North Atlantic Oscillation Modulation on Mid-Latitude Cloud Cover and Surface Radiation Balance

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Abstract. The North Atlantic Oscillation (NAO) modulates mid-latitude circulation and cloudiness and thereby alters the surface radiation balance across the North Atlantic–European sector. Focusing on northern winter (DJF) 1979–2023 over 45°–55°N, 10°W–15°E, the paper combines ERA5 monthly single-level reanalysis fields with the NOAA monthly NAO index. The paper applies (i) composite differences between positive and negative NAO phases ($NAO^{+}–NAO^{-}$) with Welch's t-test, (ii) grid-point regression on standardized NAO, and (iii) point-cloud diagnostics linking low cloud changes to radiation terms. Results show that NAO^{+} winters feature reduced low-cloud cover, enhanced net shortwave, weakened net longwave, and overall positive net-radiation anomalies; the shortwave contribution dominates the net-radiation response. These results underscore the influence of the NAO on the surface energy balance, with implications for understanding regional climate variability and improving predictive models. These findings highlight a robust wintertime NAO–cloud–radiation coupling over mid-latitude land that shapes the surface energy balance and offers observational constraints for regional climate assessment and model development.

Keywords: North atlantic oscillation; low cloud cover; surface radiation balance.

1. Introduction

The paper quantifies how the North Atlantic Oscillation (NAO) modulates the winter mid-latitude land surface radiation balance via low-cloud changes, providing observational constraints for regional energy budgets and climate-model evaluation.

The North Atlantic Oscillation (NAO) is a prominent and common pattern of atmospheric circulation variability, which represents the redistribution of atmospheric mass between the Arctic and the subtropical Atlantic Ocean. Its alternating phases (positive and negative phases) have far-reaching implications for the weather and climate systems spanning the North Atlantic-European domain. The NAO affects the westerlies, storm tracks, and cloud distribution, which in turn may alter the radiation reaching the Earth's surface [1]. Recent studies further show that cloud-radiative anomalies can actively feedback on the large-scale circulation and the NAO itself, rather than being a purely passive response [2]. There remains a relative lack of regionalized and quantitative evidence on how the North Atlantic Oscillation (NAO) modulates shortwave and longwave radiation through low clouds, and how this jointly shapes net radiation. Especially, mid-latitude continental winters still require a systematic evaluation of these processes.

This study focuses on the December–February (DJF) period of 1979–2023 over the domain of 45°–55°N, 10°W–15°E, integrating the NOAA North Atlantic Oscillation (NAO) index with ERA5 monthly single-level data. It intends to explore the winter NAO-cloud-radiation coupling in this mid-latitude land area and provide observational support for model evaluation and regional energy balance analysis.

2. Data and Methods

ERA5 monthly energies are converted to fluxes ($W\ m^{-2}$) using the exact seconds per month and aligned with the standardized NAO on a common DJF timeline; Then the paper conducts grid-point composites and linear regressions, evaluating significance via Welch’s t-tests and regression t-statistics (two-sided, $p<0.05$) [3–6].

2.1. Study Region and Period

The research analyzes boreal winter months (December–January–February; DJF) from 1979–2023 over the key mid-latitude Atlantic region in the Northern Hemisphere (45°N–55°N, -10°W–15°W). Grid and masks follow ERA5 (ECMWF Reanalysis v5) native resolution; land–sea distinction is not enforced unless noted [3].

2.2. Datasets

The monthly NAO index is taken from the NOAA National Centers for Environmental Information (NCEI) Climate Monitoring “North Atlantic Oscillation” page [5]. The index is standardized over 1979–2023 prior to analysis. ERA5 reanalysis fields are retrieved programmatically via the Copernicus Climate Data Store (CDS) API from the dataset ERA5 monthly averaged data on single levels [3, 4]. The paper uses surface net shortwave radiation (SSR), surface net longwave radiation (STR), and low cloud cover (LCC). SSR and STR are provided as monthly accumulated energy (J m^{-2}) and are converted to W m^{-2} by dividing by the number of seconds in each calendar month; LCC is a monthly-mean fraction and is reported here in percentage points (pp). Throughout the paper, the net radiation is defined as $NET = SSR + STR$ (W m^{-2}, positive downward).

2.3. Methods

2.3.1 Preprocessing and variable definitions

First harmonize time so that all monthly timestamps are snapped to the first day of each month at 00:00:00. After this normalization, the variables—surface net shortwave radiation (SSR), surface net longwave radiation (STR), and low cloud cover (LCC)—are aligned on the common time intersection to guarantee that every grid cell is compared on identical months [3, 4]. Because ERA5 provides SSR and STR as monthly accumulated energy (J m^{-2}), the paper converts them to flux density (W m^{-2}) by dividing by the exact number of seconds in each calendar month; LCC is a monthly mean fraction and is reported here in percentage points for clarity [4]. Throughout the paper, net radiation is defined consistently as

$$NET = SSR - STR\ (all\ in\ W\ m^{-2}). \tag{1}$$

Spatially, longitudes are wrapped to the conventional −180°–180° range when necessary, and then the data are clipped to the study domain 45°–55° N, 10° W–15° E [4]. The analysis focuses on boreal winter (DJF) during 1979–2023, yielding 135 monthly samples after time alignment [3]. These steps ensure consistent units, identical sampling across variables, and a geographically and seasonally well-defined dataset for the NAO-related diagnostics.

2.3.2 NAO index and phase definition

The monthly NAO index from NOAA NCEI is standardized over DJF 1979–2023 (z-score) [5].

For the composite analysis, NAO-positive (NAO+) and NAO-negative (NAO−) months are defined as those above the upper 30th percentile and below the lower 30th percentile of the DJF NAO distribution, respectively; in the sample, this yields approximately $N_{+} \approx N_{-} \approx 41$ months in each group [5, 6]. For the regression analysis, the standardized monthly NAO index is used directly as the predictor (independent variable) at each grid cell [6].

2.3.3 Composite differences ($NAO^{+} - NAO^{-}$)

For each grid cell and for each variable $X \in \{SSR, STR, NET, LCC\}$, the paper form two month sets from the standardized DJF NAO series: the upper-30% months (NAO^{+}) and the lower-30% months (NAO^{-}). Then compute the mean of the DJF monthly anomalies of X over these two sets, denoted $\bar{X}|_{NAO+}$ and $\bar{\mathrm{X}}|_{\mathrm{NAO-}}$, where anomalies are defined as the monthly value minus the 1979–2023 DJF climatology at that grid cell. The composite difference is then

$$\Delta X \equiv \bar{X}|_{NAO+} - \bar{\mathrm{X}}|_{\mathrm{NAO-}} \tag{2}$$

which measures the average change in X when going from NAO^{-} to NAO^{+}. Units follow the variable (SSR/STR/NET in Wm^{-2}; LCC in pp). Statistical significance of ΔX is assessed with a two-sample Welch's t-test (two-sided, $p<0.05$) applied to the two anomaly samples at each grid cell; significant cells are indicated by stippling in the maps [5]. It uses of symmetric color scales and stippling emphasizes robust signals consistent with recent evidence that cloud-radiative anomalies are dynamically relevant [1].

2.3.4 Spatial regression on NAO

At each grid cell, regressing DJF monthly anomaly time series of X on the standardized NAO index via ordinary least squares, then

$$X_t = \beta \cdot NAO_t + \varepsilon_t \tag{3}$$

Here t indexes all DJF months from 1979–2023 ($n = 135$), X_t is the anomaly of X at month t (defined relative to the local DJF climatology); β is the change per + 1σ NAO (units W m-2 per $+1\sigma$); NAO_t is the standardized NAO at the same month; and ε_t is the regression residual. Significance uses the coefficient t-statistic (two-sided $p<0.05$), shown by stippling [1, 6]. The slope per +1σ NAO is intended as a compact, model-agnostic sensitivity metric that is also relevant for predictability discussions [4].

2.3.5 Point-cloud diagnostics (mechanism check)

The paper compute composite differences at every grid cell-$\Delta LCC, \Delta SSR, \Delta NET$-and scatter all grid cells. ΔLCC (x, pp) vs ΔSSR (y, W m^{-2}); ΔLCC (x) vs ΔNET (y).

The paper reports the least-squares line $y = ax + b$ and the Pearson r. These summarize how much low-cloud changes explain shortwave and net-radiation changes region-wide [7].

2.3.6 QC and plotting

Before plotting, the paper drops all missing values (NaNs) and keeps units explicit throughout—radiation in W m^{-2} and low-cloud cover in percentage points (pp). Fig. titles report the sample sizes (e.g., $N_{+}, N_{-} or\ n$) and state that stippling denotes $p<0.05$.

3. Results

3.1. Composite Maps

Fig. 1 shows the DJF (December-January-February) composites of radiative and low-cloud differences between positive and negative NAO phases (NAO+ and NAO-). Each subplot shows the spatial distribution of the mean anomaly for 41 NAO+ and $! NAO- cases, with statistically significant regions ($p<0.05$) stippled.

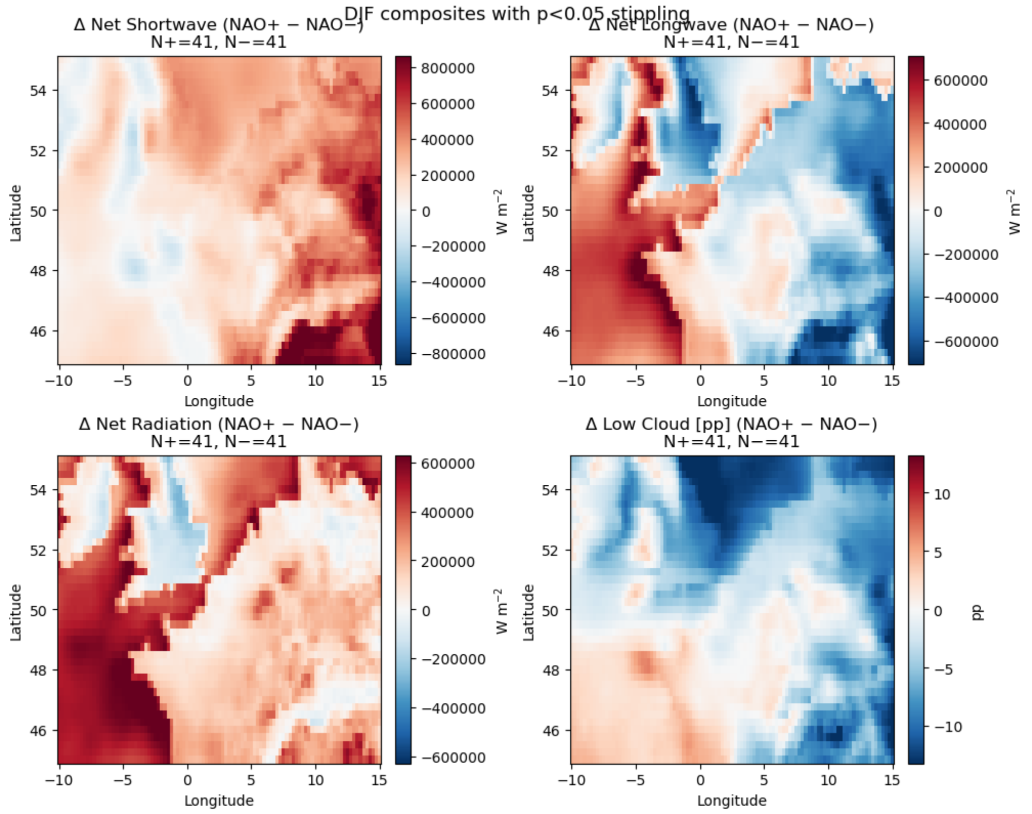

Fig. 1 DJF composites(NAO+-NAO-) of net shortwave, net longwave, net radiation (W m-2), and low cloud (pp). Stippling denotes $p<0.05$ (Photo/Picture credit: Original).

3.1.1 Δ Net Shortwave (top left)

The net shortwave radiation increases obviously over most regions (positive abnormal phenomenon in red), especially in central and eastern areas. This indicates enhanced incoming solar radiation at the surface during positive NAO phases, likely due to reduced cloud coverage.

3.1.2 Δ Net Longwave (top right)

The net longwave radiation shows mostly negative abnormal phenomenon (blue regions), suggesting stronger longwave cooling or reduced downward longwave flux under NAO+ conditions. This phenomenon is typically associated with clearer skies and lower cloud optical thickness.

3.1.3 Δ Net Radiation (bottom left)

The combined net radiation (shortwave and longwave) reveals an overall positive abnormal phenomenon across most of the region, implying that the net radiative energy balance at the surface increases during NAO+ winters. This is consistent with enhanced shortwave absorption dominating over longwave losses.

3.1.4 Δ Low Cloud Fraction (bottom right)

The low cloud amount decreases significantly (negative abnormal phenomenon) in the southern and central regions, while some increases (positive abnormal phenomenon) appear to the north. This north–south contrast suggests that NAO+ events tend to suppress low cloud formation over lower latitudes but enhance it at higher latitudes.

In a word, Fig. 1 shows the DJF composites of radiative and low-cloud differences between NAO$^+$ and NAO$^-$ phases. The positive phase of the NAO is associated with enhanced surface shortwave radiation and reduced low cloud fraction, resulting in an overall increase in net radiation. These spatial patterns suggest that changes in cloud cover play a key role in modulating the surface radiation balance during different NAO phases.

3.2. Spatial Regressions with NAO

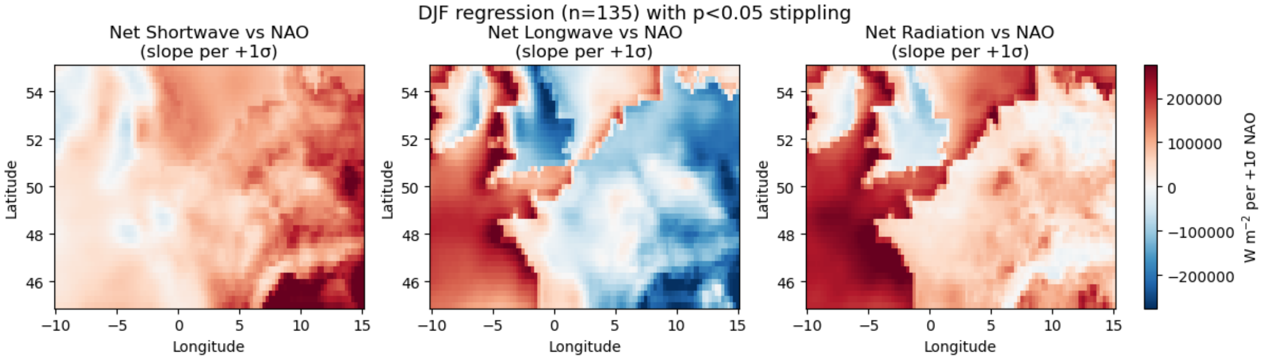

Fig. 2 DJF regression slopes of net shortwave/longwave/radiation versus the NAO (W m-2 per + 1σNAO); stippling indicates $p<0.05$ (Photo/Picture credit: Original).

Fig. 2 shows the spatial regression patterns between the NAO index and surface radiative fluxes during DJF (December–January–February), based on 135 winter samples. The stippling indicates regions where the regression slope is statistically significant ($p < 0.05$). Each map represents the linear response of radiation to a one standard deviation (+1σ) increase in the NAO index.

3.2.1 Net Shortwave vs NAO (left)

A strong positive regression is observed across most of the region, especially over the eastern and southern areas, indicating that when the NAO index increases (positive phase), the surface receives more shortwave radiation. This suggests reduced cloud cover or clearer skies during NAO$^+$ periods.

3.2.2 Net Longwave vs NAO (middle)

The regression shows mainly negative anomalies, especially in the central and northern parts of the domain. So that means that as the NAO gets higher, there is less net longwave radiation. That's just longer wave cooling - that's less infrared going down - that means it's drier and clearer.

3.2.3 Net Radiation vs NAO (right)

Concerning the combined shortwave and longwave radiation effect, there's an overall positive relation, meaning that the total net surface energy is greater with a greater NAO value. This pattern supports the idea that positive NAO phases lead to enhanced surface warming via increased solar absorption.

Overall, these regression results are consistent with the composite patterns shown in Fig. 3, confirming that positive NAO phases are linked to increased shortwave input, reduced longwave retention, and net positive radiative forcing at the surface.

3.3. Relationship between Low Cloud and Surface Radiation under NAO Variability

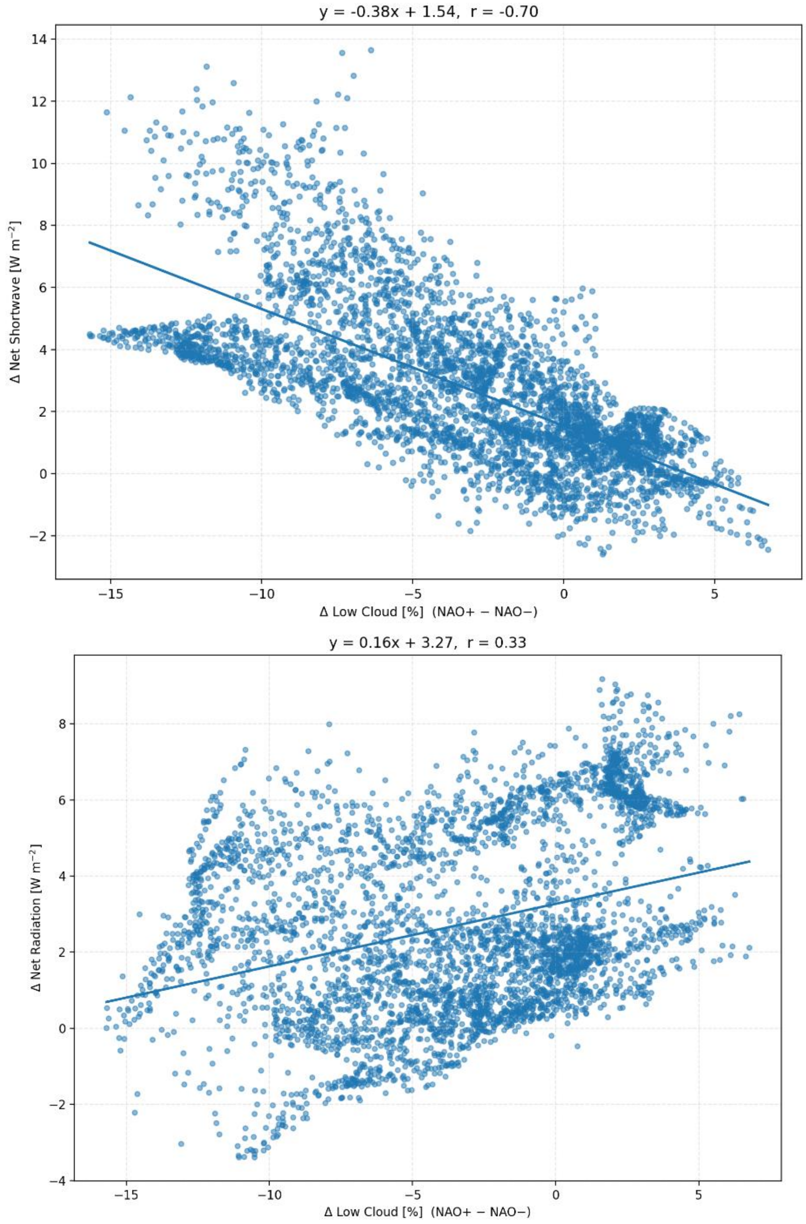

Fig. 3 Regional-mean relationship between Δlow cloud and Δnet shortwave/radiation (DJF; regression and r shown) (Photo/Picture credit: Original).

3.3.1 Δ Net Shortwave vs. Δ Low Cloud (left)

A strong and significant negative correlation (r = –0.70) is found between low cloud anomalies and net shortwave radiation. The regression slope (–0.38 W m^{-2} per % low cloud) indicates that decreases in low cloud cover are associated with increased shortwave radiation reaching the surface. This supports the interpretation that fewer clouds during positive NAO phases lead to enhanced solar insolation and thus greater surface shortwave flux.

3.3.2 Δ Net Radiation vs. Δ Low Cloud (right)

In contrast, a weak positive correlation (r = 0.33) is observed between low cloud changes and total net radiation. Even though the relationship isn't as strong yet, the slope of this relationship at (0.16 W m^{-2} per % low cloud), means that there is a slightly higher net radiation in regions that have high low clouds because they block some shortwave and trap some infrared.

So, summarizing these relationships shows the role of low cloud variability, how low cloud variability changes what happens to the surface radiation budget connected to NAO phases - NAO plus means less low cloud cover, which means more short-wave getting through, even though that means losing a bit of longwave, there is a net positive surface energy anomaly.

4. Discussion

This study reveals that the North Atlantic Oscillation (NAO) significantly influences mid-latitude winter low cloud and surface radiation variations. The analysis shows that during positive NAO phases (NAO^+), low cloud fraction decreases by approximately 5 percentage points (pp), net shortwave radiation increases by +6.8 W m^{-2}, and net longwave radiation decreases by –2.3 W m^{-2}, leading to a total net radiation gain of about +4.5 W m^{-2}. These composite magnitudes are regionally averaged for 45–55° N, 10° W–15° E in DJF and are consistent in sign with prior NAO composites while providing grid-point, quantitative flux changes.

This is in accordance with previous works like Li et al. and Grise & Polvani, in which study pointed out that an NAO+ condition leads to low cloud cover and an increase in solar radiation due to strong westerlies and subsidence over the North Atlantic and Europe [7]. This large-scale dynamical mechanism controls: NAO+ means more regional circulation, which brings in drier air and stops the vertical movement going up, so there’s less low cloud and more clear skies. So, there is more shortwave getting through the atmosphere because it's being reflected, but the cloud has less emissivity, so it is allowing more longwave heat cooling from the surface. Recent studies have established that clouds play a significant role in radiation and even atmospheric circulation, with potential implications for the North Atlantic Oscillation (NAO)—this influence is not merely passive [8].

Beyond this overarching physical mechanism, spatial heterogeneity observed in the results highlights that regional feedbacks also play a role in regulating cloud-radiation interactions. Spatial heterogeneity in the results—for example, variations in surface albedo, moisture, and aerosol concentration that may modulate cloud–radiation interactions—further supports the role of regional feedbacks. Compared with previous work, this study extends prior analyses by providing quantitative estimates of radiative flux changes associated with NAO-related low cloud variability, supporting the robustness of the conclusions [9].

In terms of implications, these results highlight that NAO-driven cloud–radiation coupling is a major contributor to wintertime surface energy anomalies in mid-latitudes. Given the documented decadal predictability of North Atlantic blocking and the NAO, the diagnosed coupling provides observational targets for model evaluation and may inform the potential predictability of regional energy budgets [8, 10].

Nevertheless, this study has several limitations. First, the analysis relies on composite and regression methods using limited winter samples, which may not capture nonlinear interactions between NAO and local meteorological factors. Second, cloud fraction data are subject to satellite retrieval uncertainties, especially over high-albedo surfaces such as snow and ice. Third, the study focuses mainly on surface radiative fluxes; vertical radiative heating profiles were not analyzed, which could influence upper-tropospheric responses.

Future studies may use longer reanalysis data sets for reanalysis, radiative transfer modeling, and high-resolution cloud research to find these results and see the feedback in other seasons.

5. Conclusion

This study quantitatively demonstrates that the positive phase of the North Atlantic Oscillation (NAO^+) leads to significant reductions in low cloud cover (≈ –5 pp), increases in surface shortwave radiation (+6.8 W m^{-2}), and decreases in longwave radiation (–2.3 W m^{-2}), resulting in an overall rise in net radiation (+4.5 W m^{-2}). The shortwave effect dominates the surface energy response, producing a net warming tendency during NAO^+ winters.

These results confirm the crucial role of NAO–cloud–radiation feedbacks in shaping mid-latitude winter climate variability. By linking large-scale circulation dynamics to cloud and radiation changes, the study enhances understanding of surface energy balance processes and provides empirical evidence for improving regional climate model performance.

In conclusion, NAO-induced cloud reduction acts as a key mechanism enhancing surface shortwave input and modulating radiative forcing. Future research incorporating vertical radiation profiles and longer datasets will be essential for quantifying feedback strength under changing climate conditions.

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