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The impact of devegetated dune fields on North American climate during the late Medieval Climate Anomaly

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[1] During the Medieval Climate Anomaly, North America experienced severe droughts and widespread mobilization of dune fields that persisted for decades. We use an atmosphere general circulation model, forced by a tropical Pacific sea surface temperature reconstruction and changes in the land surface consistent with estimates of dune mobilization (conceptualized as partial devegetation), to investigate whether the devegetation could have exacerbated the medieval droughts. Presence of devegetated dunes in the model significantly increases surface temperatures, but has little impact on precipitation or drought severity, as defined by either the Palmer Drought Severity Index or the ratio of precipitation to potential evapotranspiration. Results are similar to recent studies of the 1930s Dust Bowl drought, suggesting bare soil associated with the dunes, in and of itself, is not sufficient to amplify droughts over North America.

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1. Introduction

[2] During the Medieval Climate Anomaly (MCA), North America (NA) experienced 'megadrought' events that often persisted for periods (≥10 years) that exceeded even the worst droughts observed during the instrumental record [*Cook et al.*, 2010]. These droughts were embedded within a global pattern of hydroclimate variability during the MCA that included widespread drying in the subtropics and midlatitudes of both hemispheres [*Burgman et al.*, 2010; *Graham et al.*, 2007; *Seager et al.*, 2007], potentially a consequence of persistently cold sea surface temperatures (SST) in the eastern tropical Pacific [*Graham et al.*, 2007; *Seager et al.*, 2007]. Over NA, these megadroughts caused vegetation die-offs in the central and southern Great Plains regions, leading to large scale dune mobilization [*Forman et al.*, 2001; *Hanson et al.*, 2010; *Miao et al.*, 2007]. The role dune mobilization may have played in exacerbating the droughts during the MCA has been conjectured [e.g., *Hanson et al.*, 2010; *Seager et al.*, 2008b], but not explicitly investigated within a modeling framework.

[3] Much of our modern understanding of land surface feedbacks and drought originated from studies of drought and desertification in the Sahel over thirty years ago [*Charney*, 1975; *Charney et al.*, 1977], with subsequent research further elucidating the roles of soil moisture, vegetation, and surface energy balance feedbacks [e.g., *Dirmeyer*, 1994; *Eltahir*, 1998; *Oglesby and Erickson*, 1989]. Of most recent relevance for NA, *Cook et al.* [2008, 2009] used a general circulation model (GCM) to investigate the effect of land degradation during the North American 'Dust Bowl' drought of the 1930s. They concluded that, while the drought was initiated by SST anomalies in the Pacific and Atlantic [*Schubert et al.*, 2004], both the loss of vegetation and the increased dust fluxes over the Great Plains acted as important feedbacks, amplifying the warming and drying.

[4] Currently, GCMs forced only by either idealized [*Feng et al.*, 2008] or reconstructed [*Seager et al.*, 2008a] SSTs have difficulty reproducing the magnitude, duration, and spatial pattern of the megadroughts, pointing to a possible additional influence from the land surface changes at the time. We use an atmosphere GCM, forced by a tropical Pacific SST reconstruction and estimates of 'dune mobilization' during the late MCA, to investigate the potential for devegetation over the Great Plains to influence temperature, precipitation, and drought over central NA. Our goal is to determine whether devegetation associated with dune mobilization can significantly modify the character of the megadroughts beyond what would be expected from SST forcing alone.

2. Data and Methodology

2.1. SST Reconstruction

[5] The tropical Pacific SST reconstruction is the same as that used by *Seager et al.* [2008a] and *Burgman et al.* [2010] and is based on sub-annual resolution coral oxygen isotope data from modern (1886–2008) and fossil (1320–1462) corals on Palmyra Atoll (6°N, 160°W), as reported by *Cobb et al.* [2003]. Details, including extrapolation to global SST fields used to force the model, can be found in the auxiliary material.[1]

2.2. Dune Area

[6] Geomorphological evidence indicates that there were numerous dune mobilization events over the Great Plains during the last two millennia [*Forman et al.*, 2001; *Hanson et al.*, 2010; *Miao et al.*, 2007], and the most recent dune activity may have been as late as the 14th and early 15th centuries, coinciding with our SST reconstruction. However, dating uncertainties in the dunes and the corals make determining exact dates difficult. For our experiments, we conceptualize dune mobilization in the model as bare, devegetated soil by converting part of the Great Plains

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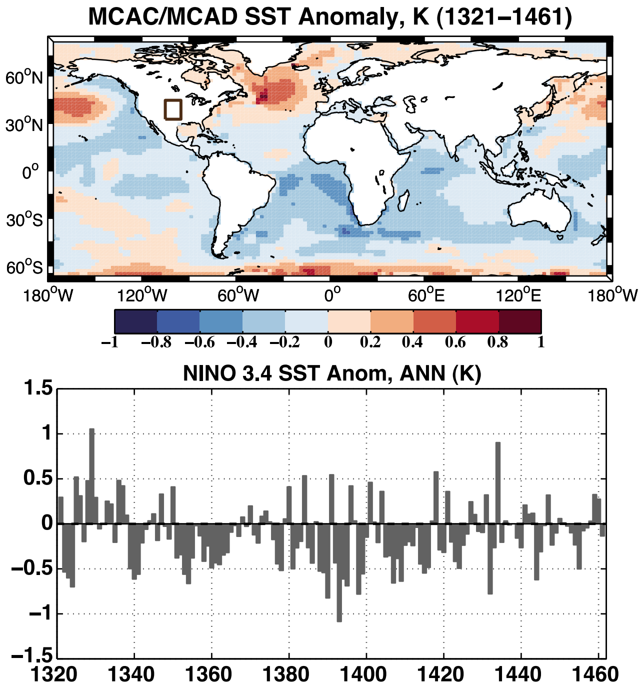


Figure 1. (top) Mean annual global SST anomalies for the MCAC and MCAD ensemble runs and (bottom) the NINO3.4 SST anomaly calculated from this reconstruction. The rectangle indicates the region of 50% devegetation, used to simulate dune mobilization in the MCAD run.

(105°E–95°E, 32°E–44°E) from 100% vegetation cover to a 50% vegetated/bare soil mix. The region chosen is based on maps from *Hanson et al.* [2010]. We realize this is a relatively coarse approximation; in reality, the dune mobilization was a consequence of complex local dynamical interactions between drought, vegetation dynamics, and wind. Despite these caveats, including timing uncertainties, our approach should still provide some useful insights into the role of devegetation on drought persistence, and serve as a baseline sensitivity study for future and possibly more complex implementations that, for example, also account for dust aerosol fluxes from the dunes.

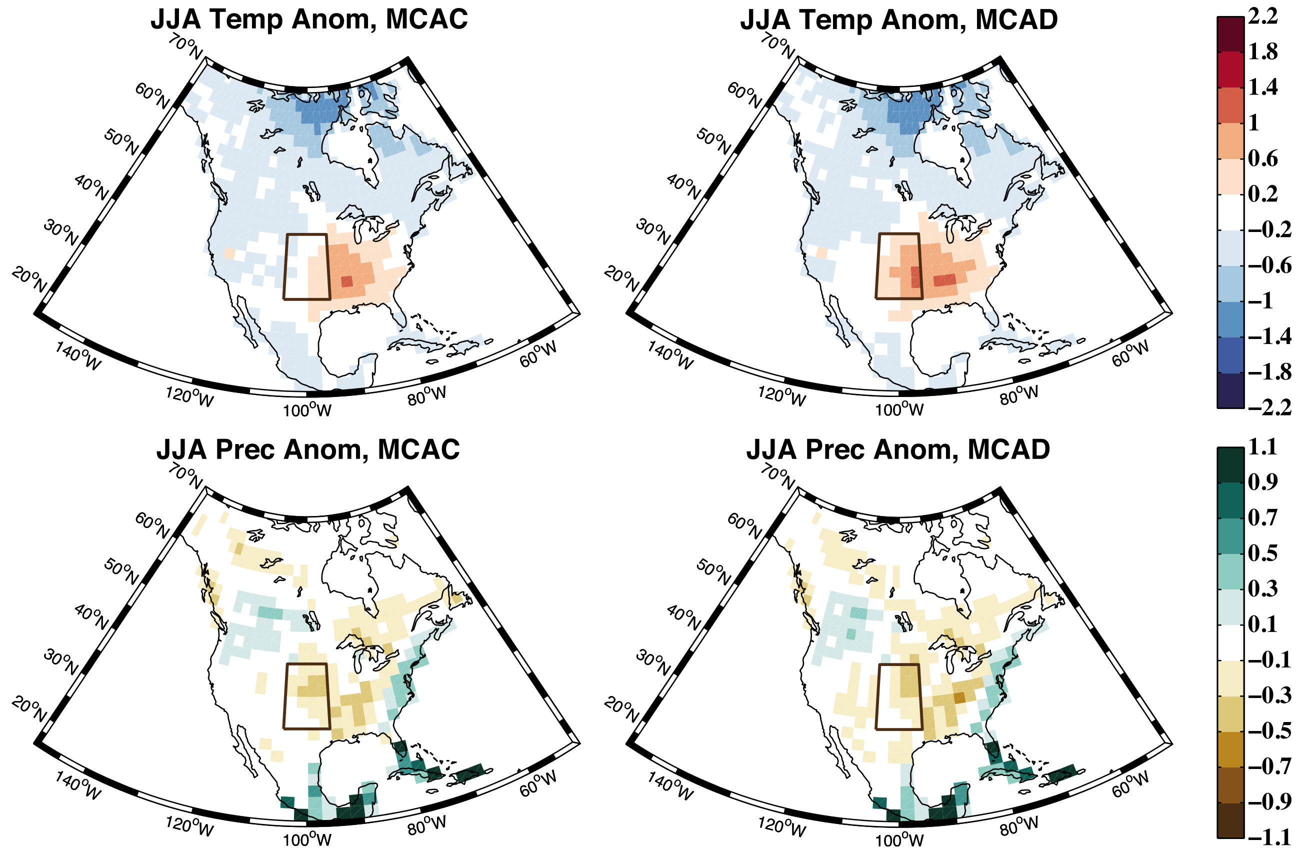
2.3. Model Description and Setup

[7] For these experiments, we use the latest version of the Goddard Institute for Space Studies atmosphere general circulation model, 'ModelE' [*Schmidt et al.*, 2006], run at F40 horizontal resolution (approximately 2° × 2.5°) with 40 vertical atmospheric layers (see the auxiliary material for more details regarding ModelE parameterizations and performance). We conduct three, five-member ensemble experiments. Our baseline run is MODC ('Modern Control'), forced by the modern Kaplan SST dataset [*Kaplan et al.*, 1998] and transient forcings (solar, volcanic, and greenhouse gas concentration) from 1858–2005. Both MCA ensemble experiments, MCAC ('Medieval Control') and MCAD ('Medieval with Dunes'), are forced with the aforementioned SST reconstruction for years 1321–1461; in addition, MCAD includes the implementation of the dune mobilization described previously. We explicitly do not allow for surface dust fluxes or dust aerosols as part of the dune mobilization in these experiments, as little or no data is currently available to constrain these (although it may be possible to derive quantitative estimates from, for example, *Miao et al.* [2007]). For our analyses, we focus on the boreal summer season (June-July-August, JJA), when we expect land surface processes to exert the strongest impact on the overlying atmosphere. Unless otherwise indicated, all anomalies are expressed relative to the 1961–1990 baseline from the MODC ensemble mean.

3. Results

[8] Boundary conditions for the MCAC and MCAD experiments are shown in Figure 1. The average SSTs are indicative of a mean 'La Niña' like state, characterized by cool SSTs in the eastern tropical Pacific and along the west coast of NA and warm conditions in the central extratropical Pacific (Figure 1, top). The NINO3.4 index, calculated from the SST field, shows persistent cold periods, with anomalies often exceeding −1 K. The region of devegetation for our dune mobilization experiment, MCAD, is outlined over NA.

[9] In the ensemble mean, both Medieval runs are characterized by warm and dry conditions in central and eastern NA (Figure 2); the spatial patterns for these anomalies generally compare favorably with previous GCM experiments during the MCA [*Burgman et al.*, 2010; *Seager et al.*, 2008a]. The warming intensifies in the MCAD ensemble, primarily over the region of dune mobilization, but the addition of dunes has little impact on the mean precipitation anomaly pattern. To test for significant differences between our MODC, MCAC, and MCAD ensembles, we use the Wilcoxon Rank Sum (WR) test for differences in the median and the Kolmogorov-Smirnov goodness-of-fit test (KS) to determine if values are drawn from the same underlying distribution. Averaged over the region of dune mobilization, both the MCAC and MCAD ensembles are significantly warmer (WR, $p \leq 0.001$) than the ensemble median calculated for the full MODC ensemble (1858–2005): anomalies are +0.27 K in MCAC and +0.88 K in MCAD (Figure 3, left). The MCAC and MCAD simulations are also significantly drier (WR, $p \leq 0.001$) than MODC (Figure 3, right), by −0.22 mm day^{-1} and −0.25 mm day^{-1}, respectively. The KS test strongly suggests that temperature and precipitation anomalies for the MCAC and MCAD ensembles are drawn from a distribution independent from MODC (KS, $p \leq 0.001$). The reduced precipitation in the MCAC ensemble comes entirely from the anomalous SST forcing, which will tend to suppress precipitation in the midlatitudes in both hemispheres, including over Central and Southern NA. This drying explains the modest warming in MCAC; over the dune region temperature and precipitation are tightly and inversely coupled during boreal summer (e.g., Spearman's Rank correlation between temperature and precipitation in the MODC ensemble is −0.74). The exceptional warmth in the MCAD simulations is not only significantly warmer compared to MODC, but is also significantly warmer than the MCAC ensemble (WR, $p \leq 0.0001$; KS, $p \leq 0.0001$), indicating a significant impact of the dune mobilization on surface temperatures. This additional warming is caused by large changes in the surface energy balance from the devegetation. The reduced vegetation cover in MCAD has only a relatively minor effect on surface reflectance, increasing albedo +4.19% and reducing net shortwave radiation at the surface by only −0.65 W m^{-2}, relative to MCAC. Other


JJA Temp Anom, MCAC

JJA Temp Anom, MCAD

JJA Prec Anom, MCAC

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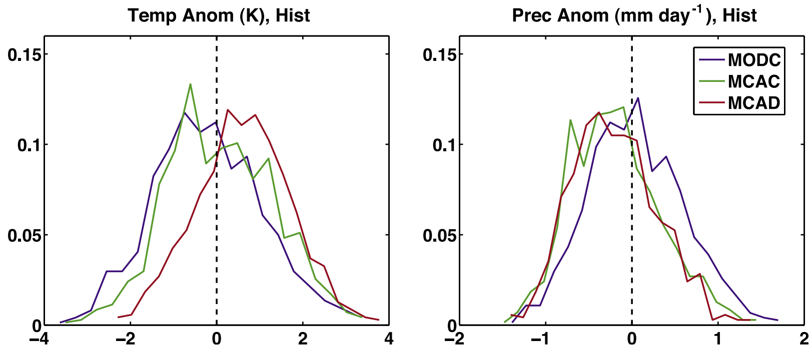
Figure 2. Ensemble mean maps of JJA (top) temperature (K) and (bottom) precipitation (mm day^{-1}) anomalies from the MCAC and MCAD runs (1321–1461), calculated relative to the ensemble mean for 1961–1990 from the MODC scenario. The region of dune mobilization (105°E–95°E, 32°E–44°E) is outlined.

shifts in the surface energy balance, however, are much larger. Devegetation sharply reduces evapotranspiration at the surface, leading to reductions (MCAD minus MCAC) in latent heat fluxes of -7.23 W m^{-2}. Reductions in latent heating are largely balanced by increased sensible heating ($+3.12$ W m^{-2}) and outgoing longwave fluxes from the surface ($+5.33$ W m^{-2}). Soil and near-surface air temperatures increase as a consequence of the shifts in the surface energy balance. Despite the reduction in surface evaporation, precipitation is not significantly reduced (at the level of $p \leq 0.05$) in MCAD compared to MCAC, implying little aggregate impact of the dunes on precipitation above and beyond the influence of the SST forcing. The ensemble median time series of temperature and precipitation anomalies from the MCAC and MCAD ensembles show that the MCAD simulation is warmer over almost the entire Medieval interval (Figure S2 in Text S1), although with large variability. As mentioned previously, precipitation differences between MCAC and MCAD are on the whole negligible and statistically insignificant, with certain periods drier in the MCAD ensemble (e.g., 1321–1360, 1430–1461) and others wetter (e.g., 1400–1420), compared to MCAC. A comparison of drought indices calculated from the model runs (Palmer Drought Severity Index and the ratio of


Temp Anom (K), Hist

Prec Anom (mm day^{-1}), Hist

Figure 3. Histograms of full ensemble (left) temperature and (right) precipitation anomalies over the region of dune mobilization (105°E–95°E, 32°E–44°E), for all three model scenarios.

precipitation to potential evapotranspiration) also indicated little impact on mean drought conditions from the devegetation (Figure S3 in Text S1).

4. Discussion and Conclusion

[10] Our experiments demonstrate that loss of vegetation associated with dune mobilization over central NA can exert a significant influence on surface temperatures beyond the influence of the SST forcing. However, the impact on precipitation and drought (as defined by the PDSI) was found to be negligible. This is largely consistent with the results of *Cook et al.* [2009], who found that increased bare soil during the Dust Bowl could explain the warm temperature anomalies over central NA, but had little impact on precipitation. In that study, the authors found it was necessary to include wind erosion and dust aerosols in order to get a significant precipitation response from land surface changes. Dust forcing may have played a role during the MCA droughts, and it may be possible to derive quantitative information on dust fluxes during this period [e.g., *Miao et al.*, 2007]. Regardless, results from these experiments should provide another point of comparison to the already existing model studies of the MCA megadroughts [*Feng et al.*, 2008; *Seager et al.*, 2008a].

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