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Sustained Late-Nineteenth-Century Monsoon Drought in Seoul and the Indian Ocean–North Atlantic Forcing of Its Circulation Weakening

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Abstract. The Cheugugi rain-gauge record of Seoul, Republic of Korea (1777–1907), is among the world's longest instrumental daily precipitation records and a rare quantitative gauge of the pre-industrial East Asian monsoon. Here, we reconcile it against the original chronicle and use it to document, and attribute, a severe sustained rainy-season drought from 1881 to 1907: rainy-season (June–August, JJA) precipitation fell ~27% and annual totals 28% (with a Pettitt change point in 1880, $p \approx 0.01$), with the contribution of days >100 mm falling by ~43%. Three distinct record channels – the gauge, a separate documentary reconstruction, and qualitative rain reports in the Seungjeongwon Ilgi – registered the same shift, arguing against any decay in observational practice. In the Twentieth Century Reanalysis, the unconstrained precipitation field did not resolve the drought, whereas its pressure-constrained circulation registered a weakened monsoon low. Pacemaker experiments (10 members each) were conducted to identify the oceanic driver, prescribing the observed sea-surface-temperature anomalies over the tropical Pacific, North Atlantic, and Indian Ocean individually and globally. The historical forcing produced a significant weakening of the low-level monsoon circulation over Korea: a nearly 8 m depression of the JJA 850 hPa geopotential height ($p < 0.001$, the most robust signal), weakened southerly inflow, and significant reduction in the vertically integrated moisture supply. The geopotential-height weakening was driven principally by the Indian Ocean, the largest single-basin contributor, together with the North Atlantic, and not by the tropical Pacific despite its El Niño-like state. The reconciled record supplies a pre-industrial monsoon baseline and, with the experiments, attributes the monsoon-circulation weakening that accompanied the historical Korean drought to Indian Ocean and North Atlantic cooling. Future work should disentangle the tropical-cyclone contribution to the heavy-rainfall deficit and confirm the attribution with additional models.

1. Introduction

Instrumental climate records that predate the twentieth century are rare, and quantitative daily precipitation records are rarer still. The Cheugugi (測雨器), a standardized bronze rain gauge introduced in Korea in 1441, has produced systematic rainfall measurements, recorded in the royal chronicles of the Joseon dynasty. The restored Seoul series (Jhun and Moon, 1997) spans 1777–1907 and constitutes one of the world's longest instrumental daily precipitation records (Wang et al., 2006, 2007). Prior analyses established long-term trends, multidecadal wet and dry regimes — including a dry period spanning approximately 1884–1910 (Jung et al., 2001) — the structure and singularity of the rainy season, and centennial variability (Ha and Ha, 2006; Wang et al., 2007), but the record's daily and event-scale information over the closing decades of the Joseon dynasty has not been exploited, and its relationship to independent reconstructions of the period has not been examined. Lee et al. (2024) have since produced an independent documentary reconstruction from the same chronicles; reconciling it with the Jhun–Moon restoration against the original chronicle entries yielded the record used in the present study, which we treat not as an end in itself but as the means to a climatic question.

The late nineteenth century saw a global cluster of monsoon failures – the "Late Victorian" droughts, including the 1876–78 North China famine – broadly linked to strong El Niño events and anomalous ocean states (Singh et al., 2018). The East Asian summer monsoon itself undergoes pronounced decadal-to-multidecadal fluctuations in precipitation – a late-1970s weakening and "southern-flood–northern-drought" shift over eastern China (Ding et al., 2008), further mid-1990s circulation change (Kwon et al., 2007), and long-term variability of the Korean changma (Ha et al., 2012; Lee et al., 2017) – yet the pre-

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industrial reach of this variability at the monsoon's northern margin has been constrained by the scarcity of quantitative observations.

The Twentieth Century Reanalysis (20CR; Compo et al., 2011; Slivinski et al., 2019), a four-dimensional weather reconstruction, extends back to 1806 by assimilating only surface and sea-level pressure, and was designed expressly as an observational validation dataset with quantified uncertainty for daily weather statistics. It has been used widely to reconstruct historical storms, tropical cyclones, and hydroclimate where direct observations are absent. However, its skill is determined by the density of the assimilated pressure network and degrades in data-sparse regions and early decades, where its trends can diverge from independent observations (Krueger et al., 2013). Validation over the East Asian monsoon has focused on the twentieth century and on China; the nineteenth-century reanalysis has not been tested against a quantitative daily precipitation record over Korea. The Cheugugi series, which is not assimilated into the 20CR, is uniquely suited to this test.

Here, we use this reconciled record to (i) document a sustained rainy-season drought in Seoul during 1881–1907 and establish its reality against independent evidence, (ii) test whether the 20CR version 3 (20CRv3) captures it, and (iii) attribute the accompanying circulation weakening to its oceanic driver with a set of sea-surface-temperature-forced ("pacemaker") atmospheric experiments that isolate the tropical Pacific, North Atlantic, and Indian Ocean contributions. Although the Late Victorian droughts are broadly ascribed to El Niño, which ocean basin drove the monsoon failure at the northern margin of the East Asian monsoon remains unclear. Unexpectedly, we found that the Indian Ocean and North Atlantic – not the tropical Pacific – were responsible for the circulation weakening.

2. Methods

The study used a newly reconciled Cheugugi daily precipitation series for Seoul, 1777–1907. The first recorded year, 1777, is incompletely observed — the peak monsoon month of July has no entry and only 32 wet days are logged, against 44–71 in the following years — and was therefore excluded, thus all epoch statistics begin in 1778. The series is based on the author's original digitization of the Seungjeongwon Ilgi and Ilseongnok chronicles, which preserves, for each fall, the gauge depth and recorded onset and end times (the latter continuing past midnight). This series (Cheugugi-Seoul v2) reconciles the earlier gauge restoration of Jhun and Moon (1997) with the independent documentary reconstruction of Lee et al. (2024), which are consistent in annual resolution (r = 0.97) but differ on individual days, against the original chronicle entries; its construction, provenance, and advantages are set out in Sect. 2.1. Analyses of dryness used the summer rainy season, June–August (JJA), which delivers ~64% of the annual total and matches the season analysed in the model experiments. The gauge does not record snow; data-quality diagnostics therefore use the snow-free window April–October, and the intraseasonal decomposition retains the extended season May–September for filter stability (Text S4); the window is stated explicitly with each statistic. Change points were detected using the non-parametric Pettitt test. We compared the gauge records against the ensemble-mean 20CRv3 (1806–1907 subset), which assimilates only surface and sea-level pressure observations and does not assimilate the Cheugugi data, supporting the independence of the gauge dataset. Sea surface temperatures are from ERSSTv5 (1854–1907). Daily correspondence was measured using rank correlation and the critical success index for wet days (JJA); circulation composites used JJA sea-level pressure, with the three decades immediately preceding the change point (1851–1880) as the pre-drought reference (1854–1880 for SST, since ERSSTv5 begins in 1854). Further details are given in the Supplement.

2.1. Reconciled dataset (Cheugugi-Seoul v2)

The three datasets differ in kind. Jhun and Moon (1997) first restored the gauge series as a single daily-total record; Lee et al. (2024) later reconstructed daily amounts independently from the same digitized chronicles; neither carries per-day provenance or sub-daily information. Cheugugi-Seoul v2 reconciles the two against the primary source. Taking the Jhun–Moon series as its base, I adjudicated every substantive day- and event-level discrepancy between the two reconstructions against the original chronicle entries, now searchable in the National Institute of Korean History online database (gauge depth in 尺/寸/分; 1 尺 = 200 mm, 1 寸 = 20 mm, 1 分 = 2 mm), which was adopted as the amount reference. Each adjudicated day was then classified by the source supported by the chronicle (Table S1): the database value (where it

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corroborates both reconstructions; 125 d), Jhun–Moon value (68 d), or Lee et al. value (111 d); where the chronicle provides no gauge reading, the Jhun–Moon value was retained provisionally (485 d), and where the database disagreed with both reconstructions, its value was taken provisionally pending source re-examination (212 d). The 697 provisional days (the last two classes) carried a manual-review flag – 69 of them high-impact – and the drought was insensitive to their treatment (Text S1). Calendar-conversion artifacts (non-leap-year 29 February entries, systematic 10 April gaps, and duplicate dates) were corrected on a continuous daily axis, and omissions were restored.

This reconciliation gives v2 three unique properties compared with either of the prior series. First, its amounts are referenced day-by-day to the original chronicle rather than to a single secondary reconstruction, each day carrying a provenance label and explicit uncertainty flag, so that every value is traceable and its confidence marked. Second, because the original digitization preserves, for each fall, the recorded onset and end times (including continuation past midnight) and the separate Seungjeongwon Ilgi and Ilseongnok readings, v2 retains within-day timing, cross-midnight continuity, and dual-source values, from which a day-boundary-independent 24 h maximum and transcription disagreement can be derived. The heavy-event and boundary-independent extreme analyses, described below, rely on this characteristic. Third, the record is archived openly with CF metadata in NetCDF and CSV (see the “Code and data availability” section). Therefore, v2 is not merely an updated series but an auditable event-resolving reconciliation suited to daily and extreme-rainfall analysis.

2.2. SST-forced attribution experiments

To identify the oceanic driver of the circulation weakening that accompanied the drought, we used the atmospheric component of the JBNU Earth System Model — a spectral atmospheric general circulation model that originated as the CCSR/NIES AGCM5 (Numaguti et al., 1997) and was subsequently developed at Seoul National University into the SNU AGCM, including an improved land-surface parameterization (Kim, 1999) — run at T42 horizontal resolution (128 × 64 Gaussian grid, ~2.8°) with 20 σ-levels, forced by prescribed sea-surface temperature (Text S5). Five experiments were conducted: a control (CTL) forced by the model's monthly SST climatology, and four in which the observed ERSSTv5 monthly SST anomaly (relative to its own 1854–1920 mean) was added to the model's monthly climatology over 1854–1920 within a tanh-tapered regional mask covering the tropical Pacific (TP), North Atlantic (NA), Indian Ocean (IO), or whole ocean (GOGA); the prescribed anomaly fields are shown in Fig. S4. Anomalies were tapered to zero under sea ice and clipped at the freezing point for consistency with the fixed ice climatology. Each experiment comprised 10 members that differ only by a one-day-staggered start date, which seeds independent internal-variability trajectories under identical forcing. For every member, we determined the boreal-summer (JJA) drought-minus-baseline difference (1881–1907 minus 1855–1880, the baseline omitting 1854, the first year of the integrations). The SST-forced response was determined as this difference in an anomaly experiment minus that in the CTL, so that the CTL epoch change – driven only by climatological SST – serves as an internal-variability null. Forced responses were tested with a two-sample (Welch) t-test between the 10-member experiment and CTL groups. Because the model's summer rain band sits ~7° too far south (a known T42 limitation) so that Seoul falls on its dry northern flank, local precipitation is an unreliable diagnostic; therefore, attributions were determined using the low-level (850 hPa) circulation over a Korea box (34–43°N, 124–130°E), for which the control-run monsoon structure matches the NCEP reanalysis (Kalnay et al., 1996). The linearity of the basin decomposition was assessed as TP + NA + IO versus GOGA. To connect the circulation response to the moisture supply, we determined the vertically integrated moisture flux ($g^{-1}\int qV\,dp$, 1000–300 hPa) and its convergence over the Korea box.

2.3. Use of generative AI and author responsibility

The author designed the study, curated the source data, made all scientific judgments, and independently verified every analysis, figure, and conclusion, taking full responsibility for the content of this paper. Within that direction, the generative AI assistant Claude (Anthropic) assisted with scripting the data-reconciliation and chronicle-parsing pipeline, checking the statistical analyses, generating figures. The AI is a tool, does not meet authorship criteria, and is not an author.

3. Results

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3.1. Sustained rainy-season drought

The annual precipitation in Seoul exhibited a downward change point in 1880 (Pettitt $p \approx 0.01$; Fig. 1a), consistent with — and sharpening the onset of — the 1884–1910 dry regime identified at monthly resolution by Jung et al. (2001). Mean annual precipitation fell 28%, from 1251 mm (1778–1880) to 904 mm (1881–1907), and rainy-season (JJA) totals fell ~27% (797 mm against 580 mm); 85% of the years after 1880 fell below the long-term mean. The epoch difference has a block-bootstrap 95% interval of [216, 478] mm (Text S2), which – evaluated at the data-selected 1880 change point – represents the effect size rather than an independent significance test; for the latter we adopted the search-corrected Pettitt value ($p \approx 0.01$). The deficit was seasonally concentrated in the high-summer monsoon: July and August precipitation fell by 27% and 31%, respectively (Fig. 1b), and the climatological rainy-season core (25 June–25 July) weakened by 28%. Crucially, the loss was dominated by heavy events: partitioning annual totals by daily intensity, the contribution of days exceeding 100 mm fell by 43% and that of 50–100 mm days by 28%, while light rain (<10 mm) changed by only 13% (Fig. 1c); the same heavy-event dominance held within the rainy season (JJA; ≥100 mm, −41%). A drought expressed through the disappearance of intense monsoon rainfall points to large-scale circulation, not to a change in light-rain detection. Based on a 27-year running mean, 1881–1907 was the single driest multidecadal window in the entire 131-year record – ranked first of 105 overlapping windows for both annual and rainy-season (JJA) totals. The robustness of the epoch difference to non-parametric, permutation, and block-bootstrap tests, and of the 1880 change point to resampling, is documented in Text S2.

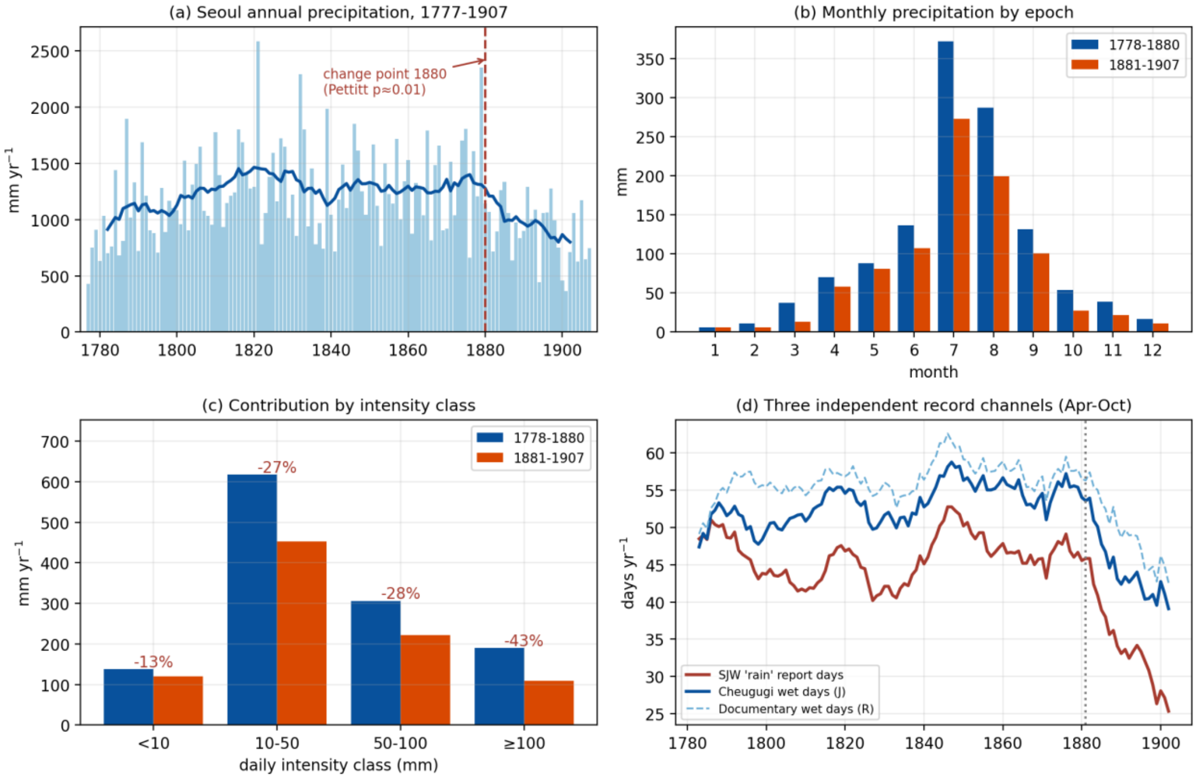

Figure 1: The 1881–1907 drought and its structure. (a) Seoul annual precipitation with 11-year running mean and the 1880 Pettitt change point (the incompletely recorded first year, 1777, is plotted but excluded from all statistics). (b) Monthly precipitation by epoch. (c) Annual precipitation partitioned by daily intensity class; the heaviest events (≥100 mm d^{-1}) decline most (the same heavy-event dominance holds within the rainy season). (d) Three record channels – qualitative “rain” report days in the Seungjeongwon Ilgi, and measured wet days in the Jhun–Moon (J) and documentary (R) reconstructions – all drop after 1881, arguing against decayed observational practice.

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3.2. The drought is real, not an observational artifact

Because the drought coincided with the final decades of the Joseon dynasty, we tested whether it reflects decaying observational practice. Three lines of evidence, drawing on distinct aspects of the record, argue against this. First, the count of days on which the Seungjeongwon Ilgi qualitatively reports rain fell with its own change point in 1881 ($p < 10^{-4}$), tracking the measured wet-day count (Fig. 1d): had the gauge simply been read less often, the qualitative reports would have persisted. Second, the amount unaccounted for by any plausible missed light rain was ~0.1 mm yr^{-1}, against an observed rainy-season (JJA) deficit of ~217 mm yr^{-1}. Third, the annual totals from the independent documentary reconstruction of Lee et al. (2024) correlated with ours (r = 0.97) and reproduced the same decline (Fig. S1). Adjudicating these substantive discrepancies against the original chronicle entries resolved most to the database value and left the drought unchanged: the reconciled series presented the same 1251 versus 904 mm across the epoch as the gauge-based values (Sect. 3.1), thus the drought does not depend on which reconstruction or reference is used. Notably, the ratio of measured to reported rain days spiked only in 1902–1904, two decades after the drought onset (Fig. S2, Text S3), indicating that any late-dynasty record degradation occurred in the qualitative diary channel rather than in the gauge measurements themselves.

3.3. The drought is absent from the reanalysis

In the 20CRv3, precipitation is a model-derived field, not an assimilated observation: the system assimilates only surface and sea-level pressure, with no station data to anchor the analysis over Korea in this period. Over the 102-year overlap, daily agreement in wet-day rainfall amount between the reanalysis and gauge precipitation was modest (Spearman rank $\rho \approx 0.2$ over matched wet days) and rose only after ~1885 as the regional pressure network densified (Fig. 2a). At the multidecadal scale, the two records decoupled entirely: after 1880 the 11-year-smoothed gauge curve fell to -0.78σ while the reanalysis rainy-season (JJA) precipitation rose to $+0.97\sigma$ (epoch means -0.55σ and $+0.27\sigma$; Fig. 2b); the reanalysis precipitation showed no decline under any baseline (a slight rise, 474 to 500 mm, was observed over the full pre-1880 period). Therefore, the pressure-only reanalysis does not recover this hydroclimatic anomaly – as is expected for an unconstrained precipitation field – providing a concrete illustration of where the reanalysis carries no hydroclimatic information over nineteenth-century Korea. (Because reanalysis precipitation here is unconstrained by assimilation, a large ensemble spread that formally encompassed the drought would not represent skill but the absence of it; the ensemble-mean field carries no drought signal.) However, the reanalysis was not uninformative about the large scale, where pressure observations do constrain it: its JJA sea-level pressure composite (Fig. 3a) showed a weakening in the Mongolian–North China thermal low (+1.0 hPa, $p < 0.05$) and southward-shifted monsoon rain belt, with circulation changes consistent with the observed suppression of the northern monsoon. This weakened-low signal was not an artifact of the sparse early pressure network: restricted to the best-observed later decades (1894–1907), it was, if anything, stronger (+1.4 hPa, $p < 0.01$), and was stable to the choice of reference period. Moreover, the geostrophic wind anomaly implied by the pressure difference was anticyclonic over the southern moisture approach to Korea – an anomalous northerly-to-easterly flow over the Yellow and East China Seas (box-mean $v' \approx -0.3$ m s^{-1}, reaching ~1 m s^{-1}) that weakens the southerly transport of monsoon moisture toward the peninsula, dynamically consistent with the gauge deficit (a surface-geostrophic proxy, mirrored by the reanalysis 850 hPa wind difference shown as vectors in Fig. 3a; the model's vertically integrated moisture flux confirms this reduction; Sect. 3.5).

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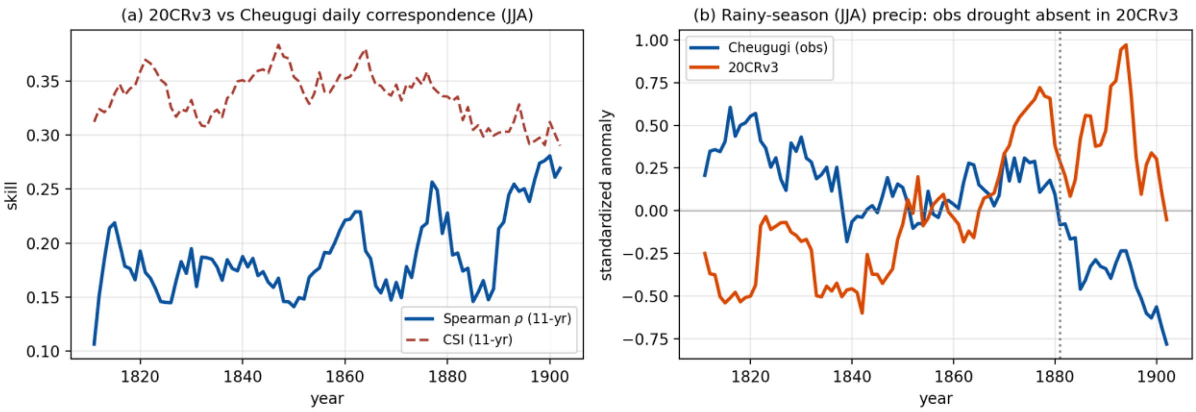

190 **Figure 2: The drought is absent from 20CRv3.** (a) Daily wet-day skill of 20CRv3 against the Cheugugi gauge over JJA (11-year running mean). (b) Standardized rainy-season (JJA) precipitation; the gauge (blue) and reanalysis (orange) decouple after 1880 (dotted line), the reanalysis showing no drought.

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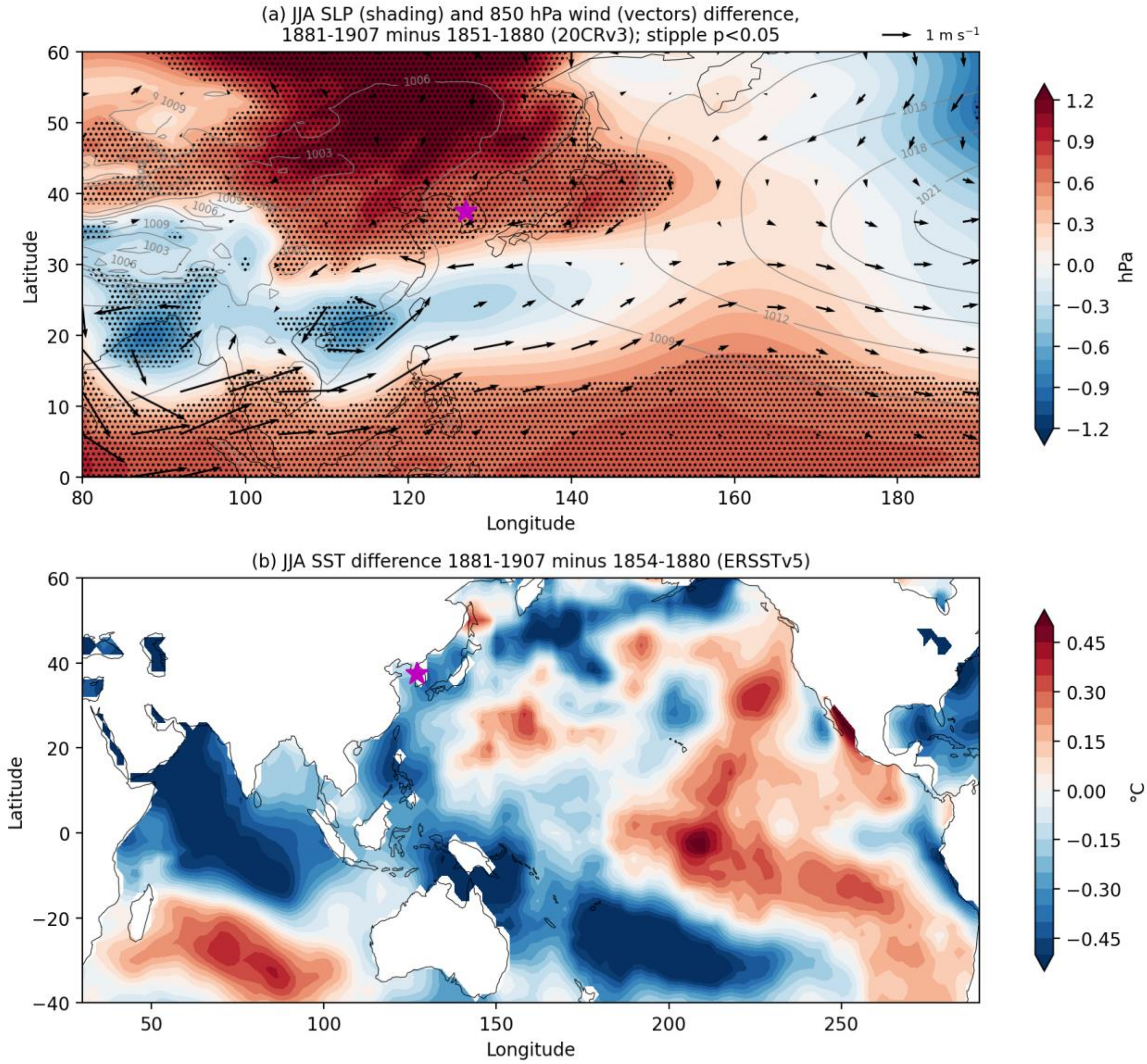

Figure 3: Concurrent circulation and ocean change. (a) JJA sea-level-pressure difference (1881–1907 minus 1851–1880) from 20CRv3; stippling, $p < 0.05$; gray contours, reference climatology; vectors, 850 hPa wind difference (reanalysis-derived); star, Seoul. (b) JJA SST difference (1881–1907 minus 1854–1880, ERSSTv5) showing El Niño-like tropical Pacific warming with Indian and North Atlantic cooling. The two reference baselines differ by 3 years because ERSSTv5 begins in 1854; the composites are insensitive to this choice.

3.4. Concurrent ocean state

The drought epoch coincided with a distinct configuration of the surrounding oceans (Fig. 3b). The JJA SST difference (1881–1907 minus 1854–1880) showed an El Niño-like warming of the central-to-eastern tropical Pacific together with cooling of the northwestern Pacific, tropical Indian Ocean, and North Atlantic, with the Atlantic Multidecadal Oscillation in its cold phase (Fig. S3). This inter-basin pattern – a relatively warm tropical Pacific set against cooler Indian and North Atlantic oceans – is generally associated with a weakened Walker circulation and suppressed East Asian summer monsoon

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(Lu et al., 2006; Zhang et al., 2018). The difference map also shows a subtropical western North Pacific warm anomaly (centered near 28° N, 158° E; Fig. 3b), collocated with the anomalous 850 hPa westerlies of Fig. 3a. Because these westerlies oppose the climatological trades, the epoch-mean wind speed over the warm anomaly is reduced (by ~0.3 m s^{-1}, ~10 %), consistent with reduced evaporative cooling – the wind–evaporation–SST footprint of a weakened circulation (Wang et al., 2000) – and hence with a coupled maintenance of the anomaly. This configuration is nearly the mirror image of the canonical summer following an El Niño peak, in which an anomalous Philippine Sea anticyclone overlies a cold western North Pacific to its east, is supported by a basin-wide warm Indian Ocean, and drives enhanced southerlies toward East Asia (Wang et al., 2000; Xie et al., 2009): in the drought epoch the surface anomaly is warm rather than cold and sits poleward of the canonical position (25–30° N, near the ridge axis, rather than 10–20° N off the Philippines), the Indian Ocean is cold rather than warm, and the flow toward Korea is anomalously easterly rather than southwesterly (Fig. 3a), so the epoch mean state cannot be read as a residue of decaying-El Niño summers. Notably, these represent concurrent mean-state differences, not an established cause: the year-to-year correlation of Niño3.4 with Seoul rainfall was weak ($r = -0.07$), and although El Niño-like summers were more frequent in the drought epoch (19% versus 4% of years), this difference was not significant given the small sample (Fisher exact test, $p \approx 0.19$; Fig. S3); thus, any linkage would operate through the multidecadal mean state. Within a single 27-year epoch, these co-occurring basin anomalies cannot be separated from observations alone; therefore, the SST-forced experiments (Sect. 3.5) were conducted to isolate the tropical Pacific, North Atlantic, and Indian Ocean contributions. A test for selective change in the 30–60-day intraseasonal band found none (Text S4, Table S2), indicating that the deficit is not a reorganization of monsoon intraseasonal variability.

3.5. SST-forced attribution of circulation weakening to Indian Ocean and North Atlantic, not Pacific

Under the full historical SST forcing (GOGA), the 10-member ensemble reproduced a weakening of the low-level monsoon circulation over Korea: the JJA 850 hPa geopotential height over the Korea box fell by ~8 m (−7.7 m, $p < 0.001$) and the 850 hPa southerly wind weakened (−0.35 m s^{-1}, $p < 0.05$; Fig. 4, Table S3), signaling a weakened western North Pacific subtropical high and reduced moisture inflow – the same circulation change inferred independently from 20CRv3 (Sect. 3.3) and consistent in sense with the gauge deficit. In particular, the forced 850 hPa wind anomaly (vectors in Fig. 4) agrees in pattern and sense with the reanalysis 850 hPa wind difference (vectors in Fig. 3a): both show an anticyclonic anomaly with anomalous easterlies over the Yellow and East China Seas that oppose the climatological southwesterly moisture flow toward Korea, although the amplitude is weaker in the reanalysis, whose winds are constrained only by assimilated surface pressure. The control ensemble showed no such change, confirming the response is SST-forced rather than internal. Decomposing the forcing by basin (Fig. 4) reversed the naive expectation from the composite: the Indian Ocean was the largest single contributor (−5.0 m, $p < 0.01$), followed by the North Atlantic (−3.7 m, $p < 0.05$), while the tropical Pacific response was weak and not significant (−1.8 m), despite the El Niño-like Pacific state in the observed SST pattern. This basin ranking was specific to the geopotential height, the field with the highest signal-to-noise ratio, and the most direct measure of the subtropical-high weakening, on which the basin attribution was based. The 850-hPa meridional wind and vertically integrated moisture flux (Table S4) weakened in the same sense but with a different basin ordering – the tropical Pacific contributed comparably here, and no single basin was more than marginally significant in these fields. The single-basin responses were sub-additive (TP + NA + IO ≈ −10.5 m versus GOGA −7.7 m; Fig. 5, Table S5), consistent with saturation of the subtropical-high response with successive basin forcing; however, the nonlinear residual was not significant (GOGA minus the basin sum ≈ +2.8 m, $t \approx 0.9$), thus the decomposition was equally consistent with additivity within the ensemble uncertainty (Text S7). The forced precipitation response over the Korea box was weak and, for the Indian Ocean, negligible – a consequence of the model's southward-displaced summer rain band; thus, the attribution was based on the circulation, which the model simulated faithfully. Physically, a cool tropical Indian Ocean weakens the western North Pacific subtropical high (an inverse of the Indian Ocean capacitor effect; Xie et al., 2009), reducing the southerly transport of monsoon moisture to Korea; the North Atlantic cooling reinforces the same response. The weak tropical Pacific contribution relative to the Indian Ocean also echoes earlier model evidence that, in summer, the anomalous western North Pacific subtropical high is governed primarily by local tropical western Pacific–Indian Ocean SST and air–sea coupling rather than by remote eastern Pacific forcing (Lee et al., 2006). Consistent with this pathway, under the full forcing the vertically integrated meridional moisture flux into the Korea box weakened (−17.5 kg m^{-1} s^{-1}, $p < 0.05$), directly linking the circulation weakening to a reduced moisture supply (Fig. 6, Text S6).

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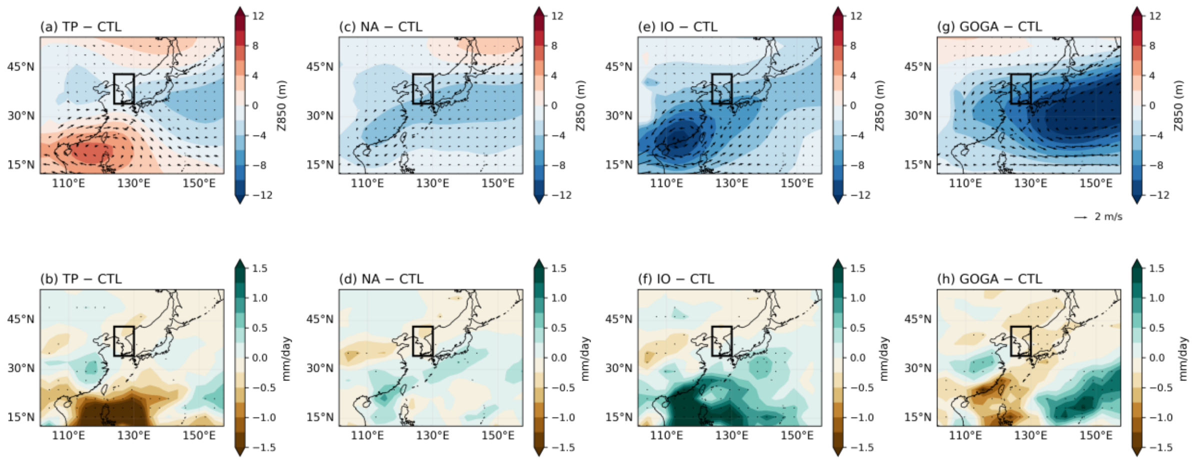

Figure 4: SST-forced JJA response by ocean basin (10-member pacemaker ensembles; drought 1881–1907 minus baseline 1855–1880, experiment minus control). Columns: tropical Pacific (TP), North Atlantic (NA), Indian Ocean (IO), and global (GOGA) forcing. Top row (a, c, e, g): 850 hPa geopotential height (shading, m) and 850 hPa wind anomaly (vectors, Tibet-masked); dots, $p < 0.05$. Bottom row (b, d, f, h): precipitation response (mm d^{-1}). The black box is the Korea diagnostic region (34–43°N, 124–130°E). The low-level circulation weakening (negative 850 hPa geopotential height and weakened southerly inflow over Korea) is driven principally by the Indian Ocean and North Atlantic, not the tropical Pacific; the precipitation response is weak over Korea, reflecting the model's southward-displaced rain band.

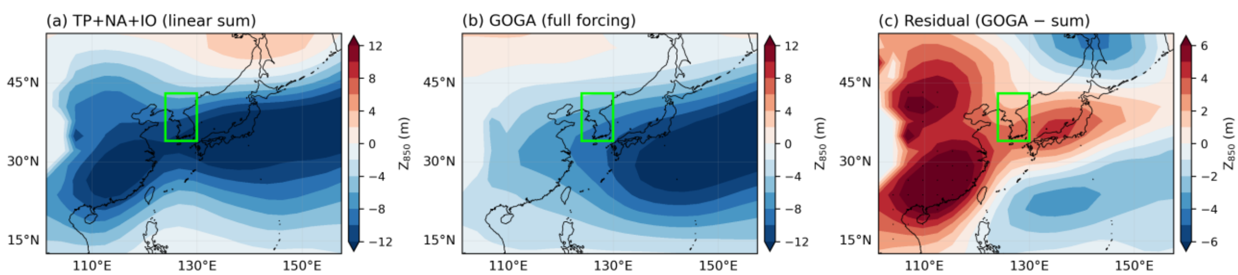

Figure 5: Basin linearity of 850 hPa geopotential height forced response. (a) Linear sum of single-basin responses (TP + NA + IO), (b) the full global response (GOGA), and (c) their residual (GOGA − sum; the residual uses a ±6 m color scale, versus ±12 m in (a) and (b)). The sum overshoots the full response by ~36%, indicating saturation, but the residual is not significant (no stippling at $p < 0.05$), thus the decomposition is consistent with additivity within the ensemble uncertainty.

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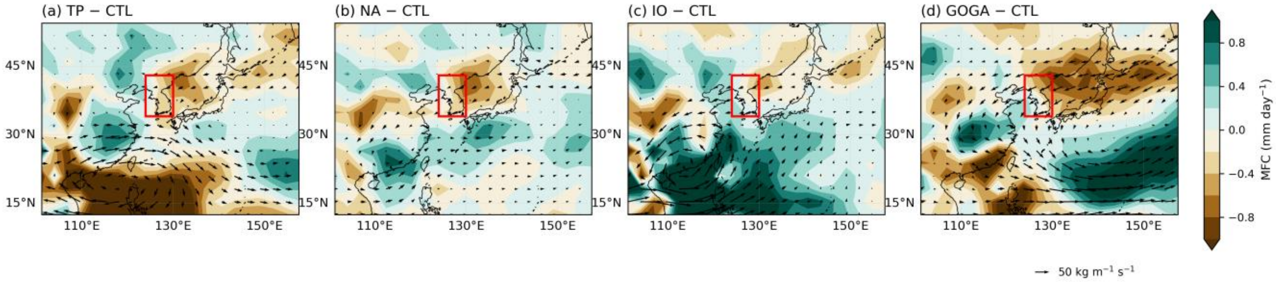

Figure 6: Physical chain – forced moisture-supply response. Forced JJA vertically integrated moisture-flux convergence (shading, mm d^{-1}) and moisture-flux anomaly vectors (Tibet-masked) for (a) tropical Pacific (TP), (b) North Atlantic (NA), (c) Indian Ocean (IO), and (d) global (GOGA) forcing (10-member ensembles; drought 1881–1907 minus baseline 1855–1880, experiment minus control; dots, $p < 0.05$; the black box marks the Korea diagnostic region (34–43°N, 124–130°E)). Under the full forcing, the vertically integrated southerly moisture flux into the Korea box weakens (−17.5 kg m^{-1} s^{-1}, $p < 0.05$), linking the circulation weakening to reduced moisture supply.

4. Conclusions

The Cheugugi record documents a real, severe, and sustained rainy-season drought in Seoul during 1881–1907, verified against independent documentary and qualitative evidence and expressed physically through the loss of heavy monsoon rainfall. Because a substantial share of Korea's heaviest summer rainfall is delivered by landfalling tropical cyclones, part of the heavy-event deficit may reflect a change in tropical-cyclone activity or tracks, which respond to the tropical Pacific through a pathway distinct from the weak mean-monsoon teleconnection (Sect. 3.5). Partitioning the ≥100 mm loss by month bounds this contribution: ~63% of it fell in the cyclone-active August–September window (August −58%, September −51%), thus a tropical-cyclone contribution cannot be excluded and may be sizeable; however, the non-cyclone monsoon core also weakened (June–July ≥100 mm −28%, July −28%), thus the drought does not solely reflect a change in cyclone rainfall. Fully disentangling the mechanisms requires further research. The drought fell within the global late-nineteenth-century cluster of monsoon failures and extends quantitative evidence of that period to Korea, specifically at the northern margin of the East Asian monsoon, where no other instrumental gauge record exists – though a single station cannot by itself delineate the drought's spatial extent. An external volcanic trigger finds no support in the record itself: although Krakatau (1883) erupted near the drought onset, a superposed-epoch analysis of the same Seoul series detects no significant post-eruption rainfall reduction at any lag — Krakatau was in fact followed by anomalously wet summers — and no persistent volcanism–rainfall coherence over 1830–2024 (Hwang and Park, 2026), so the multidecadal, ocean-forced circulation change diagnosed here remains the more plausible driver. The SST-forced experiments resolved the oceanic driver that observations alone could not: the low-level monsoon-circulation weakening over Korea was forced principally by the Indian Ocean and North Atlantic, with the tropical Pacific playing only a minor role despite its El Niño-like state (Sect. 3.5). This attribution is counterintuitive: the Late Victorian droughts are broadly ascribed to El Niño, yet at the northern margin of the East Asian monsoon the Pacific teleconnection was weak. Instead, the circulation weakening that accompanied the drought was an Indian Ocean- and Atlantic-driven response of the western North Pacific subtropical high, consistent with the known sensitivity of this high to Indian Ocean–western Pacific SST (Zhou et al., 2009), with an inverse Indian Ocean capacitor; the joint modulation of interdecadal East Asian summer-monsoon precipitation by the Pacific, Indian, and Atlantic oceans (Zhang et al., 2018); and recognition that the Indian Ocean Dipole and Atlantic state co-determined the 1876–1878 global drought (Singh et al., 2018). However, this conclusion rests on a single T42 model whose southward-displaced rain band makes local precipitation unreliable, so that the attribution is anchored in the circulation (which the control experiment simulated faithfully) rather than in modelled rainfall. Confirmation with additional models is warranted, although a moisture-budget diagnostic already ties the circulation weakening to a significant reduction in the moisture supply to Korea (Sect. 3.5).

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That the unconstrained precipitation of the 20CRv3 did not resolve the drought – while its pressure-constrained circulation registered a weakened monsoon low – marks a specific limitation of the reanalysis over data-sparse nineteenth-century East Asia, where no pressure observations anchor the analysis over Korea. The reconciled Cheugugi record represents a high-value candidate for assimilation in next-generation coupled historical reanalyses that assimilate precipitation-sensitive observations, and, through international data-rescue efforts (e.g., ACRE), the digitization of contemporaneous East Asian station pressure records would tighten the reanalysis where it is presently unconstrained. The same record can calibrate tree-ring drought atlases (Cook et al., 2010), which, to our knowledge, do not clearly register this drought over Korea, where their verification skill is limited. More broadly, the series supplies a quantitative pre-industrial baseline against which anthropogenic changes – alongside the documented late-twentieth-century regime shifts in Korean and East Asian summer rainfall (Ho et al., 2003; Kwon et al., 2007) – in East Asian monsoon precipitation and extremes can be judged, and the reconciled dataset (v2) provides an openly available baseline with per-day uncertainty.

Code and data availability

The reconciled Cheugugi-Seoul daily precipitation dataset version 2 (v2) produced in this study – daily precipitation for Seoul, 1777–1907, with within-day timing and per-day provenance and uncertainty flags, in CF-compliant NetCDF and CSV – together with the analysis code, are archived at Zenodo under a CC-BY license (https://doi.org/10.5281/zenodo.21867395). The same deposit contains the basin-masked SST forcing files, Korea-box attribution fields and statistics, and model-configuration and analysis code sufficient to reproduce the results; the full monthly pacemaker model output (five experiments × 10 members, of the order of a terabyte) has not been redistributed owing to its size but can be regenerated from the archived forcing and configuration. ERSSTv5 (Huang et al., 2017) and 20CRv3 (Slivinski et al., 2019) are from NOAA PSL; the independent documentary reconstruction is from Lee et al. (2024, Zenodo 10.5281/zenodo.11076768); and original Seungjeongwon Ilgi rain-gauge entries are from the National Institute of Korean History (sjw.history.go.kr).

Author contributions

B.-K. Moon designed the study, curated and reconciled the source data, performed all analyses, produced the figures, and wrote and revised the paper.

Competing interests

The author declares that they have no conflict of interest.

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References

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., Gleason, B. E., Vose, R. S., Rutledge, G., Bessemoulin, P., Brönnimann, S., Brunet, M., Crouthamel, R. I., Grant, A. N., Groisman, P. Y., Jones, P. D., Kruk, M. C., Kruger, A. C., Marshall, G. J., Maugeri, M., Mok, H. Y., Nordli, Ø., Ross, T. F., Trigo, R. M., Wang, X. L., Woodruff, S. D., and Worley, S. J.: The Twentieth Century Reanalysis Project, Q. J. Roy. Meteor. Soc., 137, 1–28, https://doi.org/10.1002/qj.776, 2011.

Cook, E. R., Anchukaitis, K. J., Buckley, B. M., D'Arrigo, R. D., Jacoby, G. C., and Wright, W. E.: Asian monsoon failure and megadrought during the last millennium, Science, 328, 486–489, https://doi.org/10.1126/science.1185188, 2010.

Ding, Y., Wang, Z., and Sun, Y.: Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: Observed evidences, Int. J. Climatol., 28, 1139–1161, https://doi.org/10.1002/joc.1615, 2008.

Ha, K.-J. and Ha, E.: Climatic change and interannual fluctuations in the long-term record of monthly precipitation for Seoul, Int. J. Climatol., 26, 607–618, https://doi.org/10.1002/joc.1272, 2006.

Ha, K.-J., Heo, K.-Y., Lee, S.-S., Yun, K.-S., and Jhun, J.-G.: Variability in the East Asian monsoon: a review, Meteorol. Appl., 19, 200–215, https://doi.org/10.1002/met.1320, 2012.

Ho, C.-H., Lee, J.-Y., Ahn, M.-H., and Lee, H.-S.: A sudden change in summer rainfall characteristics in Korea during the late 1970s, Int. J. Climatol., 23, 117–128, https://doi.org/10.1002/joc.864, 2003.

Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore, J. H., Menne, M. J., Smith, T. M., Vose, R. S., and Zhang, H.-M.: Extended Reconstructed Sea Surface Temperature, version 5 (ERSSTv5): upgrades, validations, and intercomparisons, J. Climate, 30, 8179–8205, https://doi.org/10.1175/JCLI-D-16-0836.1, 2017.

Hwang, S. and Park, H.: Limits on volcanic forcing of East Asian monsoon rainfall from the 247-year Seoul Chugugi precipitation record (1778–2024), EGUsphere [preprint], https://doi.org/10.5194/egusphere-2026-4101, 2026.

Jhun, J.-G. and Moon, B.-K.: Restorations and analyses of rainfall amount observed by Chukwookee, J. Korean Meteorol. Soc., 33, 691–707, 1997.

Jung, H.-S., Lim, G.-H., and Oh, J.-H.: Interpretation of the transient variations in the time series of precipitation amounts in Seoul, Korea. Part I: Diurnal variation, J. Climate, 14, 2989–3004, https://doi.org/10.1175/1520-0442(2001)014<2989:IOTTVI>2.0.CO;2, 2001.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R., and Joseph, D.: The NCEP/NCAR 40-year reanalysis project, B. Am. Meteorol. Soc., 77, 437–471, https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2, 1996.

Kim, J.-K.: Parameterization of land surface processes in an atmospheric general circulation model, Ph.D. thesis, Seoul National University, Seoul, Republic of Korea, 1999 (in Korean).

Krueger, O., Schenk, F., Feser, F., and Weisse, R.: Inconsistencies between long-term trends in storminess derived from the 20CR reanalysis and observations, J. Climate, 26, 868–874, https://doi.org/10.1175/JCLI-D-12-00309.1, 2013.

Kwon, M., Jhun, J.-G., and Ha, K.-J.: Decadal change in East Asian summer monsoon circulation in the mid-1990s, Geophys. Res. Lett., 34, L21706, https://doi.org/10.1029/2007GL031977, 2007.

Lee, E.-J., Yeh, S.-W., Jhun, J.-G., and Moon, B.-K.: Seasonal change in anomalous WNPSH associated with the strong East Asian summer monsoon, Geophys. Res. Lett., 33, L21702, https://doi.org/10.1029/2006GL027474, 2006.

https://doi.org/10.5194/egusphere-2026-4812
Preprint. Discussion started: 18 August 2026

Lee, J.-W., Shin, H.-J., and Hong, J.: Precipitation data in Seoul, Korea during 1778–1907, Sci. Data, 11, 566, https://doi.org/10.1038/s41597-024-03335-8, 2024.

Lee, J.-Y., Kwon, M., Yun, K.-S., Min, S.-K., Park, I.-H., Ham, Y.-G., Jin, E. K., Kim, J.-H., Seo, K.-H., Kim, W., Yim, S.-Y., and Yoon, J.-H.: The long-term variability of Changma in the East Asian summer monsoon system: a review and revisit, Asia-Pac. J. Atmos. Sci., 53, 257–272, https://doi.org/10.1007/s13143-017-0032-5, 2017.

Lu, R., Dong, B., and Ding, H.: Impact of the Atlantic Multidecadal Oscillation on the Asian summer monsoon, Geophys. Res. Lett., 33, L24701, https://doi.org/10.1029/2006GL027655, 2006.

Numaguti, A., Takahashi, M., Nakajima, T., and Sumi, A.: Description of CCSR/NIES atmospheric general circulation model, in: CGER’s Supercomputer Monograph Report No. 3, Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan, 1–48, 1997.

Singh, D., Seager, R., Cook, B. I., Cane, M., Ting, M., Cook, E., and Davis, M.: Climate and the global famine of 1876–78, J. Climate, 31, 9445–9467, https://doi.org/10.1175/JCLI-D-18-0159.1, 2018.

Slivinski, L. C., Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Giese, B. S., McColl, C., Allan, R., Yin, X., Vose, R., Titchner, H., Kennedy, J., Spencer, L. J., Ashcroft, L., Brönnimann, S., Brunet, M., Camuffo, D., Cornes, R., Cram, T. A., Crouthamel, R., Domínguez-Castro, F., Freeman, J. E., Gergis, J., Hawkins, E., Jones, P. D., Jourdain, S., Kaplan, A., Kubota, H., Le Blancq, F. L., Lee, T.-C., Lorrey, A., Luterbacher, J., Maugeri, M., Mock, C. J., Moore, G. W. K., Przybylak, R., Pudmenzky, C., Reason, C., Slonosky, V. C., Smith, C. A., Tinz, B., Trewin, B., Valente, M. A., Wang, X. L., Wilkinson, C., Wood, K., and Wyszyński, P.: Towards a more reliable historical reanalysis: improvements for version 3 of the Twentieth Century reanalysis system, Q. J. Roy. Meteor. Soc., 145, 2876–2908, https://doi.org/10.1002/qj.3598, 2019.

Wang, B., Ding, Q., and Jhun, J.-G.: Trends in Seoul (1778–2004) summer precipitation, Geophys. Res. Lett., 33, L15803, https://doi.org/10.1029/2006GL026418, 2006.

Wang, B., Jhun, J.-G., and Moon, B.-K.: Variability and singularity of Seoul, South Korea, rainy season (1778–2004), J. Climate, 20, 2572–2580, https://doi.org/10.1175/JCLI4123.1, 2007.

Wang, B., Wu, R., and Fu, X.: Pacific–East Asian teleconnection: how does ENSO affect East Asian climate?, J. Climate, 13, 1517–1536, https://doi.org/10.1175/1520-0442(2000)013<1517:PEATHD>2.0.CO;2, 2000.

Xie, S.-P., Hu, K., Hafner, J., Tokinaga, H., Du, Y., Huang, G., and Sampe, T.: Indian Ocean capacitor effect on Indo–western Pacific climate during the summer following El Niño, J. Climate, 22, 730–747, https://doi.org/10.1175/2008JCLI2544.1, 2009.

Zhang, Z., Sun, X., and Yang, X.-Q.: Understanding the interdecadal variability of East Asian summer monsoon precipitation: joint influence of three oceanic signals, J. Climate, 31, 5485–5506, https://doi.org/10.1175/JCLI-D-17-0657.1, 2018.

Zhou, T., Yu, R., Zhang, J., Drange, H., Cassou, C., Deser, C., Hodson, D. L. R., Sanchez-Gomez, E., Li, J., Keenlyside, N., Xin, X., and Okumura, Y.: Why the western Pacific subtropical high has extended westward since the late 1970s, J. Climate, 22, 2199–2215, https://doi.org/10.1175/2008JCLI2527.1, 2009.