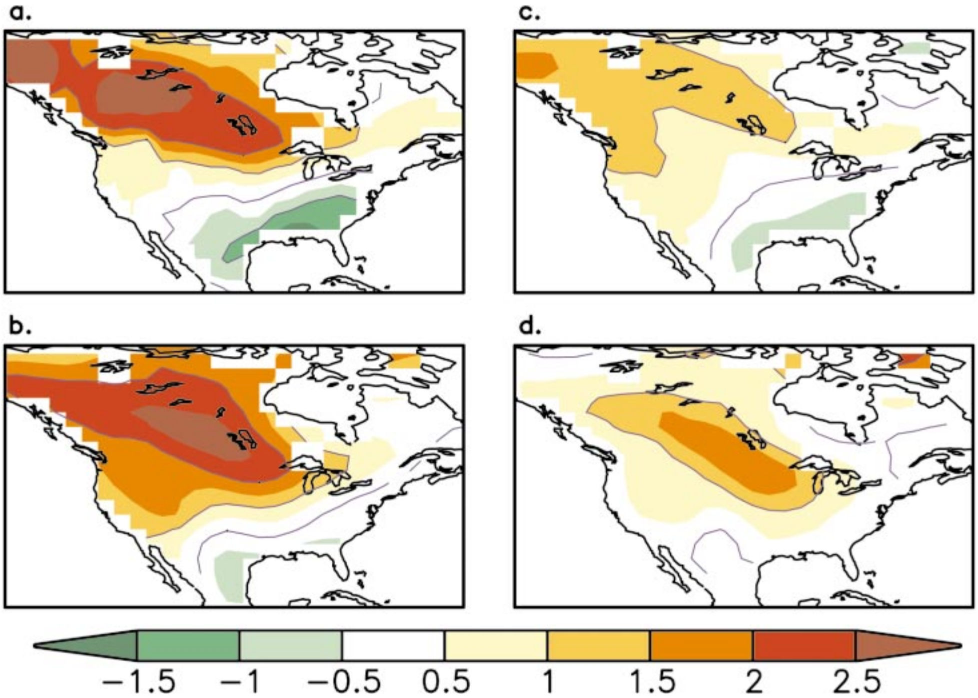

FIG. 1. ENSO composite surface air temperature anomalies (°C; El Niño composite minus La Niña composite) for the DJF season during the 1950–99 period for (a) observations, (b) AGCM simulations with interactive snow, and (c) AGCM simulations with specified snow, and (d) the difference between (b) and (c). Contours are drawn at −2°, −1°, 0°, 1°, and 2°C.

ulations starting from different atmospheric initial conditions are performed. All simulations cover the 1950–99 period and are forced with observed global SSTs. In the first set of simulations, snow depth is allowed to evolve during the AGCM integration; that is, the snow depth is predicted interactively. In the second set of simulations, the seasonal cycle of snow depth, as well as its spatial extent, is prescribed. In this set of simulations, therefore, no interannual variations in the snow depth are allowed. For consistency, the prescribed seasonally varying snow depth is the mean derived from the first set of AGCM simulations.

Observed North American surface temperatures are used to compare modeling results. They are based on 2.5° latitude–longitude gridded monthly analyses derived from the global network of surface observations maintained at NCEP (Ropelewski et al. 1985).

3. Results

For each set of simulations and for the observations, we computed the ENSO composites of North American surface air temperature anomalies (El Niño composite minus La Niña composite) averaged over the December–January–February (DJF) season (Fig. 1). Here, El Niño and La Niña events are defined such that the Niño-3.4 index (averaged SST over 5°S–5°N, 120°–170°W) is respectively larger than +0.4°C and smaller than −0.4°C, and lasts at least six months (Trenberth 1997). Further, a DJF season with at least two months falling within an El Niño (La Niña) event is counted as an El Niño (La Niña) season. During the 1950–99 period, there are 16 such-defined El Niño and 13 La Niña northern winter seasons. For the simulations with interactive snow (Fig. 1b), the spatial distribution and amplitude of the surface temperature anomalies closely resemble those in the observations (Fig. 1a). For the case of specified snow depth, on the other hand, the surface temperature anomalies are greatly reduced (Fig. 1c).

The difference between these two simulated composites (Fig. 1d) is due to the impact of snow variability on the direct response of surface temperature to ENSO. To substantiate it further, that is, to show that this difference is not due to the changes in the atmospheric large-scale circulation patterns, the ENSO composites for atmospheric heights at 500 hPa for the DJF season derived from these two sets of simulations are shown in Fig. 2. It is evident that these composites (i.e., with and without interactive snow) are almost identical. The similarity of the two height responses indicates that the changes in the surface temperature anomalies are not due to altered characteristics of tropical–extratropical teleconnection features, but are due to the impact of snow variability on the direct ENSO response.

How do the snow variations modulate the remote response of North American surface temperature climate to ENSO? In the AGCM, surface albedo over snow-covered land surface depends on snow depth (Briegleb

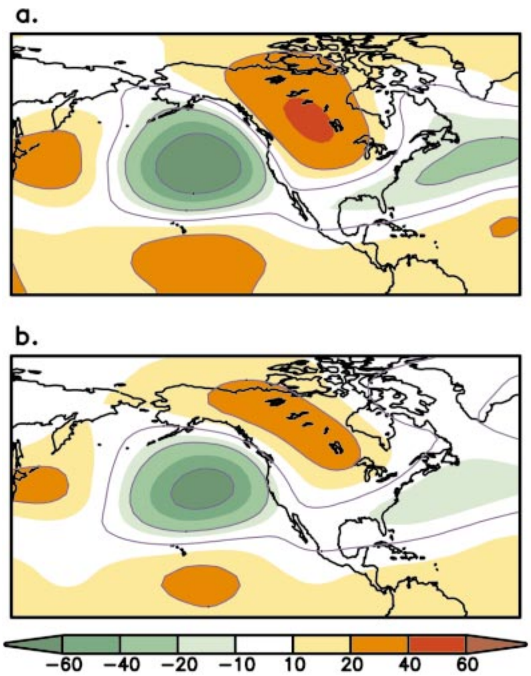

FIG. 2. AGCM-simulated ENSO composites for heights at 500 hPa (m) for (a) integrations with interactive snow and (b) integrations with specified snow. Contours are drawn at −60, −20, 0, 20, 40, and 60 m.

1992) and increases with increasing snow depth. Furthermore, the rate of increase decreases as snow depth increases (see the appendix). Changes in surface albedo lead to altered surface energy balance, providing a feedback mechanism that can influence the direct response of surface temperature to ENSO.

In Fig. 3, for the simulations with interactive snow, the composite anomalies for snow depth, surface albedo, and solar radiation absorbed by the surface are shown. These composites are for the warm phase of ENSO. Similar composites, but with opposite signs, for the cold phase of ENSO are found (not shown). For the case of specified snow and for the warm phase of ENSO, surface air temperatures are above normal (Fig. 1c). For the simulations in which snow amounts are allowed to vary, this warming leads to reduced snow depth and results in reduction of surface albedo. As the surface albedo decreases, solar radiation absorbed by the surface increases, and this process leads to further warming of the surface. As a consequence, the remote response of surface temperature to ENSO is magnified by the local snow–albedo feedback (see Fig. 1d). A similar argument can be applied to the case for the cold phase of ENSO.

This feedback mechanism works most efficiently at midlatitudes because of the latitudinal dependence of surface insolation during boreal winter and the fact that the rate of albedo change decreases as the snow depth increases. At high latitude, the surface insolation is small, mean snow depth is large, and hence albedo changes are small. At lower latitudes, although surface insolation is large, the mean snow depth amount itself diminishes, and hence no snow–albedo feedback exists. It is only in those geographical locations at which mean snow amount and its interannual variability can lead to significant changes in the surface albedo and at which the surface insolation is sufficiently large that changes in surface albedo can indeed result in altered surface energy balance and feed back on the direct response to ENSO.

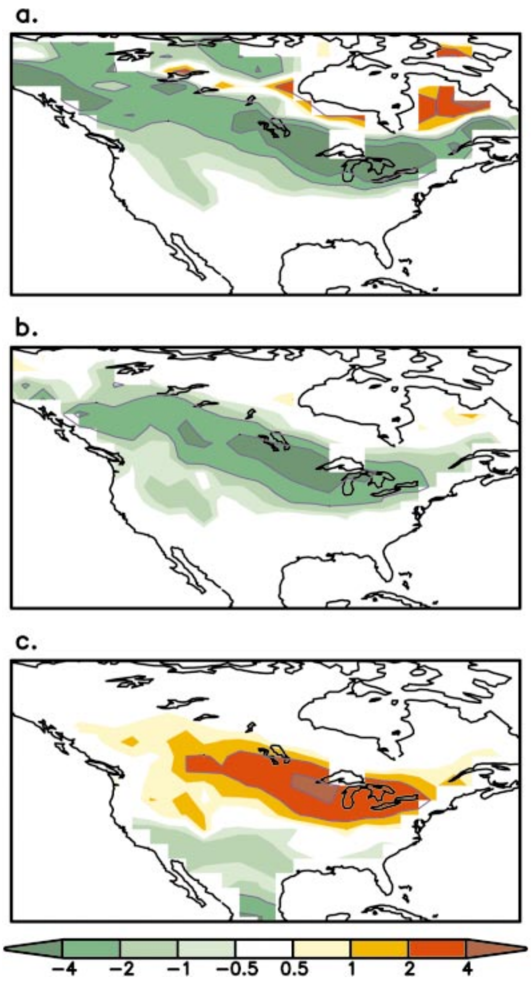

FIG. 3. Composite anomalies of (a) snow depth (mm), (b) surface albedo (%), and (c) solar radiation absorbed by the land surface (W m^{-2}) for the El Niño DJF seasons derived from the set of AGCM simulations with interactive snow. The contours are drawn at −4, −2, 2, and 4 units for the respective variables.

4. Discussion and conclusions

Using a suite of atmospheric general circulation model simulations, it is demonstrated that surface climate anomalies in the northern winter over North America during ENSO years are an end result of two distinct processes. The first is a direct response to the tropical Pacific SSTs, but the second is due to changes in snow amount. This secondary influence is found to have a strong positive feedback on the direct response and greatly enhances the North American surface temperature climate anomalies associated with ENSO. The results of this study have obvious consequences about the impact of parameterization of surface albedo over snow-covered areas on the simulations of ENSO response in different AGCMs. Different parameterizations (e.g., Betts 2000) can lead to different estimates of predictability of surface temperature anomalies over North America, even if AGCMs may agree on the predictability of upper-level heights. Our analysis also points to the importance of correctly observing and initializing snow depth for seasonal-to-interannual prediction efforts. The relationship between albedo and snow depth also has implications for the estimates of climate sensitivity and regional climate changes induced by increasing greenhouse gases (Kittel et al. 1997). In particular, different dependence between snow depth and surface albedo may lead to different estimates. For example, in AGCMs for which the dependence of surface albedo on snow amount is weak, surface temperature anomalies induced by radiative forcing change related to increased amount of greenhouse gases may not amplify further because of the lack of a positive feedback associated with snow–albedo interaction, and vice versa. Last, efforts to reconstruct paleorecords of ENSO–surface temperature relationships over extratropical regions may also be influenced by long-term changes in the mean snow amount upon which the interannual variability during different epochs is superimposed.

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APPENDIX

Parameterization of Surface Albedo in the NCEP AGCM

In the model, grid-averaged surface albedo over snow-covered land for each broad band of solar radiation is defined as (Briegleb 1992)

$$\alpha = \alpha_{\mathrm{land}}(1 - f_{\mathrm{snow}}) + \alpha_{\mathrm{snow}} f_{\mathrm{snow}}, \tag{A1}$$

where α_{land} is the zenith angle dependent spectral albedo for snow-free surface, which is estimated based on observations. Further, f_{snow} is defined as

$$f_{\mathrm{snow}} = \mathrm{SCV}/(\mathrm{SCV} + R). \tag{A2}$$

In (A2), SCV is model snow cover depth in meters, and R is the aerodynamical roughness of the underlying surface and varies between 0.025 and 1.0. Last, the spectral albedo for the snow-covered surface is defined separately for direct and diffuse incident solar radiation. For direct incident solar radiation,

$$\alpha_{\mathrm{snow}} = \begin{cases} \alpha^0_{\mathrm{snow}} + (1 - \alpha^0_{\mathrm{snow}})\left[0.5\left(\dfrac{3}{1 + 4\cos\zeta} - 1\right)\right], & 0 \le \cos\zeta \le 0.5 \\ \alpha^0_{\mathrm{snow}}, & \cos\zeta > 0.5, \end{cases} \tag{A3}$$

where ζ is the solar zenith angle. For diffuse incident solar radiation, $\alpha_{\mathrm{snow}} = \alpha^0_{\mathrm{snow}}$. Here α^0_{snow} is the prescribed spectral snow albedo estimated based on observations. In general, α_{snow} is much larger than α_{land}.

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