

Supplementary Information for

**Super El Niño events Drive Climate Regime Shifts with Enhanced Risks
under Global Warming**

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This supplementary material contains the following supplemental Figures, Table and Texts:

Supplementary Figures:

Supplementary Fig. 1 Global distributions of climatological and El Niño-Southern Oscillation (ENSO)-related increases in climate regime shift probabilities.

***Supplementary Fig. 2** Maps of increased climate regime shift probabilities due to super El Niño across multiple sea surface temperature datasets.*

***Supplementary Fig. 3** Maps of increased climate regime shift probabilities due to super El Niño across multiple surface air temperature datasets.*

***Supplementary Fig. 4** Maps of increased climate regime shift probabilities due to super El Niño across multiple surface soil moisture datasets.*

***Supplementary Fig. 5** Temporal evolutions of annual climate regime shift probabilities in multiple sea surface temperature datasets.*

***Supplementary Fig. 6** Temporal evolutions of annual climate regime shift probabilities in multiple surface air temperature datasets.*

***Supplementary Fig. 7** Temporal evolutions of annual climate regime shift probabilities in multiple surface soil moisture datasets.*

***Supplementary Fig. 8-12** Temporal Evolutions of annual climate regime shift probabilities with varying cut-off lengths $L = 6, 8, 10, 12$ and the probability levels $p = 0.01, 0.05, 0.1$.*

***Supplementary Fig. 13** Super El Niño events induce SST regime shifts in the Central-North Pacific through the “Reemergence” mechanism.*

***Supplementary Fig. 14** Precipitation (December–February) and surface soil moisture (March–May) anomalies during three super El Niño periods.*

***Supplementary Fig. 15** Precipitation (March–May) and surface soil moisture (June–August) anomalies during the decaying phases of three super El Niño events.*

***Supplementary Fig. 16** Surface soil moisture memory in observations.*

***Supplementary Fig. 17** Climate regime shift probabilities in the Community Earth System Model version 2 Large Ensemble (CESM2-LE) under historical and SSP3–7.0 scenarios.*

Supplementary Fig. 18 Climatological mean and El Niño-Southern Oscillation (ENSO)-
composite changes in climate regime shift probabilities in the Community Earth System
Model version 2 Large Ensemble (CESM2-LE) historical simulations.

Supplementary Fig. 19 Climatological mean and El Niño-Southern Oscillation (ENSO)-
composite changes in climate regime shift probabilities in the Community Earth System
Model version 2 Large Ensemble (CESM2-LE) SSP3–7.0 simulations.

Supplementary Fig. 20 Climate regime shift probabilities in the Coupled Model
Intercomparison Project Phase 6 (CMIP6) models under historical and SSP5–8.5
scenarios.

Supplementary Fig. 21 Super El Niño-induced climate regime shifts in polar sea ice.

Supplementary Table:

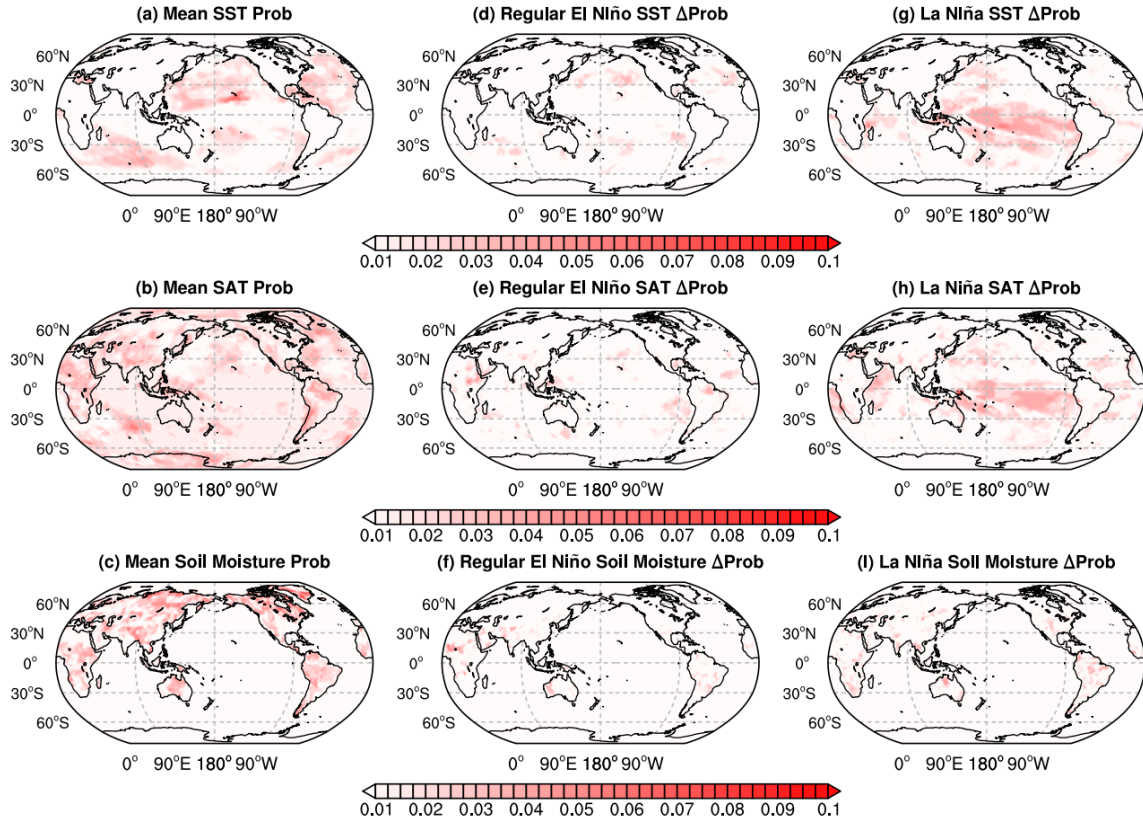
Supplementary Table1 List of 48 models from the Coupled Model Intercomparison Project
Phase 6 (CMIP6) used in this study.

Supplementary Texts:

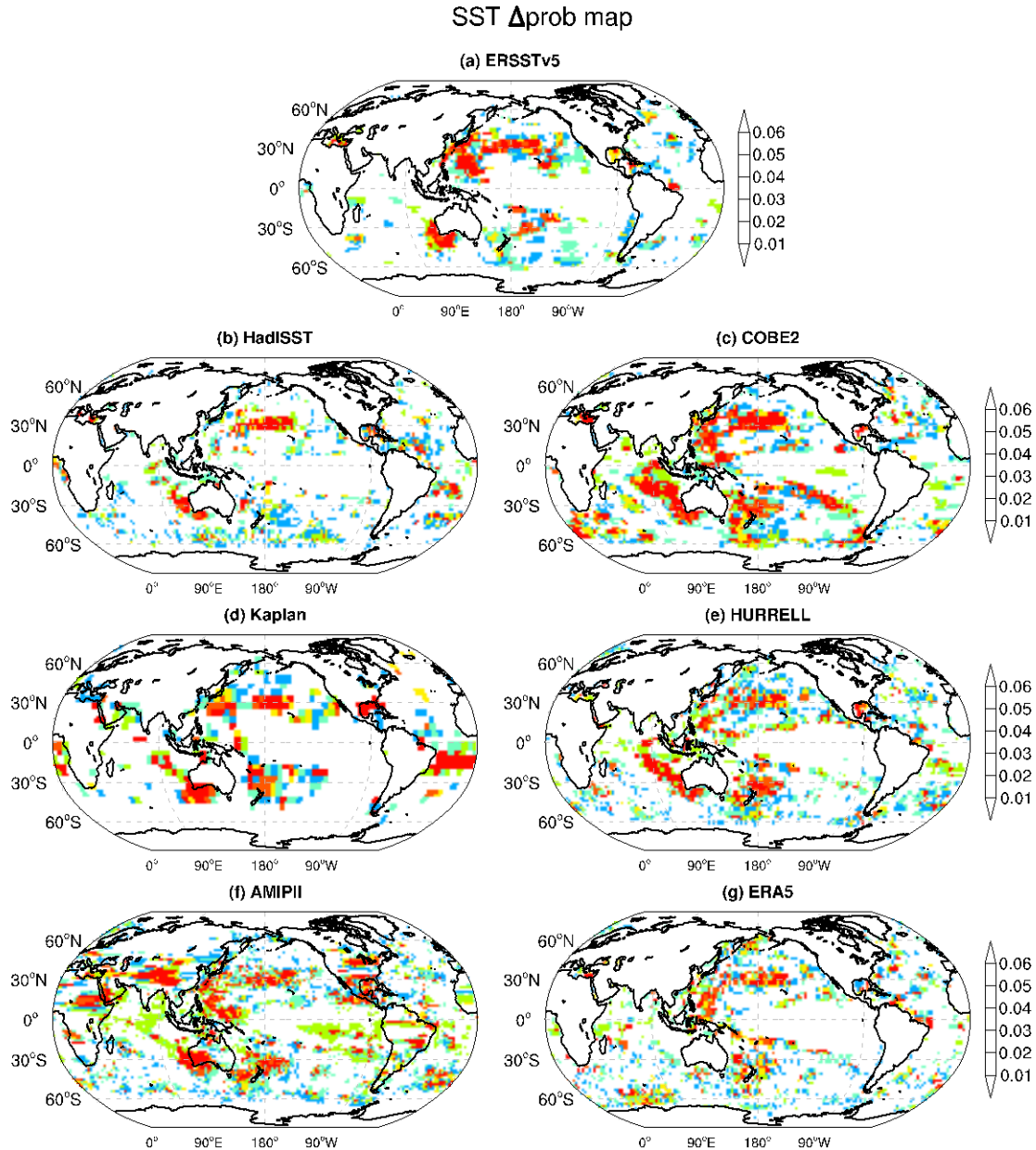
Supplementary Text 1 Mechanisms on super El Niño-induced sea surface temperature
regime shifts.

Supplementary Text 2 Mechanisms on super El Niño-induced surface air temperature
regime shifts.

Supplementary Text 3 Mechanisms on super El Niño-induced surface soil moisture regime
shifts.

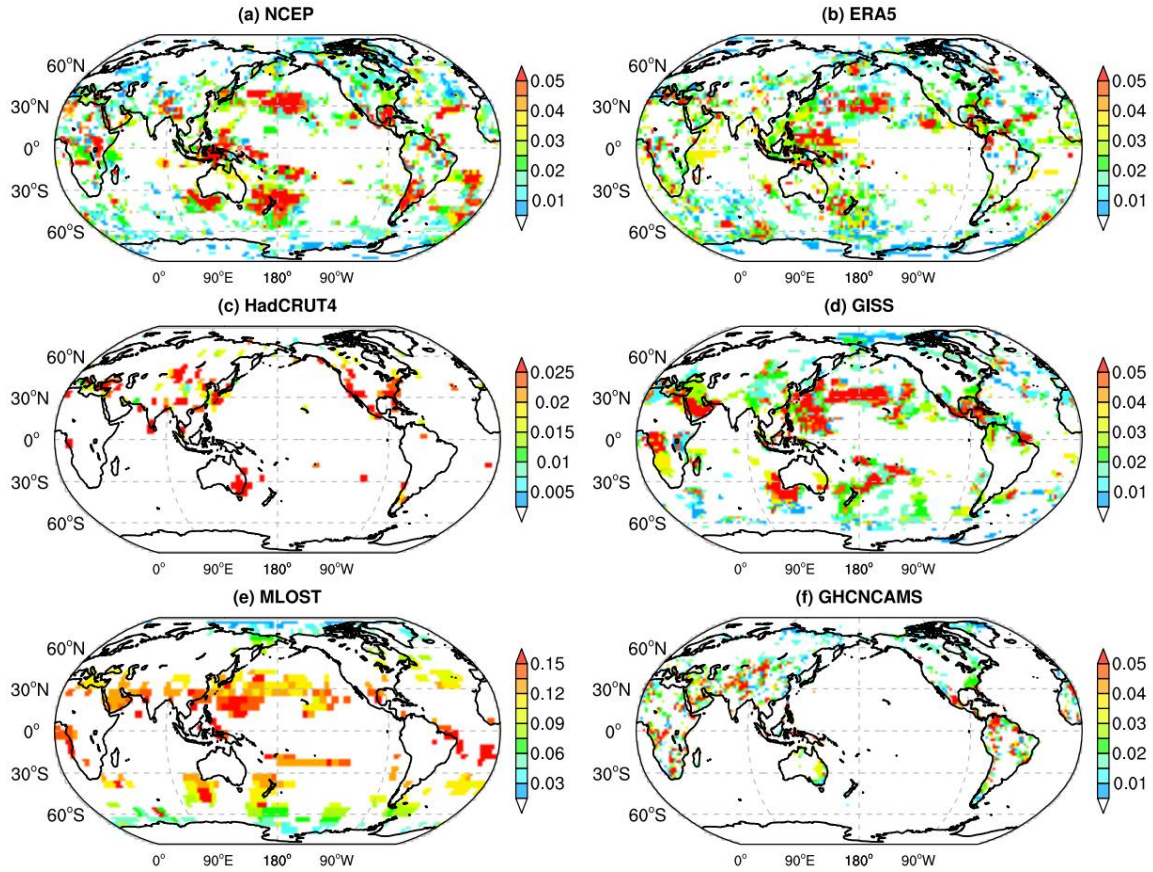


Supplementary Fig. 1 | Global distributions of climatological and El Niño-Southern Oscillation (ENSO)-related increases in climate regime shift probabilities (Δprob). Annual probabilities of regime shifts are derived from multiple observational datasets for sea surface temperature (SST; **a, d, g**), surface air temperature (SAT; **b, e, h**), and surface soil moisture (**c, f, i**). Panels show (**a–c**) climatological mean probabilities, (**d–f**) changes in probabilities during regular El Niño years relative to the climatological mean, and (**g–i**) changes in probabilities during La Niña years relative to the climatological mean.



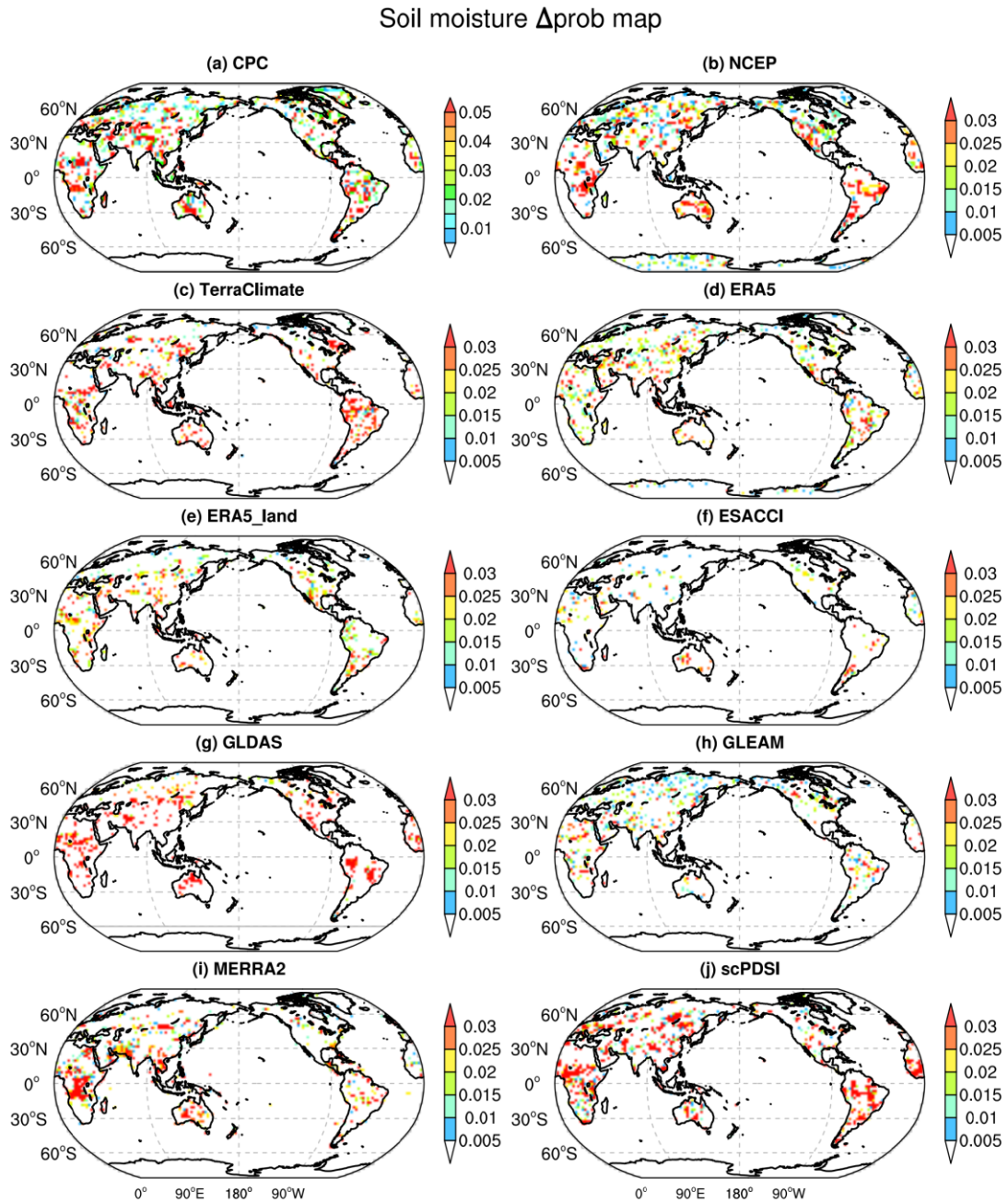
Supplementary Fig. 2 | Maps of increased climate regime shift (CRS) probabilities due to super El Niño (Δ prob) across multiple sea surface temperature (SST) datasets. Increased SST regime shift probabilities of four seasons in **(a)**, ERSSTv5 ($2.5^\circ \times 2.5^\circ$); **(b)**, HadISST ($2.5^\circ \times 2.5^\circ$); **(c)**, COBE2 ($2.5^\circ \times 2.5^\circ$); **(d)**, Kaplan ($5^\circ \times 5^\circ$); **(e)**, HURRELL ($2.5^\circ \times 2.5^\circ$); **(f)**, AMIP2 ($2.5^\circ \times 2.5^\circ$); **(g)**, ERA5 ($1^\circ \times 1^\circ$). These datasets are linearly detrended and cover the period from 1948 to present.

SAT Δ prob map



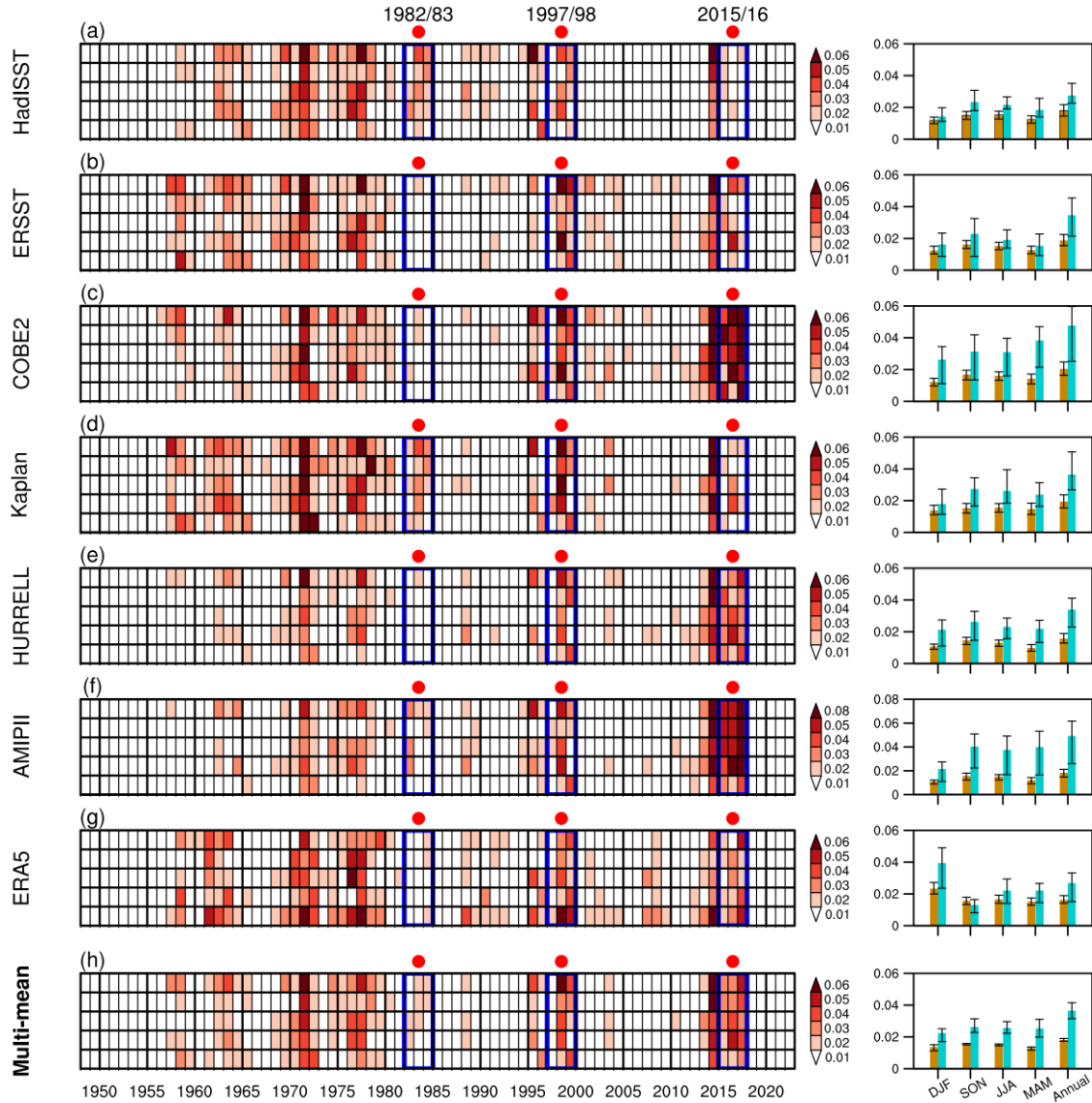
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84 **Supplementary Fig. 3 | Maps of increased climate regime shift (CRS) probabilities**
85 **due to super El Niño (Δ prob) across multiple surface air temperature (SAT) datasets.**
86 Increased SAT CRS probabilities of four seasons in **(a)**, NCEP (2.5°x2.5°); **(b)**, ERA5
87 (1°x1°); **(c)**, HadCRUT4 (2.5°x2.5°); **(d)**, NASA GISS (2°x2°); **(e)**, NOAA MLOST
88 (5°x5°); **(f)**, GHCNCAMS land (0.5°x0.5°). These datasets are linearly detrended and
89 cover the period from 1948 to present.

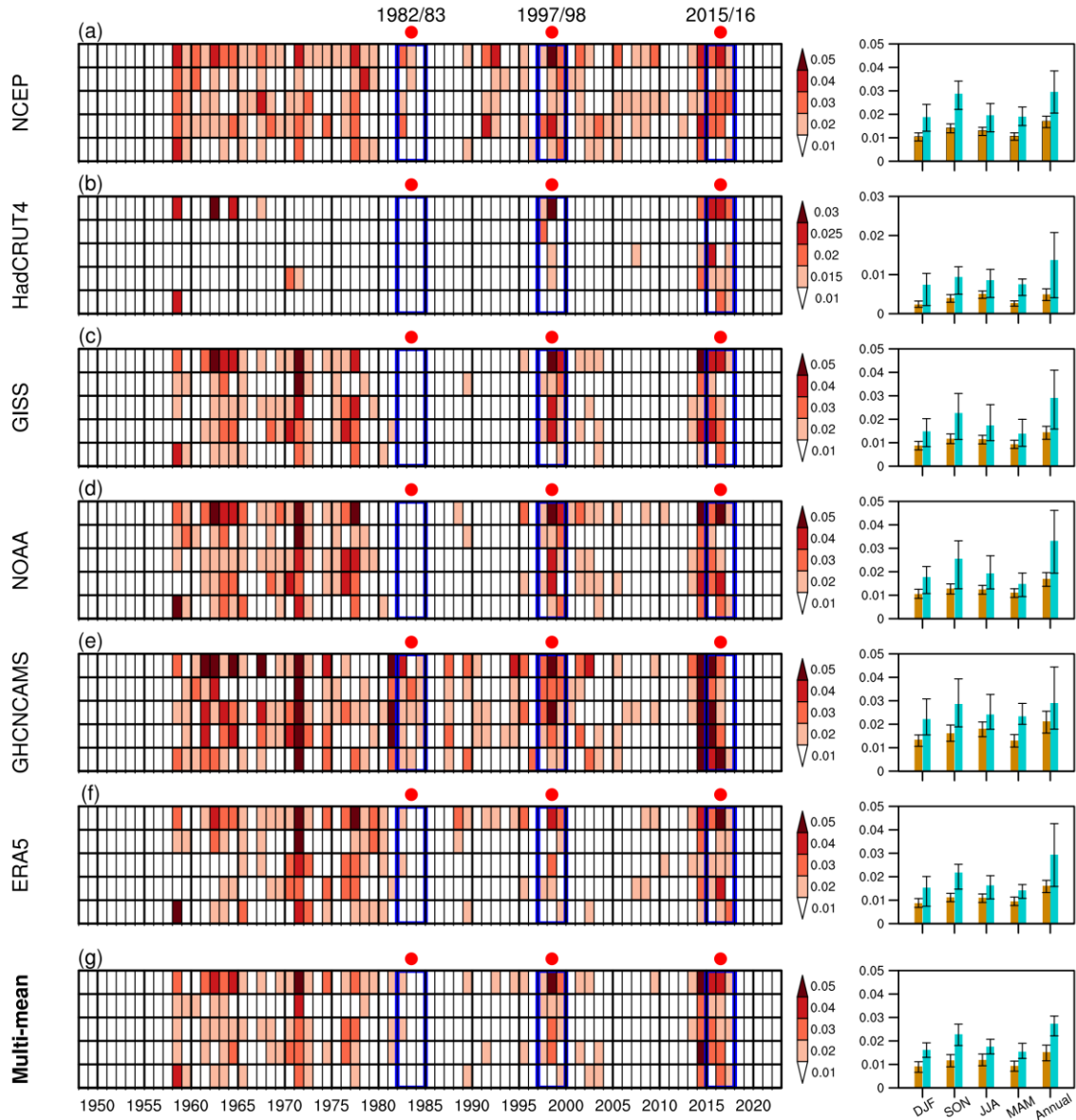


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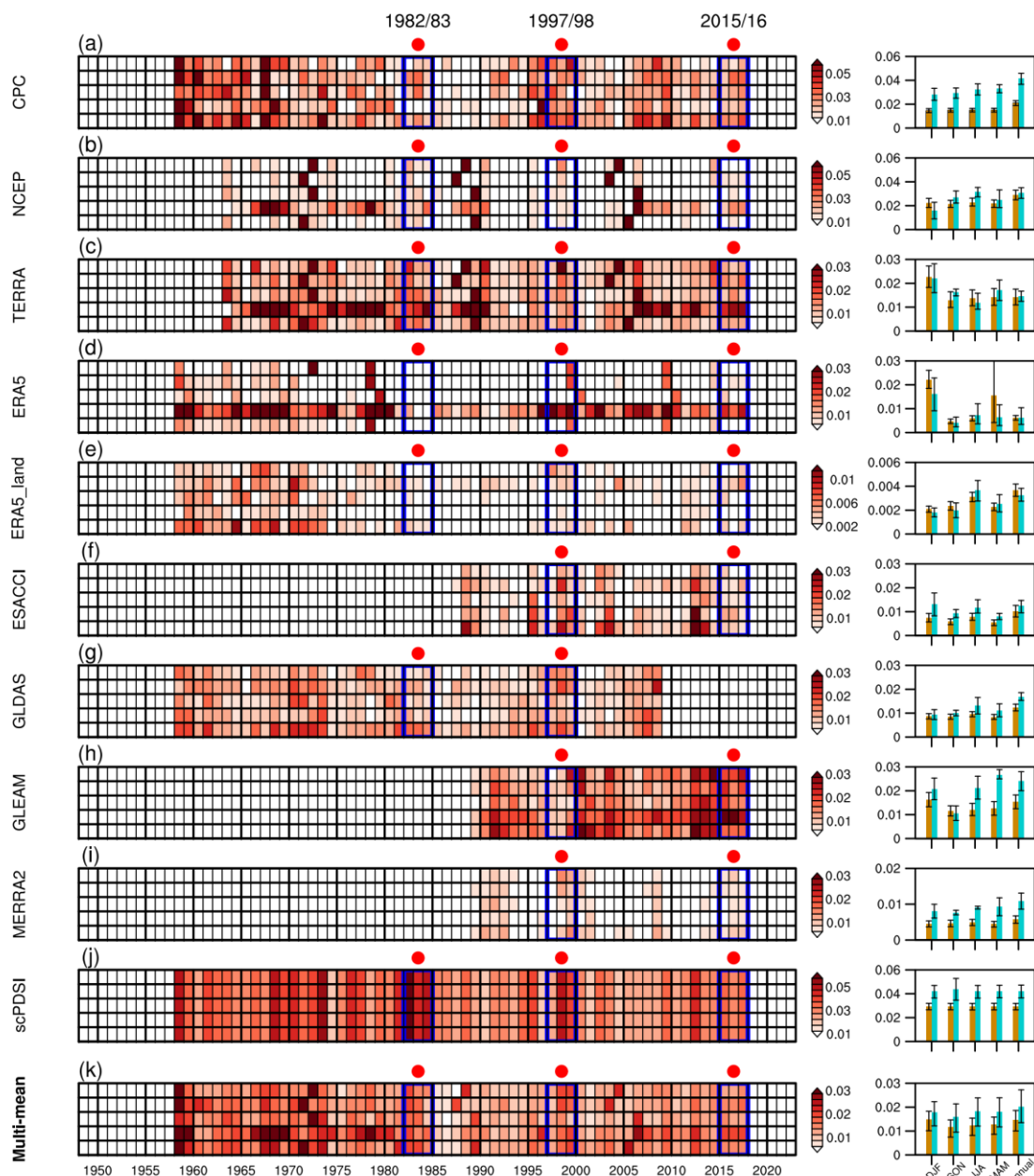
91 **Supplementary Fig. 4 | Maps of increased climate regime shift probabilities due to**
 92 **super El Niño (Δprob) across multiple surface soil moisture datasets.** Increased soil
 93 moisture regime shift probabilities of four seasons in (a), CPC; (b), NCEP; (c),
 94 TerraClimate; (d), ERA5; (e), ERA5-Land; (f), ESACCI; (g), GLDAS; (h), GLEAM; (i),
 95 MERRA2; (j), scPDSI. All datasets have been linearly detrended and regridded to a
 96 common $1^\circ \times 1^\circ$ spatial resolution prior to analysis.



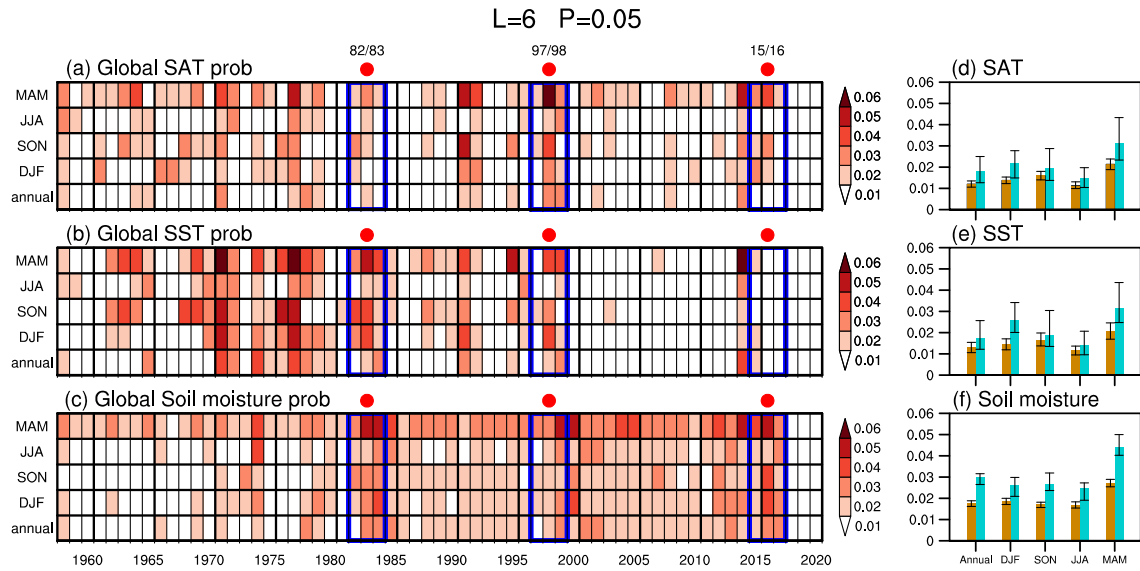
Supplementary Fig. 5 | Temporal evolutions of annual climate regime shift (CRS) probabilities in multiple sea surface temperature (SST) datasets. The annual CRS probabilities for the periods 1948–2022 based on various datasets **(a)**, HadISST; **(b)**, ERSSTv5; **(c)**, COBE2; **(d)**, Kaplan; **(e)**, HURRELL; **(f)**, AMIPII; **(g)**, ERA5. Panel **(h)** presents the multi-dataset mean. The color bars represent the comparisons of regime shift probabilities between non-super El Niño years (yellow) and super El Niño years (cyan), highlighting the enhanced likelihood of regime shifts during super El Niño events across datasets.



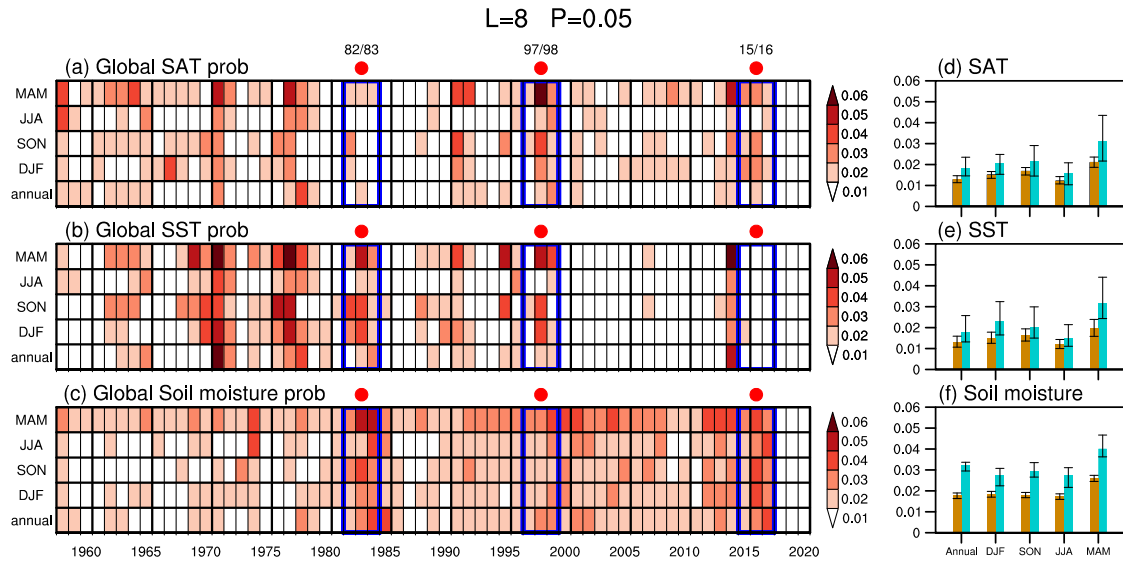
Supplementary Fig. 6 | Temporal evolutions of annual climate regime shift (CRS) probabilities in multiple SAT datasets. The annual CRS probabilities for the periods 1948–2022 based on various datasets (a), NCEP; (b), HadCRUT4; (c), NASA GISS; (d), NOAA MLOST; (e), GHCNCAMS land; (f) ERA5. Panel (g) presents the multi-dataset mean. The color bars represent the comparisons of regime shift probabilities between non-super El Niño years and super El Niño years for these datasets.



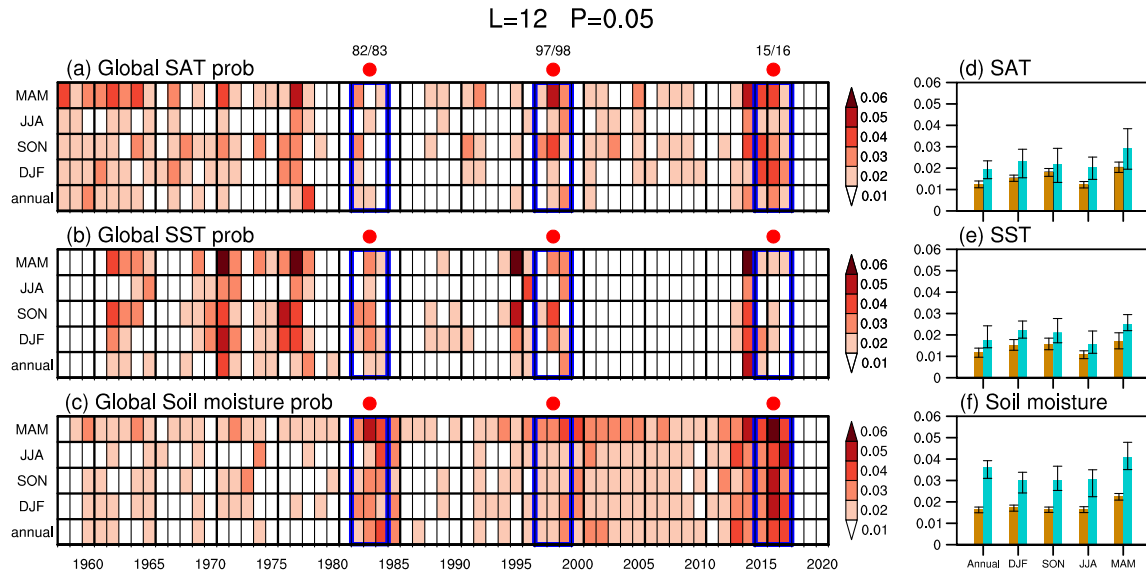
Supplementary Fig. 7 | Temporal evolutions of annual climate regime shift (CRS) probabilities in multiple surface soil moisture datasets. The annual CRS probabilities based on ten observational and reanalysis soil moisture datasets: **(a)**, CPC; **(b)**, NCEP; **(c)**, TerraClimate; **(d)**, ERA5; **(e)**, ERA5-Land; **(f)**, ESA CCI; **(g)**, GLDAS; **(h)**, GLEAM; **(i)**, MERRA2; **(j)**, scPDSI. Panel **(k)** presents the multi-dataset mean. The side bar plots summarize average regime shift probabilities for super El Niño years (cyan) and non-super El Niño years (yellow), highlighting their differences across datasets. All datasets are linearly detrended and regridded to $1^{\circ} \times 1^{\circ}$ horizontal resolution prior to analysis.



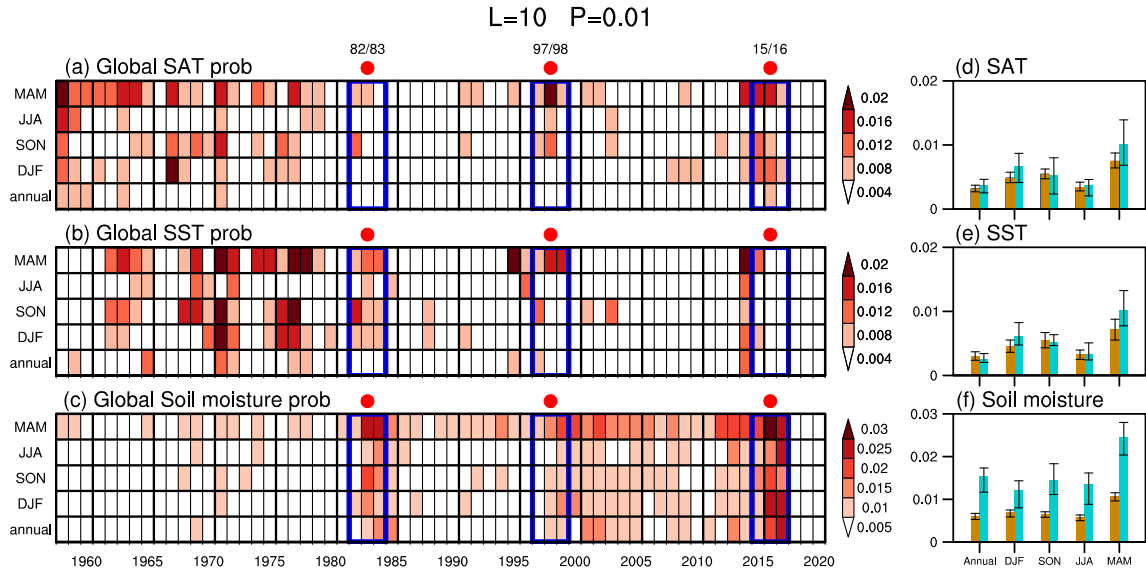
Supplementary Fig. 8 | Temporal evolutions of annual climate regime shift (CRS) probabilities with cut-off length $L = 6$ and the probability level $p = 0.05$. (a–c) The annual CRS probabilities during the periods 1948–2022 for surface air temperature (SAT), sea surface temperature (SST) and surface soil moisture, respectively. (d–f) The color bars represent the comparisons of regime shift probabilities between non-super El Niño years and super El Niño years for three climatic variables.



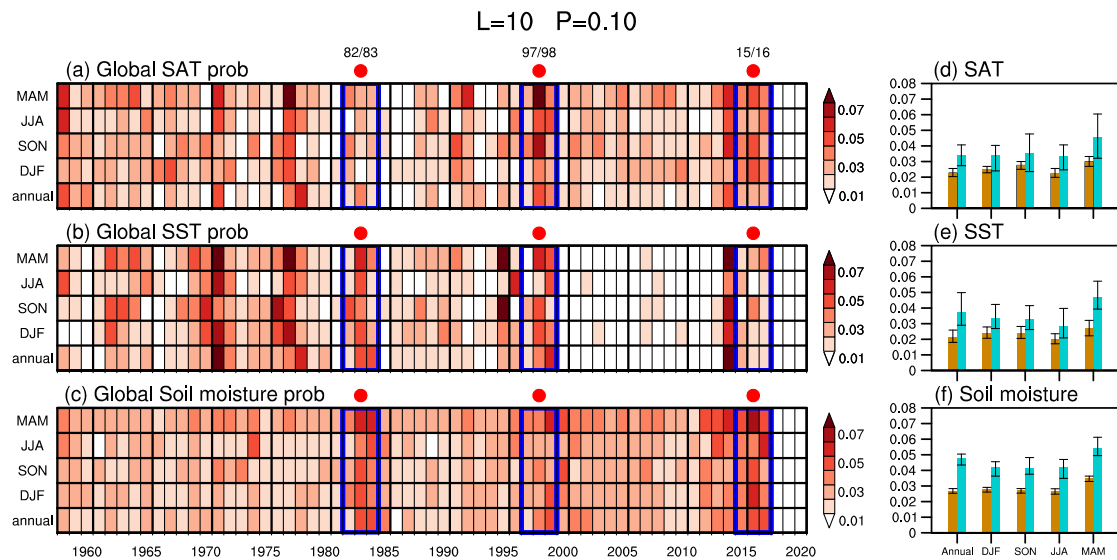
Supplementary Fig. 9 | Temporal evolutions of annual climate regime shift probabilities with cut-off length $L = 8$ and the probability level $p = 0.05$.



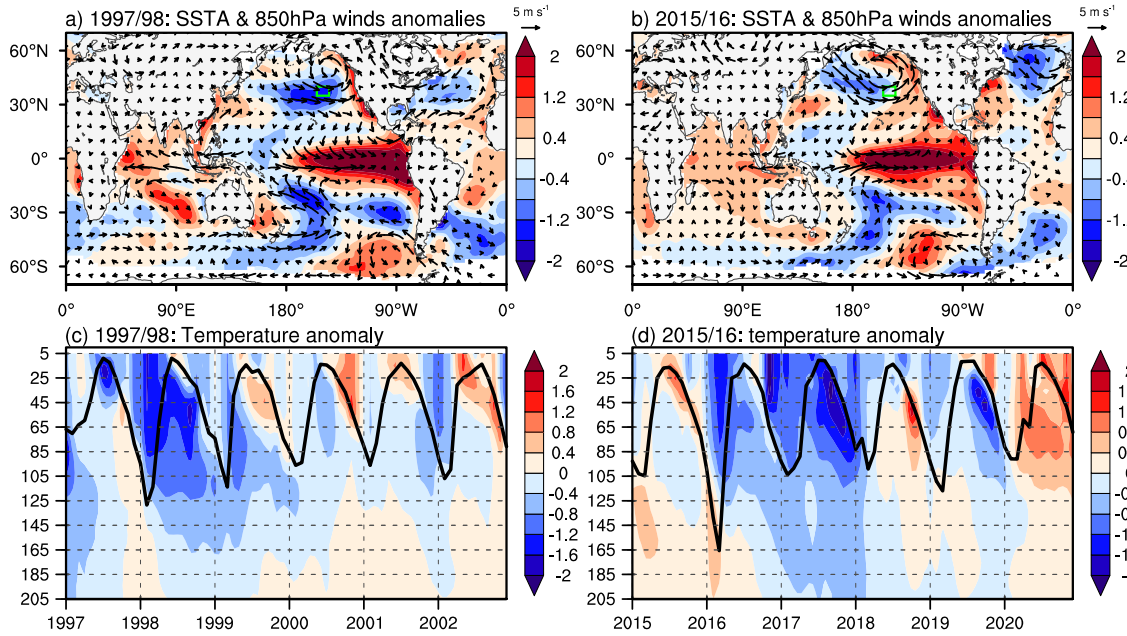
Supplementary Fig. 10 | Temporal evolution of annual climate regime shift probabilities with cut-off length $L = 12$ and the probability level $p = 0.05$.



Supplementary Fig. 11 | Temporal evolutions of annual climate regime shift probabilities with cut-off length $L = 10$ and the probability level $p = 0.01$.

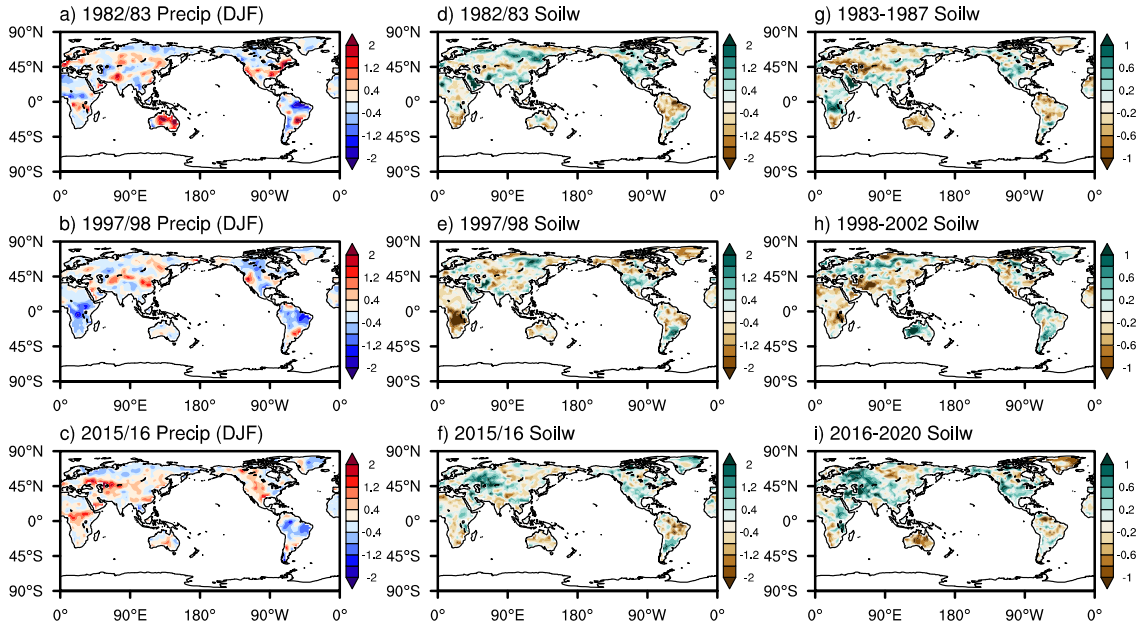


Supplementary Fig. 12 | Temporal evolutions of annual climate regime shift probabilities with cut-off length $L = 10$ and the probability level $p = 0.10$.



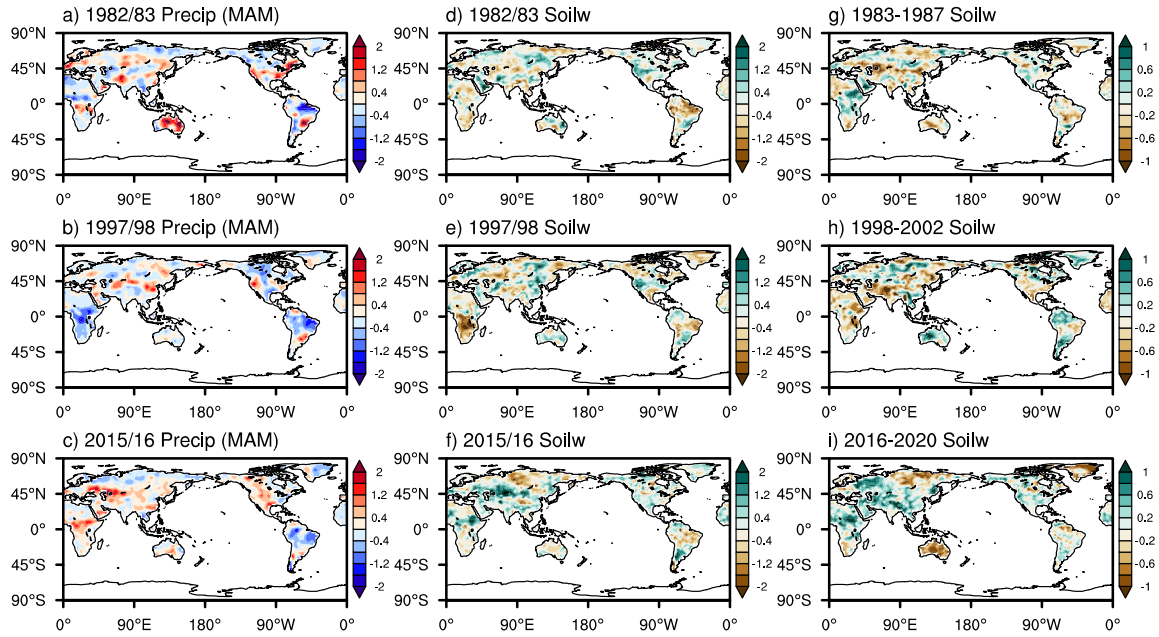
Supplementary Fig. 13 | Super El Niño events induce sea surface temperature (SST) regime shifts in the Central-North Pacific through the “Reemergence” mechanism. (a), (b) SST anomalies (SSTA; shading; units: °C) and 850-hPa wind anomalies (vectors, see scale arrow at the upper right; units: m s^{-1}) during 1997/98 and 2015/16 super El Niño mature phase (DJF; December–February), respectively. (c), (d) Vertical section of temperature anomalies in the upper 200 m (shading, in °C) and mixed layer depth (black) averaged over the Central-North Pacific (35°N–40°N, 155°W–145°W; blue boxes in (a), (b) during 1997–2002 and 2015–2020, respectively.

MAM Soil moisture (March-April-May)



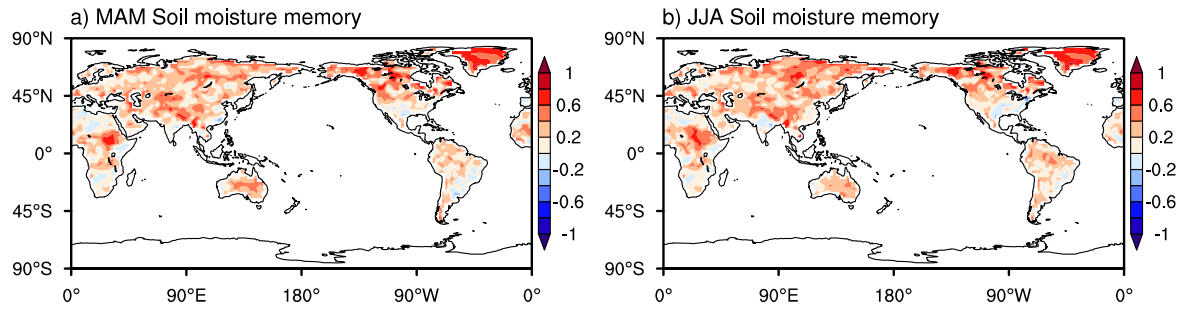
Supplementary Fig. 14 | Precipitation (December–February; DJF) and surface soil moisture (March–May; MAM) anomalies during three super El Niño periods. (a–c) normalized DJF averaged precipitation anomalies during 1982/83, 1997/98, and 2015/16 El Niño period (shadings; unit: mm/day) from NCEP reanalysis; (d–f) normalized MAM averaged soil moisture anomalies following the mature phases of three super El Niño events (shadings; unit: mm); (g–i) normalized five-year MAM mean soil moisture anomalies after the 1982/83, 1997/98, and 2015/16 super El Niño events (shadings; unit: mm).

JJA Soil moisture (June-July-August)

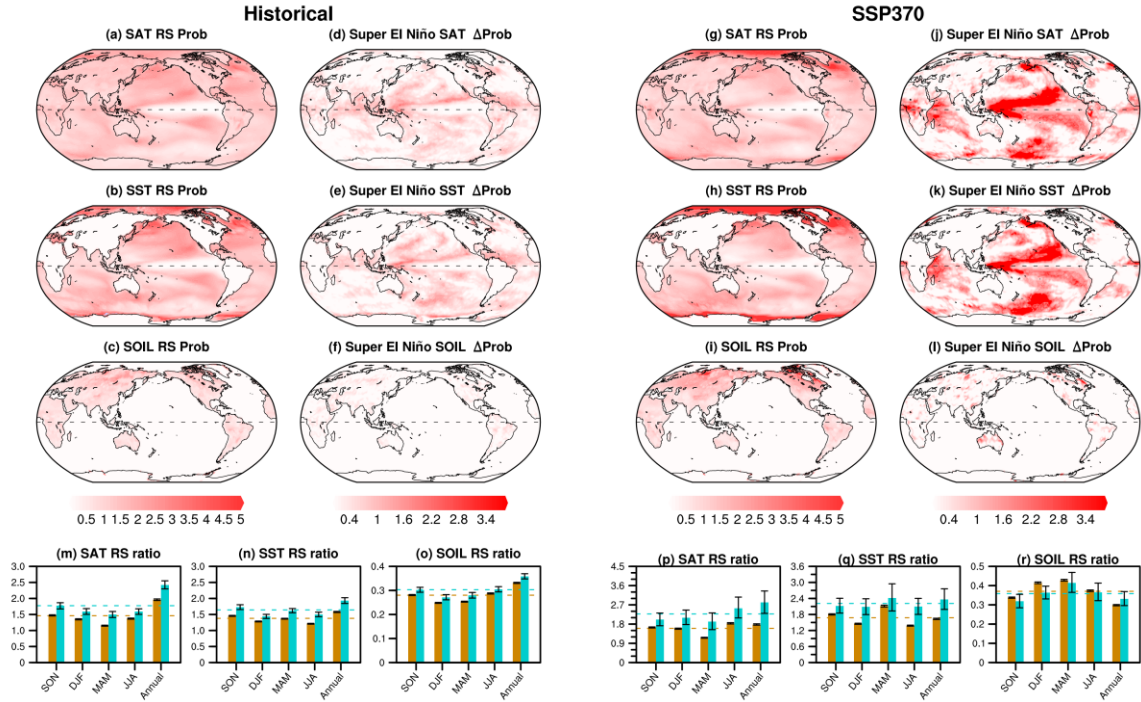


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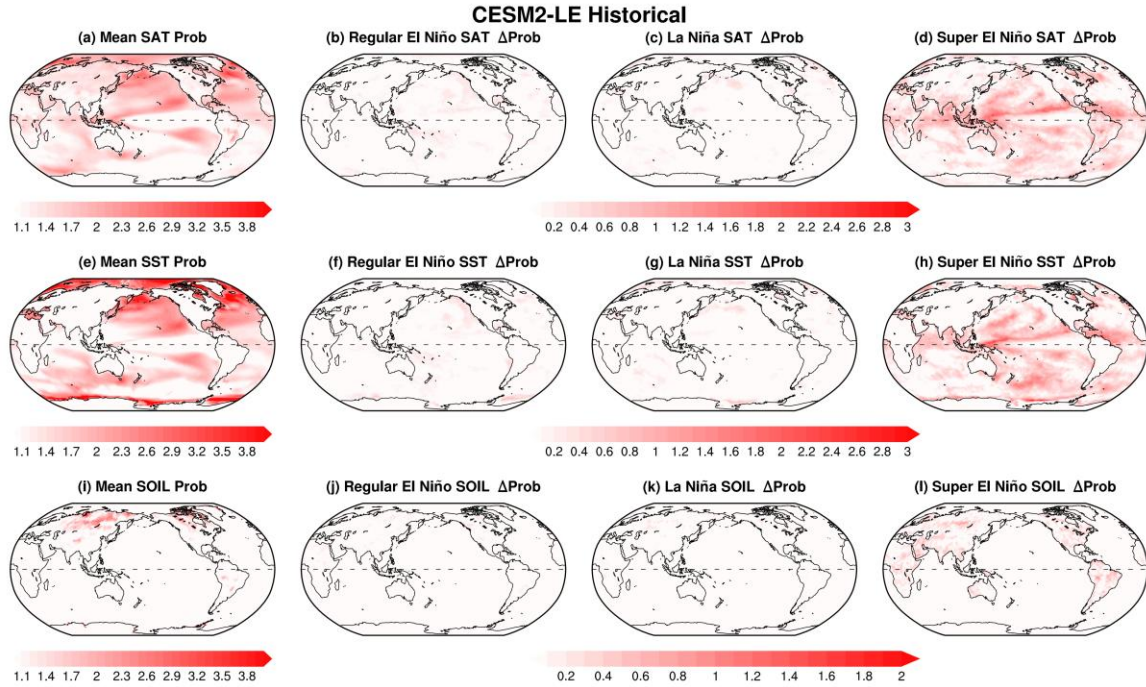
160 **Supplementary Fig. 15 | Precipitation (March–May; MAM) and surface soil moisture**
 161 **(June–August; JJA) anomalies during the decaying phases of three super El Niño**
 162 **events. (a–c) normalized MAM averaged precipitation anomalies during 1982/83, 1997/98,**
 163 **and 2015/16 El Niño periods (shadings; unit: mm/day) from NCEP reanalysis; (d–f)**
 164 **normalized JJA averaged soil moisture anomalies after the mature phases of 1982/83,**
 165 **1997/98, and 2015/16 El Niño events (shadings; unit: mm); (g–i) normalized five-year JJA**
 166 **mean surface soil moisture anomalies after the 1982/83, 1997/98, and 2015/16 El Niño**
 167 **events (shadings; unit: mm).**



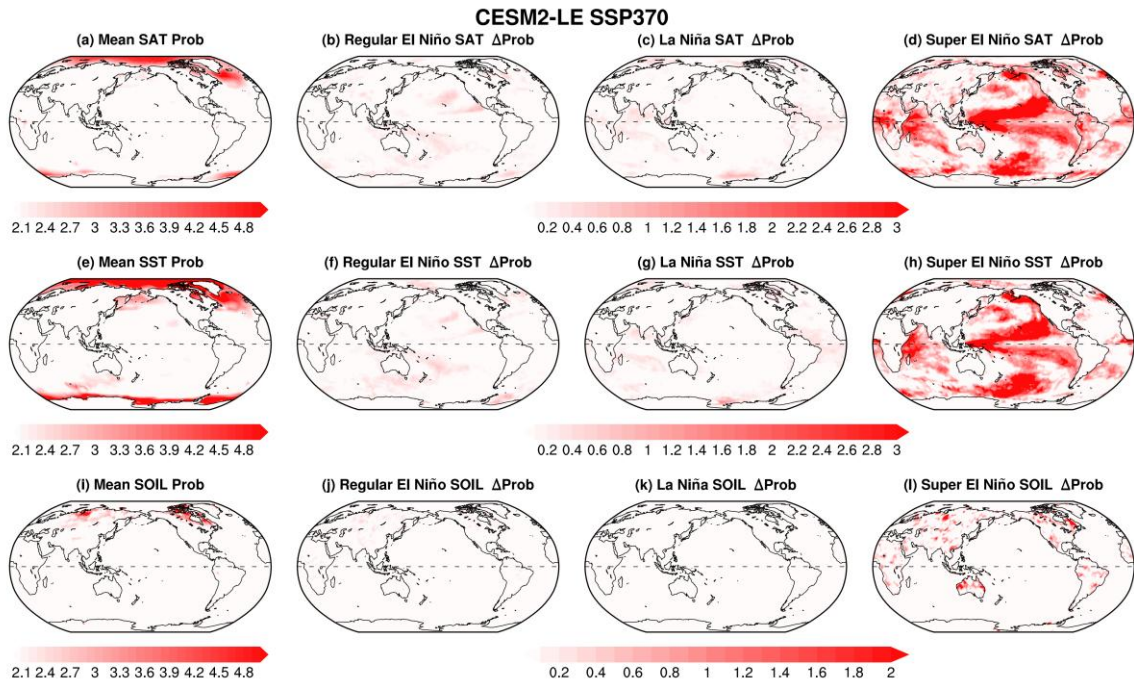
Supplementary Fig. 16 | Soil moisture memory in observations. (a), (b) 1-year autocorrelation of boreal spring (March–May; MAM) and boreal summer (June–August; JJA) surface soil moisture anomalies. Correlations greater than 0.30 are statistically significant at the 95% confidence level (degree of freedom = 42).



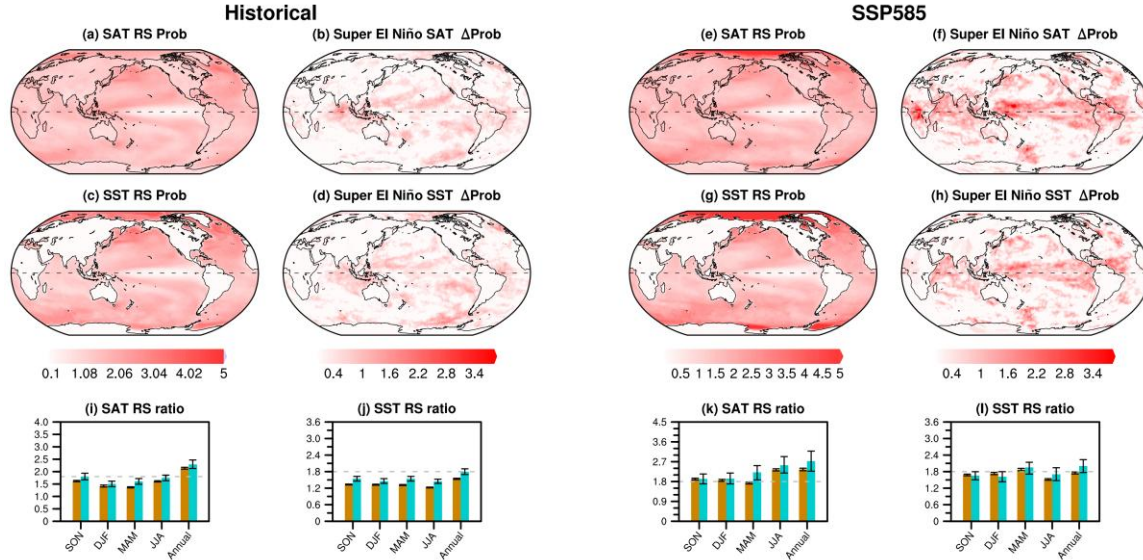
Supplementary Fig. 17 | Climate regime shift (CRS) probabilities in the Community Earth System Model version 2 Large Ensemble (CESM2-LE) under historical and SSP3–7.0 scenarios. (a–c) Spatial patterns of historical regime shift probabilities for surface air temperature (SAT), sea surface temperature (SST) and surface soil moisture, respectively. **(d–f)** Increased regime shift probabilities due to super El Niño events under the historical scenario. **(g–i)** Same as **(a–f)** but for the SSP3–7.0 scenario. **(m–o)** Averaged historical global mean regime shift probabilities during the non-super El Niño years (yellow) and during the super El Niño events (cyan). **(p–r)** Same as **(m–o)** but for the SSP3–7.0 scenario. Error bars indicate the 5th and 95th percentiles based on bootstrap resampling.



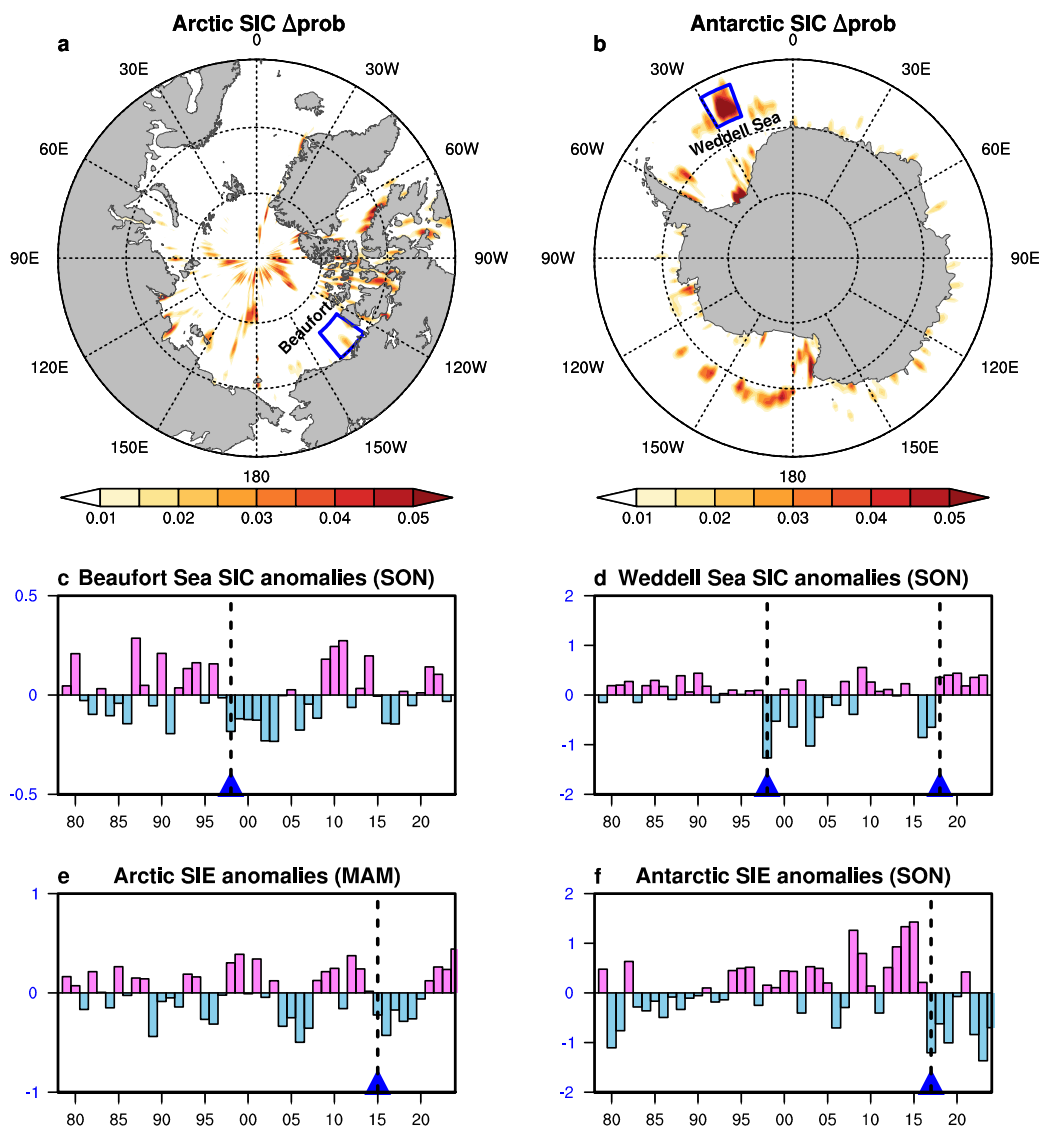
Supplementary Fig. 18 | Climatological mean and El Niño-Southern Oscillation (ENSO)-composite changes in climate regime shift (CRS) probabilities (Δ prob) in the Community Earth System Model version 2 Large Ensemble (CESM2-LE) historical simulations. Spatial patterns of (a, e, i) climatological mean CRS probability (%), and changes relative to this mean during (b, f, j) regular El Niño, (c, g, k) La Niña, and (d, h, l) super El Niño years for surface air temperature (SAT) (a–d), sea surface temperature (SST) (e–h), and surface soil moisture (i–l). Super El Niño events are associated with substantially higher and more spatially extensive CRS probabilities across both oceanic and continental regions, whereas regular El Niño and La Niña years show weaker and more localized increases.



Supplementary Fig. 19 | Same as Fig. Supplementary Fig. 18 but for the Community Earth System Model version 2 Large Ensemble (CESM2-LE) SSP3–7.0 simulations.



Supplementary Fig. 20 | Climate regime shift (CRS) probabilities in the Coupled Model Intercomparison Project Phase 6 (CMIP6) models under historical and SSP5–8.5 scenarios. (a), (c) Spatial patterns of historical regime shift probabilities for surface air temperature (SAT) and sea surface temperature (SST), respectively. **(b), (d)** Increased regime shift probabilities due to super El Niño events (Δ prob) under the CMIP6 historical scenario. **(e–h)** Same as **(a–d)** but for the SSP5–8.5 scenario. **(i), (j)** Averaged historical global mean regime shift probabilities during the non-super El Niño years (yellow) and during the super El Niño events (cyan). **(k), (l)** Same as **(i), (j)** but under the SSP5–8.5 scenario. Error bars indicate the 5th and 95th percentiles based on bootstrap resampling.



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209 **Supplementary Fig. 21 | Super El Niño-induced climate regime shifts (CRSs) in polar**
 210 **sea ice. (a), (b)** Spatial patterns of increased CRS probabilities in sea ice concentration
 211 (SIC) anomalies associated with super El Niño events in the Arctic and Antarctic,
 212 respectively. **(c), (d)** Evidence of super El Niño-induced SIC regime shifts in the Beaufort
 213 Sea and Weddell Sea during boreal autumn, highlighted by the blue boxes. **(e), (f)** Super
 214 El Niño-induced regime shifts of sea ice extent (SIE) in the Arctic during boreal spring and
 215 in the Antarctic during boreal autumn. Blue triangles indicate the timing of regime shifts
 216 occurring during Super El Niño and subsequent La Niña events.

217 **Supplementary Table 1** List of 48 models from the Coupled Model Intercomparison

218 Project Phase 6 (CMIP6)

Model number	Model Name	Model number	Model Name
1	ACCESS-CM2	25	FGOALS-f3-L
2	ACCESS-ESM1-5	26	FGOALS-g3
3	AWI-CM-1-1-MR	27	FIO-ESM-2-0
4	BCC-CSM2-MR	28	GFDL-ESM4
5	CAMS-CSM1-0	29	GISS_E2-1-G
6	CanESM5-1	30	HadGEM3-GC31-LL
7	CanESM5-CanOE	31	HadGEM3-GC31-MM
8	CanESM5	32	INM-CM4-8
9	CAS-ESM2-0	33	INM-CM-5-0
10	CESM2	34	IPSL-CM6A-LR
11	CESM2-WACCM	35	KACE-1-0-G
12	CIESM	36	KIOST-ESM
13	CMCC-CM2-SR5	37	MCM-UA-1-0
14	CMCC-ESM2	38	MIROC6
15	CNRM-CM6-1	39	MIROC-ES2H
16	CNRM-CM6-1-HR	40	MIROC-ES2L
17	CNRM-ESM2-1	41	MPI-ESM1-2-HR
18	E3SM-1-0	42	MPI-ESM1-2-LR
19	E3SM-1-1-ECA	43	MRI-ESM2-0
20	E3SM-1-1	44	NESM3
21	EC-Earth3-CC	45	NorESM2-LM
22	EC-Earth3	46	NorESM2-MM
23	EC-Earth3-Veg	47	TaiESM1
24	EC-Earth3-Veg-LR	48	UKESM1-0-LL

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Supplementary Text 1 Mechanisms on super El Niño-induced sea surface temperature (SST) regime shifts

In the Central-North Pacific, super El Niño events initially induce a strong cooling anomaly during boreal winter through the “atmospheric bridge”^{1,2} (Supplementary Fig. 13a, b), establishing a new oceanic condition which is significantly different from their previous states. The long-lasting negative SSTA in boreal winter could be well explained by the “Reemergence” mechanism^{3–5}. In this process, winter SST anomalies that extend throughout a winter deep mixed layer go into the subsurface layer in the shoaling phase of the mixed layer from spring to summer. Since the subsurface layer is insulated from the surface atmospheric forcing, the temperature anomalies persist beneath the thin summer mixed layer. When the mixed layer deepens again in the subsequent autumn and winter, these subsurface temperature anomalies are re-entrained into the surface mixed layer, reestablishing the SST cooling states. The magnitude of recurrent SSTA depends on the strength of the detrained temperature anomalies stored beneath the shallow summer mixed layer. This strong vertical entrainment sustains the negative SST anomalies in the Central-North Pacific following the 1997/1998 and 2015/16 super El Niño events (Supplementary Fig. 13c, d). This mechanism can also explain the SST regime shifts due to super El Niño in the North Atlantic region^{6,7}.

Super El Niño can also excite oceanic Rossby waves through atmospheric forcing that propagate into the KOE region and contribute to the SST regime shifts over this region⁸. The further investigation of the detailed processes of super El Niño-induced regime shifts across different regions is essential for a comprehensive understanding of SST regime shift dynamics.

Supplementary Text 2 Mechanisms on super El Niño-induced surface air temperature (SAT) regime shifts

Here are some possible mechanisms responsible for super El Niño-induced SAT regime shifts. (1) the prolonged SST regime shifts due to super El Niño can lead to the synchronous local SAT persistence over ocean regions. Over land, long-lasting SST signals induced by super El Niño can influence low-frequency surface temperature on remote regions of globe through the atmospheric teleconnections⁹. (2) The aftermath of a super El Niño, marked by extreme weather events such as severe droughts or intense rainfall, can trigger a SAT regime shift through local positive soil moisture-atmosphere feedback processes^{10–12}. For instance, reduced soil moisture from drought can enhance surface temperatures through the soil moisture-temperature feedback loop^{11,13}, where lower moisture levels lead to higher surface temperatures, further exacerbating the initial climatic disruptions. Together, these processes demonstrate how super El Niño events can initiate and amplify shifts in SAT regimes, with lasting impacts on global weather patterns and ecosystems.

Supplementary Text 3 Mechanisms on super El Niño-induced surface soil moisture regime shifts

Soil moisture is also a key variable in the climate system which influences local and remote climate and hydrological cycle. Similar to the oceans, which can store heat and induce year-to-year persistence of SST anomalies (i.e., ocean memory), soil moisture reflects the water storage of land and thus can help improve predictions of drought and pluvial transitions. Extreme precipitation serves as the primary input source of soil moisture, with effects that can persist for a long term. Conversely, reduced precipitation can lead to persistent drought conditions. Super El Niño events have been shown to trigger extremely strong precipitation and severe drought globally¹⁴. The reduced precipitation causes abrupt declines in soil moisture in boreal winter (December–February; DJF) and spring (March–May; MAM) over some land regions such as the Amazon and South Africa through atmospheric teleconnections (Supplementary Figs. 14–15). These sharp declines can result in soil moisture regime shifts in subsequent seasons, as rainfall typically influences soil moisture with a delay about one month¹⁵. Additionally, super El Niño can induce heavy precipitation over Eastern Europe, Central Africa, and the western US regions, terminating droughts and creating long-lasting wet conditions. The consecutive La Niña events that often follow super El Niño can also prolong drought and flooding in several affected regions through the accumulative effects on soil moisture^{16,17}. The spatial patterns of soil moisture memory (Supplementary Fig. 16) closely resemble the super El Niño-related regime shift probability patterns, particularly in the tropical and subtropical regions, suggesting an important role of super El Niño in changing the soil moisture memory. The soil moisture surplus and deficit could also persist for some years through the positive soil

281 moisture-temperature feedback^{10,18–20} and soil moisture-precipitation feedback^{12,21,22} after
282 the strong climate impacts due to super El Niño events, which need to be further
283 investigated.

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