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The preseason warming of the Indian Ocean resulting in soybean failure in US

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Supplementary

Note: References cited in the Supplementary Material are included in the main manuscript reference list.

Table S1: Meteorological variables used in this study, their definitions, sources, and references.

Variable	Definition / Source	References
Tmx	Maximum temperature (°C), CRU TS v4.07	Gaupp et al., 2020; Hamed et al., 2021
Tmp	Mean temperature (°C), CRU TS v4.07	Joshi et al., 2021; Ray et al., 2015
Tmn	Minimum temperature (°C), CRU TS v4.07	Schauberger et al., 2017
Pre	Precipitation ($mm \cdot d^{-1}$), CRU TS v4.07	Leng and Hall, 2019; Li et al., 2019
DSRF	Downward shortwave radiation flux ($W \cdot m^{-2}$), CRU TS v4.07	Schauberger et al., 2017
Wet	Wet day frequency (days), CRU TS v4.07	Gobin and Van de Vyver, 2021
SMroot	Soil moisture ($m^3 \cdot m^{-3}$), ERA5, Layer 2 (7-28 cm)	Otkin et al., 2016
VPD	Vapor pressure deficit (hPa), derived from Tmp and ea	Ergo et al., 2018
DTR	Diurnal temperature range (°C), CRU TS v4.07	Joshi et al., 2021
Cld	Cloud cover (%), CRU TS v4.07	Exploratory (this study)

Table S2: Oceanic indices used in this study and their definitions and source

Index	Definition	Source
Niño1+2	The averaged SSTA in the region (0°-10° S, 90°-80° W)	https://psl.noaa.gov/data/correlation/nina1.anom.data
Niño3.4	The averaged SSTA in the region (5° N-5° S, 150°-90° W)	https://psl.noaa.gov/data/correlation/nina34.anom.data
Niño3	The averaged SSTA in the region (5° N-5° S, 170°-120° W)	https://psl.noaa.gov/data/correlation/nina3.anom.data
Niño4	The averaged SSTA in the region (5° N-5° S, 160° E-150° W)	https://psl.noaa.gov/data/correlation/nina4.anom.data
SOI	A measure based on the difference in SLP anomalies between Tahiti and Darwin, Australia	https://psl.noaa.gov/data/correlation/soi.data
PDO	The leading principal component of monthly SSTA in the North Pacific Ocean	https://psl.noaa.gov/data/correlation/pdo.data
NPI	The area-weighted SLP over the region (30° N-65° N, 160° E-140° W)	https://psl.noaa.gov/data/correlation/np.data
TSA	The averaged SSTA in the region (0°-20° S, 10° E-30° W)	https://psl.noaa.gov/data/correlation/tsa.data
TNA	The averaged SSTA in the region (5.5°N-23.5°N, 15°-57.5°W)	https://psl.noaa.gov/data/correlation/tna.data
AMO	The averaged SSTA in the North Atlantic Ocean (0°-70° N)	https://psl.noaa.gov/data/correlation/amon.us.data
IOD	The difference in SSTA between the western equatorial Indian Ocean (50°-70° E, 10° S-10° N) and the southeastern equatorial Indian Ocean (90°-110° E, 10° S-0°)	calculated
IOB	The averaged SSTA in the region (20° S-20° N, 40° -110° E)	calculated

Table S3: Regression coefficients of various meteorological factors in ridge regression

Variable	Coefficient
DTR	-0.66735
SMroot	0.627568
Tmx	-0.527428
Tmp	-0.446923
Pre	-0.402184
Tmn	-0.030895
Cld	0.328608
Wet	-0.108994
VPD	-0.106505
DSRF	0.089041

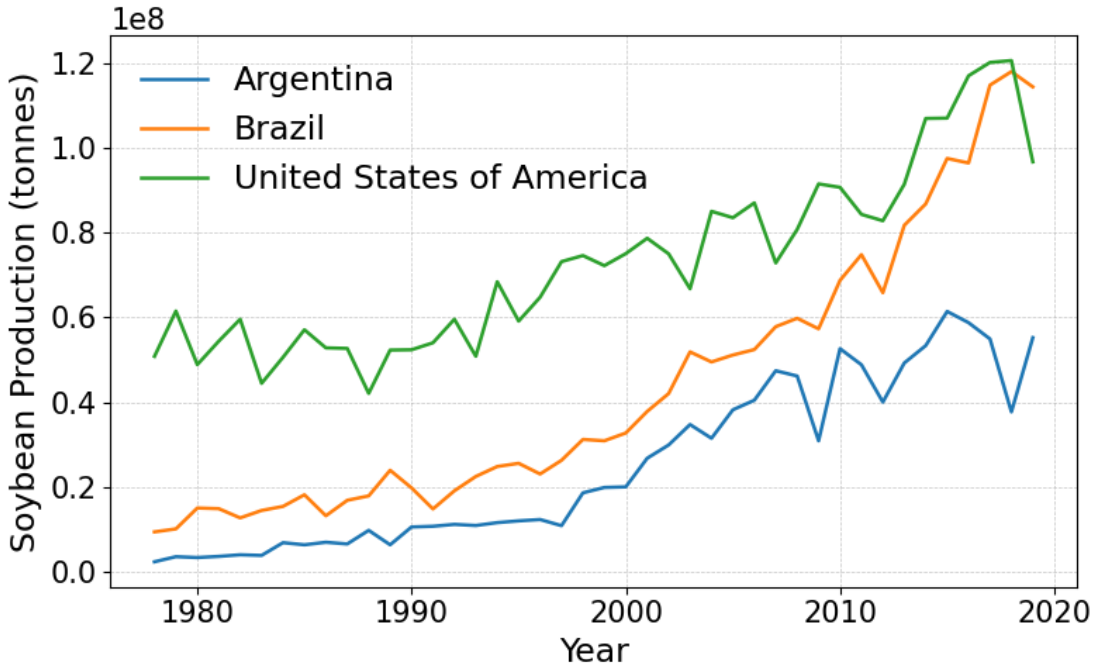

Figure S1: Time series of total soybean production in Argentina, Brazil, and the United States of America from 1978 to 2019, based on FAOSTAT data. Values are reported in tonnes (t).

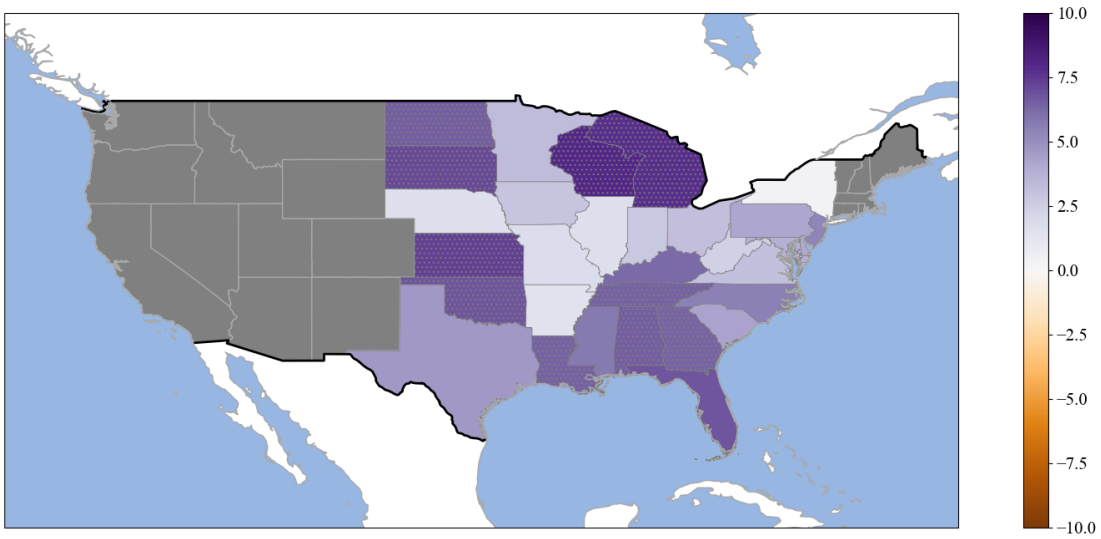

Figure S2: Spatial distribution of the sensitivity of soybean yield anomalies to the standardized Niño3.4 index during MJJ (May–July) from 1980 to 2017. The values represent the change in the percent yield anomaly per one standard deviation (1σ) increase in the standardized Niño3.4 index. Dots indicate statistically significant correlations at the 90% confidence level (t-test).

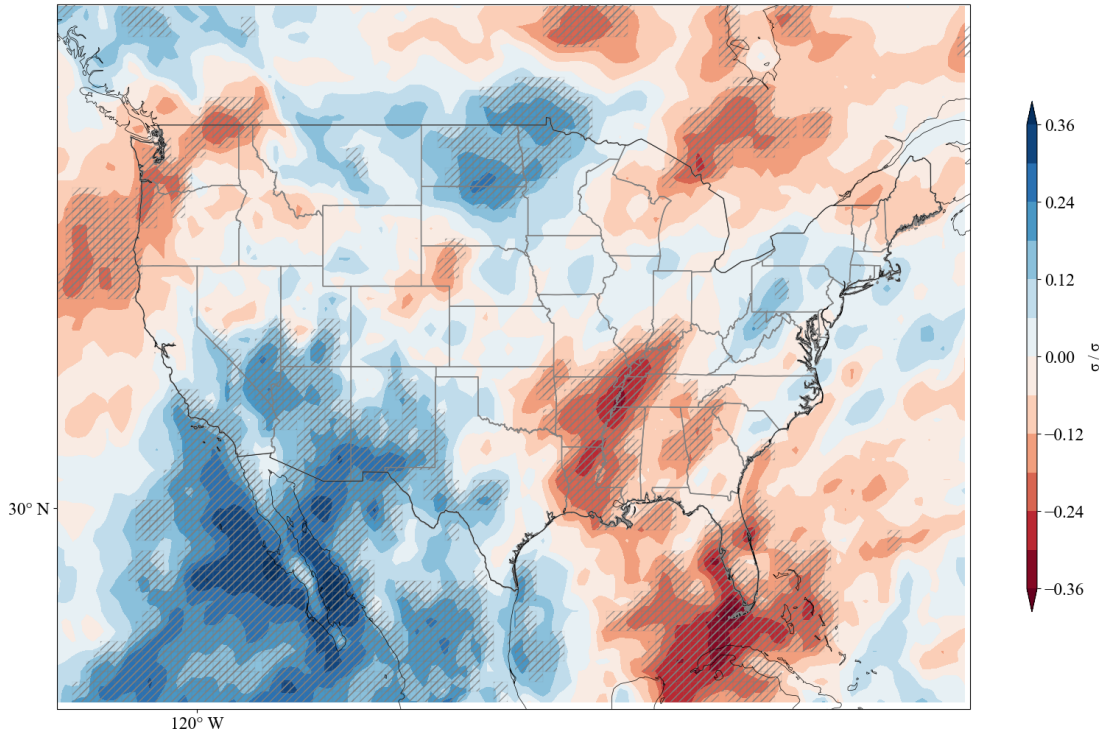

Figure S3: Responses of vertically integrated moisture divergence ($kg \cdot m^{-2}$) to the standardized IOB index during ND(–1)J. The variable was standardized before analysis. Values indicate the standardized change (in σ units) in vertically integrated moisture divergence per 1σ increase in the standardized IOB index. Shaded areas with diagonal hatching indicate regions where the response is statistically significant at the 90% confidence level (t-test).

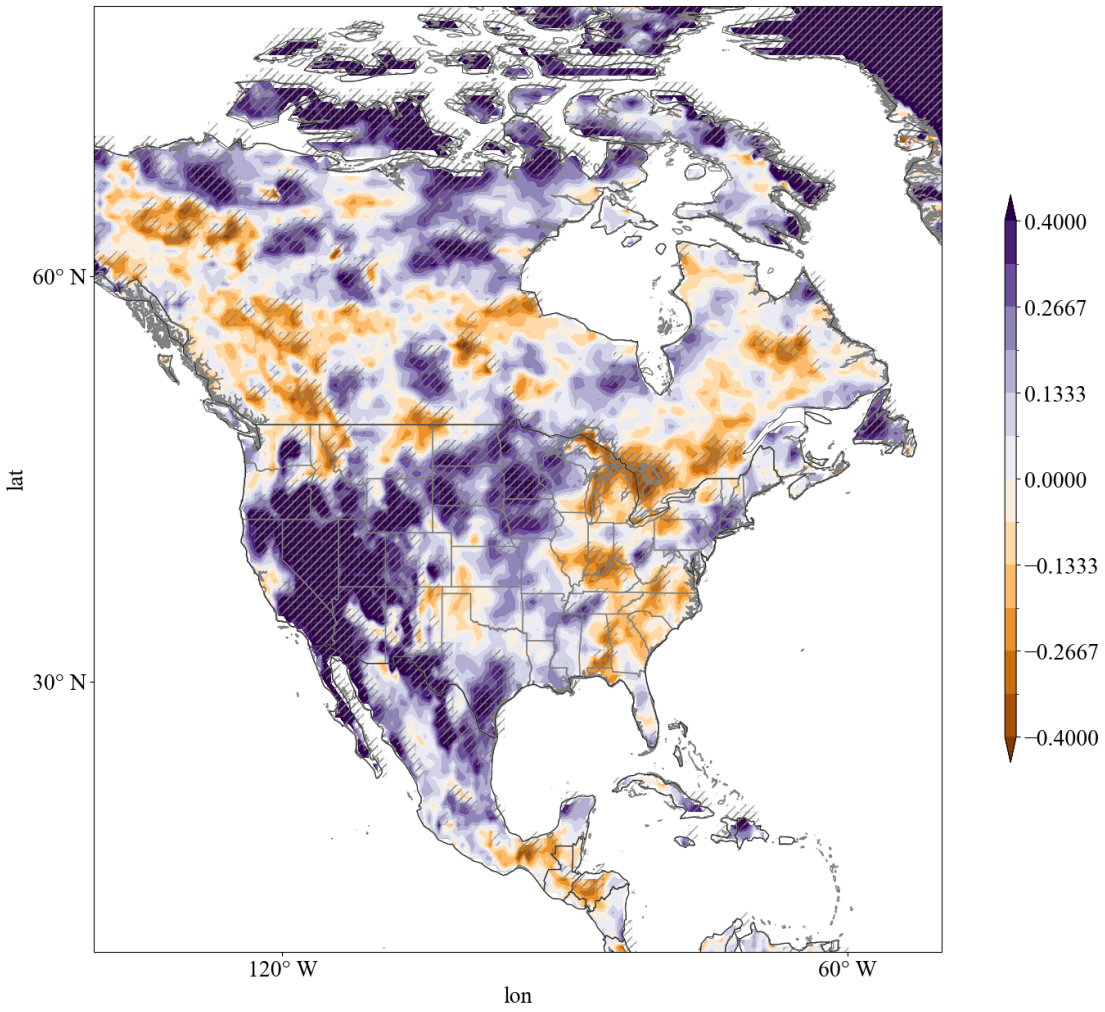

Figure S4: The correlation between SMroot during ND(-1)J and during JAS. Shaded areas with diagonal hatching indicate regions where the response is statistically significant at the 90% confidence level (t-test).

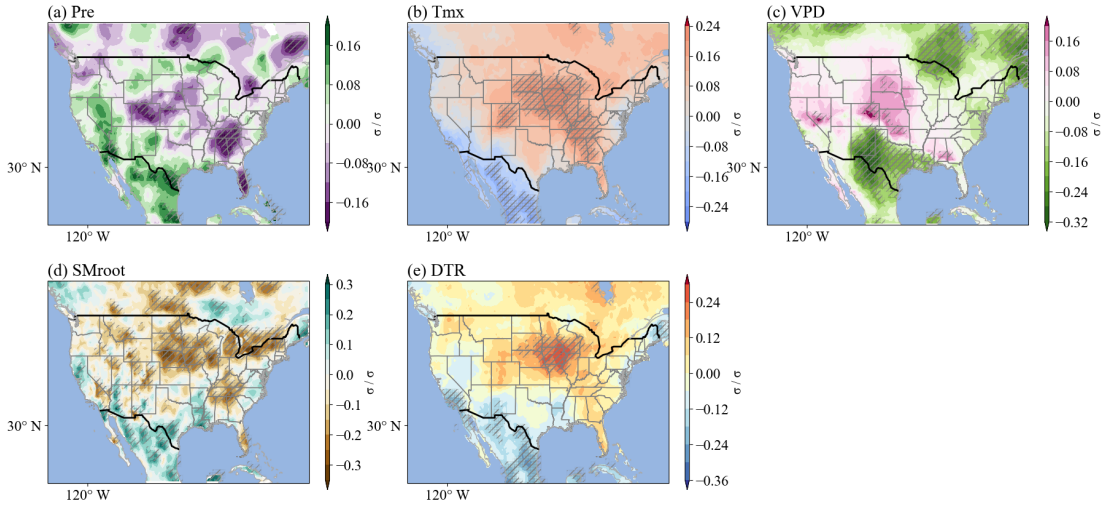

Figure S5: Responses of (a) precipitation (Pre, mm·d−1), (b) maximum temperature (Tmx, °C), (c) vapor pressure deficit (VPD, hPa), (d) root zone soil moisture (SMroot, m3·m-3), and (e) diurnal temperature range (DTR, °C) during JAS to the standardized IOB index during ND(–1)J. All variables were standardized before analysis. Values represent standardized changes (in σ units) in each variable per 1σ increase in the standardized IOB index. Shaded areas with diagonal hatching indicate regions where the response is statistically significant at the 90% confidence level (t-test).