

Climate and weather drivers increase landfalling typhoons during the Maunder (Solar) Minimum

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Abstract

Multi-decadal variability in Western Pacific (WP) tropical cyclone (TC) frequency and landfall is difficult to attribute, given the short satellite record (~ 45 years). Leveraging the preindustrial era (1500–1850 AD) as a window into the natural variability of WP TCs, we investigate drivers of TC frequency and landfall changes by uniquely bridging the digitized Chinese historical handwritten record (REACHES) with large-ensemble simulations from the Ai2 deep-learning Climate Emulator Version 2 and two high-resolution physical climate models. The unprecedented peak in Chinese TC landfalls during the Maunder (Solar) Minimum (1651–1680 AD) reflects both climate and weather drivers. On the climate side, solar dimming disproportionately cooled the extratropics, steepening the meridional temperature gradient, strengthening the Hadley circulation, and driving a basin-wide increase in WP TC activity – similar effects may arise in response to solar forcing from volcanic eruptions or anthropogenic intervention and may be overlooked. On the weather side, randomness in seed disturbances caused anomalous TC genesis east of the Philippines and over the South China Sea, producing more landfalls along the south coast of China. The pronounced role of synoptic-scale randomness driving multi-decadal TC variability underscores the need for large-ensemble simulations to project long-term changes in TC frequency and landfall.

Introduction

Western Pacific tropical cyclones (TCs) account for roughly one-third of all global TCs and affect a large share of the world's population¹. Recent decades have seen a westward and poleward shift in TC tracks^{2–3}, altering landfall probabilities and societal exposure⁴ – yet how much of this reflects natural variability versus anthropogenic forcing remains debated^{2–3}, in part because the satellite record spans only ~ 45 years¹. Our limited understanding of decadal-to-centennial drivers of TC variability also leads to large uncertainties in future projections of TC frequency and track^{5–6}. By drawing on a 350-year preindustrial record (1500–1850 AD), this study isolates the natural factors driving multi-decadal variability in Western Pacific TC frequency and landfalls – a timescale that precedes the modern observational network and has a limited effect from anthropogenic greenhouse gas emissions.

Recent studies have examined the climate-scale drivers of the multi-decadal variability in regional or global TC frequency. For example, sea surface temperature (SST) variability predominantly drives the basin-wide change in Atlantic TC number over the past millennium⁷ and the north-south dipole in regional TC frequency over the Atlantic⁸. Globally, an El Niño-like SST pattern associated with the onset of the Little Ice Age in the 15th Century suppressed TC frequency by strengthening wind shear and drying the midtroposphere via a strengthened Hadley circulation⁹.

Beyond climatic drivers, weather variability may play a larger role in multi-decadal TC variability than previously recognized. Hurricane frequency over the Bahamas over the past millennium, for instance, is dominated by the randomness of weather disturbances rather than climate conditions¹⁰. Similarly, the

eastward shift of Atlantic TC tracks over the past 50 years is attributable to genesis-location changes driven by randomness in weather-scale disturbances, rather than to shifts in the large-scale steering flow¹¹.

The relative importance of weather versus SST-forced climate drivers of multi-decadal Western Pacific TC variability remains unknown; this study investigates both drivers by leveraging a long preindustrial proxy record and global TC-resolving simulations, both spanning from 1500 to 1850 AD.

Sediment-based proxies have supported millennium-scale TC studies in the Atlantic^{7–8}, but comparable basin-wide coverage in the Western Pacific is limited^{12–15}. A recent advance is the Reconstructed East Asian Climate Historical Encoded Series (REACHES), a digitized Chinese handwritten historical record of TC landfalls spanning the past 500 years¹⁶. Unlike sediment proxies, which typically have a coarse temporal resolution of ~ 40 years⁷, REACHES resolves TC activity to the monthly, and sometimes daily, timescale – enabling studies of seasonal variability and revealing that recent changes in the TC seasonal cycle fall within the range of natural variability over the past 500 years¹⁷. The most prominent feature of the REACHES record is an unprecedented peak in Chinese TC landfalls between 1650 and 1680 AD¹⁶, the cause of which remains obscure. Because REACHES captures only landfalling TCs, it is unclear whether this peak reflects enhanced basin-wide TC activity, a shift in genesis location, or changes in the steering flow that deflected tracks toward the coast.

Answering this question requires TC-resolving simulations spanning centuries, yet traditional climate models are computationally expensive – only one prior study, to our knowledge, has attempted millennium-scale TC-resolving simulations⁹. Recent advances in deep-learning global climate emulators^{18–20} now make it feasible to run long simulations efficiently. The AI2 Climate Emulator Version 2 (ACE2)¹⁸ is a promising tool, given ACE2's good representation of the TC climatology and its physically consistent relationship between environmental conditions and TC frequency, both in the current 21st century^{21, 22} and a few centuries earlier in the Little Ice Age⁹. We run large ensembles of ACE2 over the preindustrial era (1500–1850 AD) and force them with reconstructions of SST²³ and sea ice²⁴ to disentangle the weather and climate drivers of Western Pacific TC frequency and landfall. The ACE2 results are validated against the REACHES historical record and various experiments from two high-resolution physical climate models from the Geophysical Fluid Dynamics Laboratory (GFDL): the dynamical high-resolution atmospheric model (HiRAM²⁵) and the atmospheric component of the GFDL coupled atmosphere-ocean global climate model CM2.5 (AM2.5²⁶).

Results

Chinese landfall TCs increase during the Maunder Minimum

Both single-member ACE2 and HiRAM simulations over 1500–1850 reproduce the elevated TC landfall over 1650–1680 AD seen in REACHES, though the peak is less pronounced (Fig. 1a-c, blue shading). To

better sample internal variability, we run 13 additional ACE2 ensemble members over 1550–1750 AD; three of the fourteen members closely match the REACHES landfall peak (Fig. 1b); other members are shown in Fig. S7 and discussed further in the last section of Results. This high-landfall period coincides with the Maunder (Solar) Minimum²⁷ — one of the coldest intervals of the Little Ice Age, characterized by a prolonged minimum in solar radiation (Fig. 1d), near-absent sunspot activity, and anomalously cold European winters²⁸. On the contrary, a few decades before (1611–1630 AD) features the low-landfall period and stronger solar forcing (Fig. 1, green shading). The high- and low-landfall periods of the selected ACE2 members are consistent across REACHES and HiRAM, with minor timing offsets in HiRAM likely due to internal variability not fully represented by a single member. The realistic representation of long-term TC landfall variability in a few ACE2 members enables us to fully investigate the drivers of these low- and high-TC landfall periods (the Low and High periods hereafter).

Comparing SST between the low- and high-landfall periods in the Pacific Ocean reveals an El Niño-like pattern (i.e., warming over the Eastern Pacific and cooling over the Western Pacific) (Fig. 1e). Although other basins exhibit slight deviation from a typical El Niño event (e.g., warming over the Atlantic and cooling over the Indian Ocean), we name it the El Niño-like pattern given the similarity in the Pacific Ocean (Fig. 1e). Both this SST change and the solar dimming may modulate TC frequency and landfalls.

Western Pacific TC frequency increases under solar dimming and El Niño-like SST patterns

To investigate the roles of SST and solar dimming, we run 100-member timeslice ensembles using ACE2 with SST and sea ice fixed to the climatology of the low-landfall period (1611–1630, CTL) and high-landfall period (1651–1680, EXP1). An additional experiment (EXP1_weak sun) retains the 1651–1680 SST but reduces solar radiation by 2.5% — mimicking solar reduction amplitude due to volcanic forcing²⁹ — to incorporate the top-of-atmosphere solar dimming effect. Although this solar reduction is stronger than the observed solar radiation change, this magnitude is chosen to account for uncertainty in reconstructing solar radiation when the sunspot number is low²⁷. Note that the last-millennium SST reconstruction already incorporates solar forcing²³, so the SST difference between CTL and EXP1 partially reflects the bottom-up solar effect of the Maunder Minimum; the weak-sun experiment includes the top-down effect. Since ENSO can be triggered by both external solar forcing and internal ocean dynamics, the El Niño-like SST anomalies from CTL to EXP1 likely reflect both.

Western Pacific TC frequency increases by 9.7% from CTL to EXP1, and by 18.2% from CTL to EXP1_weak sun (Fig. 2a; Fig. 3a, black&green). The overall increase in genesis in the Northwestern Pacific basin overlaps with the climatological high-genesis region from CTL to EXP1_weak sun, when both El Niño and solar dimming are applied (Fig. 2i), while the genesis increase shifts eastward under only the El Niño-like SST change (Fig. 2d).

Applying the seed-probability framework³¹ (i.e., TC frequency equals seed disturbances multiplied by transition probability), the basin-wide TC increase is driven by more seed disturbances rather than transition probability, which is broadly negative (Figs. 2e) — consistent with a previous study finding that

Western Pacific TC frequency uniquely increased via seed disturbances as the climate entered the Little Ice Age⁹. The increase in seed disturbances in our experiments is due to enhanced vorticity (Fig. 2h) and large-scale precipitation in the Pacific's upward Hadley branch (Fig. 2g).

The strengthening of the Hadley circulation from CTL to the El Niño-like experiment (EXP1), shown by stronger tropical meridional wind convergence in the lower troposphere (Fig. 2c, black), leads to stronger upward motion in off-equatorial regions (Fig. 2g) and larger vorticity (Fig. 2h), which are favorable for the development of seed disturbances (SPI, Fig. 2f), thus increasing TCs. The strengthening of Hadley circulation stems from a steeper meridional temperature gradient between extratropical cooling and tropical warming (Fig. 2b&3, black). The top-down effect of solar dimming further amplifies this meridional temperature gradient in EXP1-weak sun, amplifies extratropical cooling in the Northern Hemisphere (because extratropical land fraction is larger and land cooling exceeds ocean cooling), reinforcing the Hadley circulation strengthening (Fig. 2b-c&3, green). The contribution due to solar dimming is corroborated by comparing EXP1-weak sun with EXP1 at the same SST (Fig. 3&S1b, blue), which shows that solar dimming alone causes Hadley cell strengthening.

To verify robustness across models and climate states, we run the high-resolution TC-resolving physical climate model AM2.5²⁶ with current-climate SST (1986–2005) and 2% solar reduction. Western Pacific TC activity increases by 12.1% (Fig. 3, purple; Fig. S2f) via the same mechanism — solar dimming steepens the meridional temperature gradient and strengthens the Hadley circulation (Fig. 3&S1b, purple). The single-member HiRAM paleo experiment similarly shows Western Pacific TC activity increases and a stronger Hadley circulation, though with weaker magnitude than the 100-member ACE2 ensemble mean (Fig. 3, red vs. black; Fig. S3).

ACE2's realistic response to solar dimming was unexpected given its training data lacks decadal-to-centennial solar variability¹⁸, but likely reflects that a 2.5% solar reduction falls within the local seasonal and diurnal range, or hemispheric changes in equator to pole gradient of the annual cycle, both of which the model may learn during training — suggesting potential for broader solar radiation applications (e.g., volcanic eruptions or solar radiation management experiments such as stratospheric aerosol injection), though careful validation is recommended for out-of-sample forcing magnitudes.

The consensus across ACE2 and physical models, from paleo to current climate, robustly supports that the El Niño-like SST pattern and amplified effect of solar dimming at high latitudes together steepen the meridional temperature gradient (Fig. 3b), strengthening the Hadley circulation and increasing Western Pacific TC frequency via enhanced seed disturbances (Fig. 3a).

Genesis location of weather-scale seed disturbances enhances South Coast TC landfall

While the previous section suggested that basin-wide TC activity increases under El Niño and solar dimming, how this translates into landfalls along the Chinese coastline remains unclear. This section examines in detail the changes in track and genesis among the three categories of ACE2 experiments: (1) members of the time-evolving simulation that show a similar peak to REACHES, (2) the ensemble

mean of the time-slice El Niño experiment (EXP1) compared to the CTL, and (3) the ensemble mean of the time-slice El Niño with solar dimming (EXP1_weak sun) compared to the CTL.

REACHES reveals a dominant landfall peak in 1650–1680, driven largely by south coast landfalls exceeding 100% above the low-landfall period (Figs. 4g&S4) – a magnitude unprecedented over the full preindustrial era and consistent across REACHES and the three similar ACE2 members (Fig. 4g). TC track changes in these members are driven primarily by genesis location shifts – more genesis occurrences east of the Philippines and over the South China Sea (Fig. 4b) – rather than the anomalous steering flow, which is offshore and disfavors south coast landfall (Fig. S5b). More genesis near the eastern Philippines, steered northwestward by the climatological flow, directs more TCs through the Philippines onto the south coast of China. East coast Chinese landfalls also increase, though less dramatically and not unprecedented within the preindustrial record (Fig. S4).

Unlike the three similar members, the 100-member ACE2 ensemble mean of EXP1 shows more TC tracks deflecting northeast into the open ocean (Fig. 4b), driven by an eastward shift in genesis (Figs. 2d&4e), consistent with the typical El Niño response in the Western Pacific³². Despite this, the basin-wide increase in Western Pacific TCs sustains a net rise in total landfalls, particularly along the east coast (Fig. 4h, blue).

In the EXP1-weak sun ensemble mean – combining the El Niño-like SST change with solar dimming – more TC tracks shift toward Taiwan, eastern China, Japan, and Korea (Fig. 4c), as enhanced genesis spreads across the full basin, particularly east of Taiwan and the northern Philippines (Fig. 4f). Relative to the response only to El Niño-like Pacific SSTs (Figs. 4b&e&h), combining the SST and solar dimming response produce an even greater increase in total landfalls – especially along the east coast (Fig. 4i, blue) – while south coast landfalls decline slightly (Fig. 4i, red), contradicting REACHES. This discrepancy underscores the dominant role of genesis location over steering flow in shaping TC tracks in these experiments: steering flow cannot account for the south coast enhancement in REACHES (Fig. S5), whereas genesis location shifts can (Figs. 4d–f). The steering flow changes show that El Niño-like SST can induce the anticyclone over the Western Pacific, while solar dimming further enhances the Northwestern Pacific subtropical high and monsoon trough (Fig. S5); none of the changes can account for the south coast enhancement in REACHES, highlighting the importance of genesis location change (Figs. 4d-f).

Discussion

The enhanced landfall in REACHES reflects both climate and weather drivers (Figs. 4–5). On the climate side, disproportionate extratropical cooling under solar dimming steepens the meridional temperature gradient, strengthening the Hadley circulation and increasing basin-wide Western Pacific TC activity through enhanced seed disturbances. On the weather side, randomness in synoptic-scale weather disturbances drives anomalous TC genesis east of the Philippines, steering more TCs onto the south coast of China. This genesis enhancement cannot be explained by large-scale monthly environmental

conditions — the selected members similar to REACHES and the ensemble mean of the time-slice experiments share comparable transition probability and seed propensity index yet produce very different genesis patterns (Fig. S6) — nor by the Madden-Julian Oscillation (MJO) subseasonal variability, which shows no clear phase amplitude differences between the two periods (Fig. S7). The role of weather noise is further supported by the spread across the 14 time-evolving ACE2 members: only 3 reproduce a REACHES-like landfall peak, while others show a minimum during the same period (Fig. S8), highlighting that synoptic-scale noise can leave a lasting imprint on multi-decadal TC variability.

The enhanced genesis east of the Philippines is consistent with historical records showing that voyage times between Acapulco (Mexico) and Manila were significantly longer during 1650–1680 (~ 110–120 days) than in the rest of the 16th–18th centuries (~ 90 days), with meteorological conditions — including TCs — identified as the most likely cause³³. Our findings on the enhanced genesis east of the Philippines directly support this hypothesis and, in turn, are corroborated by it.

Previous studies speculated that the 1650–1680 TC landfall peak can be attributed to La Niña SSTs¹⁶, a southward shift of the intertropical convergence zone (ITCZ)³⁴, and an extended monsoon trough¹⁵ — conditions conventionally associated with more TC formation in the southwestern Western Pacific. Their argument is mostly based on empirical knowledge without solid evidence that those conditions occurred during 1650–1680. However, our results indicate that this period is characterized by more El Niño-like SSTs, with no robust evidence of a large shift in the ITCZ or monsoon trough.

In addition to climate drivers, randomness in synoptic weather-scale disturbances contributes significantly to multi-decadal regional TC landfall variability — a surprising result given the vast timescale difference, yet consistent with a past-millennium Atlantic island study¹⁰ and the recent multi-decadal eastward shift of Atlantic TC tracks since 1970¹². Thus, these findings extend beyond Chinese landfall and the paleoclimate era, having broader implications for TCs across all basins in the current climate. A key open question is how much of the recently observed decadal shift in Western Pacific TC tracks stems from changes in genesis location versus large-scale climate forcing³⁵. Fully accounting for weather noise is essential for projecting future TC landfalls; large-ensemble simulations³⁶, now increasingly feasible with AI emulators^{18–20}, are the natural tool for this purpose.

Our results also have implications for greenhouse warming and solar radiation management³⁷. While the effect of greenhouse emissions on global TC frequency remains debated^{4–6}, an estimated 8% chance of a return to Maunder Minimum conditions by the end of the century³⁸ means solar dimming alone could increase basin-wide Western Pacific TC frequency — underscoring the need to account for both forcings in future projections. Geoengineering through global solar dimming could simultaneously increase Western Pacific TC activity and landfalls, though its effect may depend on ENSO state³⁹. How differential cooling at different latitudes affects Hadley circulation strength under varying greenhouse gas scenarios remains an open question⁴⁰. Finally, as solar forcing and ENSO feedback are treated

independently here, future coupled Earth system models^{20, 41–42} may better resolve their interactions with greenhouse gases.

This study demonstrates the value of combining Chinese historical records, AI emulators, and physical models to investigate multi-decadal TC variability. Future work should incorporate a basin-wide Western Pacific proxy from existing island records^{12–15} — as has been done for the Atlantic⁷ — to better constrain simulations and capture regional landfall patterns. Richer proxy coverage and advances in AI emulators will open the door to examining global millennium-scale TC variability. This long-timescale investigation could improve understanding of TC-climate interactions and reduce uncertainties in future projections.

Methods

Chinese historical written record (REACHES)

The Reconstructed East Asian Climate Historical Encoded Series (REACHES) data is based on digitized Chinese historical written records, which document extreme events (cold waves, heat waves, heavy rain, and tropical cyclones)¹⁶. In the Ming and Qing Dynasties, specific officers were responsible for these records. During the summer, when the wind blows from all directions and heavy rain occurs simultaneously, the traditional officers report it as a tropical cyclone event. A recent study has conducted a comprehensive comparison between modern ship track data and the late 19th Century data and found them comparable¹⁶. The REACHES data record the monthly number of tropical cyclones along the East Coast (Jiangsu, Zhejiang, and Fujian provinces) and the South Coast (Guangdong, Guangxi, and Hainan provinces) of China from 1368 to 1911 AD. However, because of the limited data in the 14th and 15th centuries, which may lead to an inaccurate count of storms, we use only data after 1500 AD, consistent with the previous study¹⁶.

Ai2 Climate Emulator (ACE2)

Ai2 Climate Emulator Version 2 (ACE2)¹⁸ is an autoregressive deep-learning emulator trained on ERA5 reanalysis⁴³ using the Spherical Fourier Neural Operator⁴⁴. It consists of 1-deg horizontal resolution with eight vertical levels, with 6-hourly output of prognostic variables. It is an atmospheric-only model, prescribed by sea surface temperature, sea ice, and CO₂.

We run a single-member time-evolving simulation from 1500 to 1850 AD by forcing with Last Millennium Reanalysis (LMR2.1) data²³ of sea surface temperature and the Northern hemispheric Sea Ice Reconstruction²³. We obtain the real initial condition of the time-evolving simulation by running ACE2 for 1 year, with forcing starting in 1500 AD and initialization on 1940, Jan 1. We also run another 13-member time-evolving ensemble from 1550 to 1750 AD. Initial conditions of each member are obtained by running ACE2 with the repeating forcing of 1550. For example, starting from 1940, Jan 1, we get the member 1 initial condition by running ACE2 with forcing of 1550 for 1 year. Then, we use the output of

that 1-year simulation and further run for another year with the 1550 forcing to get the member 2 initial condition, and so on and so forth. The paleo simulation approach follows a recent study⁹.

We also perform 100-member time-slice experiments. The forcing file of the control run (CTL) is from the time-averaged period 1611-1630 (the inactive TC landfall period). Two experiments are run: EXP1 and EXP1-weak sun, prescribing SSTs from 1651 to 1680, the active TC landfall period. The Weak Sun experiment reduces solar radiation by 2.5% to maximize the impact of the solar minimum during this period (the Maunder Minimum¹⁶). The choice of magnitude is justified by a magnitude roughly comparable to the climate effect of a volcanic eruption²⁹.

High-resolution atmospheric model (HiRAM)

Princeton Geophysical Fluid Dynamics Laboratory dynamical high-resolution atmospheric model (HiRAM) is an atmosphere-only global dynamical model that has a grid spacing of roughly 50 km, representing TC frequency and track reasonably⁴⁵. Similar to the time-evolving simulation in ACE2, we also perform a time-evolving HiRAM simulation of a single member from 1500 to 1850 AD. The HiRAM simulation also uses the last millennium reconstructed sea surface temperature from the last millennium reanalysis (LMR2.1)²³. The solar forcing of the simulation remains at the level of the year 1880.

Solar Radiation Reconstruction

Solar radiation in Fig. 1e comes from the PMIP3 data²⁷. Because of the uncertainty in each estimate, we chose to use the estimate from a previous study⁴⁶, which represents one of the largest variations in minimum and maximum values among PMIP3. However, it is worth noting that significant uncertainty remains when quantifying the minimum solar radiation during the low sunspot period²⁷.

Solar experiment using the dynamical model AM2.5

To quantify the effect of solar dimming and compare it with the ACE2 simulation, we conduct an additional solar dimming experiment using a different atmospheric-only dynamical model (AM2.5). AM2.5 is the atmospheric component of the GFDL coupled atmosphere-ocean GCM CM2.5²⁶. The control run is run for 50 years, forced by climatological SST averaged between 1986 and 2005, with radiative forcing fixed at the 1990 level. The weak sun experiment is prescribed to have the same SST as the control run, while solar radiation is reduced by 2%.

Tropical cyclone tracking in ACE2

Following previous studies that analyze TCs in ACE2^{21, 22}, we use the TempestExtremes package⁴⁷ to track TCs under the same criteria of minimum sea level pressure (i.e., closed contour sea level pressure decreasing by 2 hPa within 5.5 deg), warm core (i.e., air temperature at the third vertical level [$\sim$ 250-400hPa] at the TC center greater than 0.4K over a 6.5 deg distance from the TC center), and the

maximum 10-meter wind at least 10 m/s for 60 hours, with a consecutive 60 hours occurring between 60S-60N. Other detailed justifications for the criteria can be found in the previous study²².

Tropical cyclone tracking in HiRAM and AM2.5

We track TCs in HiRAM and AM2.5 following the algorithm developed by (25), with lifetime and threshold criteria similar to (45). The TC tracking criteria are mostly identical in HiRAM and AM2.5, except that the critical temperature difference parameter for the warm core definition differs to match the modeling skills of TCs (i.e., AM2.5 uses 1K while HiRAM uses 2.5K) (details can be found in (48)). Because HiRAM tends to produce more TCs than observed, we only detect hurricane-level TCs in HiRAM to represent its TC activity. The criteria we use for TC detection in HiRAM include at least 72 hours of total lifetime, 48 cumulative hours of warm core, and 36 continuous hours of both warm core and max wind speed > 15.75 m/s. Hurricane-level TCs are identified if the peak intensity is over 30 m/s.

Even if we use slightly different tracking criteria in ACE2 and HiRAM/AM2.5, it is appropriate because we mainly compare the percent change of TCs in ACE2 and HiRAM/AM2.5 relative to the model's own baseline (i.e., the model's TC number climatology), instead of comparing the absolute number of TCs. The different tracking criteria are tuned to suit each simulation model.

Tropical cyclone trend, density, and landfall

To focus on the low-frequency variability of TC frequency, we conduct a 40-year running mean of Western Pacific TC frequency. For the spatial distribution of TC genesis and track density, we apply a moving 9-deg-by-9-deg window. We split TCs that make landfall in China into the South Coast (south of 23.5N) and the East Coast (North of 23.5N), matching the REACHES data.

Seed propensity index and transition probability of TCs

We use the seed-probability framework to investigate spatial and temporal changes in TC frequency³¹. The seed-probability framework models tropical cyclone formation as a two-step binomial process, in which seed disturbances form first and then transition into TCs. The number of TCs is thus the product of the number of seeds and the transition probability from seeds to TCs. Previous studies have verified that this framework explains the annual cycle⁴⁸ and interannual variability⁴⁹ of TCs in all basins. A recent study also verified that this framework can explain the TC frequency in most basins in ACE2 over the past millennium⁹. Following their approach⁹, this study also calculates the transition probability based on vertical wind shear at 200 and 850 hPa, potential intensity, and saturation moisture deficit (i.e., moisture difference between 600 hPa and the boundary layer) (details in (9), Eq. [4]-[5]). We also calculate the seed propensity index (SPI)³¹ as a proxy for the number of seed disturbances. The SPI is calculated from monthly mean precipitation and 850 hPa vorticity, following (9) (details in (9), Eq. [7]-[8]).

Steering flow analysis

We examine the 500 hPa climatological horizontal wind in boreal summer (June-Nov) as the steering flow for TCs.

Madden-Julian Oscillation

We examine the Madden-Julian Oscillation and convectively coupled equatorial waves (CCEWs) over the inactive (1611-1630 AD) and active (1651-1680 AD) landfall TC periods in the ACE2 simulation. We use precipitation anomalies and zonal wind anomalies at 200 and 850 hPa to calculate the RMM index⁵⁰. We perform a combined EOF analysis to obtain the MJO zonal EOF structure, and then project the raw data onto the EOF to derive the RMM index⁵⁰. Following, we conduct the 8-phase composite of the MJO of the two periods.

Declarations

Data Availability

All critical data used in this study are available at <https://github.com/muting-chien/WestPac>

_TC_ACE2_REACHES_public. The solar radiation data is downloaded from <https://wiki.lsce.ipsl.fr/pmip3/doku.php/pmip3:design:download>. The ACE2 checkpoints can be found at <https://huggingface.co/allenai/ACE2-ERA5/tree/main>.

Code Availability

All analysis code is available on GitHub at https://github.com/muting-chien/WestPac_TC_ACE2_REACHES_public.

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Competing Interests

The authors have no competing interests.

Author Contributions

M.C. contributed to conceptualization, methodology, investigation, visualization, and writing an initial draft; W.T., K.L., E.D.M, and E.A.B. contributed to conceptualization, methodology, and editing the manuscript; W.Y. contributed to methodology, investigation, and editing the manuscript.

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Figures

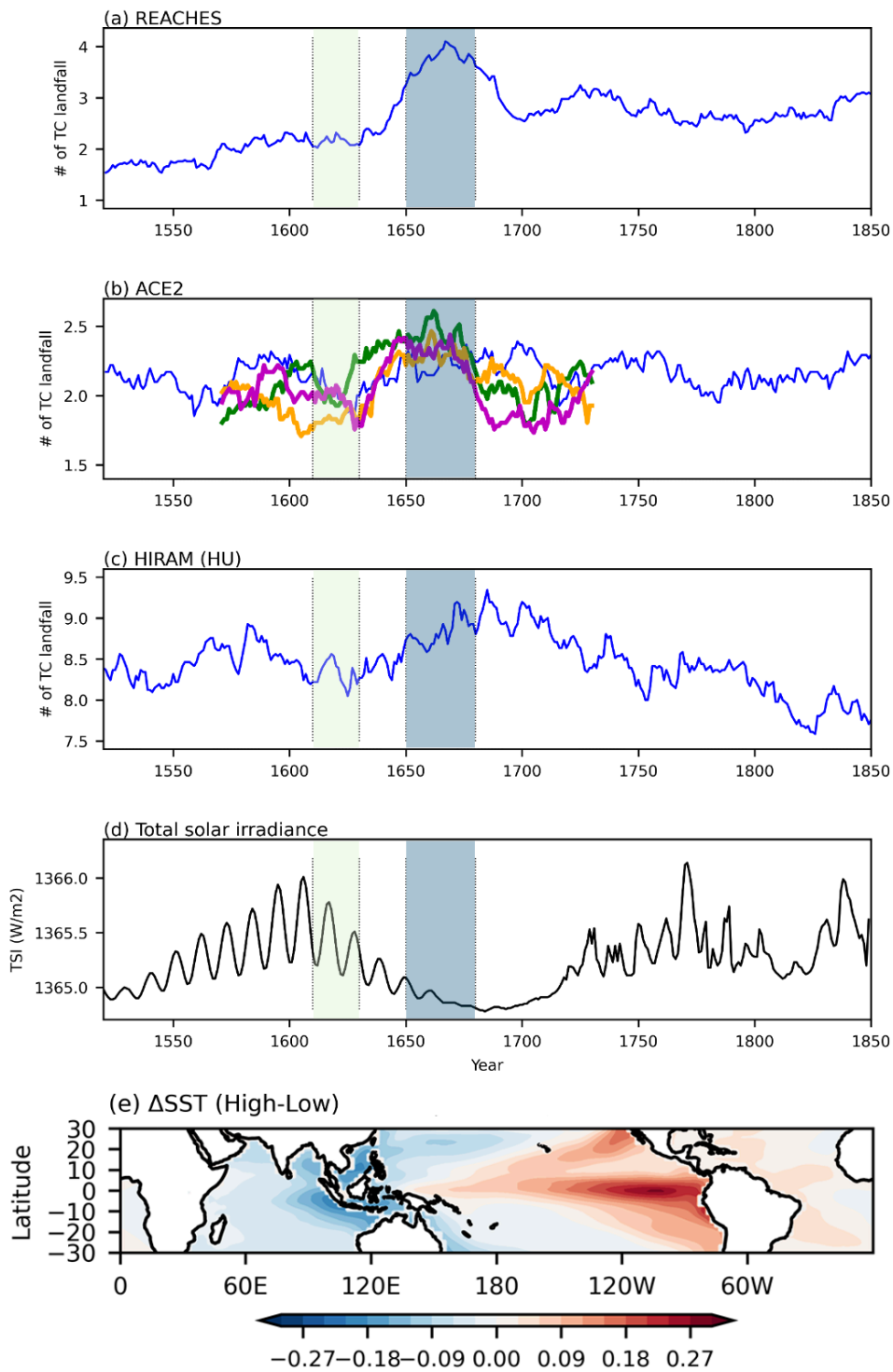


Figure 1

(a-d) Time series of Chinese landfall tropical cyclones from 1500-1850 AD: (a) the digitized historical written record, (b) the Ai2 Climate Emulator (ACE2), with 3 additional members, (c) the high-resolution physics-based atmospheric model (HiRAM). (d) Time series of total solar irradiance from the PMIP project. The blue shading corresponds to the high landfall period (1650-1680 AD), and the green shading

corresponds to the low landfall period (1611-1630 AD). (e) The change in sea surface temperature from the Low (low landfall) to the High (high landfall) period.

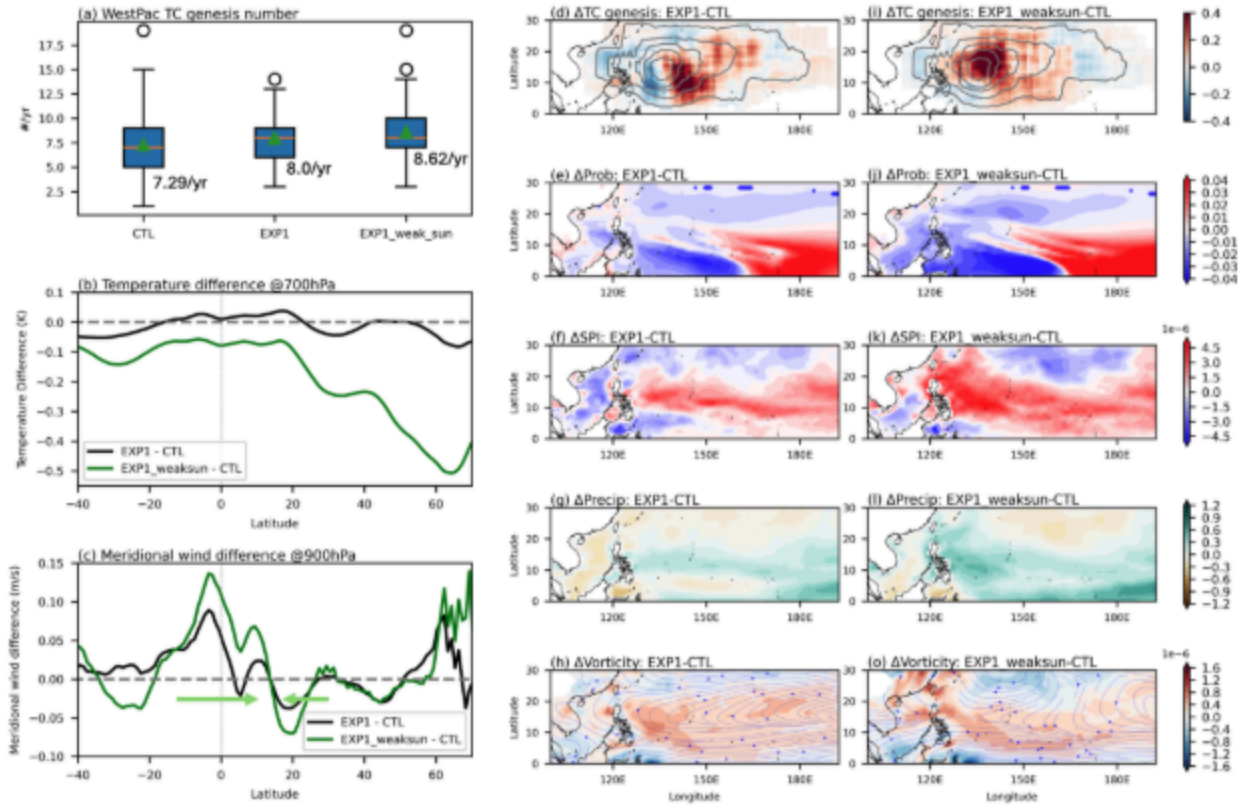


Figure 2

Climate impact on Western Pacific TC activity in each ACE2 time-slice experiment. (a) Western Pacific TC number, (b) climatological meridional wind at 900 hPa averaged between June-Nov, (c) climatological temperature at 700 hPa averaged between May-Oct, (d) TC genesis difference from CTL to EXP1, (e) seed-to-TC transition probability difference from CTL to EXP1, (f) seed propensity index difference from CTL to EXP1, (g) precipitation difference from CTL to EXP1, and (h) difference in relative vorticity at 850 hPa from CTL to EXP1, streamline shows the difference in horizontal wind at 850 hPa. (i-o) similar to (d-h), except that it is showing the difference from CTL to EXP1_weak sun.

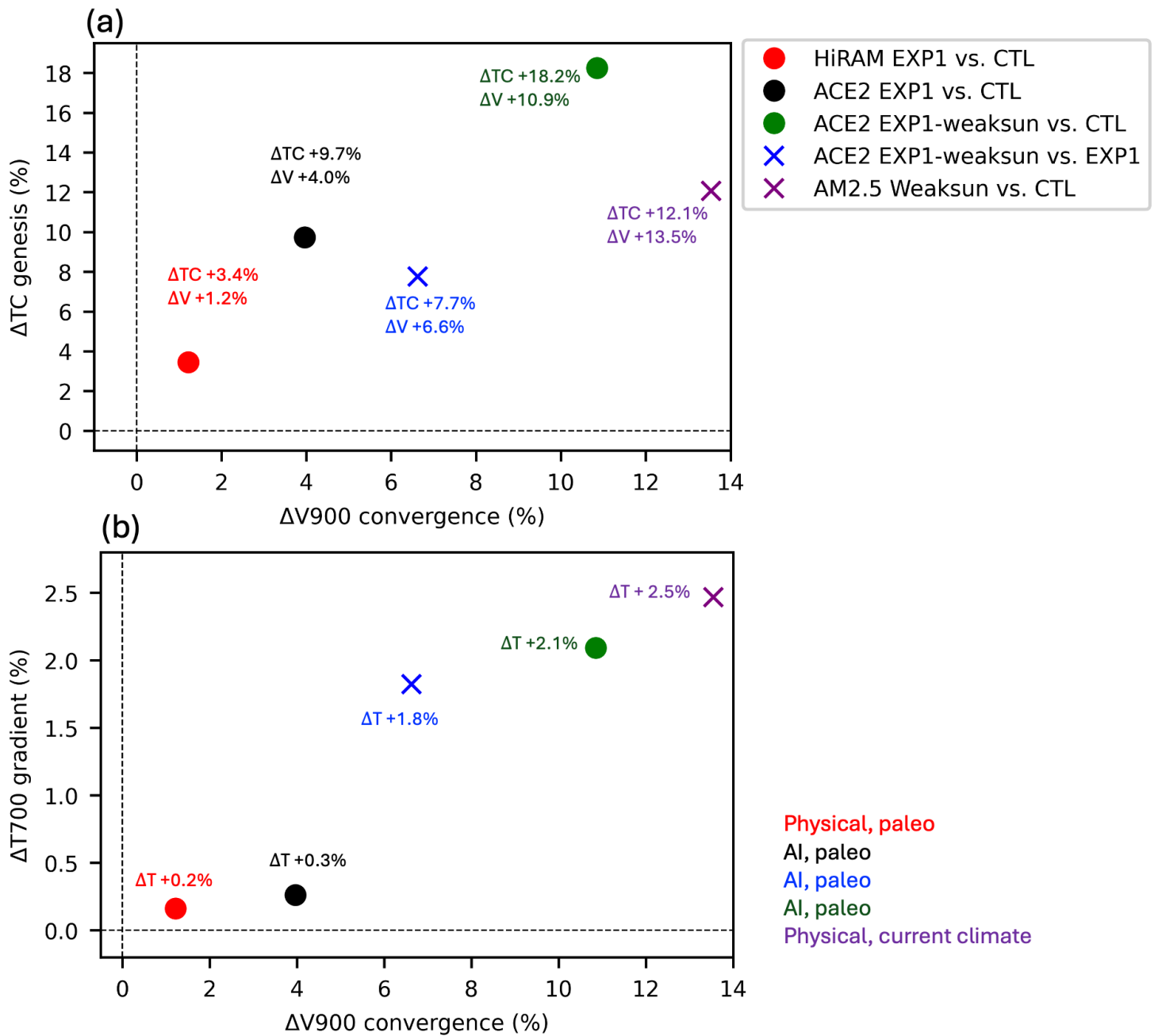


Figure 3

Summarized percentage changes from various experiments in the physical models (HiRAM and AM2.5) and the Ai2 Climate Emulator Version 2 (ACE2): (a) the Western Pacific tropical cyclone number and the meridional wind convergence at 900 hPa between 0-30N, and (b) the meridional wind convergence at 900 hPa and the meridional temperature gradient, calculated from the tropical (0-30N) minus the extratropical (30-60N) temperature at 700 hPa. Dots represent experiments from the paleo run with both changes in SST and solar forcing. Crosses represent changes solely due to solar dimming, while SST remains unchanged.

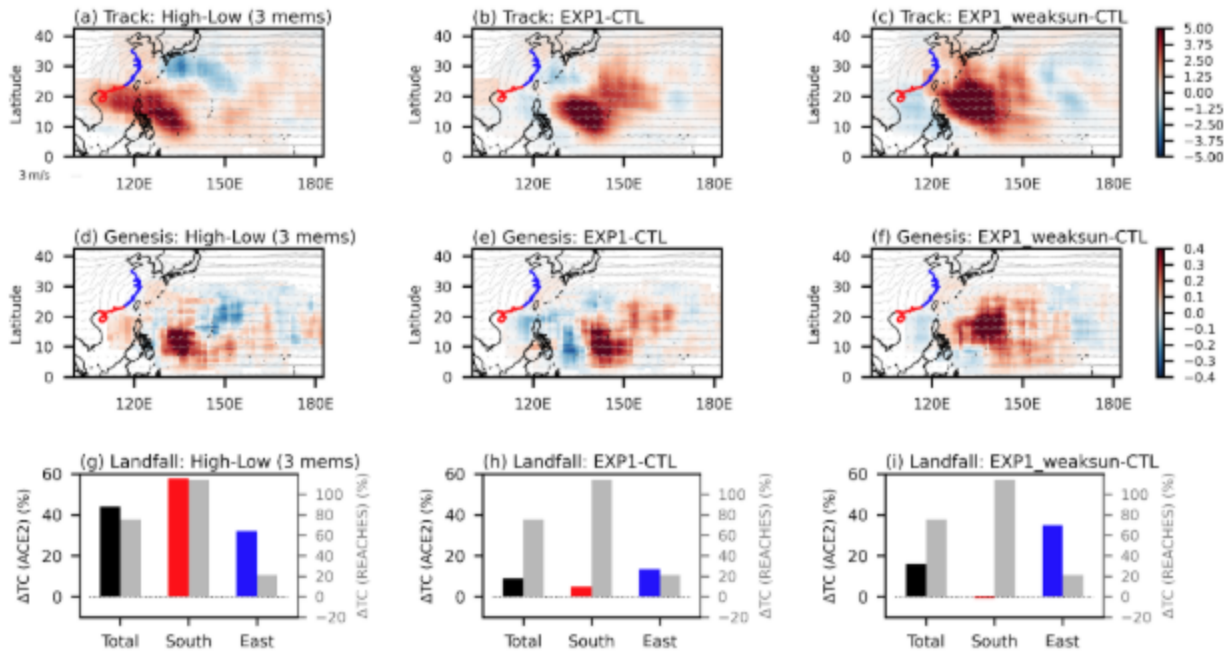


Figure 4

Changes in TC track (a-c), genesis (d-f), and landfall (g-i) from ACE2 experiments. The left-most column (a, d, g) represents changes from the low to high landfall periods from 3 ACE2 members of the time-evolving simulation that capture the peak landfall as in REACHES. The middle column (b, e, h) represents the 100-member ensemble mean of the time-slice experiment (EXP1) relative to the control (CTL); this reflects response due to SST changes. The right-most column (c, f, i) represents the 100-member ensemble mean of the time-slice experiment with solar dimming (EXP1_weak sun) relative to the control (CTL); this reflects response due to both SST changes and solar dimming. The grey bars in (g, h, i) represent landfall changes from REACHES data.



Weaker solar activity

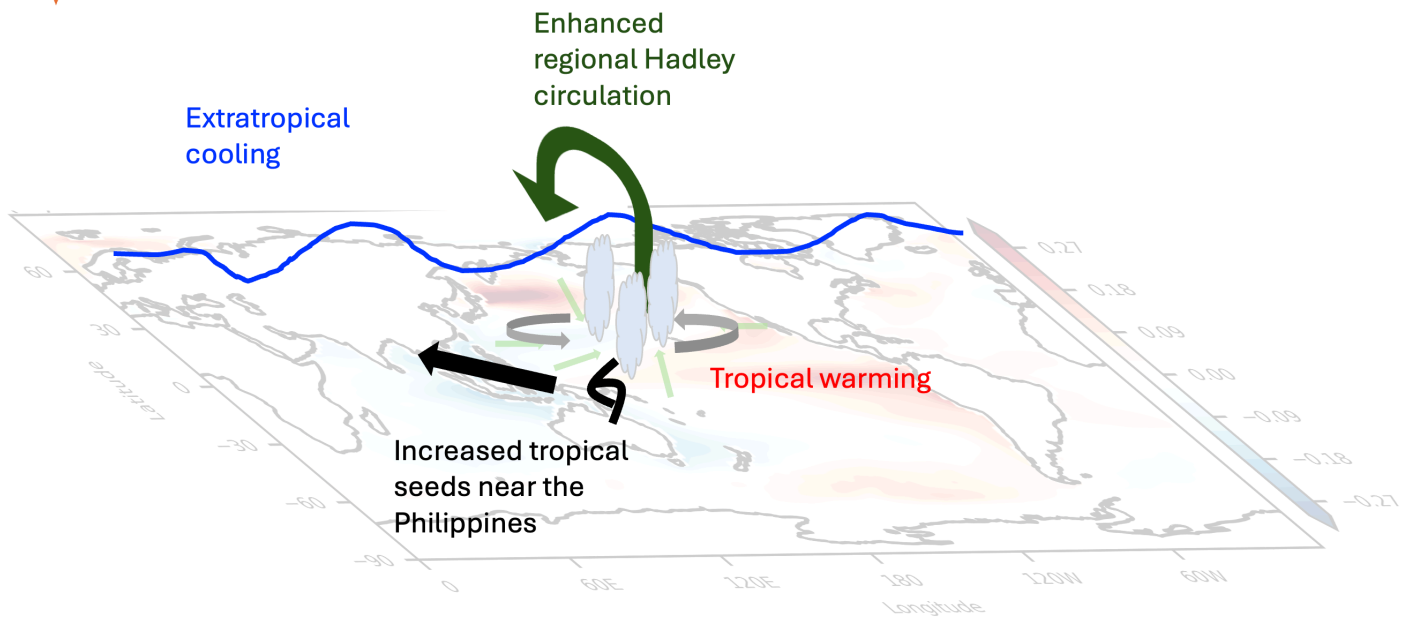


Figure 5

The schematic summarizes mechanisms that enhance tropical cyclone landfalls during the Maunder Minimum, including both climate forcings (i.e., stronger Hadley circulation) and weather noise.

Supplementary Files

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