environmental and earth sciences proceedings

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Proceeding Paper

Integrating NWCSAF Nowcasting Tools into the Regional Cloud Seeding Program: A Case Study on 1 November 2023 in Saudi Arabia †

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† Presented at the 17th International Conference on Meteorology, Climatology, and Atmospheric Physics—COMECAP 2025, Nicosia, Cyprus, 29 September–1 October 2025.

Abstract

The Kingdom of Saudi Arabia launched a Regional Cloud Seeding Program in 2022 to enhance rainfall in central and southwestern regions. This study highlights a cloud seeding case on 1 November 2023, using convective development products derived from the Nowcasting Satellite Application Facility (NWCSAF), part of the SAF Network coordinated by the European Organization for the Exploitation of Meteorological Satellites. NWCSAF provided real-time satellite data for assessing cloud dynamics and precipitation. Analysis focused on Convection Initiation (CI) products issued 30–90 min before cloud seeding activities. Results showed the CI+30, +60, and +90 min outputs had high predictive accuracy, aligning with observed convection and demonstrating the value of satellite-based nowcasting in potential adaptation during cloud seeding operations.

Keywords: nowcasting; cloud seeding; convection initiation; rainfall enhancement; Saudi Arabia; remote sensing; NWCSAF

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Academic Editors: Panagiotis T. Nastos and Diofantos G. Hadjimitsis

Published: 10 September 2025

Citation: Matsangouras, I.; Logothetis, S.-A.; Albar, A. Integrating NWCSAF Nowcasting Tools into the Regional Cloud Seeding Program: A Case Study on 1 November 2023 in Saudi Arabia. *Environ. Earth Sci. Proc.* **2025**, *35*, 13. https://doi.org/10.3390/eesp2025035013

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1. Introduction

The Arabian Peninsula has been experiencing a significant increase in water demand, mainly caused by population growth, urbanization, and an overall increase in living standards. In response to mounting water resource pressures, the Kingdom of Saudi Arabia (KSA) launched the Regional Cloud Seeding Program (RCSP) in 2022 to enhance rainfall. This initiative targets the southwestern and central regions of the KSA, areas climatologically favorable for convective cloud development, through coordinated airborne cloud seeding operations targeting convective cloud systems. A core component of the RCSP's operational framework is the integration of advanced meteorological ground-based observation infrastructure, a dense dual-polarization Doppler weather radar network, satellite reception datasets, and a nowcasting system, to monitor the evolution of convective clouds and identify suitable seeding targets. Among these advanced monitoring systems and applications employed, the Nowcasting Satellite Application Facility (NWCSAF) products are also implemented as a supportive decision-making tool during cloud seeding operations.

The NWCSAF was initiated in December 1996 with the aim of providing operational services that enhance the use of meteorological satellite data for nowcasting and very short-range forecasting. Led by the National Meteorological Agency of Spain, the NWCSAF was developed by a project team composed of National Meteorological Services and Institutes of France, Sweden, Romania, and Austria. The NWCSAF system uses both numerical

weather prediction (NWP) data and satellite data, acquired from either geostationary (GEO) or polar orbiting (PPS) satellites, to generate a suite of nowcasting products. Further details are available on the NWCSAF website [1]. Key NWCSAF products include Clouds, Precipitation, Extrapolation Imagery, and the Convection Initiation (CI) and Convective Rainfall Rate algorithms, which have been evaluated for their ability to detect rapidly evolving convective systems and estimate precipitation rates [2–6].

This study aims to explore the benefits of NWCSAF nowcasting products within the operational workflow of the RCSP, using a case study of a cloud seeding mission conducted on 1 November 2023 over the central parts of KSA. The analysis focuses on the predictive skill of the CI product issued 30, 60, and 90 min prior to the seeding events in identifying convective onsets related to cloud target seeding locations. The structure of the paper is as follows: Section 2 describes the datasets and NWP inputs, including the cloud seeing aircraft and methodology context. Section 3 presents and discusses the results of the analysis. Section 4 concludes with a summary of the main findings and their implications for future cloud seeding operations.

2. Data and Methodology

This section presents the datasets and analytical methods used to explore the performance of the CI product during a cloud seeding operation over central Saudi Arabia on 1 November 2023. In this study, the latest version (v2021.3) of the NWCSAF/GEO software package was employed, utilizing all 12 spectrum channels of the geostationary satellite. Satellite data was processed over the full analysis period from 03:00 to 15:00 UTC on 1 November 2023, at 15-min intervals. NWP data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS) were utilized (IFS Cycle 49r1, released on 12 November 2024). The data were based on the 00:00 UTC forecast run issued on 1 November 2023, with forecasts provided at three (3) hour intervals and include surface-level and pressure-level variables.

The NWCSAF CI algorithm provides a probabilistic assessment of a cloudy pixel developing into a thunderstorm within 30, 60, or 90 min (CI30, CI60, CI90) using statistical and physical methods [7–9]. It filters pixels based on atmospheric instability (e.g., Lifted Index, Showalter Index, K Index), cloud properties, motion vectors, and glaciation indicators. Probabilities are categorized into five classes based on threshold criteria [7–9]. The validation of the CI product has been conducted by NWCSAF through objective and case study-based assessments using radar-derived and satellite-based ground truth datasets [9].

On 1 November 2023, RCSP conducted a cloud seeding operation over central Saudi Arabia. Two aircraft operated from 10:00 to 14:00 UTC, releasing 40 silver iodide (AgI) flares targeting convective systems near Hail, Qassim, and Riyadh (Figure 1). Using a glaciogenic method, flares were deployed on top of actively growing cumulus within the -10 °C to -20 °C range (~5–7 km altitude), optimal for AgI ice nucleation [10]. Cloud targets were selected based on guidance from RCSP's operations center and onboard measurements, as in other dryland seeding programs [11]. Aircraft paths and flare releases are shown in Figure 1. The NWCSAF CI outputs (CI30, CI60, CI90) were used to assess convective evolution at seeding points.

The neighborhood-based validation technique described by Schwartz et al. [12] was employed to assess the predictive performance of CI. The validation algorithm analyzed a 2 × 2 pixel (each pixel approximately 3 km × 3 km at nadir, based on MSG SEVIRI data) window centered on each cloud seeding location. Within this neighborhood, the maximum CI probability was extracted for each of the 40 cloud seeding events conducted on 1 November 2023. A CI "hit" was defined as a case where this maximum value exceeded 0%

and met high-quality control values, ensuring that only credible CI signals were included in the assessment.

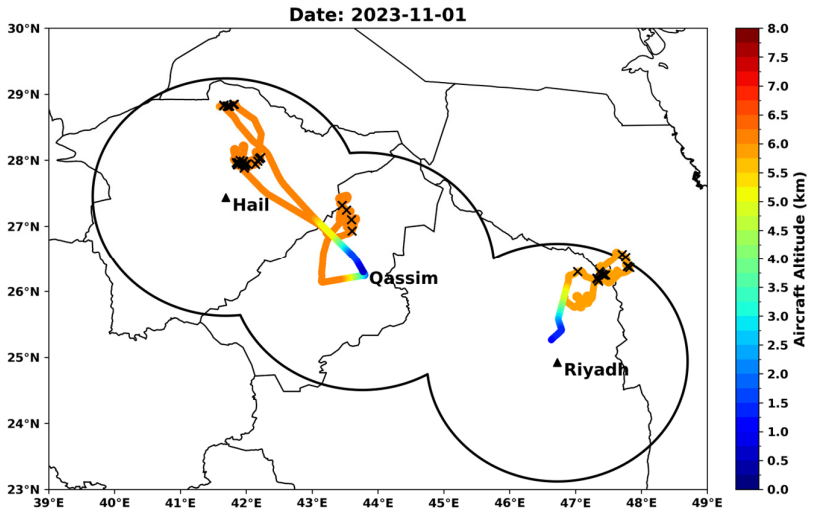


Figure 1. Flight paths of the two RCSP cloud seeding aircraft on 1 November 2023 over central Saudi Arabia. Black Xs mark AgI ejected points, black triangles indicate radar stations (Hail, Qassim, and Riyadh), and the bold black line indicates the 200 km radar coverage area.

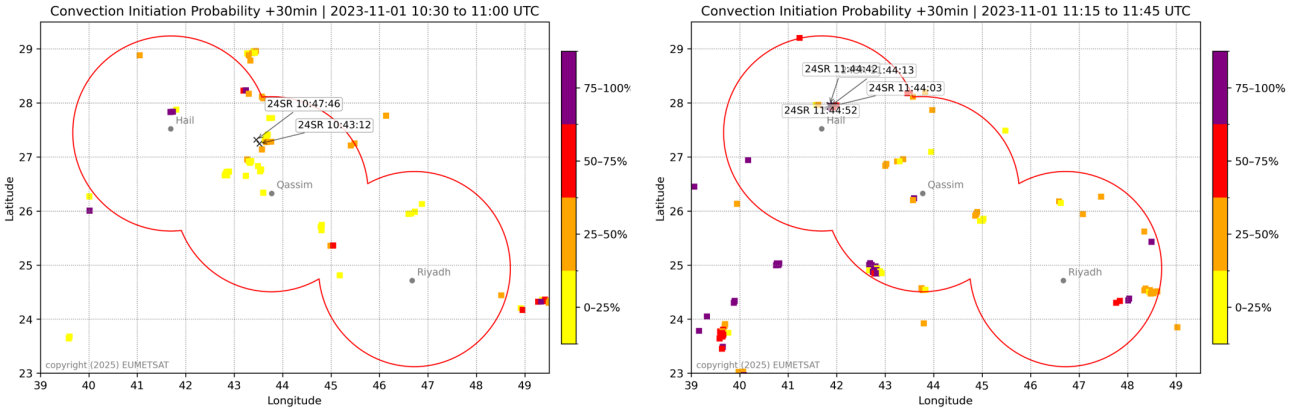
3. Results and Discussion

On 1 November 2023, synoptic conditions over central Saudi Arabia were favorable for convective development and glaciogenic cloud seeding operations. A mid- to upper-level shortwave trough over the northwest of the KSA propagated east-southeast, enhancing vertical motion through upper-level jet streak divergence at 250 hPa and positive vorticity advection at 500 hPa. At lower levels, moisture was advected into central areas via southwesterly winds from the Red Sea and southeasterly inflow from the Arabian Gulf. A Skew-T diagram for Riyadh at 12:00 UTC revealed an unstable atmosphere, with a steep lapse rate and a well-mixed boundary layer extending up to approximately 850 hPa.

Despite the favorable synoptic and thermodynamic setup, early-stage cumulus clouds observed over central Saudi Arabia between 07:00 and 09:00 UTC did not immediately evolve into precipitating systems. This delayed development is consistent with findings by Freud and Rosenfeld [13], who linked increased cloud droplet number concentrations—common in aerosol-rich arid environments—to the need for deeper cloud development and colder tops for precipitation initiation. RGB Day Microphysics imagery supported this progression, showing an increase in green and reddish pixels after 11:00 UTC, indicative of glaciation and colder cloud tops, with mature convection and anvil outflow becoming apparent between 12:00 and 13:00 UTC. A study by Rosenfeld et al. [14] demonstrated that targeted cloud seeding in such environments can enhance precipitation efficiency by accelerating ice-phase processes within supercooled cloud layers.

It is important to note that the operational cloud seeding decisions during this period were based on weather radar observations. In this study, we do not evaluate the decision process itself, but rather assess how CI values spatially and temporally relate to seeding activity. The CI30 product displayed a clear and progressive intensification from 08:00 to 13:00 UTC. More specifically, from 08:15 UTC to 09:15 UTC, initial CI30 signals were weak and scattered around Qassim with low probabilities (0–25%). By 09:15 to 10:30 UTC, the activity began to consolidate and intensify, with higher-probability CI clusters (25–75%) developing close to Qassim and gradually shifting northward toward Hail. From 10:00 to 12:15 UTC, these signals evolved into more organized and persistent zones, with several areas exceeding 75% CI probability, especially northeast of Hail. At

10:43 UTC, the aircraft (24SR) started seeding cloud targets between Qassim and Hail, where CI30 values exceeded 50% (Figure 2a), and later at 11:43 UTC, the convective system close to Hail had values more than 75% (Figure 2b). This trend continued and intensified between 12:15 and 13:15 UTC, as CI30 probability expanded both in magnitude and spatial coverage, with numerous high pixel values around Hai, Qassim, and Riyadh.



(**a**) (**b**)

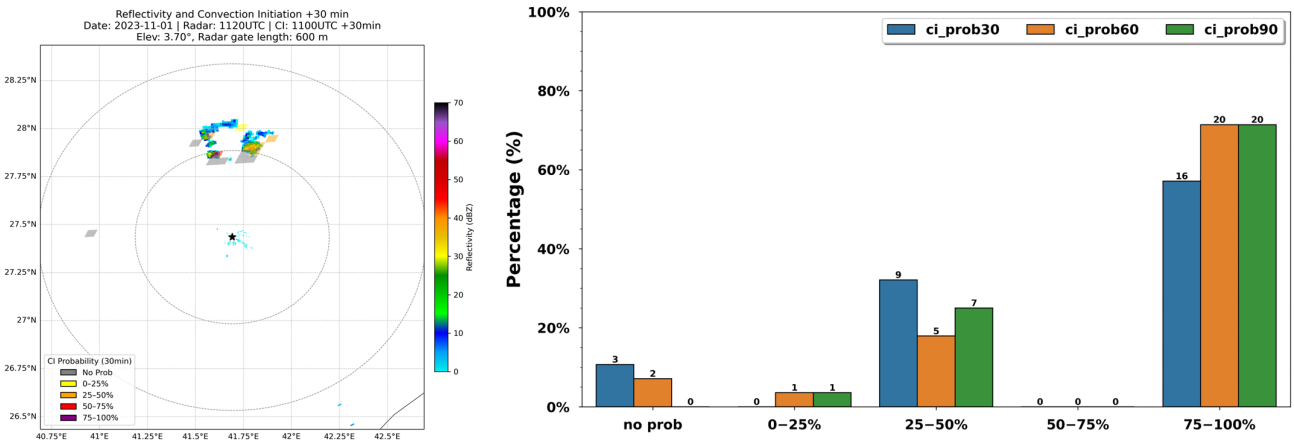
Figure 2. CI30 for 10:30–11:00 UTC (**a**) and 11:15–11:45 UTC (**b**) on 1 November 2023, over central Saudi Arabia. Black Xs and labels indicate AgI flares ejected points, black triangles denote radar stations (Hail, Qassim, and Riyadh), and the bold red line shows the 200 km combined radar coverage.

Both the CI60 and CI90 spatial distributions are closely aligned with the CI30 spatio-temporal analysis across the Hail, Qassim, and Riyadh regions. For CI60, no signals were detected by 08:15 UTC. However, by 08:30 UTC, low probabilities (0–25%) began emerging to the north and west of Qassim. These early indicators expanded by 09:00 UTC, evolving into moderate (25–50%) and high (50–75%) probability zones northwest of Qassim, suggesting active cloud development. This upward trend remained, with convective high signals extending toward Hail, spreading around Qassim, and reaching the southeastern Riyadh area.

Similarly, CI90 showed a steady increase in probabilities—initially around Qassim, followed by Hail and later Riyadh. While early signals were weak, by 09:30 UTC, scattered 25–50% probabilities were evident, with some areas reaching the 50–75% range. By 10:00 UTC, a concentrated cluster of high probability (75–100%) was observed just north of Qassim, which subsequently extended toward Hail and Riyadh.

The CI performance was also explored using radar reflectivity from the weather radar stations as ground-truths within the forecast time of CI. The radar scans at the lowest (0.6°) elevation scan regarding reflectivity are available every five minutes. The radars capture low reflectivity values (between 20 and 30 dBZ) close to CI high values, and gradually, radar reflectivity increased significantly to values between 40 and 50 dBZ. Figure 3a shows the combined plot of CI30 and the radar scan at the lowest scan, 25 min after CI30 issued time.

In this case, CI30 probabilities above 75% were detected (valid for 11:15 to 11:45 UTC, time window where cloud seeding activity took place north of Hail), overlapping with radar reflectivity values initially around 30 dBZ. These echoes gradually intensified over time, reaching and exceeding 50 dBZ at 11:40 UTC (Figure 3a). This evolution indicates active convective growth and serves as a strong ground truth confirmation of the CI product's skill in anticipating convective initiation. Notably, similar spatial and temporal consistency between CI output and radar-observed convection was evident during the cloud seeding operation window later in the day.



(**a**) (**b**)

Figure 3. (**a**) CI30 issued at 11:15 UTC and radar reflectivity from Hail station at 11:40 UTC (0.6° scan). Black star marks the Hail radar; dashed circles show 50 km range intervals. (**b**) Classification probability performance of CI30, CI60, and CI90 over central Saudi Arabia during the 1 November 2023 cloud seeding event.

To explore the effectiveness of the CI30, CI60, and CI90 as forecasting signals to cloud seeding locations, we applied the neighborhood-based validation technique introduced by Schwartz et al. [12]. By focusing on a 2 × 2 pixel domain around each seeded location and extracting the maximum CI probability, we ensured a spatially relevant and quality-controlled assessment of forecast performance, as only CI pixels with the highest quality were taken into consideration. Figure 3b illustrates the performance of CI30, CI60, and CI90 forecasts aligned with actual seeding events. As shown in Figure 3b, most of the predictions (~60% for CI30 and ~70% for both CI60 and CI90) fell within the highest forecast probability confidence of CI (75–100%), indicating consistent confidence in this region during that day. Only a small fraction of CI values was classified with moderate probability (25–50%).

4. Conclusions

This study demonstrates the effective integration of NWCSAF CI products within the operational decision-making framework of the RCSP in Saudi Arabia. Through detailed analysis of a seeding event on 1 November 2023, the CI30, CI60, and CI90 outputs showed high skill in predicting convective development, with over 70% of seeding locations coinciding with high-probability CI signals (≥75%). These predictions were supported by weather radar reflectivity, confirming the real-time utility of NWCSAF-derived CI products in anticipating cloud evolution in semi-arid environments.

The findings highlight that NWCSAF CI products, particularly when combined with neighborhood-based validation, offer valuable early indicators of convective potential and provide operationally actionable guidance for targeted glaciogenic seeding. Future enhancements could focus on utilizing effective radius outputs of NWCSAF for further optimizing precipitation enhancement strategies.

Author Contributions: Conceptualization, I.M. and S.-A.L.; methodology, I.M. and S.-A.L.; validation, I.M. and S.-A.L.; formal analysis, I.M. and S.-A.L.; investigation, I.M. and S.-A.L.; writing—original draft preparation, I.M. and S.-A.L.; writing—review and editing, A.A.; visualization, I.M. and S.-A.L.; supervision, I.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created.

Acknowledgments: The authors express their gratitude to the Regional Cloud Seeding Program (RCSP) and the National Center for Meteorology (NCM) of Saudi Arabia for the operational support and access to cloud seeding mission data. Appreciation is extended to the EUMETSAT, ECMWF for value data, and the NWCSAF project team for the NWCSAF/GEO (v2021.3). We express our thanks to the NCM and Weather Modifications International flight and technical crews for their vital role in seeding missions.

Conflicts of Interest: The authors declare no conflicts of interest.

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