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A Declining Longwave Cloud Radiative Effect over Iraq: Satellite-Based Climatology and Dynamical Attribution

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Abstract

The longwave cloud radiative effect (LWCRE) over Iraq during spring remains poorly constrained by independent observation, given the region's climatological complexity and the internal-consistency limits of reanalysis-based cloud diagnostics. This study presents a multi-source, satellite-based characterization of spring LWCRE over Iraq for 2001–2024, combining CERES EBAF radiation and cloud retrievals with ERA5 used exclusively for dynamical attribution.

Spring LWCRE averages 26.5 W/m^2 and peaks at 29.7 W/m^2 in April, with a northeast-to-southwest gradient consistent with orographically enhanced cloud development along the Zagros foothills (37.4 W/m^2 maximum) versus subsidence over the southwestern desert (16.5 W/m^2 minimum). A significant declining trend of 1.72 W/m^2 per decade ($p = 0.044$) is found, with cloud-top warming plausibly contributing about half. Deep convective clouds dominate spring cloudiness (62.5% of months), but thin cirrus show $\sim 37\%$ higher LWCRE per unit optical thickness. LWCRE shows no significant association with ENSO ($r = -0.02$, $p = 0.92$); a composite analysis instead links the most extreme years to upper-level trough positioning, with 250-hPa heights 51.6 m lower and ascent significantly stronger in high- versus low-LWCRE years ($p < 0.05$). Iraq's inland lakes show a nearly five-fold enhancement in surface latent heat flux relative to the surrounding desert, consistent with a role as local moisture sources.

These findings establish an independently observed, physically coherent picture of high-cloud radiative behavior over Iraq and provide a benchmark for evaluating cloud–radiation representation in regional reanalysis and climate models.

Keywords: Longwave cloud radiative effect; Iraq; CERES EBAF; cloud-top temperature; upper-level trough; spring climatology

1. Introduction

Clouds are the largest single source of uncertainty in the global radiation budget, and their longwave radiative effect (the extent to which they trap upward thermal radiation that would otherwise escape to space) is a first-order term in regional and global energy balance (Ramanathan et al. 1989) (Michibata et al. 2025). High clouds contribute disproportionately to this effect: because their tops emit at low temperatures, they can produce substantial longwave warming even when optically thin, a behavior documented across extratropical and tropopause-region observations (Spang et al. 2024); (Gil-Díaz et al. 2025). Despite this recognized importance, quantifying the longwave cloud radiative effect (LWCRE) at the regional scale required for process-level understanding remains difficult, because doing so requires independent, simultaneous observation of cloud amount, cloud-top height, and radiative flux, a combination that most operational reanalysis products do not provide independently, since they generate cloud and radiation fields from the same internally coupled model.

This regional heterogeneity is well documented for the Middle East, where cloud behavior varies sharply across the arid-to-semi-arid transition zone. Climatologies of the Arabian Peninsula report a winter–spring cloud maximum concentrated along frontal boundaries that collapses almost completely under the summer subtropical high (Yousef et al. 2020) while studies of spring convective initiation over the southern peninsula link cloud development to orographic lifting along elevated terrain (Nelli et al. 2021). These studies, however, are primarily descriptive: they establish where and when clouds occur, but do not extend to the radiative consequence of that occurrence, nor do they distinguish cloud regimes with different radiative behavior. A shift from mapping cloud occurrence to explaining its radiative effect, and the mechanisms driving its variability, is a necessary next step for this region.

Three mechanisms plausibly govern this variability. The first is cloud-type-dependent radiative efficiency: cold, optically thin cirrus and warmer, optically thick deep convective clouds trap longwave radiation through different physical pathways, such that cloud fraction alone is an incomplete predictor of radiative effect. The second is atmospheric dynamics: upper-level tropospheric troughs are known to trigger Mediterranean cyclogenesis and downstream moisture transport into the eastern Mediterranean during the spring transition season (Flaounas et al. 2025), providing a circulation-based driver of cloud variability distinct from the El Niño–Southern Oscillation, whose influence on Middle Eastern climate is generally strongest in winter rather than spring. The third is surface moisture: inland water bodies are known elsewhere to raise boundary layer humidity and alter boundary layer structure over adjacent land, preconditioning the atmosphere for cloud development (Ma et al. 2026). Each mechanism is physically

82 plausible for Iraq, given its combination of high-altitude terrain, position at the eastern end of the
83 Mediterranean storm track, and several substantial inland lakes, yet none has been directly tested there.

84 It is worth being precise here about what “covered” actually means, because Iraq’s clouds are not an unstudied
85 subject — existing work has mapped where they occur, how they vary by season, and how their base height changes
86 with latitude. What none of it has done is measure what those clouds do to the radiation budget. Cloud occurrence and
87 cloud radiative effect are related but genuinely different quantities: a region can be thoroughly mapped in the first
88 sense and essentially unmeasured in the second, and Iraq, as it turns out, is exactly that region.

89 Existing work on Iraq's cloud climate illustrates clear room for extension. A recent ERA5-based
90 analysis (2010–2019) (Ibraheem et al. 2025) mapped the monthly spatial distribution of cloud base height
91 and cloud cover by type across Iraq, finding higher high-cloud fractions in the north than the south and
92 establishing a basic spatial cloud climatology for the country. This prior study, however, has two specific
93 limitations. Empirically, it covers only a single decade and does not extend to any radiative quantity, so the
94 consequence of this cloud distribution for Iraq's energy budget remains unknown. Methodologically, both
95 the cloud diagnosis and any implied radiative interpretation derive from the same reanalysis model, so any
96 cloud–radiation relationship inferred from it cannot be distinguished from the model's own internal
97 parameterization. To our knowledge, no study of Iraq has yet paired independent satellite observations of
98 cloud properties and radiative flux, differentiated cloud regimes by their radiative efficiency, tested the
99 dynamical drivers of interannual cloud variability against both tropical and regional circulation
100 mechanisms, or quantified the boundary-layer moisture contribution of the country's inland lakes.

101 We address this here with an observational design that separates cloud–radiation measurement from
102 dynamical attribution. Top-of-atmosphere radiative fluxes and cloud properties for March–May, 2001–
103 2024, were obtained from the CERES EBAF satellite record (Loeb et al. 2018), independent of any reanalysis
104 model. These data were used to characterize the seasonal cycle, spatial distribution, and long-term trend of
105 spring LWCRE, and to classify spring cloud populations into high-thin-cirrus, high-thick-convective, and
106 mid-level regimes based on cloud-top temperature and optical thickness. The relationship between LWCRE
107 and ENSO was tested using the Oceanic Niño Index, and the dynamical drivers of interannual variability
108 were identified through composite analysis of ERA5 250 hPa geopotential height and 500 hPa vertical
109 velocity, used here strictly for circulation diagnosis rather than cloud or radiation estimation. Boundary
110 layer moisture over Iraq's principal inland lakes was compared against a desert reference region using ERA5
111 surface fields.

112 By combining independent satellite observations of clouds and radiation with reanalysis-based
113 dynamical attribution, this study provides, to our knowledge, the first multi-source characterization of high-

cloud radiative behavior over Iraq, and establishes an observational benchmark against which regional reanalysis and climate model performance can be evaluated.

2. Data and Methods

2.1 Study Area

Iraq is located between 29.0°N–38.0°N and 38.5°E–49.0°E in the eastern Mediterranean–Middle East transition zone. The country's topography ranges from the Zagros mountain foothills in the northeast, exceeding 3000 m in elevation, to the low-lying Tigris–Euphrates alluvial plain in the center, and the arid western and southwestern desert. Iraq's climate is classified as arid to semi-arid, with approximately 90% of annual precipitation occurring between November and April (Bandar and Muslih 2025). Three major inland water bodies (Lake Tharthar, Lake Habbaniyah, and Lake Razzaza) are located in central Iraq and represent significant anomalous moisture sources within an otherwise hyperarid landscape.

2.2 Data Sources

This study employs four independent datasets, each serving a distinct analytical purpose.

2.2.1 Top-of-atmosphere radiation and cloud properties

Monthly top-of-atmosphere (TOA) longwave radiative fluxes and cloud properties were obtained from the Clouds and the Earth's Radiant Energy System Energy Balanced and Filled (CERES EBAF), Edition 4.2.1 product, for the period January 2001 to December 2024. The following variables were extracted over the Iraq domain: all-sky outgoing longwave radiation, clear-sky outgoing longwave radiation, total cloud fraction, cloud top pressure, cloud top temperature, and cloud optical thickness. CERES EBAF provides independent satellite-based estimates of both radiative fluxes and cloud properties, providing an observational basis independent of atmospheric model parameterization.

2.2.2 Atmospheric reanalysis

The ERA5 reanalysis, produced by the European Centre for Medium-Range Weather Forecasts, was used exclusively for dynamical attribution. Monthly mean geopotential height and vertical velocity (ω) were extracted at the 250 and 500 hPa pressure levels over an extended domain (15°N–55°N, 15°E–75°E) to capture large-scale circulation patterns. Boundary layer height, surface latent heat flux, and total column water vapor were extracted over Iraq at the surface level. Accumulated surface flux variables in the ERA5 monthly-averaged-reanalysis product represent an effective one-day accumulation period and were

converted to W/m² by dividing by 86,400 s, following ECMWF's documented convention. ERA5 was not used to derive any cloud or radiation quantity in this study.

2.2.3 ENSO index

The Oceanic Niño Index (ONI), based on three-month running mean sea surface temperature anomalies in the Niño 3.4 region, was obtained from the NOAA Climate Prediction Center for the period 2001–2024.

2.2.4 Lake locations

The geographic coordinates of Lake Tharthar, Lake Habbaniyah, and Lake Razzaza were used to define a lake-influenced sub-region (33°N–35°N, 42°E–45°E) for comparison against a southwestern desert reference sub-region (29°N–31°N, 38°E–42°E).

2.3 Definitions and Methods

2.3.1 Longwave cloud radiative effect

The longwave cloud radiative effect (LWCRE) at the top of the atmosphere is defined as:

$$LWCRE = OLR_{clear} - OLR_{all}$$

where OLR_{clear} and OLR_{all} are the clear-sky and all-sky outgoing longwave radiation, respectively. Positive values indicate that clouds reduce the amount of longwave radiation escaping to space, corresponding to a net atmospheric warming (greenhouse) effect.

2.3.2 Spatial averaging

Area-weighted regional means were computed using cosine-of-latitude weighting to account for the convergence of meridians at higher latitudes.

2.3.3 Seasonal and interannual analysis

Monthly climatologies were computed by averaging each calendar month across all 24 years. Spring (March–April–May, MAM) was identified as the focus season based on its dominant contribution to the annual LWCRE cycle. Interannual variability was assessed using area-weighted spring means for each year from 2001 to 2024. Linear trends were estimated using ordinary least-squares regression, with statistical significance evaluated at the 95% confidence level ($p < 0.05$).

2.3.4 Cloud regime classification

Spring months were classified into three cloud regimes based on the joint distribution of cloud top temperature and cloud optical thickness: high thin cirrus (cloud top temperature $< -20^{\circ}\text{C}$, optical thickness < 3.6), high thick deep convective clouds (cloud top temperature $< -20^{\circ}\text{C}$, optical thickness ≥ 3.6), and mid-level clouds (cloud top temperature $\geq -20^{\circ}\text{C}$). The $\tau = 3.6$ optical-thickness boundary follows the classic cirrus/cirrostratus division used by the International Satellite Cloud Climatology Project (ISCCP) (Wilks 2006) to account for the multiple-testing and spatial-autocorrelation issues inherent to testing several hundred grid points independently within a single, relatively small domain.

2.3.7 Spatial trend analysis

Pixel-level linear trends in spring LWCRE were computed independently at each grid point over the 2001–2024 period, with statistical significance assessed using the same t-test criterion; this analysis was not subjected to the FDR correction described above, a limitation discussed in Section 4.

2.3.8 Regional comparison domains

It is worth emphasizing that only this single area-weighted average was extended regionally — no other part of the analysis (seasonal cycle, trend, composite, or regime classification) was repeated beyond Iraq. For the regional context comparison (Section 3.10) alone, spring LWCRE was additionally averaged, using the same area-weighted method described in Section 2.3.2, over four neighboring reference domains in addition to Iraq: the Arabian Peninsula (15°N – 28°N , 38.0°E – 55.0°E), the eastern Mediterranean (30°N – 38°N , 28.0°E – 38.5°E), Iran (25°N – 38°N , 49.0°E – 63.0°E), and the eastern Turkey/Caucasus region (36°N – 42°N , 36.0°E – 48.0°E). These boxes were defined to approximate each region's extent without overlapping the Iraq domain (29°N – 38°N , 38.5°E – 49.0°E) or each other, using the same CERES EBAF grid, spring (MAM) months, and 2001–2024 period as the Iraq analysis; no additional land/sea or elevation masking was applied beyond the domain boundaries themselves.

3. Results

3.1 Seasonal Cycle of Longwave Cloud Radiative Effect

The annual cycle of LWCRE over Iraq exhibits a pronounced single-peak structure, closely tracking the seasonal evolution of total cloud fraction (Figure 1). LWCRE rises from a winter baseline of approximately 18 – 21 W/m^2 in December–February to a clear spring maximum of 29.7 W/m^2 in April. Cloud fraction reaches 41.5% in the same month. Following this peak, both quantities decline sharply through May (24.4 W/m^2) and collapse to a summer minimum of 5.0 – 7.2 W/m^2 between June and September, when cloud fraction falls below 11% . This summer minimum coincides with the region's dry,

subtropical high-pressure season. LWCRE and cloud fraction recover gradually in autumn, reaching 18.4–18.5 W/m² by November–December. Given that spring accounts for the strongest and most variable radiative signal of the annual cycle, all subsequent analyses focus on the March–April–May (MAM) season.

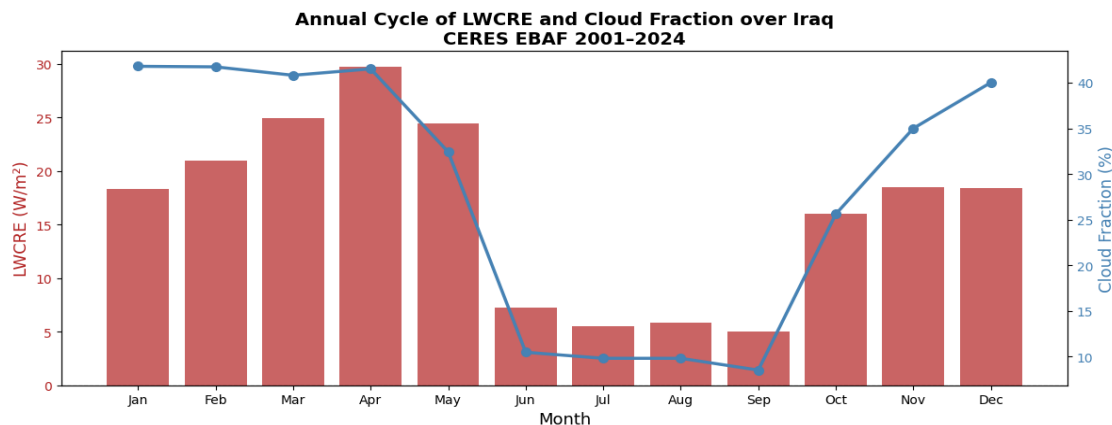


Figure 1. Annual cycle of longwave cloud radiative effect (bars) and total cloud fraction (line) over Iraq, CERES EBAF 2001–2024 climatology.

3.2 Spatial Distribution and Monthly Evolution

The climatological spring-mean LWCRE over Iraq (2001–2024) displays a pronounced northeast-to-southwest gradient (Figure 2). Values peak above 37 W/m² over the northeastern Zagros mountain foothills and decline to a minimum of 16.5 W/m² over the southwestern desert, with a domain-mean of 26.5 W/m². This pattern is consistent with orographic lifting along the Zagros front (Alijani 2008), in contrast to the stable, subsiding atmosphere characteristic of the arid southwest. This maximum sits close to Iraq's northeastern political boundary; a sensitivity test against a wider domain confirms the 37.4 W/m² value is representative of the terrain-driven feature within Iraq itself, but also shows the broader orographic signal continues to strengthen just beyond the border, likely reflecting the further rise of Zagros elevations inside neighboring Iran. The value reported here should therefore be read as the maximum within Iraq's territory specifically, not necessarily the peak of the wider regional feature. This gradient also parallels the positive relationship between cloud fraction and LWCRE documented in Section 3.4, indicating that the spatial pattern reflects underlying differences in cloud occurrence rather than radiative efficiency alone.

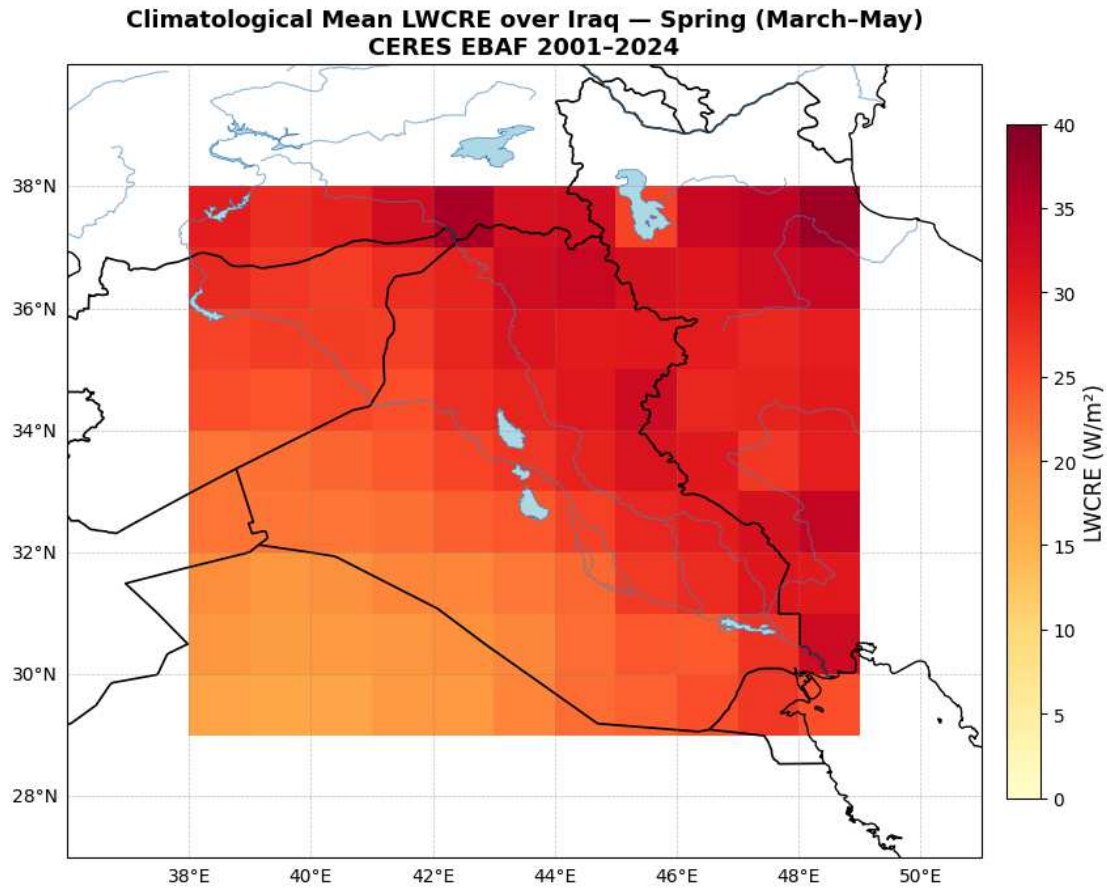


Figure 2. Climatological spring (March–May) mean LWCRE over Iraq, CERES EBAF 2001–2024.
Lakes shown in light blue.

Examining the individual spring months separately reveals that this spatial pattern is not static. March (25.1 W/m²) shows a moderate northeast gradient still developing; April (29.8 W/m²) shows the gradient at its most intense, with values locally exceeding 40 W/m² near the Zagros front; and May (24.5 W/m²) shows a marked weakening and southward retreat of the high-value region, consistent with the onset of the dry season (Figure 3). This monthly progression indicates that the spring LWCRE maximum is not a static seasonal average; the dynamical mechanism behind this April concentration is examined in Section 3.7.

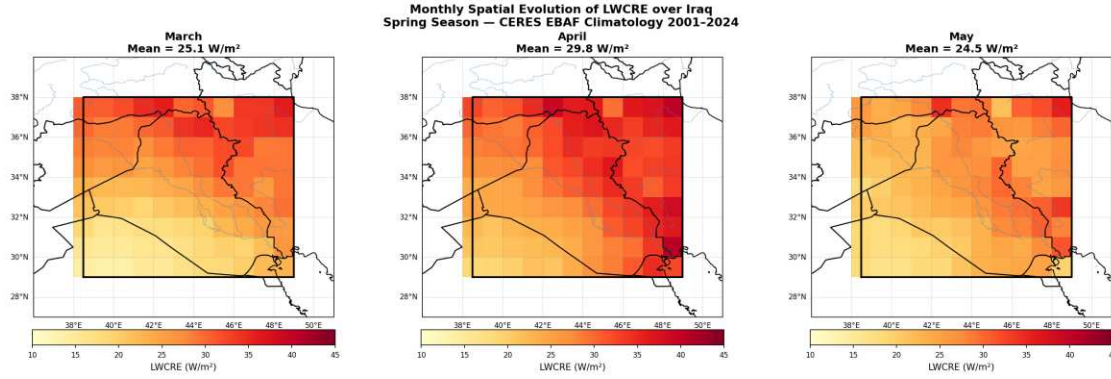


Figure 3. Monthly spatial evolution of spring LWCRE over Iraq: March, April, and May climatological means, CERES EBAF 2001–2024.

3.3 Interannual Variability and Long-Term Trend

Spring LWCRE exhibits substantial year-to-year variability, ranging from 21.5 W/m² (2021) to 32.4 W/m² (2007) over the 24-year record (Figure 4). A linear trend analysis reveals a statistically significant decline of -1.72 W/m² per decade ($p = 0.044$), corresponding to a reduction of approximately 4.1 W/m² over the full study period.

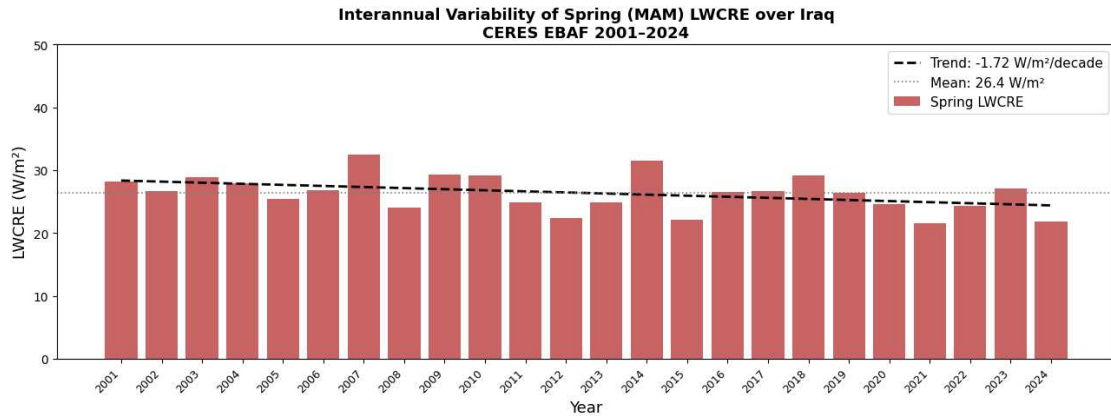


Figure 4. Interannual variability of spring (MAM) LWCRE over Iraq, CERES EBAF 2001–2024, with linear trend.

Pixel-level trend analysis (Figure 5) shows that this decline is spatially heterogeneous rather than uniform across Iraq. Approximately 24% of grid points show trends significant at the 95% confidence level, concentrated primarily in central and southeastern Iraq, while the northeastern Zagros region (where LWCRE is climatologically strongest) shows a comparatively weaker and less consistent decline. This suggests that the mechanisms driving the long-term decline may operate more strongly on desert-

influenced, non-orographic cloud systems than on terrain-forced convection. Because this map has not been corrected for multiple testing (Section 2.3.7), the 24% figure is best read as a descriptive spatial pattern rather than a formally tested one.

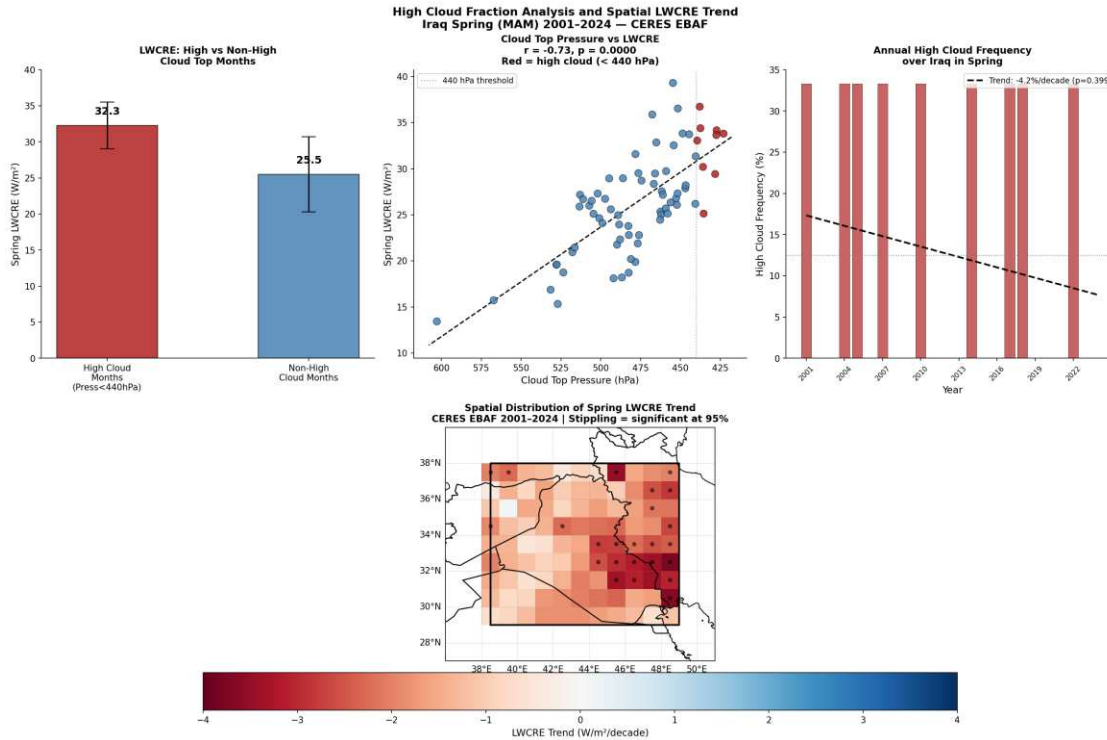


Figure 5. High-cloud analysis (top) and spatial distribution of the spring LWCRE linear trend, 2001–2024 (bottom); CERES EBAF.

3.4 Relationship Between Cloud Properties and LWCRE

To establish the direct physical link between cloud characteristics and radiative trapping, LWCRE was correlated against total cloud fraction and cloud top pressure at the monthly scale across all 72 spring months (2001–2024) (Figure 6). Cloud fraction shows a strong positive correlation with LWCRE ($r = 0.82$, $p < 0.0001$), while cloud top pressure shows a strong negative correlation ($r = -0.73$, $p < 0.0001$). Both greater cloud coverage and higher (colder) cloud tops are therefore strongly associated with enhanced longwave trapping. Since cloud fraction and cloud top pressure are themselves correlated and were not tested against each other directly, this reflects two separate univariate relationships rather than evidence that each variable exerts an independent effect.

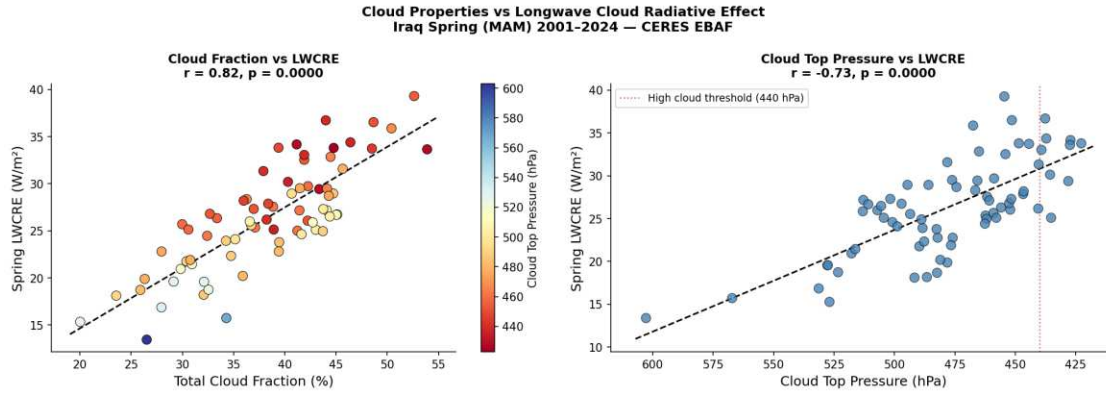


Figure 6. Cloud fraction and cloud top pressure versus LWCRE across all 72 spring months, 2001–2024, colored by cloud top pressure (left) and by high-cloud months (right); CERES EBAF.

Isolating specifically high clouds (cloud top pressure < 440 hPa) shows that these months account for only 12.5% of spring months but produce a mean LWCRE of 32.3 W/m², compared to 25.5 W/m² in non-high-cloud months, a difference of 6.8 W/m² (Figure 5). This result indicates that high clouds specifically, rather than clouds in general, exert a disproportionate influence on Iraq's spring radiative budget. This 12.5% figure uses cloud top pressure as the high-cloud criterion and is not directly comparable to the combined cirrus-plus-deep-convective share (77.8%) reported from the cloud-top-temperature-based classification in Section 3.5; the two sections apply different variables and thresholds to define "high cloud" and are intended as complementary rather than reconciled estimates.

3.5 Cloud Regime Classification and Cirrus Radiative Efficiency

Classifying spring months by the joint distribution of cloud top temperature and optical thickness identifies three distinct regimes (Figure 7): high thick deep convective clouds dominate, accounting for 62.5% of spring months and producing the highest mean LWCRE (28.6 W/m²); high thin cirrus account for 15.3% of months with a mean LWCRE of 26.1 W/m²; and mid-level clouds account for 22.2% of months with the lowest mean LWCRE (20.3 W/m²).

High Thin
(Cirrus)

High Thick
(Deep Conv.)

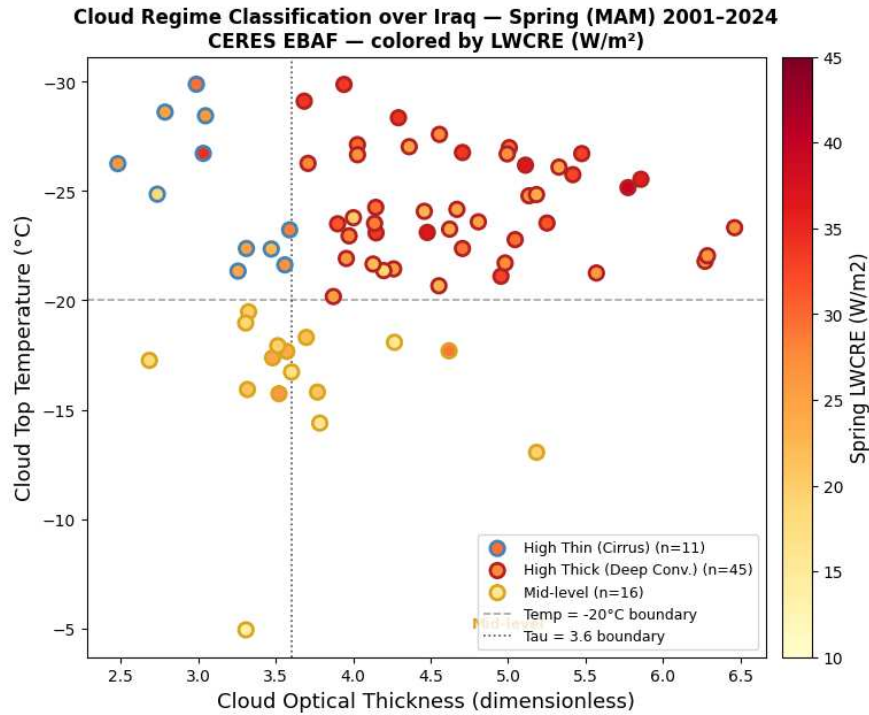


Figure 7. Cloud regime classification over Iraq in spring (MAM), 2001–2024, by cloud top temperature and optical thickness, colored by LWCRE; CERES EBAF.

Despite contributing less frequently and at lower optical thickness, cirrus clouds exhibit a substantially higher LWCRE per unit optical thickness than deep convective clouds: 8.45 versus 6.17 W/m² per unit optical thickness, a ratio of 1.37 (Figure 8). Across all cloud regimes combined, cloud top temperature is strongly and significantly related to LWCRE (Pearson $r = -0.65$, $R^2 \approx 0.42$, $p < 0.0001$); the ordinary-least-squares regression slope indicates that each 1°C decrease in cloud top temperature is associated with a 0.81 W/m² increase in LWCRE. This slope is consistent with basic radiative physics, though this regional value has not, to our knowledge, been previously quantified for Iraq. Cirrus occurrence is concentrated in March (21% of months) relative to April and May (12% each), and shows no significant trend in frequency over the study period, though spring-mean cloud top temperature shows a near-significant warming trend of 1.11°C per decade ($p = 0.077$) (Figure 9).

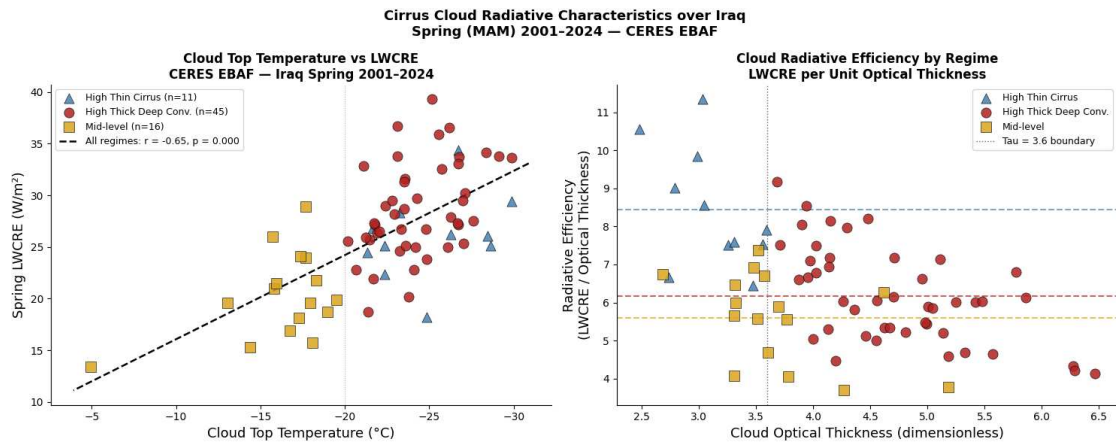


Figure 8. Cirrus cloud radiative characteristics over Iraq: cloud top temperature vs. LWCRE (left) and LWCRE per unit optical thickness by regime (right); CERES EBAF.

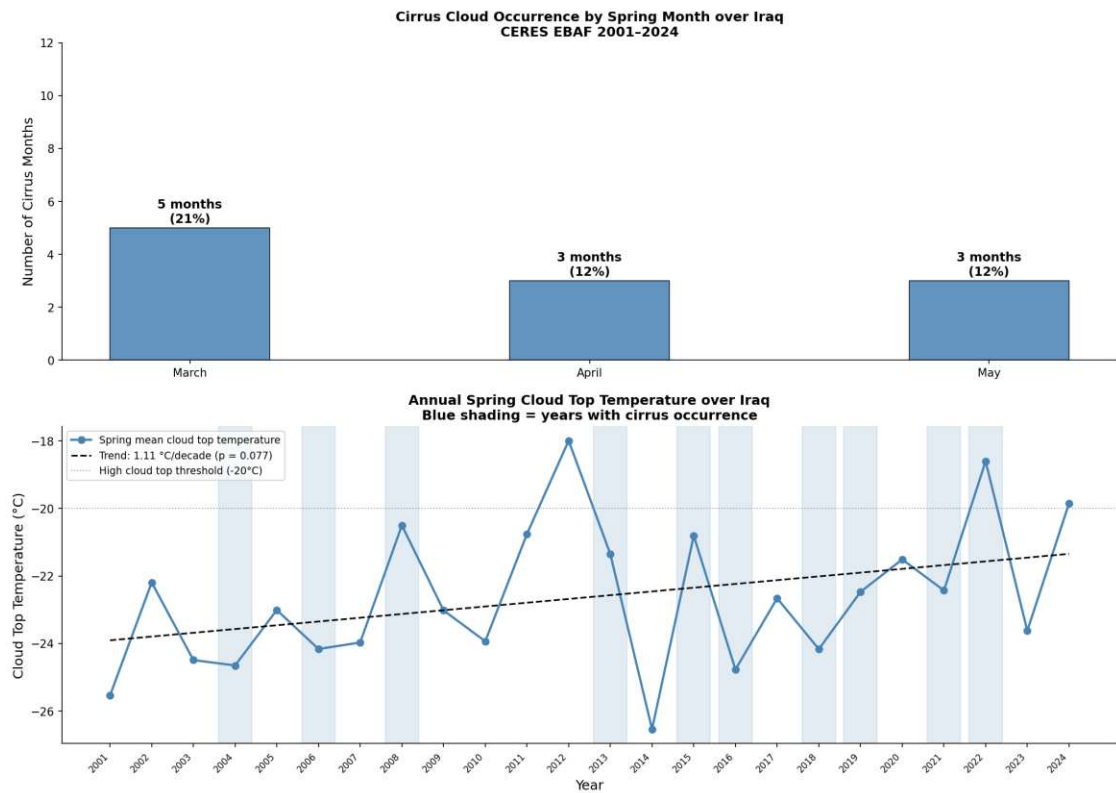


Figure 9. Cirrus cloud occurrence by spring month (top) and annual spring cloud-top temperature with linear trend (bottom), 2001–2024; CERES EBAF.

3.6 Relationship with ENSO

No statistically significant relationship was found between spring LWCRE and the Oceanic Niño Index ($r = -0.02$, $p = 0.92$) (Figure 10). The two years with the highest spring LWCRE in the record (2007 and 2014) both occurred under ENSO-neutral conditions, while the strong El Niño year of 2015 recorded one of the lowest LWCRE values (22.2 W/m^2). This indicates that, contrary to patterns reported for precipitation elsewhere in the Middle East, spring LWCRE variability over Iraq shows no significant linear, contemporaneous association with the tropical Pacific ENSO signal, motivating the dynamical analysis presented in the following section.

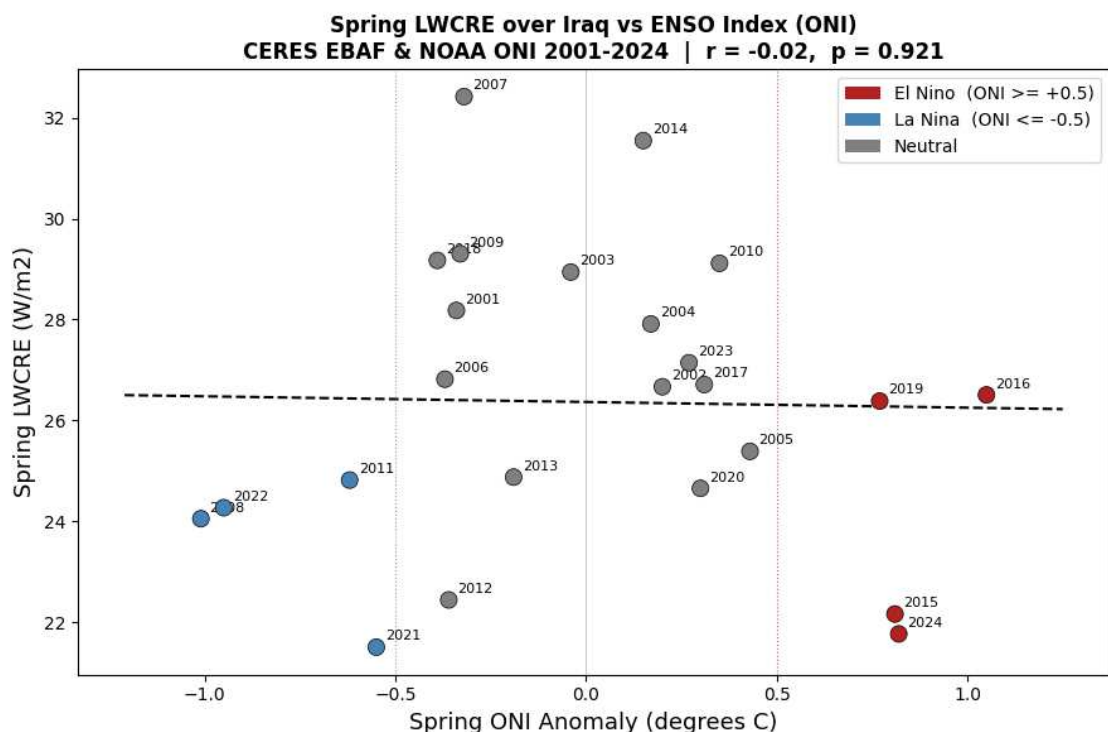


Figure 10. Spring LWCRE over Iraq versus the Oceanic Niño Index (ONI), 2001–2024, classified by ENSO phase; CERES EBAF and NOAA ONI.

3.7 Dynamical Drivers of Interannual Variability

Composite analysis of spring LWCRE extreme years reveals a physically consistent but sample-size-sensitive circulation signature. Across every group size tested ($n = 5$ to 10 years per group, ranked by spring LWCRE), the 250 hPa geopotential height difference and the 500 hPa vertical velocity difference between high- and low-LWCRE years point in the same direction: high-LWCRE years are associated with a deeper 250 hPa trough and stronger ascent than low-LWCRE years, consistent with an upper-level-trough-driven

mechanism. The magnitude of this difference, and its statistical significance as an Iraq-area mean, decline as the composite groups widen from the most extreme years toward the full distribution (Table 1).

The $n = 6$ composite provides the strongest joint area-mean statistical separation of the tested group sizes, while the consistent sign across $n = 5$ – 10 indicates that the circulation contrast is concentrated in the most extreme years (high: 2003, 2007, 2009, 2010, 2014, 2018; low: 2008, 2012, 2015, 2021, 2022, 2024, for $n = 6$): a 250 hPa geopotential height difference of -51.6 m ($p = 0.022$) and a 500 hPa vertical velocity difference of -0.034 Pa/s ($p = 0.004$), both significant at the 95% confidence level for the Iraq-area mean. Beyond $n = 6$, neither variable's area-mean difference remains significant (Table 1). Grid-point-level significance, evaluated without correction for the substantial spatial autocorrelation present in these fields, does not survive false discovery rate correction (Wilks 2006) at any sample size tested, including $n = 6$, and is therefore not reported as a mapped result.

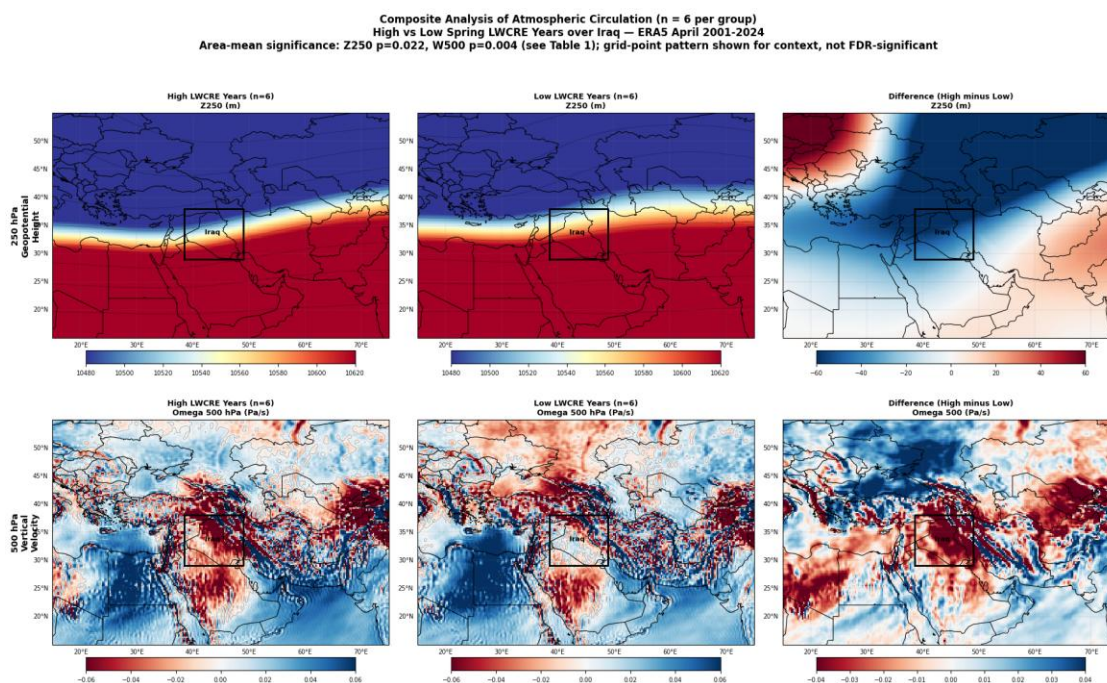


Figure 11. Composite fields of 250 hPa geopotential height (top) and 500 hPa vertical velocity (bottom) for the six highest- versus six lowest-LWCRE spring years, April 2001–2024 (ERA5). Area-mean differences are statistically significant (Table 1); the grid-point spatial pattern is shown for context and is not itself field-significant after false discovery rate correction (Section 3.7).

Table 1. Sensitivity of the 250 hPa geopotential height (Z250) and 500 hPa vertical velocity (W500) composite difference (high-LWCRE minus low-LWCRE years) to composite group size, evaluated as an Iraq-area-mean two-sample t-test. * indicates $p < 0.05$.

N per group	Z250 diff (m)	Z250 p-value	W500 diff (Pa/s)	W500 p-value	Grid-point sig. (FDR-corrected)
5	-52.0	0.049*	-0.0332	0.011*	n/a
6	-51.6	0.022*	-0.0342	0.004*	0.0% (both vars.)
7	-34.6	0.112	-0.0241	0.045*	n/a
8	-30.7	0.148	-0.0174	0.140	n/a
9	-25.1	0.197	-0.0141	0.198	n/a
10	-28.9	0.106	-0.0133	0.179	n/a
±1 SD threshold (3 high / 4 low)	-63.7	0.093	-0.0346	0.049*	n/a

Rather than treating this sensitivity as a failure of the underlying analysis, we interpret it as evidence that the dynamical signal is concentrated in the most extreme LWCRE years rather than present as a linear relationship across the full 24-year distribution, a pattern reinforced by a fully independent, threshold-based composite (years beyond ± 1 standard deviation of the mean: high = 2007, 2009, 2014, $n = 3$; low = 2012, 2015, 2021, 2024, $n = 4$) that reproduces the same sign and approximate magnitude despite being derived from an entirely different year-selection rule (Table 1, final row). These results are consistent with upper-level trough positioning and enhanced ascent as a dynamical signature associated with extreme high-LWCRE springs over Iraq, best interpreted as characteristic of the most anomalous years rather than as a continuously graded circulation–LWCRE relationship.

3.8 Diagnostic Attribution of the Long-Term LWCRE Trend

To diagnostically attribute the declining LWCRE trend to its underlying cloud properties, its two principal components were examined separately (Figure 12). This is a diagnostic, sensitivity-based attribution: applying the cross-sectional cloud-top-temperature–LWCRE regression slope (Section 3.5) to the temporal trend in cloud-top temperature, rather than a strict causal decomposition. Neither the trend in

cloud fraction ($-0.95\%/decade$, $p = 0.35$) nor the trend in cloud top pressure ($+8.2$ hPa/decade, $p = 0.15$) reached statistical significance individually. The warming trend in cloud top temperature ($+1.11^\circ\text{C}/decade$, $p = 0.077$) falls just short of the conventional 95% significance threshold; combined with the empirically derived regression slope of 0.81 W/m² per $^\circ\text{C}$ (Section 3.5), it may account for approximately 0.90 W/m² per decade of the observed 1.72 W/m² per decade LWCRE decline (roughly half of the total trend), though this attribution should be treated as indicative rather than conclusive given the marginal significance of the underlying temperature trend. This is consistent with gradual warming of cloud tops contributing to the long-term weakening of Iraq's spring cloud radiative effect, alongside other, individually smaller and non-significant changes in cloud amount and height.

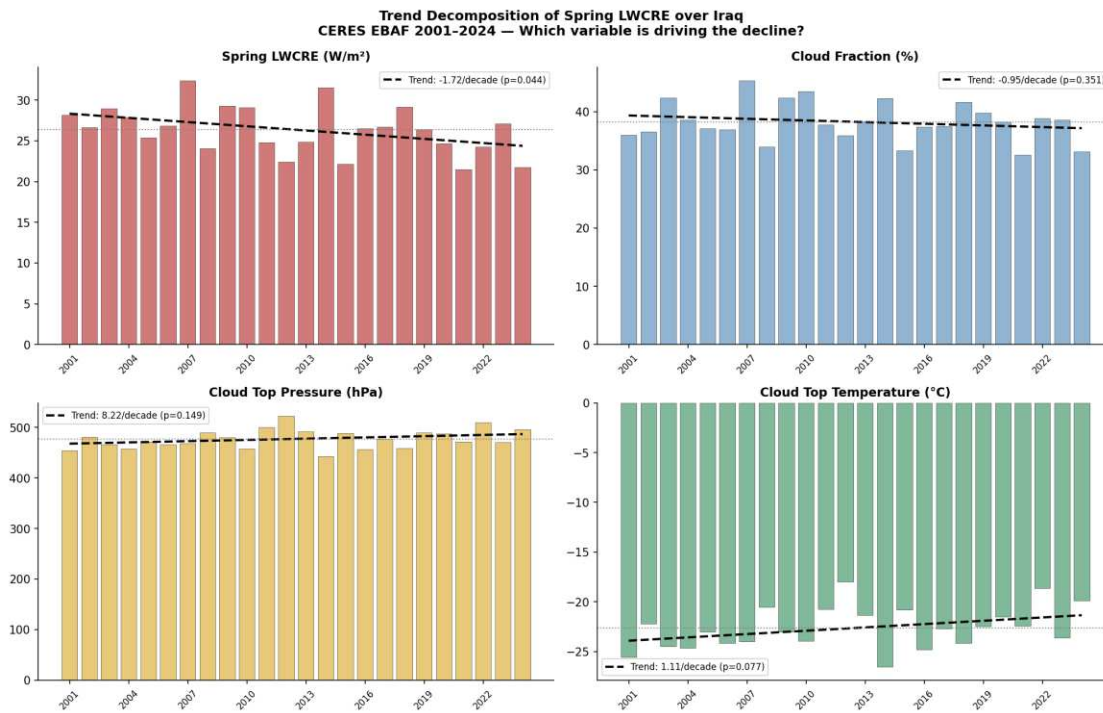


Figure 12. Diagnostic attribution of the spring LWCRE trend to its cloud-property components over Iraq, 2001–2024; CERES EBAF.

3.9 Role of Surface Moisture and Inland Lakes

Comparison of boundary layer conditions between the lake-influenced region of central Iraq and the southwestern desert reveals a substantial moisture contrast (Figure 13). Surface latent heat flux over the lake region (26.8 W/m²) is 4.66 times higher than over the desert region (5.8 W/m²), and total column water vapor is 27% higher (15.6 vs. 12.3 kg/m²). Boundary layer height is marginally lower over the lake region (796 m vs. 857 m), consistent with the cooling and stabilizing influence of open water on the daytime

boundary layer. These results are consistent with Iraq's inland lakes acting as localized moisture sources that may contribute to preconditioning the atmosphere for cloud development in an otherwise arid environment, though as a spatial association rather than a direct causal test (see Section 4.8).

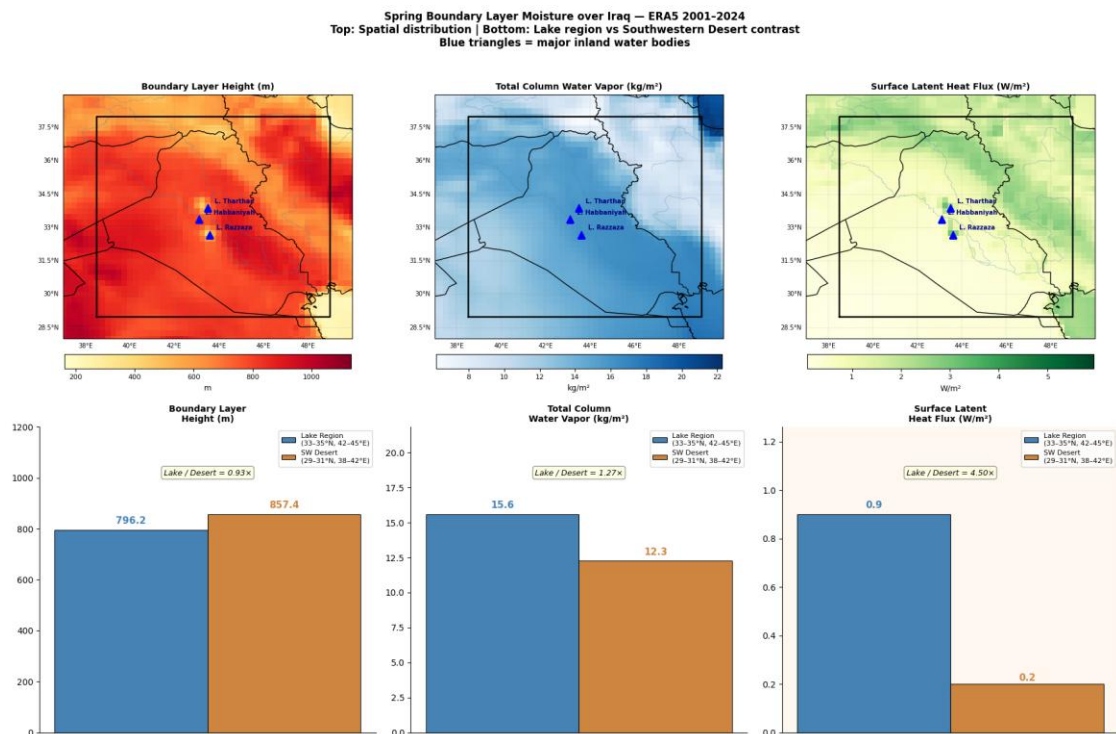


Figure 13. Spring boundary layer moisture over Iraq: spatial distribution (top) and lake-region-versus-desert contrast (bottom); ERA5, 2001–2024.

3.10 Regional Context

Placing Iraq's spring LWCRE within its broader regional setting, the domain mean of 26.5 W/m² is substantially higher than the Arabian Peninsula (17.3 W/m²) and the eastern Mediterranean (22.3 W/m²), but lower than Iran (29.2 W/m²) and the eastern Turkey/Caucasus region (34.5 W/m²) (Figure 14). This positions Iraq as climatologically distinct from the hyperarid Arabian Peninsula to its south, reflecting the influence of Mediterranean-linked spring moisture and orographic lifting along its northeastern border, while remaining less radiatively active than the more consistently mountainous regions to its north and east.

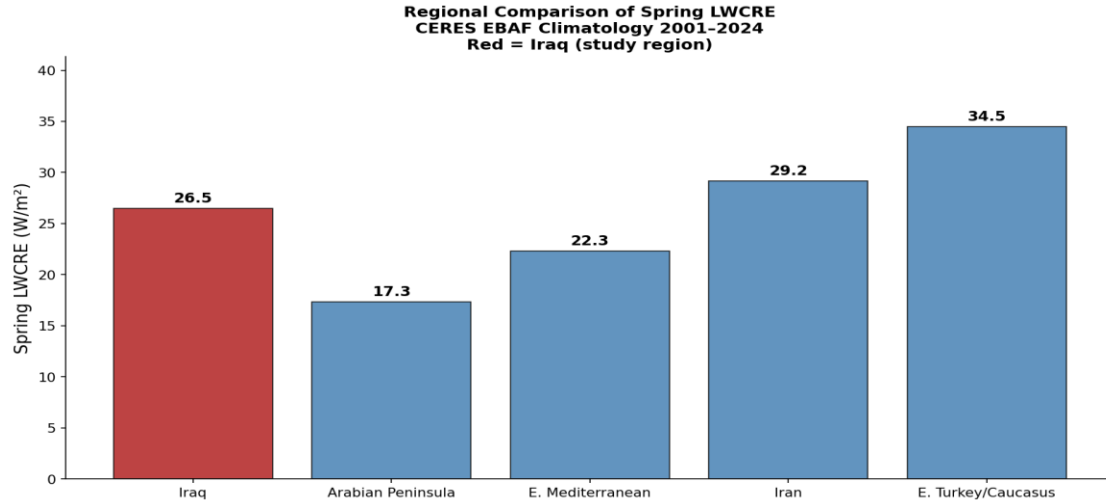


Figure 14. Regional comparison of climatological spring LWCRE: Iraq, Arabian Peninsula, eastern Mediterranean, Iran, and eastern Turkey/Caucasus; CERES EBAF, 2001–2024.

4. Discussion

To our knowledge, this is the first satellite-observation-based characterization of spring longwave cloud radiative effect (LWCRE) over Iraq. The seasonal and spatial patterns found here (Sections 3.1–3.2) extend the broader regional cloud climatology of the Middle East into the radiative domain. Iraq's LWCRE cycle, peaking at 29.7 W/m² in April and collapsing through the dry summer, follows the same winter–spring cloud maximum and summer subtropical-high dominance reported across the Arabian Peninsula (Yousef et al. 2020), consistent with the same synoptic controls extending into the radiative domain. The spatial gradient shows a similar link: the 37.4 W/m² LWCRE maximum along the Zagros foothills, against a 16.5 W/m² minimum over the southwestern desert, is consistent with the orographic convective initiation reported for elevated terrain in the southern Arabian Peninsula (Nelli et al. 2021). One difference stands out, though: that work describes a more zonally uniform cloud distribution, while Iraq's gradient is sharper and more tightly locked to the Zagros front, suggesting terrain plays an outsized role here compared to the rest of the region.

The high-cloud results (Section 3.4) also match recent CERES-based work outside the region. (Xu et al. 2024) used the same joint cloud-top-pressure/optical-thickness classification over tropical convective zones and likewise found that radiative effect depends on cloud type, not just cloud amount. Their net CRE range was wider than what we find over Iraq (−121 to +51 W/m² versus our narrower spring-season range), which is expected: a fully tropical convective regime simply contains more cloud diversity than a seasonally constrained semi-arid one.

Cirrus radiative behavior is where the cross-study agreement is strongest. The ~37% higher LWCRE per unit optical thickness for cirrus relative to deep convection found here (Section 3.5) sits well within the range reported using entirely different methods: (Spang et al. 2024) found thin cirrus longwave warming of 21.8 W/m² against only 16.7 W/m² of shortwave cooling using radiative transfer modeling, and (Gil-Díaz et al. 2025) reported a comparable disproportionate impact from four years of lidar data. Three regions, three methods, one consistent conclusion: this is a general property of cold, optically thin ice clouds, not an Iraq-specific artifact.

Two results were, honestly, unexpected. First, spring LWCRE shows no significant association with ENSO ($r = -0.02$, Section 3.6), despite ENSO's documented influence on Middle Eastern winter precipitation and its associated shifts in regional jet-stream position (Attada et al. 2019); (Hochman and Gildor 2025). The most likely explanation is seasonal timing: ENSO's grip on Middle Eastern circulation is strongest in winter and may simply have relaxed by March–May. Second, the composite analysis (Section 3.7) points to upper-level trough positioning, rather than tropical forcing, as the dynamical pattern associated with the most extreme LWCRE years: the six highest-LWCRE years show a 51.6 m deeper 250 hPa trough and significantly stronger ascent than the six lowest. This fits the known role of upper-level troughs in triggering Mediterranean cyclogenesis (Flaounas et al. 2025), and together these two results are consistent with a coherent picture in which spring cloud variability over Iraq, at least among its most extreme years, is more closely tied to regional atmospheric dynamics than to tropical teleconnection. This relationship weakens steadily as more moderate years are added to the composite (Table 1) and does not survive multiple-testing correction at the grid-point level, so it is best read as a signature of extreme seasons rather than a precisely quantified, continuous circulation–LWCRE relationship.

The declining LWCRE trend (-1.72 W/m²/decade, Section 3.8) is, to our knowledge, new for this region. Cloud-top warming may account for roughly half of it, though this attribution is indicative rather than conclusive given the cloud-top-temperature trend itself falls just short of conventional significance ($p = 0.077$); the remainder is likely spread across small, individually insignificant changes in cloud fraction and cloud-top pressure, though changes in cloud microphysics we did not measure directly cannot be ruled out.

The lake result deserves a caveat. A nearly five-fold difference in latent heat flux between the lake region and the desert (Section 3.9) is consistent with lakes acting as local moisture sources and matches a broader global pattern of lake-driven boundary layer moistening (Ma et al. 2026), but this is a spatial association, not a causal test. Elevation or river proximity could partly explain the same contrast, and isolating the lake effect specifically would need a dedicated follow-up study.

Finally, Iraq's regional standing, above the Arabian Peninsula and below Iran and the Caucasus (Section 3.10), fits its geography: the eastern edge of the Mediterranean storm track and the northern edge of the Arabian desert regime.

Limitations. The CERES EBAF footprint ($\sim 1^\circ$) cannot resolve sub-grid convective structure over the topographically complex northeast, and the spring LWCRE maximum reported in Section 3.2 reflects the value within Iraq's political boundary rather than necessarily the peak of the broader orographic feature. The 24-year record is long enough for a significant trend but short relative to multi-decadal variability, so the diagnostic attribution in Section 3.8 is a first-order estimate, not a full accounting. The pixel-level trend map in Section 3.3 was not corrected for multiple testing or spatial autocorrelation and should be interpreted descriptively; the same correction applied to the composite analysis in Section 3.7 removed its grid-point-level significance entirely, a caveat that likely extends to the trend map as well. ERA5's dynamical fields, while independent of the CERES radiative data, carry their own model uncertainty, especially in fine-scale vertical velocity.

5. Conclusion

This study provides, to our knowledge, the first satellite-observation-based characterization of spring longwave cloud radiative effect over Iraq, addressing gaps left open by earlier reanalysis-only cloud climatologies for the region. Spring LWCRE peaks in April at 29.7 W/m^2 , concentrated over the northeastern Zagros foothills, and has declined significantly over the 2001–2024 record at a rate of 1.72 W/m^2 per decade, with cloud-top warming ($p = 0.077$) providing a plausible contribution to approximately half of this decline. Cloud regime classification shows that while deep convective clouds dominate spring cloudiness, thin cirrus clouds exhibit a $\sim 37\%$ higher LWCRE per unit optical thickness than deep convection. LWCRE shows no significant linear association with ENSO; instead, the most extreme high- and low-LWCRE springs are distinguished by a significantly deeper 250 hPa trough and stronger ascent over Iraq, a dynamical pattern concentrated in extreme years rather than continuous across the full record. Iraq's inland lakes, meanwhile, are associated with a nearly five-fold enhancement in surface latent heat flux relative to the surrounding desert, consistent with a possible role as local moisture sources.

Together, these results replace a largely untested set of assumptions about Iraq's cloud–radiation system with a set of independently observed, quantified relationships, and provide an observational benchmark against which the representation of cloud radiative effects in regional reanalysis and climate model simulations of Iraq and the broader Middle East can be evaluated, a role made possible specifically because the cloud and radiation quantities used here are independent of any single reanalysis product.

Future work extending this satellite-based approach to a longer record, and to a directly attributive test of the lake-moisture mechanism identified here, would further strengthen these conclusions.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Both authors contributed to the study conception and design. Data acquisition, analysis, and interpretation were performed by Aqeel D. Salman and Ahmed S. Hassan. The first draft of the manuscript was written by Aqeel D. Salman, and both authors commented on previous versions of the manuscript. Both authors read and approved the final manuscript.

Data Availability

The datasets analyzed in this study are publicly available: CERES EBAF data from the NASA Langley Research Center Atmospheric Science Data Center (<https://ceres.larc.nasa.gov/data/>), ERA5 reanalysis data from the Copernicus Climate Data Store (<https://cds.climate.copernicus.eu>), and the Oceanic Niño Index from the NOAA Climate Prediction Center (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php).

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