Impact of ENSO on Wintertime Land Surface Variables in Northern Hemisphere Extratropics: Role of Atmospheric Moisture Processes

LINYUAN SUN,a XIU-QUN YANG,a,b AND LINGFENG TAOa

a China Meteorological Administration Key Laboratory for Climate Prediction Studies, School of Atmospheric Sciences, Nanjing University, Nanjing, China
b Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, China

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ABSTRACT: El Niño–Southern Oscillation (ENSO) is the strongest interannual signature in the tropical air–sea system and can affect global atmospheric variables, but ENSO’s climatic impact on land surface variables such as skin temperature, snow cover, and soil moisture that can serve as seasonal climate predictors remains relatively little known. Here we examine ENSO’s impact on the three land surface variables in Northern Hemisphere extratropics by regression analysis, using a combination of ERA5 reanalysis, GLDAS, satellite-based observations, and CESM2 simulations. Our results show that during El Niño winters anomalous land surface warming occurs in Northern Hemisphere midlatitudes, accompanied by snow cover reduction, especially in northern North America and eastern Europe, while anomalous cooling occurs in southern North America and the Tibetan Plateau, accompanied by increased snow cover. Meanwhile, increased soil moisture is observed in southern North America, central Asia, and southeast China. Further analysis indicates that atmospheric moisture processes dominate the formation of the land surface anomalies, for which the changes in water vapor and precipitation induced by the ENSO-related large-scale atmospheric teleconnection are critical. The anomalous land surface warming in midlatitudes mainly results from the increased downward longwave radiation due to the increase of water vapor, whereas the physical pathway causing water vapor anomalies is different over North America and Eurasia. Controlled by ENSO-induced changes in atmospheric circulation and moisture transport, anomalous precipitation explains most of the snow cover and soil moisture anomalies, which play a certain role in shaping the skin temperature anomalies in some regions through snow–albedo feedback and evaporation, respectively.

KEYWORDS: ENSO; Atmosphere–land interaction; Snow cover; Soil moisture; Soil temperature; Climate variability

1. Introduction

As the leading mode of the tropical coupled ocean–atmosphere variability, the El Niño–Southern Oscillation (ENSO) phenomenon profoundly affects the global climate and ecosystem, serving as the primary source of interannual climate predictability (Philander 1990; McPhaden et al. 2020). Tremendous studies have well documented ENSO’s climatic impacts, which can be generally classified into two categories. One is the wintertime impact through the atmospheric fast response to tropical diabatic heating of mature-phased ENSO events, such as the ENSO-related Pacific–North America (PNA)-like anomaly pattern and the associated changes in the jet stream and storm tracks over the extratropical North America–Europe sector (e.g., Horel and Wallace 1981; Held et al. 1989; Trenberth et al. 1998; Straus and Shukla 2002; Brönnimann 2007). The other is the delayed impact in subsequent seasons during the ENSO-decaying period, which can better reflect the prediction value of ENSO as a precursory signal, and typically, one prominent case is the influence on the East Asian monsoon climate in the following summer (Zhang et al. 2017; Li et al. 2017).

The physical basis for the delayed climatic impact of ENSO is the memory and relay effect related to the interaction between ENSO-induced slowly varying underlying surface anomalies and atmosphere. Under a classical conceptual framework, ENSO drives globally persistent sea surface temperature (SST) anomalies via the “atmospheric bridge” (Lau and Nath 1996; Alexander et al. 2002; Liu and Alexander 2007), providing the physical interpretation of the delayed ENSO-related climate variation. Traditionally, previous studies emphasized the role of pan-tropical SST anomalies [e.g., tropical Indo-Pacific (Wang et al. 2000; Xie et al. 2009, 2016; Stuecker et al. 2013, 2015; Wu et al. 2017a,b) and Atlantic Ocean (Rong et al. 2010)], and the role of midlatitude North Pacific SST anomaly is also detected in recent years (Sun et al. 2021), which can be summarized as the oceanic pathway for transmitting the ENSO signal.

In parallel, land surface processes also provide an important forcing for the atmosphere, and in the Northern Hemisphere as the main distribution of global continents, ENSO is bound to leave abnormal imprints on the land surface in addition to producing oceanic SST anomalies (e.g., Zhang et al. 2020); accordingly, an alternative hypothesis naturally emerges whether there exists the land pathway responsible for the ENSO-related delayed climatic impact. Actually, the role of the land surface in storing and modulating ENSO-related climatic influences has been noticed. For example, Chen and Kumar (2002) early reported the delayed response of North American...
terrestrial systems to ENSO signal and attributed it to the role of soil moisture in prolonging the influence of ENSO on the terrestrial climate, and in a recent study, Chen et al. (2022) confirmed the effect of central Asian soil moisture on enhancing the precipitation response to the preceding strong El Niño events through increasing the local evaporation. The role of Eurasian snow depth (Wang et al. 2017) and Tibetan Plateau snow cover (Jin et al. 2018) in the influence of ENSO on the East Asian summer climate has also been proposed. But as the prerequisite for transmitting ENSO climatic signals, the impact and mechanism of ENSO on land surface variables still necessitate comprehensive investigation. On the other hand, based on the land–atmosphere interaction, many observational and modeling studies have paid attention to the direct impact of land surface variables (e.g., skin temperature, snow cover, and soil moisture) on climate variability at different time scales (e.g., Yeh et al. 1984; Barnett et al. 1989; Eltahir 1998; Duan and Wu 2005; Seneviratne et al. 2010; Xue et al. 2018; Chen 2022). However, taking land surface anomalies as the starting point to explore their climatic effects, an unavoidable problem arises that how the initial land surface anomaly forms. As the strongest interannual variability, ENSO events can cause anomalies of land surface variables in winter, and through persistence and/or interaction with the atmosphere, the ENSO-induced land surface anomaly could feedback on the atmospheric circulation locally and perhaps remotely in the following seasons, thus playing a role in the memory and transmission of ENSO signal. From this point of view, it still needs the first investigation on what and how land surface anomalies will be induced by ENSO.

As compared with substantial progresses in understanding the ENSO-related influence on SST and meteorological fields, the studies on the impact of ENSO on land surface are relatively insufficient, partly due to the difficulty in accumulating long-time land surface data. Some early studies examined the ENSO-related variation of land hydrological processes in tropical South America using station-measured records (Aceituno 1988; Poveda and Mesa 1997; Poveda et al. 2001). The improved quality and prolonged length of data in the past two decades allow more systematic studies of the tropical land surface response to ENSO forcing. For example, Solander et al. (2020) described the pantropical response of soil moisture to three super El Niños and identified the obvious soil moisture reduction in the Amazon basin and maritime southeastern Asia. Based on satellite observations and advanced reanalyses, it is found that ENSO events can modulate tropical land hydrology through dynamical effects of atmospheric teleconnections and further regulate continental evaporative (Miralles et al. 2014; Bosilovich et al. 2020).

Although the ENSO signature can cause tropical land surface anomalies more directly, its impact on the extratropical land surface has also received concern due to the potential benefit for climate prediction of midlatitude land feedback. Especially in North America where there are more in situ observations, the significant influence of ENSO on the snowpack (Ge and Gong 2009; Seager et al. 2010), terrestrial energy budget (Chen and Kumar 2004), and hydrologic extremes (Cayan et al. 1999) has been well recognized. Through a comprehensive examination of the U.S. surface temperature response to ENSO, Zhang et al. (2011) explained the formation and asymmetry of observed land surface temperature anomalies during El Niño and La Niña winters. For the Eurasian land surface variables, the ENSO’s impact on land skin temperature (Bartholomew and Jin 2013; Tyrrell et al. 2015), snow cover (Frei and Robinson 1999; Clark et al. 1999; Seager et al. 2010), and soil moisture (Le and Bae 2022) is also examined. However, possibly due to the uncertainty of land surface data and the small sample size of ENSO events analyzed, the ENSO influence on the extratropical land surface remains controversial in some respects, such as on the Tibetan Plateau snow condition, with some suggesting the negligible influence of ENSO on the wintertime snow cover on the Tibetan Plateau (Yuan et al. 2009) and others finding significant impacts on snow condition there (Shaman and Tziperman 2005; Wang and Xu 2018; Jiang et al. 2019).

In general terms, current studies on the ENSO-related land teleconnection mainly focus on the tropical hydrological processes or one single land variable in extratropics, but lack comprehensive analysis of the spatial pattern, formation mechanism and possible interconnection of land surface anomalies on the hemispherical scale. Therefore, using multiple high-quality datasets with a long period of record, we aim to present a broader picture of the ENSO’s impact on the key land surface variables [i.e., land surface temperature (skin temperature used in this paper), snow cover, and soil moisture] in Northern Hemisphere extratropics, and advance the understanding of underlying physical mechanisms. Through this work, we try to enrich the framework of ENSO teleconnection and provide a basis for exploring the land pathway of ENSO’s delayed climatic effect. The rest of this paper is organized as follows. Section 2 describes the data and method used. Section 3 identifies the distribution of ENSO-related land surface anomalies. Section 4 examines the shaping process of land surface anomalies under the control of atmospheric circulation anomalies. Section 5 is devoted to a summary and discussion.

2. Data and method

a. Data

Multiple datasets are used to investigate the ENSO-related anomalies of wintertime land surface variables in Northern Hemisphere extratropics. Table 1 provides an overview of all datasets utilized. For the key land surface variables diagnosed in this study (i.e., skin temperature, snow cover, and soil moisture), we mainly use the monthly data from the land component of the fifth generation of ECMWF Re-Analysis (hereinafter simply ERA5-Land) with a horizontal resolution of 1° × 1°. As a state-of-the-art global reanalysis for land applications, ERA5-Land provides a wide variety of land variables with extensive spatial–temporal coverage and shows consistent improvements in the description of water and energy cycle over land (Li et al. 2020; Muñoz-Sabater et al. 2021; Lavers et al. 2022). Note that soil moisture is represented by volumetric water content in ERA5-Land, which can be obtained in four soil layers; we only use the data in the top layer (0–7 cm).
Land assimilation and satellite observational datasets are also used for mutual verification. For instance, Global Land Data Assimilation System (GLDAS) provides high-quality, global land surface fields and has been widely applied to climate prediction and hydrologic cycle studies (Rodell et al. 2004); here we use the skin temperature and soil moisture (0–10 cm) data derived from the Noah land surface model in GLDAS-2. The International Satellite Cloud Climatology Project (ISCCP) focuses on cloud radiative variables to improve understanding of the way clouds affect climate (Young et al. 2018) and provides various ancillary data, skin temperature, and snow cover that are used to support our study as well. In addition, we also use the observations of snow cover extent from the U.S. National Snow and Ice Data Center (Brodzik and Armstrong 2013) and the model-calculated soil moisture water height equivalents from the NOAA Climate Prediction Center (Fan and van den Dool 2004), so that the ENSO-related anomalies of each land surface variable can be identified by three different datasets to ensure the insensitivity of results to data choices.

Considering the physically consistent relationship with ERA5-Land, we continue to use the ERA5 reanalysis to reveal the physical processes shaping the ENSO-related land surface anomalies, including the monthly atmospheric variables at a 1° × 1° resolution on single or pressure levels (Hersbach et al. 2020), such as geopotential height, wind, and vertical integral of water vapor flux. The ENSO variability is measured by the oceanic Niño index (ONI, Fig. 1), which is the most commonly used index to determine El Niño events, defined as the 3-month running mean of SST anomalies in the Niño-3.4 region (5°N–5°S, 170°–120°W), based on centered 30-yr periods updated every 5 years to remove the warming trend (L’Heureux et al. 2013). In this work, the time span of all of the data is from 1979 to 2021, except the ISCCP data, which is available only from 1983 to 2018, and the winter-time refers to the average across the months of December–February (DJF).

### b. Method

We focus on the interannual variability associated with ENSO signal, so all the monthly data is treated with a 2–8-yr bandpass Lanczos filter (Duchon 1979) to get the interannual anomaly. The ENSO-related anomalies analyzed in this study are expressed by linear regression upon the ONI index in winter, and the confidence level of regression coefficient is estimated by the Student’s t test. Accounting for the autocorrelation of time-filtered series, the effective sample size is measured by the method proposed in Bretherton et al. (1999).

To understand the processes shaping the land surface anomalies, we examine the budget equations that govern the changes in land surface variable. For skin temperature, it is required to satisfy the surface energy balance that is given by

\[
\text{SW}^i - \text{SW}^\uparrow + \text{LW}^i - \text{LW}^\uparrow - \text{SH} - \text{LH} = 0, \tag{1}
\]

where \(\text{SW}^i\) and \(\text{SW}^\uparrow\) are the downward and upward shortwave radiative flux; \(\text{LW}^i\) and \(\text{LW}^\uparrow\) are the downward and

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**Fig. 1.** The wintertime (DJF) oceanic Niño index for 1978–2022 (bar chart). The yellow line represents the interannually filtered value.
upward longwave radiative flux; and SH and LH are the upward sensible and latent heat flux, respectively. In response to the change of any term in Eq. (1), the land surface tends to maintain the energy balance through altering the upward longwave radiation (LW), which relates to skin temperature by Stefan–Boltzmann law. Following the equation form adopted here, each term is defined to be positive, so as to ensure that the regressed positive anomaly represents the increase in physics and the regressed negative anomaly represents the decrease in physics.

For snow cover, the computation of snow cover in the ERA5 reanalysis follows the scheme \( c_{sn} = \min[1, (S/\rho_{sn})/0.1] \), where the \( S \) is the snow mass (usually represented by snow depth water equivalent) and the \( \rho_{sn} \) is the snow density. In fact, the formula roughly reflects a quasi-linear relationship between snow cover and snow mass (or snow depth) that is supported by the generally consistent match between the anomaly pattern of snow cover and snow depth in midlatitudes (see Fig. S1 in the online supplemental material). Therefore, we use the snow mass budget equation derived by Douville et al. (1995) to understand the changes in snow cover, and the equation is basically expressed as

\[
\frac{\partial S}{\partial t} = F_{sn} - M_{sn} - E_{sn},
\]

indicating that the changes in snow mass (left-hand side) can be affected by the snowfall \( F_{sn} \), snowmelt \( M_{sn} \), and snow evaporation (i.e., sublimation; \( E_{sn} \)). As for soil moisture, we analyze the surface water balance equation used in numerical studies on the climatic impact of soil wetness (Yeh et al. 1984; Delworth and Manabe 1989), as given by

\[
\frac{\partial M}{\partial t} = P - E - R,
\]

which shows that the changes in soil moisture (left-hand side) are controlled by the precipitation \( P \) (mainly in the form of rainfall), evaporation \( E \), and surface runoff \( R \). But one point to note is that the above budget Eq. (3) is a simplified description of the changes in wintertime soil moisture, since the soil moisture in high-latitude frozen areas is dominantly affected by the thawing processes of snow and frozen soil (Luo et al. 2003; Qiao et al. 2022), which need to be considered when explaining the soil moisture anomalies in those regions. Fortunately, all relevant variables used in the budget equation diagnosis can be downloaded from the ERA5-Land dataset.

To illustrate the dynamic connection of ENSO-related atmospheric anomalies in Northern Hemisphere extratropics, wave-activity flux (WAF) is calculated to diagnose the energy propagation of associated steady Rossby waves. Here we use the wave-activity flux \( W \) derived by Takaya and Nakamura (2001), which is applicable for stationary quasigeostrophic eddies on a zonally varying basic flow. The horizontal component of \( W \) is defined by the formula

\[
W = \frac{1}{2|\mathbf{U}|} \left[ \mathbf{U} (\psi'_u - \psi'_u_{xy}) + \nabla (\psi'_p - \psi'_p_{xy}) \right] + \mathbf{U} (\psi'_u - \psi'_u_{xy}) + \nabla (\psi'_p - \psi'_p_{xy}),
\]

where \( \mathbf{U} = (\mathbf{U}, \nabla)^T \) is the steady zonally varying basic flow and \( \psi' \) is the streamfunction anomaly calculated from regressed geopotential height anomalies through quasigeostrophic approximation.

3. ENSO-related anomalies of land surface variables

a. Skin temperature

Figure 2 shows the climatology and ONI-regressed anomaly pattern of skin temperature in winter, from which three datasets all capture an evident overall feature: the midlatitudes of the Northern Hemisphere, more specifically, the land surface between 40° and 60°N except northern East Asia, is dominated by warm anomalies during El Niño winters, including northern North America, most of Europe, and central Asia. For the subtropics, there is a latitudinally alternating distribution of temperature anomalies with the cold anomalies prevailing in southern North America and the Tibetan Plateau, and with the warm anomalies in western North Africa and southern East Asia. Focusing poleward, a pronounced cold anomaly is widely present in the high latitudes of Eurasia, especially in the Russian Far East. In general, in addition to the North American sector where the key features of skin temperature anomalies agree well with previous studies (Hoerling et al. 1997; Chen and Kumar 2004; Zhang et al. 2011), and as we have seen, ENSO also has a significant impact on the Eurasian land surface temperature indeed.

b. Snow cover

Figure 3 shows the climatology and ONI-regressed anomaly pattern of snow cover in winter, and there remains a very basic similarity in the results revealed by the three datasets. Generally, snow cover anomalies are mainly observed in the midlatitude continental regions at 30°–50°N where the climatologically snow-covered fraction is between 10% and 90% as areas of “active snow fluctuation” called by Frei and Robinson (1999). The climatological snow cover in the high latitudes of Eurasia usually exceeds 90% and the interannual variability of snow cover here is small, so the impact of ENSO on the high latitude snow conditions is mainly reflected in the snow depth (Fig. S2 in the online supplemental material), not the snow cover. For El Niño winters, the regression pattern of snow cover presents certain dipolar distribution in both North America and Eurasia: the former features a typical north–south dipole bounded by 40°N [consistent with the analysis based on snow water equivalent by Seager et al. (2010)], and the latter is mainly characterized by a west–east dipole with less snow cover in most of Europe but with more in the Tibetan Plateau and Mongolia–North China. Recalling the observations of skin temperature anomalies (Figs. 2d–f), we can find that snow cover anomalies keep a close association with the thermal condition of land surface in some places, which implies a coupling relationship between the two variables through the positive snow–albedo feedback, that is, places with warm (cold) skin temperature anomalies are accompanied by less (more) snow cover, such as northern-central United States and eastern Europe (southwestern United States and the Tibetan Plateau) (Figs. 3d–f). Meanwhile, the anomalously increased snow cover in Mongolia–North China
is consistent with the fact that the skin temperature anomaly here is not as warm as that in other regions at the same latitude (e.g., eastern Europe and central Asia; Figs. 2d–f).

c. Soil moisture

Figure 4 illustrates the climatology and ONI-regressed anomaly pattern of soil moisture in winter. Owing to more uncertainty of soil moisture simulation in the land surface model (e.g., Kim et al. 2015; Cheng et al. 2017), differences in the spatial distribution of soil moisture revealed by the three datasets are slightly larger. But even so, some key features of the ENSO-related soil moisture anomalies are still consistently revealed by all three datasets; that is, during El Niño winters, the increased soil moisture in Northern Hemisphere midlatitude is primarily located in southern North America, central Asia, and southeast China. Notably, the wet soil moisture anomalies in northern North America are well coherent with the cold skin temperature anomalies (recall Figs. 2d–f), suggesting that soil moisture may also play a role in the formation of skin temperature anomaly here; for instance, Zhang et al. (2011) argued that the change of soil moisture can affect skin temperature through its influences on surface albedo. Moreover, if we carefully check the high latitude of Eurasia, the soil moisture in the Ural region is anomalously wet and the soil moisture in the Russian Far East is anomalously dry, and these features are also captured by all three datasets, indicating that the response of soil moisture in these regions to ENSO may be also robust. Thus, for the above regions with consistent signals revealed by different datasets, data uncertainties may have little impact on the results. But in addition to these common features, the results in some high-latitude regions (e.g., northern North America, central Siberia, and northeast Asia) lack consistency among different datasets, suggesting that great uncertainty exists in the wintertime soil moisture simulation in those areas and the result revealed by one single dataset may be not reliable.

d. Results from CESM2 simulations

The above regression maps present an observation-based picture of ENSO-related land surface anomalies in Northern Hemisphere extratropics, and we further examine the wintertime land surface response to ENSO in CESM2 simulations. CESM2 leads the way in the ENSO simulation among state-of-the-art climate models (Planton et al. 2021), allowing for a direct comparison with observations, and longer-time data output (1850–2014) ensures larger sample size of ENSO.
To assess statistical significance, we check the ENSO-related anomaly pattern of the surface temperature, snow area percentage, and moisture in the upper portion of the soil column from one member of CESM2 historical runs (r1i1p1f1), in which the SST output is used to compute ONI index for regression analysis (Figs. 5a–c). Moreover, we investigate the result from CESM2 tropical Pacific pacemaker experiment conducted by Climate Variability and Change Working Group (CVCWG), which makes use of fully coupled climate models but with observed SST anomalies prescribed only in the tropical Pacific (i.e., ENSO is the pacemaker) under historical forcing prior to 2014, with the rest of global coupled ocean–atmosphere–land system to respond (Deser et al. 2017), and thus, the pacemaker run can be considered as the realistic setting for evaluating the model’s response to ENSO forcing. To avoid contamination by internal variability, we calculate the ensemble mean of land surface variables from 10 pacemaker members and regress them onto the observed ONI index for 1950–2014 (Figs. 5d–f). A 2–8-yr band-pass filter processes all the used variables from CESM2 simulation for the analysis on interannual time scales.

From a comparative perspective, regression patterns produced by CESM2 historical simulations exhibit considerable commonality with observations, and some key features of ENSO-related land surface anomalies in Northern Hemisphere extratropics are captured by the model, such as the anomalous land surface warming (cooling) with snow cover decrease (increase) in northern North America (southern North America and Tibetan Plateau) and the wet soil moisture anomalies in southern North America, central Asia, and southeast China (Figs. 5a–c). Furthermore, similar results are found in the tropical Pacific pacemaker ensembles (Figs. 5d–f), in which the regression pattern shares consistency with the observed anomalies in Figs. 2–4 albeit with smaller amplitudes, confirming that a significant portion of the observed land surface anomaly pattern is exactly driven by ENSO forcing. Admittedly, the simulated land surface response in mid- to high-latitude Eurasia is much attenuated in comparison with the observed regression (e.g., Figs. 5a,d), which suggests that the impact of ENSO on the land surface in corresponding regions may receive large interference from internal atmospheric variability and thus has greater uncertainties.

4. Processes shaping the ENSO-related land surface anomalies

In the previous section, we have demonstrated the impact of ENSO on the wintertime land surface variables (i.e., skin temperature, snow cover, and soil moisture) in Northern Hemisphere extratropics through regression analysis. Next, we will reveal the underlying physical processes that shape

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**Fig. 3.** (a)–(c) Climatology and (d)–(f) ONI-regressed anomalies of wintertime snow cover (%) for 1979–2021 from (top) ERA5-Land, (middle) NSIDC, and (bottom) ISCCP. The yellow stippling indicates statistical significance at 95% confidence level.
the land surface anomalies and essentially aim to establish linkages with the ENSO-induced atmospheric teleconnections.

a. Diagnoses on budget equations of land surface variables

First, the surface energy budget is examined to identify relevant contributors to ENSO-related skin temperature anomalies. Based on the ERA5-Land data, the ONI-regressed anomalies of each component of the surface energy balance equation [Eq. (1)] are shown in Fig. 6. We focus on six extratropical regions with significant skin temperature anomalies mentioned in section 3, including northern North America, southern North America, eastern Europe, central Asia, the Tibetan Plateau, and Russian Far East, of which their respective domains are indicated by the green box in Figs. 2 and 6.

In the surface energy balance, the effect of changes in upward longwave radiation merely represents the radiative response to anomalous skin temperature following the Stefan–Boltzmann law. Accordingly, the anomaly pattern of upward longwave radiative flux naturally exhibits well coherence with the regressed skin temperature anomalies (cf. Fig. 2d with Fig. 6d). Thus, the other terms in Eq. (1) could be the drivers of skin temperature anomalies, containing the net shortwave radiation (i.e., difference from the downward shortwave radiation minus the upward, Figs. 6a, b), downward longwave radiation (DLR, Fig. 6c), and turbulent heat flux (i.e., sensible and latent heat flux, Figs. 6e, f). To quantify their contribution, we derive an equation for the skin temperature anomaly. Using the radiation–temperature relation \( \text{LW}^\uparrow = \varepsilon \sigma T_s^4 \), where \( T_s \) is the skin temperature, \( \sigma \) is the Stefan–Boltzmann constant, \( \varepsilon \) is the land surface emissivity (set equal to 1.0), and, applying the differential operator \( \delta \) to Eq. (1), the surface energy balance equation can be rearranged to get the expression for the skin temperature anomaly \( \delta T_s \):

\[
\delta T_s = \frac{\delta \text{SW}^\downarrow - \delta \text{SW}^\uparrow + \delta \text{LW}^\downarrow - \delta \text{SH} - \delta \text{LH}}{4\varepsilon \sigma T_s^3}.
\]

where \( T_s \) is the wintertime climatology of skin temperature (Lu and Cai 2009; Clark et al. 2021). Based on Eq. (4), the area-mean skin temperature anomalies of six key regions and the corresponding contribution by each term are shown in the bar chart (Fig. 6g).

One key point emerges from the comparison with the regression patterns in Fig. 6, that is, in terms of the amplitude of regressed anomalies and the spatial coherence with the anomaly pattern of upward longwave radiation, the anomalous DLR plays a dominant role in the changes of surface energy budget and in shaping skin temperature anomalies in most of the Northern Hemisphere extratropics. Specifically, the warm
(cold) skin temperature anomalies in northern North America, eastern Europe, and central Asia (Russian Far East) are almost entirely caused by the increased (decreased) DLR anomalies (Fig. 6c), which is supported by the quantitative result in Fig. 6g. However, in southern North America and the Tibetan Plateau, there are obvious mismatches in anomaly patterns between the DLR and upward longwave radiation, indicating that the anomalous DLR is not the leading contributor to skin temperature anomalies there. In fact, in southern North America, the cold skin temperature anomalies are jointly driven by decreased downward shortwave radiation and increased latent heat flux (Figs. 6a,f,g), of which the latter is possibly associated with wet soil moisture anomalies here (recall Fig. 4d); in the Tibetan Plateau, especially to the west of it, accompanied by more extensive snow cover (recall Fig. 3d) that favors reflecting more solar radiation, it is observed that the decreased upward longwave radiation is largely balanced by increased upward shortwave radiation (Fig. 6b), which can explain a considerable fraction of the total skin temperature anomaly (Fig. 6g).

Considering the possible uncertainty of radiation and heat flux in reanalysis dataset, we conduct the same analysis based on GLDAS data (Fig. S3 in the online supplemental material). In general, the GLDAS data confirms the previous results, except for the quantitative contribution in the Tibetan Plateau, in which the skin temperature anomaly is underestimated and seems to be primarily determined by downward shortwave radiation rather than upward shortwave radiation. This inconsistency does reflect the data uncertainty on the plateau, but in fact, if we look at the regression pattern given by GLDAS data, the pronounced positive anomaly of upward shortwave radiation can be still observed on the west of the Tibetan Plateau (Fig. S3b), which is consistent with ERA5-Land indeed, while the small amount of its quantitative contribution is due to the cancellation by area averaging. Moreover, recalling the increased snow cover on the Tibetan Plateau during El Niño winters revealed by three datasets (Figs. 3d–f), which supports the local snow–albedo feedback in physics, it is reasonably argued that the cold skin temperature anomaly here is mainly caused by increased upward shortwave radiation.

**Fig. 5.** ONI-regressed anomalies of wintertime (a) skin temperature, (b) snow cover, and (c) soil moisture for 1850–2014 from a member (r1i1p1f1) of CESM2 historical run, in which the ONI index is calculated from SST output from this member. Also shown are ONI-regressed anomalies of ensemble mean of wintertime (d) skin temperature, (e) snow cover, and (f) soil moisture from 10 members of the CESM2 tropical Pacific pacemaker experiment for 1950–2014, in which the ONI index is derived from NOAA/CPC. The white stippling indicates statistical significance at 95% confidence level.
The ENSO-related radiative forcing in the surface energy balance plays an important role in shaping the skin temperature anomaly, and further understanding such the abnormal surface radiation needs to illuminate the physics associated with the atmospheric process and land surface feedback. Generally, atmospheric water vapor is the important contributor to the DLR during winter (Sokolowsky et al. 2020; Clark et al. 2021): the downward shortwave radiation and upward shortwave radiation anomalies are related to the change of clouds and surface albedo, respectively. We next check the regression patterns of these variables to confirm the corresponding physical processes.

Figure 7 shows the ONI-regressed anomaly patterns of total column water vapor, low-cloud cover, and surface albedo from ERA5 reanalysis. The anomaly pattern of total column water vapor (note that blue shading represents positive anomaly) is consistent with that of DLR (cf. Fig. 7a with Fig. 6c), that is, in northern North America, eastern Europe and central Asia (Russian Far East) where the DLR increases (decreases), the atmospheric water vapor content exhibits positive (negative) anomalies and then facilitates the land surface warming (cooling). For southern North America, the enhanced reflection for incoming solar radiation due to the low-cloud radiative effect is readily apparent from the close association between
In comparing the regression patterns of the factors affecting snow cover (Figs. 8a–c), it can be concluded that the snow cover anomaly is mainly driven by the change in snowfall. In particular, significantly positive (negative) snowfall anomalies are observed in the abnormally more (less) snow-covered regions (cf. Fig. 8a with Fig. 3d), such as the southwestern United States, the west Tibetan Plateau, and the Mongolia–North China sector (the northern-central United States and eastern Europe). Interestingly, there is also obviously increased snowfall in the Ural region but where the snow cover anomaly is near zero (Figs. 3d and 8a), that is because the climatological snow cover here has exceeded 90% in winter, the increased snowfall will not further enlarge the snow cover fraction, but mainly deepen the snow depth (Fig. S2 in the online supplemental material). Moreover, regions with increased snowfall in midlatitudes naturally tend to be accompanied by more snowmelt (Fig. 8b), whereas the magnitude of snow evaporation anomaly is very small and can be ignored (Fig. 8c).

Figures 8d–f show the regression patterns of forcing terms in the soil water budget equation. It is easily deduced that the ENSO-related rainfall anomaly is the primary driver of anomalous soil moisture, as the positive rainfall anomalies are correspondingly observed in the areas with anomalously wet soil moisture (i.e., southern North America, central Asia, and southeastern China, Fig. 4). But in the high latitude of Eurasia, considering the effect of snowmelt and frozen ground thawing on soil moisture in winter, the wet soil moisture anomaly in the Ural region may be jointly caused by the increased rainfall and more snowmelt (Figs. 8bd); and as for the dry soil moisture anomaly in the Far East, since the anomalies of rainfall and snowmelt here are both not obvious, we can only reasonably speculate that is due to the reduction of frozen ground thawing during El Niño winters (recalling the cold skin temperature anomalies here in Fig. 2). Collocated with increased rainfall and wet soil moisture anomaly in southern North America, positive evaporation anomalies are also remarkably obvious (Fig. 8e), which further supports that the increased soil moisture plays an important role in shaping the cold skin temperature anomaly here through enhancing the evaporation and latent heat flux (recall Figs. 2d, 4d, and 6f), while probably not through the soil moisture–induced change in surface albedo proposed by Zhang et al. (2011). Moreover, increased rainfall promotes surface runoff in dense river-covered areas such as the southeastern United States and southeast China (Fig. 8f).

In summary, as could be expected intuitively, the above analysis demonstrates that anomalous precipitation (in the form of snowfall and rainfall) dominates the ENSO-related variability of snow cover and soil moisture. Similarly, in order to avoid the uncertainty of analyzing one single dataset, we also check the relevant regression patterns from GLDAS data (Fig. S5 in the online supplemental material), in which the overall consistency with ERA5-Land confirms the robustness of results. Up to now, we have clarified the impact of ENSO on the wintertime skin temperature, snow cover, and soil moisture in Northern Hemisphere extratropics, and identified the associated key physical processes. In the next subsection, we will further address how ENSO events modulate...
the change in relevant physical variables (especially water vapor and precipitation) via atmospheric teleconnections to shape the observed land surface anomalies.

b. ENSO-related atmospheric teleconnection and moisture budget

The ENSO-induced atmospheric circulation anomaly acts as a bridge to communicate SST anomaly in the equatorial central-eastern Pacific with global meteorological fields (Lau and Nath 1996; Klein et al. 1999; Alexander et al. 2002). As the basis for the climatic effect of ENSO events, a thorough investigation of the atmospheric teleconnections over Northern Hemisphere extratropics during El Niño winters is a crucial requisite for understanding the atmospheric water vapor and precipitation anomalies of our concern.

Figure 9 shows the ENSO-related anomaly patterns of wintertime atmospheric circulation and moisture transport field. As widely recognized by numerous previous studies (e.g., Horel and Wallace 1981; Fraedrich 1994; Trenberth et al. 1998; Toniasso and Scaife 2006), the extratropical Northern Hemisphere circulation response to El Niño events includes the atmospheric teleconnections over upstream Pacific–North America and North Atlantic, mainly characterized by the positive PNA-like and negative NAO-like pattern, respectively (Figs. 9a–c). The dynamical mechanism of these responses is relatively well advanced, albeit still incomplete. In general, the midlatitude ENSO atmospheric teleconnections can be understood within the general framework of poleward-propagating Rossby waves forced by anomalous upper-tropospheric divergence associated with latent heat release in deep convection and subsequently modified by transient eddy–mean flow interactions (Hoskins and Karoly 1981; Sardeshmukh and Hoskins 1988; Held et al. 1989; Hoskins and Ambrizzi 1993; Trenberth et al. 1998; Deser et al. 2017). Moving downstream, a barotropic low-pressure anomaly controls the eastern Europe–Ural sector (Fig. 9b), indicating the enhancement of climatological European shallow trough and the decrease of Ural blocking activity during El Niño winters and conversely the weakening of climatological European shallow trough and the increase of Ural blocking activity during La Niña winters (Luo et al. 2021), causing the southwesterly wind anomaly over central
Asia (Fig. 9c). Along the East Asian coast, an anomalous western North Pacific anticyclone (WNPAC) occurs in the lower troposphere, which contains two separate centers of geopotential height anomaly with the principal one over the tropical Philippine Sea and the other over the midlatitude Kuroshio extension (Fig. 9c). In their seminal paper on the ENSO-related Pacific–East Asia teleconnection, Wang et al. (2000) proposed that the tropical portion of WNPAC confined to the lower troposphere is mainly induced by the local air–sea interaction associated with a positive circulation–convection–SST feedback. Meanwhile, the anticyclone over the midlatitude Kuroshio extension exhibits a considerable barotropic structure and links with the western Pacific anomaly pattern (Fig. 9b), of which the kinetic energy is maintained through transient eddies feedback and the barotropic energy conversion associated with the dynamical instability of climatological-mean westerlies (Tanaka et al. 2016). In general, the anomalous WNPAC indicates the weakening of winter monsoon and climatological trough over East Asia during El Niño winters, manifested as southwesterly wind anomalies along the East Asian coast and positive geopotential height anomaly over Northern Asia (Figs. 9b,c), and thus bridges the wintertime East Asian climate variation and ENSO events.

The ENSO-related hemispherically atmospheric circulation anomalies determine the basic features of the corresponding moisture transport field. In particular, the anomaly pattern of moisture flux upstream highly resembles that of the associated low-level atmospheric circulation anomaly (Figs. 9c,d), characterized by the anomalous moisture flux converging (diverging) over the south (north) of North American continent. Furthermore, the anomalous moisture transport from the North Atlantic can extend to and then converge over eastern Europe, of which the other branch flowing via North Africa merges with the moisture transport from the Indian Ocean. Through flowing around the plateau terrain, the merged moisture transport can affect central Asia and East Asian coast, resulting in the anomalous convergence of water vapor flux therein (Fig. 9d). Thus, the ENSO-related atmospheric teleconnection dynamically drives the moisture transport anomaly, and then, the moisture flux convergence causes the observed increased rainfall (cf. Fig. 9d with Fig. 8d), resulting in the anomalously wet soil moisture in southern North America, central Asia, and southeast China. Under the condition that the air temperature in midlatitude winter easily reaches the freezing point, the increased precipitation naturally occurs in the form of snowfall somewhere (cf. Fig. 9d with Fig. 8a), which further explains the increased snow cover in southern United States and Tibetan Plateau.

Driven by the ENSO-related atmospheric teleconnection and associated moisture transport, the change in precipitation, as one of the important atmospheric moisture processes, dominates the formation of soil moisture and snow cover anomaly. In addition, the changes in cloud cover and the abundance of atmospheric water vapor, as pointed out above, are also the key atmospheric moisture processes that shape the skin temperature anomalies, of which the former is also associated with the ENSO-related atmospheric circulation and moisture flux anomaly (cf. Fig. 9d with Fig. 7b), while understanding the latter requires a detailed diagnosis of the atmospheric water vapor equation.

To clarify the process driving the atmospheric water vapor anomaly during ENSO events, we examined the total column water vapor (TCWV) budget equation:

$$\frac{\partial w}{\partial t} = - \nabla \cdot \left( \frac{\rho V}{g} \right) dp + \frac{E - P}{\text{source} - \text{sink}}.$$  

FIG. 9. ONI-regressed wintertime (a)–(c) geopotential height anomalies (shading), associated wave activity flux [vector in (a) and (b)], and 850-hPa wind anomalies [vector in (c)], along with (d) vertically integrated moisture flux (blue vector) and its divergence (shading) for 1979–2021. The black contour in (b) denotes the climatology of 500-hPa geopotential height. Stippling in white and black indicates values significant at 90% and 95%, respectively.
The form of this equation indicates that the change in atmospheric water vapor content (left-hand side) can be induced by the anomalous evaporation $E$, precipitation $P$, and the convergence of vertically integrated moisture flux

$$-\nabla \cdot \left( \frac{1}{g} \int_0^Z q V \, dp \right),$$

of which each term is explicitly provided by ERA5 dataset with the mean evaporation rate and mean total precipitation rate used here.

Figure 10 shows the ENSO-related anomaly patterns of forcing terms in the TCWV budget equation, in which the pattern of evaporation minus precipitation $(E - P)$ is specially examined so that the drivers of atmospheric water vapor anomaly can be categorized as moisture transport convergence (Fig. 10a) and localized source–sink term representing the net effect of evaporation and precipitation processes (Fig. 10b). In terms of the continental-scale anomaly pattern, the observed anomalous TCWV dipole over North America mainly results from the source–sink term dominated by precipitation, which is supported by the basically in-phased (out-phased) relationship between the anomaly pattern of source–sink term (precipitation) and TCWV therein (cf. Fig. 7a with Figs. 9a,b,d), rather than the moisture transport convergence.

This result signifies that, especially in North America, the causality of ENSO-related anomalies of atmospheric water vapor, precipitation, and moisture transport convergence needs to be carefully considered, that is, precipitation dominates the change in atmospheric water vapor here. Such a relationship suggests that the ENSO-related precipitation anomalies in North America are not only affected by moisture transport convergence traditionally, but also the anomalous vertical motion dynamically associated with large-scale atmospheric teleconnection, and the change of atmospheric moisture-holding capacity caused by the thermodynamic adjustment of troposphere (e.g., Zhang et al. 2011). For example, in northern North America, the equivalent-barotropic high-pressure anomalies embedded in the positive PNA-like pattern induce the anomalous descending motion and then raise tropospheric temperature within the static equilibrium constraint during El Niño winters (Figs. 9a,b and Fig. 11a), causing the decrease of precipitation and increase of saturated water vapor pressure (Fig. 11b). Consequently, more water vapor is apt to retain in the air to induce the positive TCWV anomaly (Fig. 7a), which dominates the formation of skin temperature anomalies via DLR.

Over Eurasian continent, the moisture flux convergence has a qualitatively positive pattern correlation with total column water vapor (cf. Fig. 10a with Fig. 7a), suggesting that the ENSO-related atmospheric water vapor anomaly here can be directly explained by moisture transport. Specifically, in the light of moisture flux and its convergence anomaly pattern (Figs. 9d and 10a), the anomalously more water vapor over eastern Europe and central Asia is driven by the convergence of moisture flux associated with the atmospheric circulation anomalies downstream of the PNA-like pattern, while the increased water vapor over East Asia is mainly driven by the moisture transport convergence caused by the anomalous WNPAC, and the negative water vapor anomaly over the Russian Far East is induced by the anomalous divergence of water vapor flux due to the northeasterly wind anomaly associated with abnormally enhanced Aleutian low pressure upstream of PNA-like pattern. Eventually, as pointed out in the previous subsection, the atmospheric water vapor anomalies over these
regions all play a prominent role in shaping skin temperature anomalies via altering the DLR.

5. Summary and discussion

Using a combination of reanalysis, land assimilation, satellite observations, and CESM2 simulation output, this study advances the knowledge of ENSO’s impact on the wintertime land surface variables in the Northern Hemisphere extratropics, focusing on skin temperature, snow cover, and soil moisture, which are the potential climate predictors. The ENSO-related anomaly patterns of land surface variables are identified with regression analysis, and then, the underlying physical processes are examined based on the budget diagnosis, with emphasis on establishing the linkage with the better-known ENSO atmospheric teleconnection.

As a summary of our principal findings, Fig. 12 schematically synthesizes the typical features of land surface anomalies during El Niño winters and the associated atmospheric circulation anomalies that determine the observed anomaly pattern of land surface variables of our concern. First, from a phenomenological perspective, in addition to the prominent ENSO-related land surface anomalies in North America that are consistent with the result of U.S. surface temperature response to ENSO revealed by Zhang et al. (2011), in the vaster Eurasian continent, ENSO events can also leave significant imprints on the skin temperature, snow cover, and soil moisture therein. Specifically, for most areas in the midlatitudes of Northern Hemispheric extratropics (40°–60°N), warm skin temperature anomalies are mainly concentrated in northern North America, eastern Europe, and central Asia, the former two of which are accompanied by the obvious snow cover reduction. At the relatively low latitudes (30°–40°N), the land surface of southern North America and Tibetan Plateau both exhibit anomalous cooling, collocated with increased snow cover. Meanwhile, a cold skin temperature anomaly is also observed in the Russian Far East to the north of 60°N. As for soil moisture, significantly wet anomalies in Northern Hemisphere extratropics are observed mainly in southern North America, central Asia and southeast China. In addition, three datasets have also consistently revealed some signals in high-latitude Eurasian regions, characterized by the wet soil moisture anomalies in the Ural region and dry anomalies in the Far East. Furthermore, from the perspective of numerical modeling, results from CESM2 simulation confirm most of

![Fig. 12. Schematic diagram on the distribution (for El Niño condition) and mechanism of ENSO-related wintertime land surface anomalies in Northern Hemisphere extratropics.](image-url)
the observed ENSO’s impact on the Northern Hemisphere land surface in winter, and especially the regression patterns based on tropical Pacific pacemaker ensembles provide direct evidence on the robust land surface response to ENSO forcing.

Combined with the understanding of ENSO-related atmospheric circulation and moisture transport anomalies, diagnoses on the budget equations of land surface variables further clarify how ENSO events modulate atmospheric moisture processes including the change in water vapor and precipitation to shape the land surface anomalies. The change in atmospheric water vapor dominates the formation of skin temperature anomalies via altering the DLR in most areas, except for southern North America and Tibetan Plateau where the shortwave radiative processes are important in balancing the upward longwave radiation and affecting skin temperature. Notably, the pathways of causing water vapor anomalies are different in North America and Eurasia, which may be linked to the distinction between the amplitude of atmospheric response to ENSO over the two continents. Over North America, atmospheric circulation responds intensely to ENSO-related SST forcing, characterized by the upstream PNA-like pattern with stronger geopotential anomaly and tropospheric air temperature adjustment, thereby causing anomalous precipitation by the thermodynamic control, not just by the dynamical moisture transport. As a result, precipitation drives the water vapor anomalies here, and the warm, moister tropospheric air favors shaping the warm skin temperature anomaly in northern North America through increasing the DLR. But for southern North America, a substantial part of the skin temperature anomalies here is due to the reduced downward shortwave radiation resulting from the increased low-cloud cover, physically consistent with the prevailing low-pressure and moisture flux convergence anomalies here. Different from the North American continent, the change in water vapor over Eurasia is directly driven by anomalous moisture transport, which also determines the distribution of precipitation anomalies. In particular, collocated with the anomalous moisture flux convergence, the significantly warm skin temperature anomaly in eastern Europe and central Asia is largely due to the increased DLR anomaly induced by more water vapor. Conversely, collocated with the anomalous moisture flux divergence, the significantly cold skin temperature anomaly in the Russian Far East is largely due to the decreased DLR anomaly induced by less water vapor.

For the soil moisture and snow cover anomalies, they are mainly driven by the ENSO-related anomalous precipitation in the form of rainfall and snowfall, in which increased rainfall induces anomalously wet soil moisture, and more snowfall favors increasing the snow cover near the climatic snow line. Moreover, these two variables are closely related to the local skin temperature anomalies in some regions. For example, the wet soil moisture anomaly in southern North America enhances evaporation and upward latent heat flux, primarily causing the anomalous land surface cooling here; and snow cover anomalies dominantly contribute to the formation of cold skin temperature anomalies through the snow–albedo feedback, especially in the Tibetan Plateau. In fact, it must be pointed out that soil moisture–related processes are actually more complicated than skin temperature and snow cover. As mentioned earlier, the change of wintertime soil moisture in high-latitude areas is significantly affected by seasonal expansion and thaw of snow cover and frozen soil (Qiao et al. 2022), which causes considerable uncertainty in soil moisture simulation and thus brings difficulties in finding the robust soil moisture response to ENSO in those regions. Meanwhile, soil moisture has close links with local hydrologic recycling through evaporation, particularly in the interior of continents during warm seasons with strong land–air coupling (e.g., Chen et al. 2022).

Overall, this study integrates the ENSO-related land surface anomalies with the associated atmospheric teleconnection, more specifically, the impact of ENSO on skin temperature, snow cover, and soil moisture is exerted by the changes in atmospheric moisture processes that concurrently modulate the surface energy balance. However, we just understand the influence and mechanism of ENSO on the wintertime land surface anomalies under a linear framework at present. Although it is temporarily beyond the scope of our investigation, considering the asymmetric features in ENSO itself and its atmospheric impacts (Hoerling et al. 1997; An and Jin 2004; Wang et al. 2021), it can be reasonably argued that the influence of ENSO on land surface would also present quite an obvious asymmetry and such an argument needs further investigation. More important, from the perspective of gaining new insights into seasonal climate prediction, since ENSO can induce the Northern Hemisphere land surface anomalies in winter, whether land surface anomalies in some key areas will persist in subsequent seasons and then act as land pathway relaying ENSO signal to affect the climate locally and remotely, such a hypothesis is being tested in our follow-up study.

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Data availability statement. The ERA5-Land monthly data are downloaded at https://doi.org/10.24381/cds.68d2bb30, the ERA5 monthly averaged data on pressure levels are from https://doi.org/10.24381/cds.6860a573, and the ERA5 monthly averaged data on single levels are from https://doi.org/10.24381/cds.6f17050d7. GLDAS data are downloaded from https://hydro1.gesdisc.eosdis.nasa.gov/data/GLDAS/. The ISCCP data are from https://www.nci.noaa.gov/data/international-satellite-cloud-climate-project-iscrp-h-series-data/access/iscrp/hgml/. The NSIDC snow cover data are downloaded from https://nsidc.org/data/nsidc-0046/. The CPC soil moisture are downloaded from https://psl.noaa.gov/data/gridded/data.cpcsoil.html. The ONI index is obtained from https://www.cpc.ncep.noaa.gov/data/indices/oni.asci.txt. CESM2 historical run is derived from CMIP6 data archive https://esgf-node.llnl.gov/search/cmip6/. CESM2 Pacific pacemaker ensemble is from https://www.earthsystemgrid.org/dataset/ucar.cgd.cesm2.pacific.pacemaker.html.


