Improving Thunderstorm Prediction for Aviation using Artificial Intelligence

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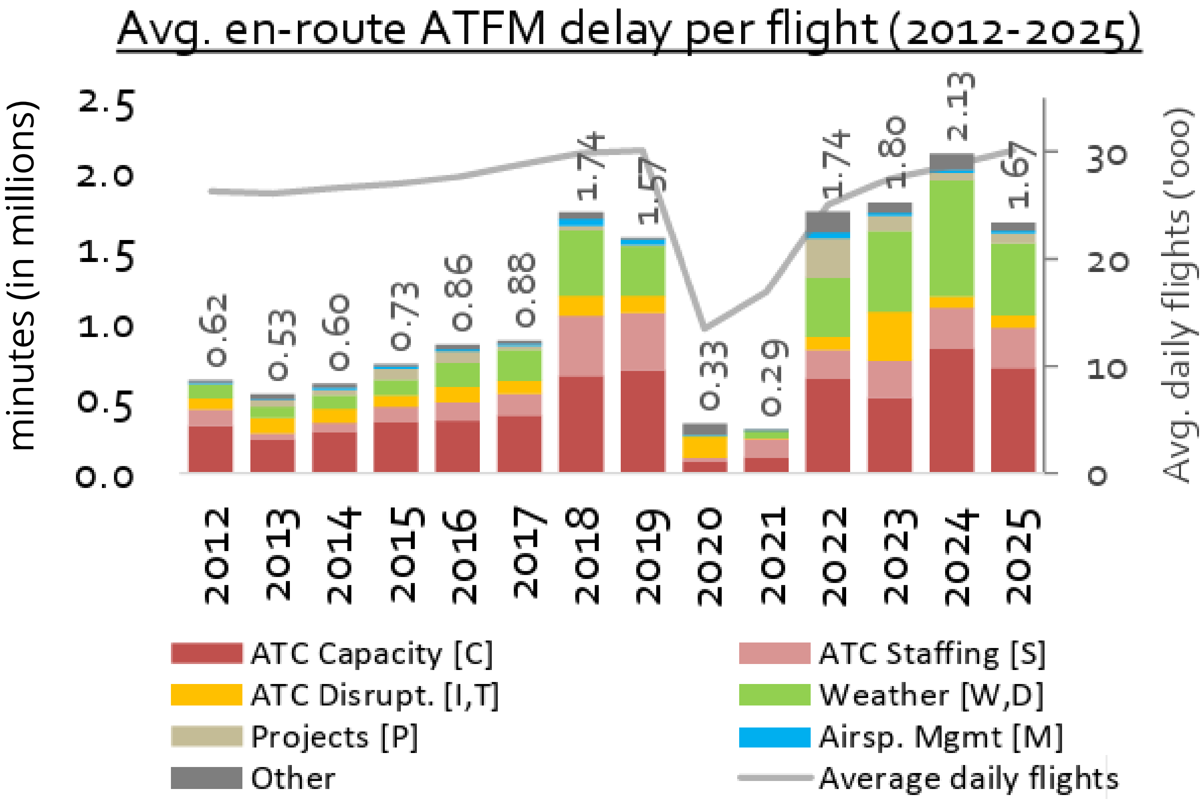
Supervisor/s: Manuel Soler

PhD Aerospace Engineering UC3M
Doctoral Meetings 2026
2nd and 3rd June 2026

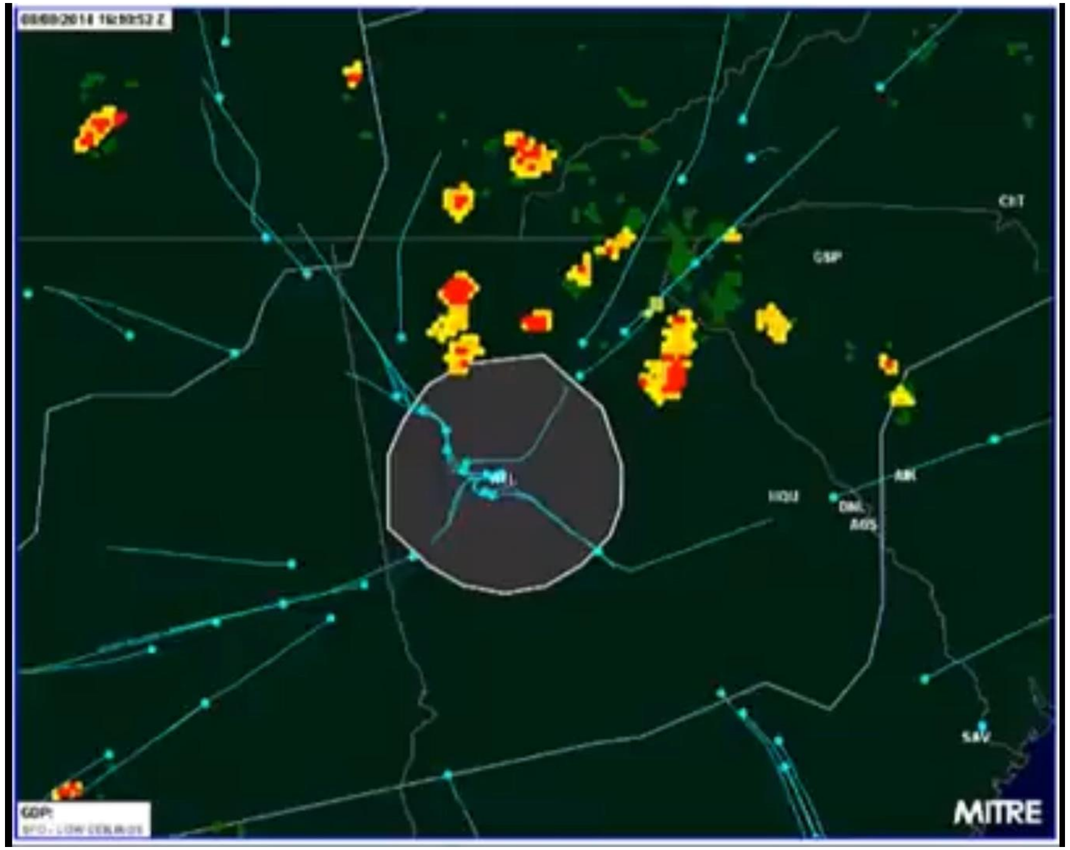
Weather remains a challenge for aviation: safety

Plane makes bumpy landing at London Heathrow during Storm Gerrit

Weather remains a challenge for aviation: operational impact



EUROCONTROL Performance Review Report 2025



Thunderstorms striking Atlanta-Hartsfield airport

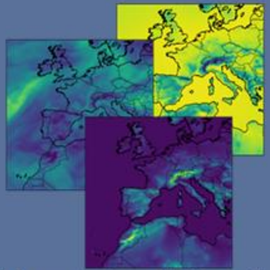
ATFM delay cost estimation 100€ / min Cook and Tanner, 2015)

Enhanced weather information is critical for Air Traffic Flow and Capacity Management decision making

OUTLINE

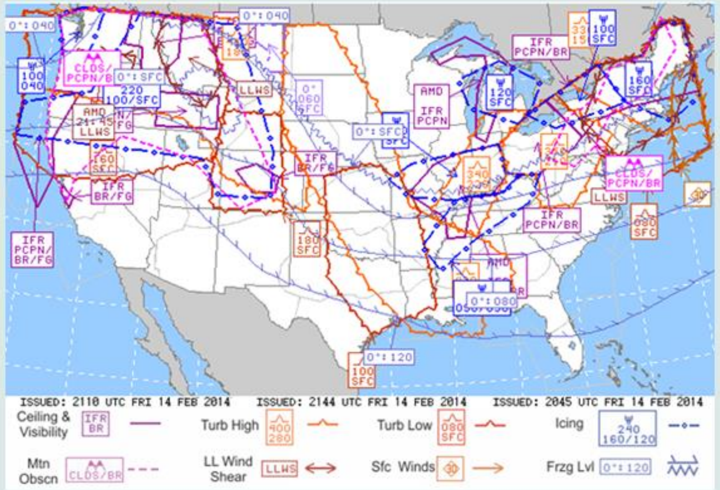
- State of the Art
- Research Objectives
- Results
- Next Steps
- Achievements

State of the Art: Aviation Weather Products

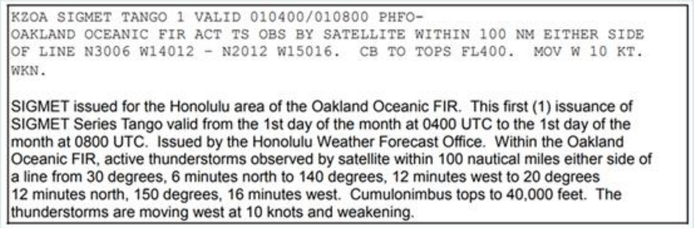


Numerical Weather Products + Meteorologists

AIRMETs

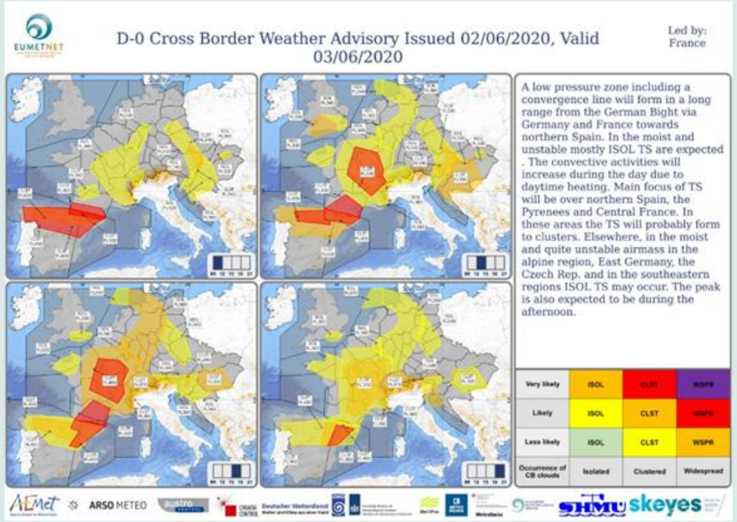


SIGMETs



KZOA SIGMET TANGO 1 VALID 010400/010800 PHFO-
OAKLAND OCEANIC FIR ACT TS OBS BY SATELLITE WITHIN 100 NM EITHER SIDE
OF LINE N3006 W14012 - N2012 W15016. CB TO TOPS FL400. MOV W 10 KT.
WKN.

SIGMET issued for the Honolulu area of the Oakland Oceanic FIR. This first (1) issuance of SIGMET Series Tango valid from the 1st day of the month at 0400 UTC to the 1st day of the month at 0800 UTC. Issued by the Honolulu Weather Forecast Office. Within the Oakland Oceanic FIR, active thunderstorms observed by satellite within 100 nautical miles either side of a line from 30 degrees, 6 minutes north to 140 degrees, 12 minutes west to 20 degrees 12 minutes north, 150 degrees, 16 minutes west. Cumulonimbus tops to 40,000 feet. The thunderstorms are moving west at 10 knots and weakening.



TAF 7/11/20, 19:43 LT

KJFK 112343Z 1200/1306 19012KT P6SM
VCSH SCT050
FM120300 24012KT P6SM FEW050
FM121700 22012G19KT P6SM SCT050
FM130000 21010KT P6SM FEW050

State of the Art: Aviation Weather Products

AIRMETs

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SIGMETs

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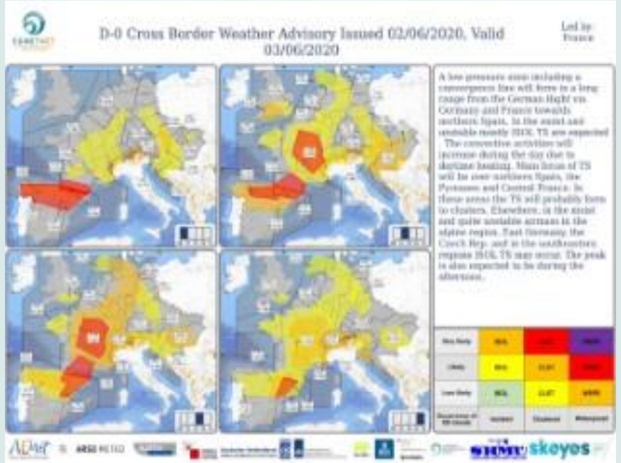
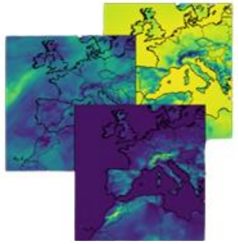


Historically, aviation weather products have been designed to condense a lot of information. While efficient they are limited in the information they provide.

- Alphanumeric
- Handmade by meteorologists
- Static images
- Lack of spatial and temporal resolution

These products limit the strategic planning capability of aviation stakeholders

State of the Art: Artificial Intelligence Paradigm Shift


Numerical Weather Products

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Weather Observations

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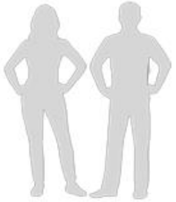
Meteorologists

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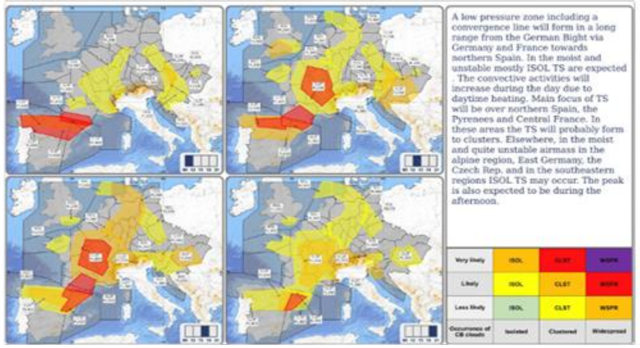
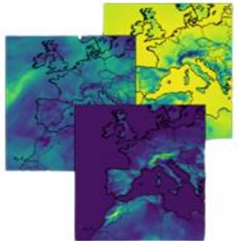

Conventional Weather Products


Numerical Weather Products

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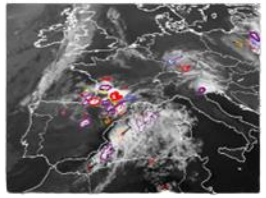
Weather Observations

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Meteorologists


AI Models

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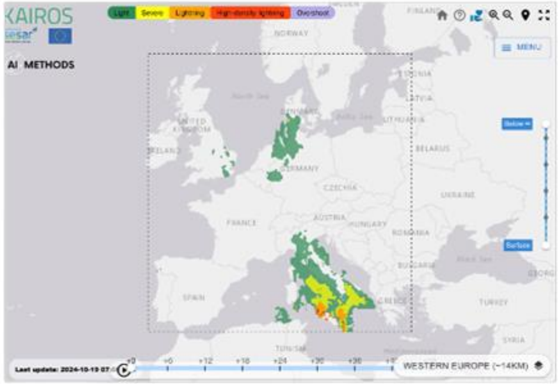
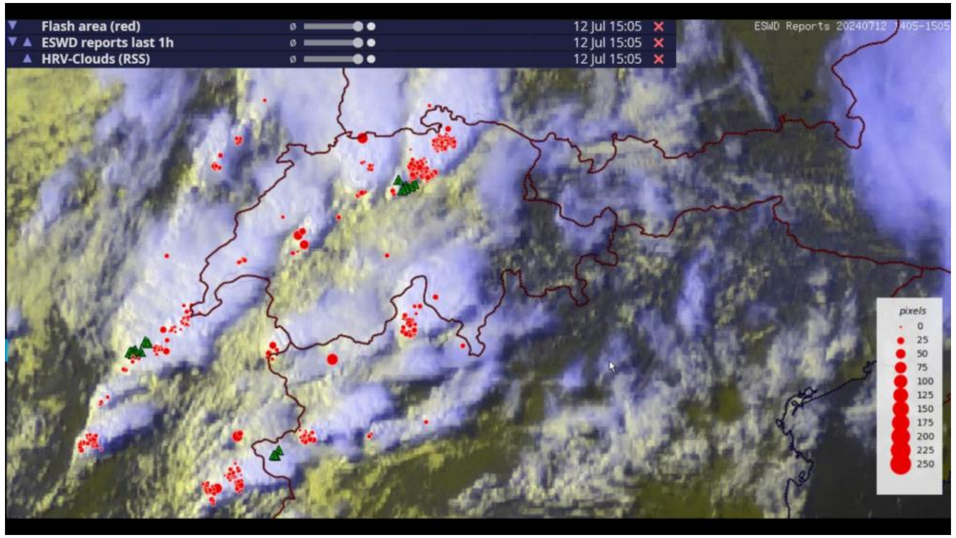


AI Digital Weather Products

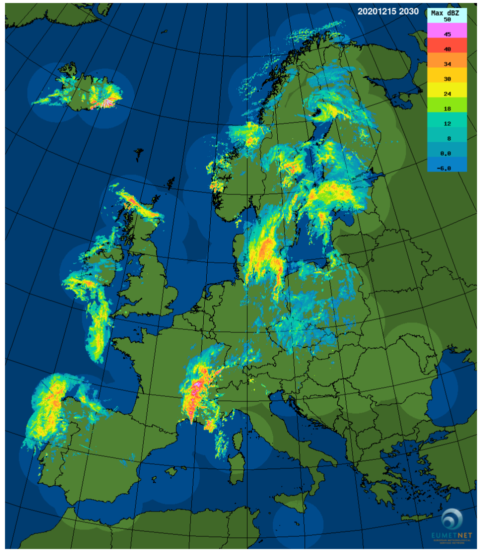
State of the Art: Data Foundations

Predicting convective weather integrates a multimodal suite of observations and numerical weather prediction model data

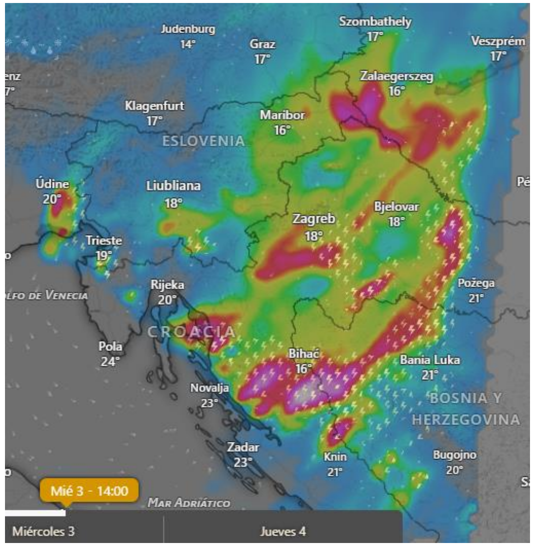
	Lightning Observations	Satellite Remote Sensing	Radar Observations	Numerical Weather Prediction Models
	Proxy for convective intensity and updraft vigour; the only direct sensor of in-cloud electrification and charge dynamics.	Provides high-frequency, top-down radiative profiles to capture pre-convective thermodynamic changes and structural signatures	Provide high-resolution 3D reflectivity and Doppler fields, to directly observe precipitation structure, storm kinematics, and convective organisation	Delivers physics-based model outputs solving fluid equations to characterize pre-convective instability, kinematic forcing, and atmospheric state
Operational Examples	• **Ground Networks:** EUCLID (Europe), LINET, NLDN (US), WWLLN (Global tracking). • **Spaceborne Geostationary:** MTG-LI*, GOES-R GLM** **MTG-LI: Meteosat Third Generation Lightning Imager* ***GOES-R GLM: Geostationary Lightning Mapper*	• **Instruments:** MTG-FCI*, GOES-ABI**, Himawari AHI***, SEVERI**** * *MTG-FCI: Meteosat Third Generation Flexible Combined Imager* ** *GOES-ABI: Geostationary Advanced Baseline Imager* *** *HIMAWARI AHI: Advanced Himawari Imager* **** *SEVERI: Spinning Enhanced Visible Infra-Red Imager*	• **Ground Networks:** OPERA (Europe), NEXRAD (US)	• **Convection Allowing Models (CAMs):** ICON-D2 (DWD), AROME (Meteo-France), HRRR (NOAA). • **Global Models:** ECMWF IFS, GFS (NOAA), ICON Global (DWD), ERA5 (reanalysis).



MTG Lightning Imager on top of SEVERI High Resolution Visible Band



OPERA Radar



DWD ICON D2 Storm Prediction

State of the Art: Data Foundations

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Convective Weather Proxy Examples	• **Flash rate density (FRD)** — flash counts per unit area and time • **Flash extent density (FED)** — total number of flashes illuminating a specific grid cell, tracking core storm vigor • **Lightning jump (LJ)** — rapid increase in flash rate dN/dt preceding severe weather onset	• **Convective Initiation (CI)** probability — likelihood of new convective cell formation • **Overshooting Top (OT)** frequency — penetration of the tropopause indicating intense updrafts • **Brightness temperature (BT)** tendencies — rapid cloud-top cooling rate.	• **Vertically Integrated Liquid (VIL)** — total liquid fgwater content in a column • **Maximum Expected Size of Hail (MESH)** — estimated hail diameter for severe warnings (1-inch threshold) • **Echo top height (ETH)** — altitude of the 18 dBZ reflectivity surface.	• **Convective Available Potential Energy (CAPE)** — energy available for convective ascent • **Convective Inhibition (CIN)** — energy barrier to convection onset • **Lifted Index (LI)** — stability measure based on parcel ascent • **Composite hazard score** combining the above and/or other NWP fields
Prediction Step	An advection or prediction step is needed to project these fields forward in time.	An advection or prediction step is needed to project these fields forward in time.	An advection or prediction step is needed to project these fields forward in time.	NWP output is already a forecast — no additional prediction step is needed.

State of the Art: Convective Weather Forecasting for ATFCM operations. Needs

NOWCASTING 0 – 2 h	VERY SHORT-RANGE 2 – 12 h	SHORT-RANGE 12 – 72 h
ATFCM PHASE		
Tactical En-route deviation decisions · arrival sequencing and holding · approach clearance · suspension of outdoor ground operations near active lightning	**Tactical (D-0; day-of operations)** **2–6 h :** pre-flight planning, dispatch, departure slot **6–12 h:** same-day route and sector reconfiguration	**Pre-tactical (D-2 → D-1)** Network-level identification of impacted sectors and routes · publication of flow regulations and alternative routings
KEY STAKEHOLDERS		
Air traffic controller · Approach and tower controller · Pilot (airborne) · Ground handling crews	Flow manager · Dispatcher and flight operations officer · Pilot (pre-flight briefing) · Meteorological forecaster	Network manager · Airline operations centre · Airport planning team · Meteorological day-ahead briefing
PRODUCT REQUIREMENTS		
Update: every 5 min **Resolution:** 1–2 km **Output:** cell polygons and motion vectors	**Update:** 30–60 min **Resolution:** ~5 km **Output:** cumulonimbus area polygons and probability	**Update:** 3–6 h **Resolution:** ~10–25 km **Output:** probabilistic area forecast
METEOROLOGICAL CONTENT		
Cumulonimbus cell boundary and motion vector · lightning proximity · convective initiation and decay signal · cumulonimbus tops	Cumulonimbus zone location and tops (flight level) · corridor free of convection · storm onset timing and expected duration	Convective threat probability by area · affected flight information regions and sectors · storm timing and duration · severity index

Air Traffic Control Tower Operator watching radar screens at East Midlands Airport, UK.

Pilot preflight weather briefing cockpit tablet

EUROCONTROL Network Manager Operations Center. Cross Border Convection Forecast (CBCF)

Framework references used to build this table — [A] EUROCONTROL ATFCM Operations Manual (Ed. Wave 2.3, 2026): ATFCM phases and NMOC/FMP roles · [B] ICAO Annex 3 (21st ed., 2025): Meteorological Service for International Air Navigation; aviation meteorological stakeholders · [C] WMO No. 49 Vol. II: Technical Regulations, Aeronautical Meteorology · [D] WMO Nowcasting Guidelines (2017): definitions of 0–2 h / 2–12 h / 12–72 h forecast horizons · [E] SESAR JU PJ.27 / Solution 109: meteorological information for air traffic management, product specifications per planning horizon

State of the Art: Convective Weather Forecasting for ATFCM operations. Methods

NOWCASTING 0 – 2 h	VERY SHORT-RANGE 2 – 12 h	SHORT-RANGE 12 – 72 h
METEOROLOGICAL CHALLENGE		
Rapid cumulonimbus lifecycle (initiation and decay) · high observation latency · capturing growth, not just movement	Transition zone: observations losing validity and numerical weather prediction spin-up errors	Pinpointing where/when instability becomes a storm · high false alarm rate · limited convective detail at synoptic scale
TRADITIONAL APPROACH		
Radar extrapolation: *Pulkkinen et al. 2019* — PySTEPS: probabilistic Lagrangian extrapolation of radar reflectivity; generates ensemble of perturbed nowcasts capturing forecast uncertainty ***James et al. 2025*** — NowCastMIX: fuzzy-logic integration of radar extrapolation, lightning observations and numerical weather prediction up to 2h; operational at German Weather Service	**Linear radar–NWP blending:** ***Haiden et al. 2011*** — INCA (Integrated Nowcasting through Comprehensive Analysis): altitude-corrected radar merged with NWP background; handles complex terrain; 0–12h ***Golding 1998*** — NIMROD: UK Met Office system blending radar nowcast with NWP via time-weighted linear interpolation; performance degrades as radar loses validity beyond ~2h **Rapid-update of Convection Allowing Models: *DWD ICON D2***	**NWP-derived convective indicators: *Taszarek et al. 2020*** — systematic analysis of European thunderstorm environments using ERA5-derived instability indices (CAPE, CIN, lifted index); European benchmark for NWP-based convective diagnosis **Operational product: *EUMETNET/EUROCONTROL CBCF*** — collaborative convective forecast issued D-1 at 07:00 UTC; probabilistic area polygons valid 12–36h; shared baseline across European air navigation service providers
AI APPROACH		
Radar (precipitation proxy): *Zhang et al. 2023* — NowcastNet: hybrid physics-evolution scheme and generative adversarial network trained on radar; captures convective initiation patterns; up to 3h **Satellite: *Cintineo et al. 2023*** — ThunderCast: U-Net trained on GOES-16 satellite bands and radar reflectivity; directly predicts thunderstorm location 0–60 min; day and night, land and ocean **Hybrid multi-source: *Leinonen et al. 2023*** — recurrent-convolutional network fusing radar, satellite imagery, lightning detection and numerical weather prediction; probabilistic output for lightning, hail and precipitation up to 60 min	**Satellite (convection-direct): *Dai et al. 2025*** — DDMS: diffusion model on geo satellite brightness temperature convective cloud growth and dissipation up to 4h; no lightning output; 4 km resolution **Lightning-direct: *Geng et al. 2021*** — LightNet+: ConvLSTM ingesting lightning observations, surface stations and numerical weather prediction; up to 6h; skill degrades beyond 2–3h — cannot predict new convection initiation where no prior lightning signal exists **General weather — not convection-specific: *Andrychowicz et al. 2023 (Google DeepMind)*** — MetNet-3: transformer-based model ingesting dense multi-source observations; state-of-the-art precipitation and weather variable prediction	**Physics-guided AI post-processing of NWP:** ***Guidotti et al. 2024*** — FlashNet: neural network correction layer on deterministic NWP output; predicts lightning occurrence at medium range; hybrid AI-physics architecture ***Jardines 2024*** — machine learning applied to air traffic flow management decision support for convective weather; NWP-derived features predict flow management impact; direct aviation application ***Yousefnia et al. 2025*** — feedforward neural network trained on convection-permitting ensemble (ICON-D2) output; predicts thunderstorm occurrence probability at 6–48h; European domain

Research Objectives

RESEARCH QUESTION *Can AI deliver convective forecasting products tailored to each Air Traffic Flow Capacity Management (ATFCM) planning horizon — covering the full spectrum from pre-tactical to tactical decisions — by exploiting the data sources best suited to each?*

✓ OBJECTIVE 1 · DONE (TO BE PUBLISHED)

Short-range (12–72 h)

MODEL
ConvLSTM model interpreter of ECMWF NWP fields

INPUT
NWP only (no observations) — vertically resolved thermodynamic & kinematic fields
Topography Fields (elevation & soil type)

OUTPUT
Hourly lightning probability heatmaps; polygons derived downstream via user-chosen decision threshold

BENCHMARK
CBCF (EUMETNET / DWD cross-border product)

CONTRIBUTION
Hourly resolution (vs CBCF's 3-h blocks) and designed to support stakeholder-specific operating points — depending on the trade-off between precision and recall

▶ OBJECTIVE 2 · NEXT

Very short-range (2–12 h)

GOAL
Extend AI convective forecasting into the gap zone (2–6 h) and beyond (6–12 h)

APPROACH
Hybrid AI model fusing geostationary satellite (infrared & visible channels), radar and lightning observations with NWP fields

CHALLENGE
Bridging the transition where observation-based skill decays and NWP spin-up errors dominate (the gap zone)

OUTPUT
Probabilistic CB area forecast at ~5 km, 30–60 min update, lead time 2–12 h

CONTRIBUTION
First operational-ready AI product for the convective gap zone in European ATFCM

◷ OBJECTIVE 3 · PLANNED

Nowcasting (0–2 h)

GOAL
AI-based 0–2 h nowcasting of CB cells and lightning for tactical ATM decisions

APPROACH
Generative or recurrent-convolutional models fusing radar, geostationary satellite (MTG-FCI imagery, MTG Lightning Imager) and ground-based lightning networks

CHALLENGE
Capturing convective initiation and growth — not just advection — at 1–2 km / 5 min resolution

OUTPUT
Cell-level polygons + motion vectors

CONTRIBUTION
Closes the AI convective forecasting chain across all three forecast horizons within one PhD

THESIS CENTRAL CLAIM A coherent AI-based convective forecasting framework — ***from D-2 pre-tactical planning to real-time tactical execution*** — built on the principle that each horizon requires its own data fusion strategy and model architecture.

Results. Cross Border Convection Forecast Baseline Comparison

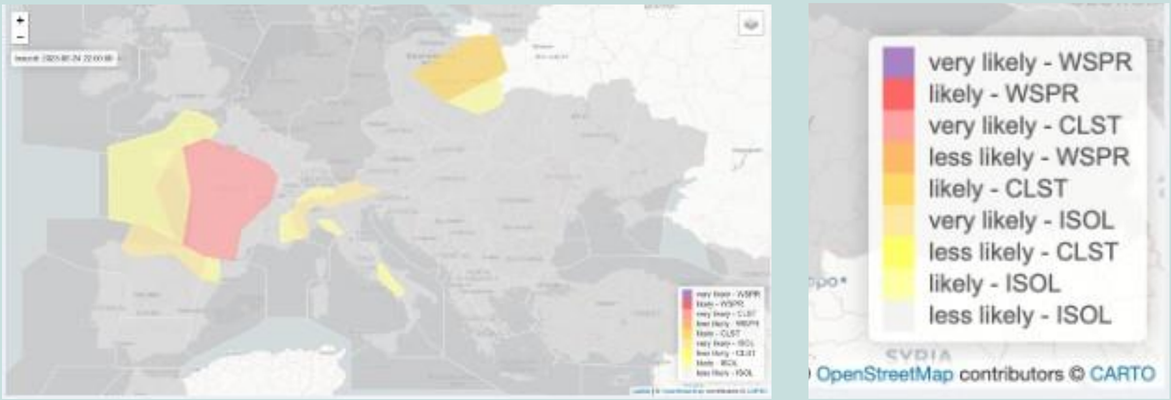
Cross Border Convection Forecast (CBCF):

- 2 releases per day (7H/22H)
- D +1 predictions between 6H-21H
- 3-hour window forecasts (5 images per day)
- Operational May 1st - Oct 15th
- Risk based on probability / extent

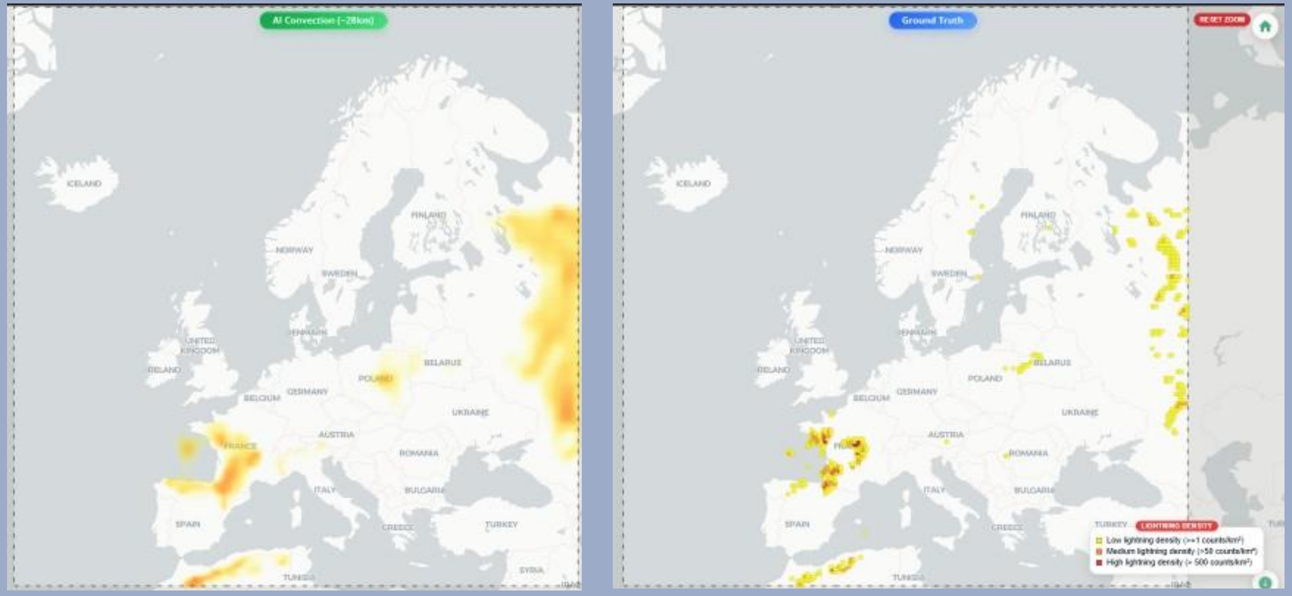
AI Short Range Forecast Model (AI SRFM):

- 4 releases per day
- D +2 predictions (24H)
- Hourly forecasts
- Continuously operational
- Risk based on model confidence – forecast extent comes naturally from model output

CBCF



AI SRFM

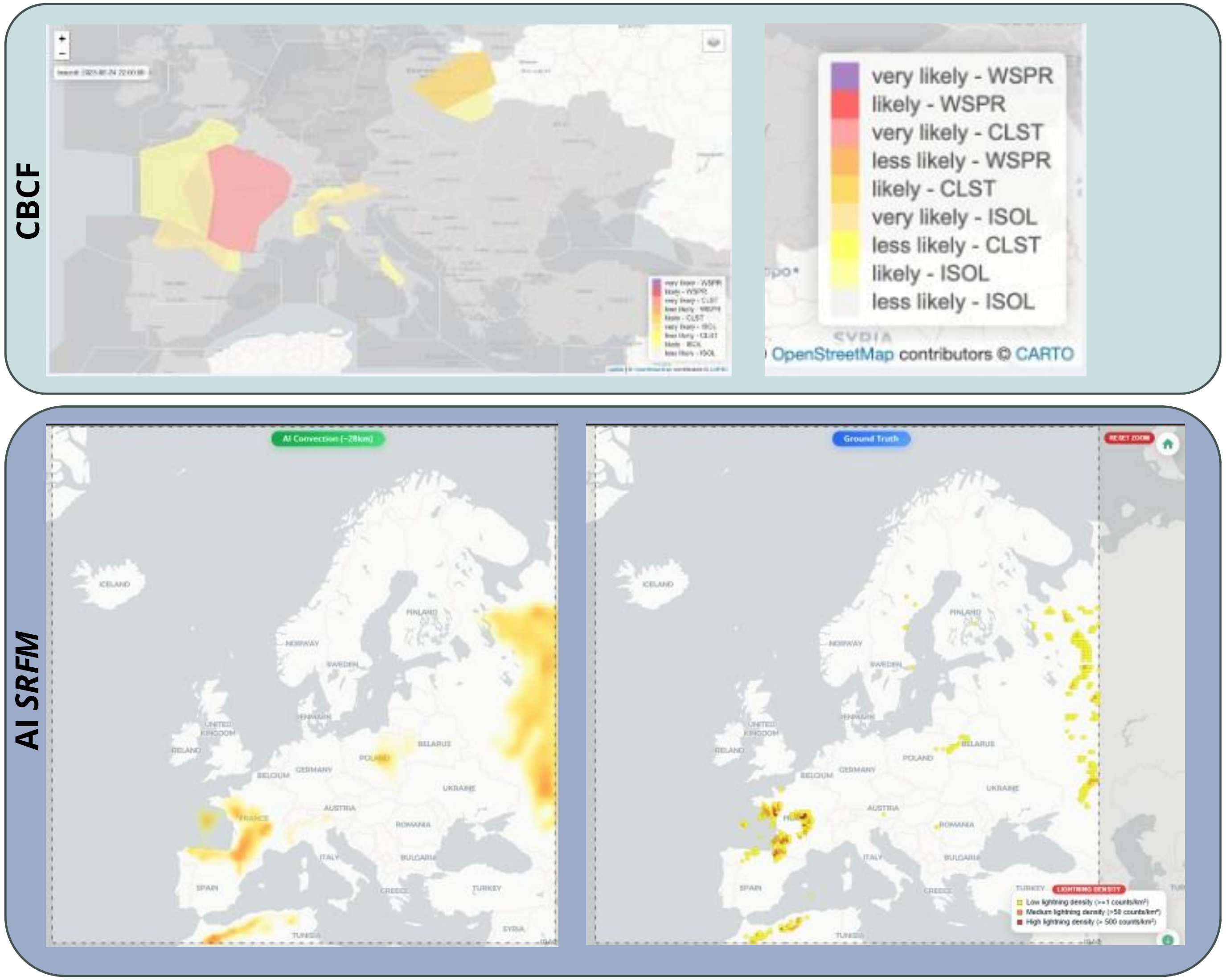


CBCF / AI SRFM comparison. 2025-06-25 15:00Z.

Results. Cross Border Convection Forecast Baseline Comparison

Cross Border Convection Forecast		AI Short-Range Forecast Model	
Convective Fraction	**Likeliness**	**Lightning Threshold**	**Risk Level**
Isolated	Less Likely	>1 Lightning	Yellow
Clustered	Less Likely		
Isolated	Likely		
Widespread	Less Likely	>50 Lightning	Orange
Clustered	Likely		
Isolated	Very Likely		
Widespread	Likely	>500 Lightning	Red
Isolated	Very Likely		
Widespread	**Very Likely**		

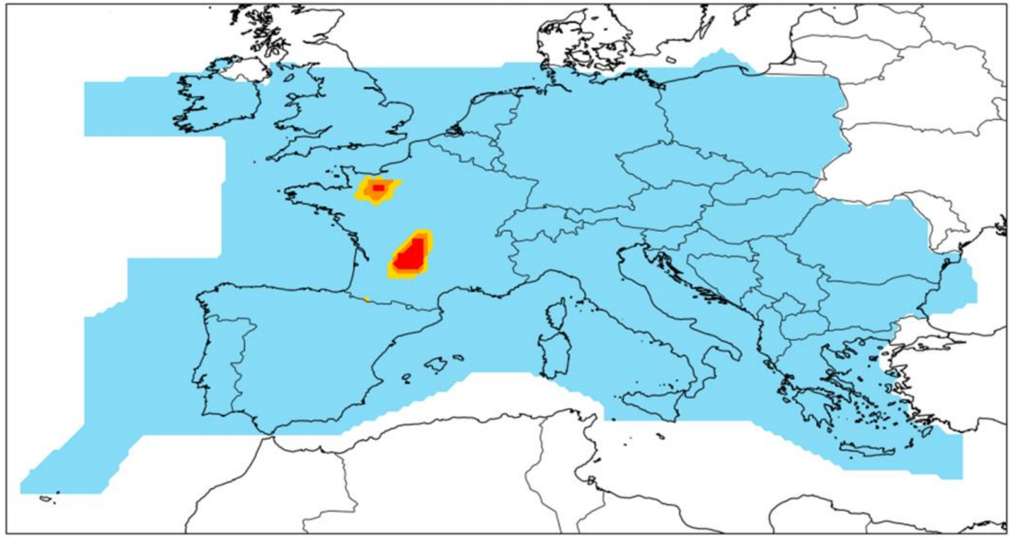
CBCF / AI SRFM risk mapping



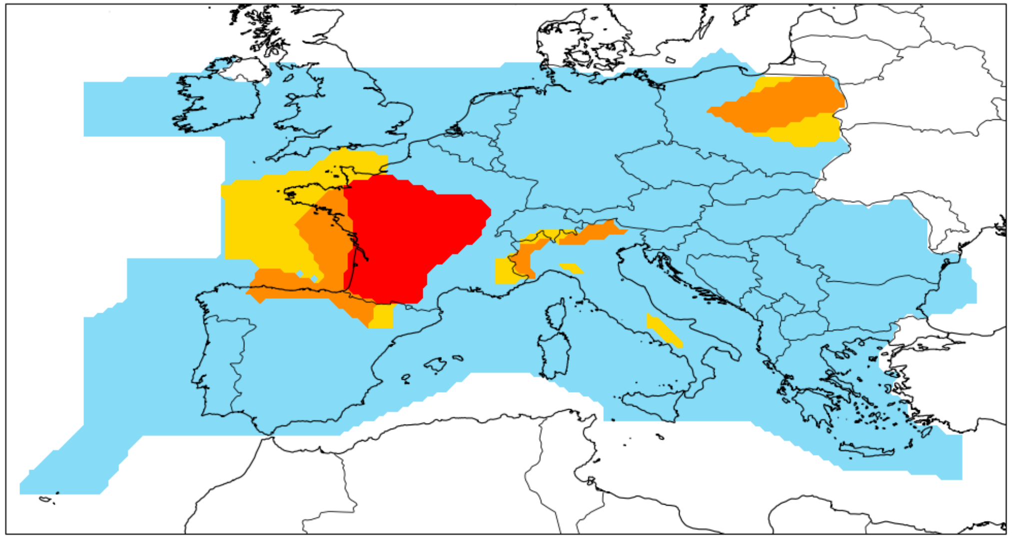
CBCF / AI SRFM comparison. 2025-06-25 15:00Z.

Results. Cross Border Convection Forecast Baseline Comparison

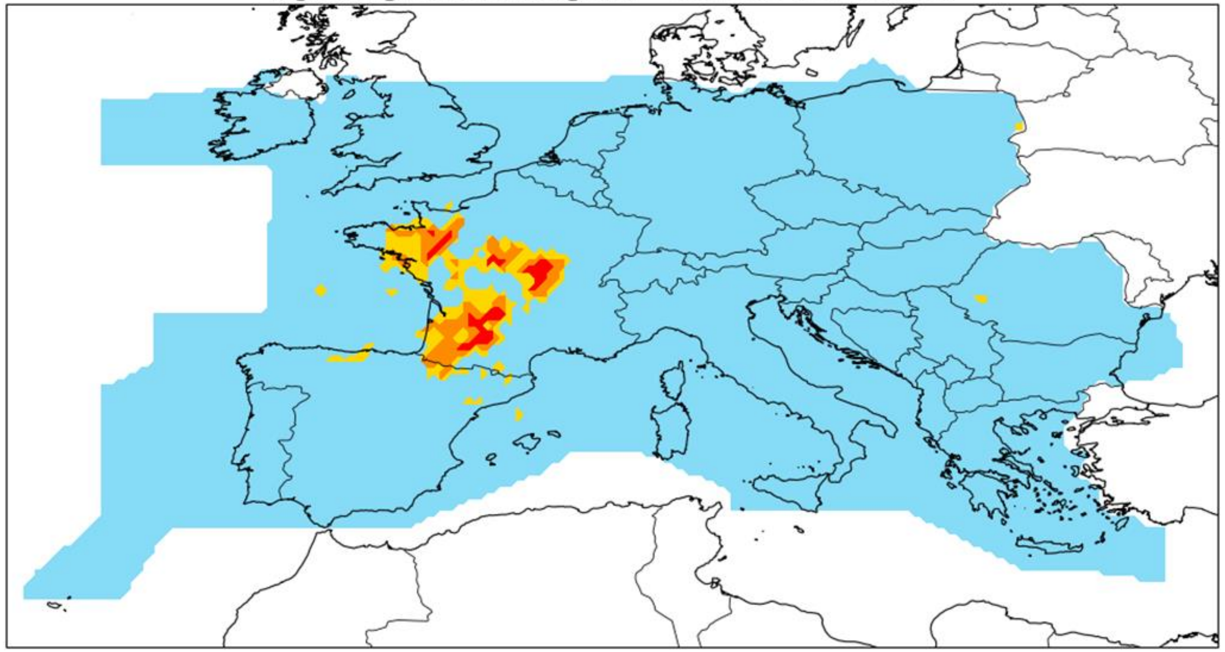
AI Convection Predictions - 2025-06-25 15:00:00



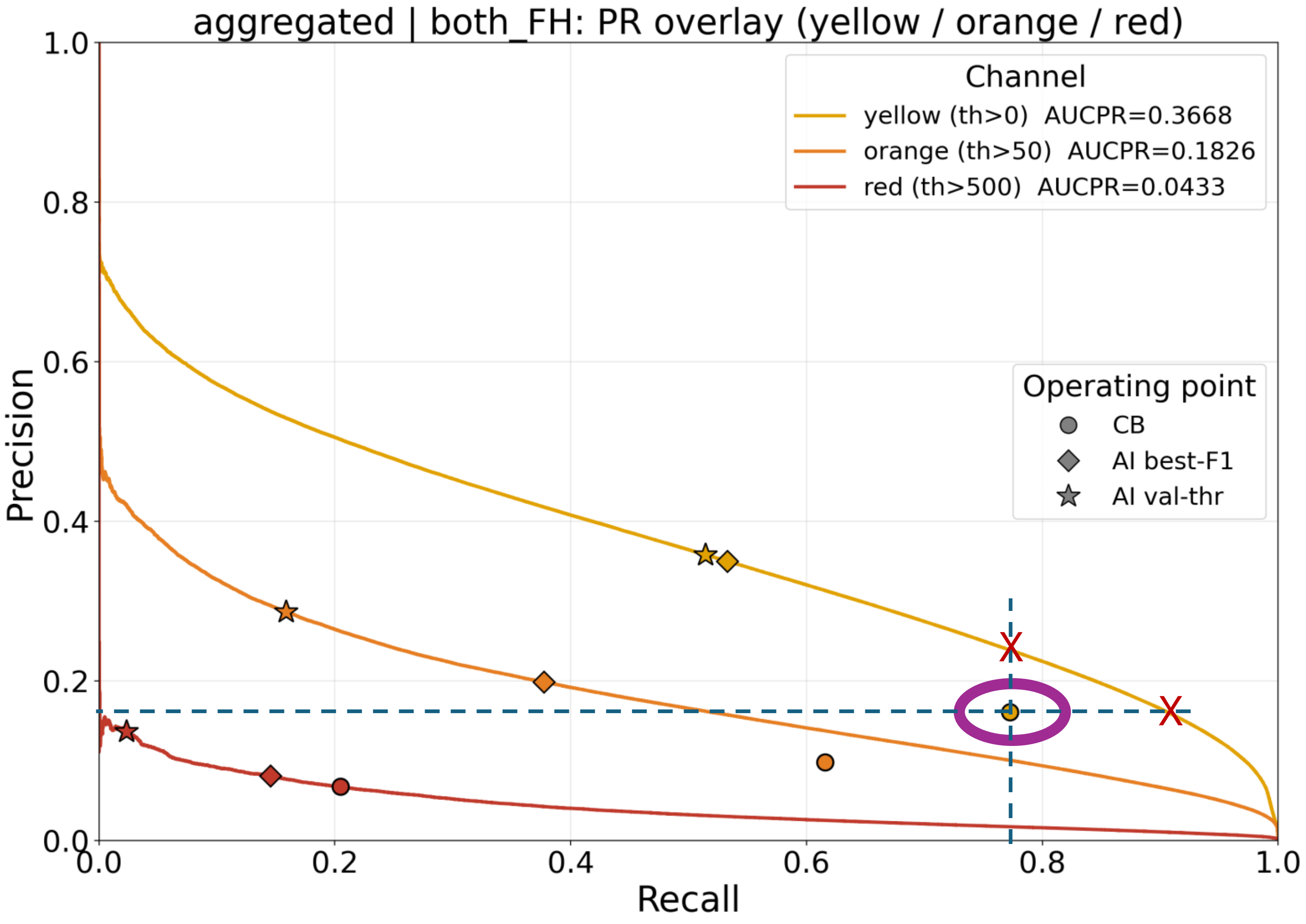
CBCF Predictions - 2025-06-25 15:00:00



Lightning Strikes (Targets) - 2025-06-25 15:00:00

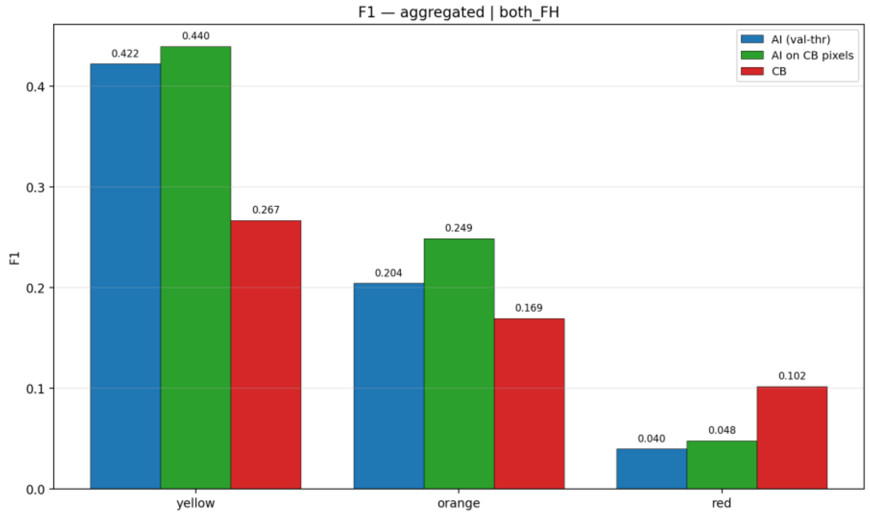


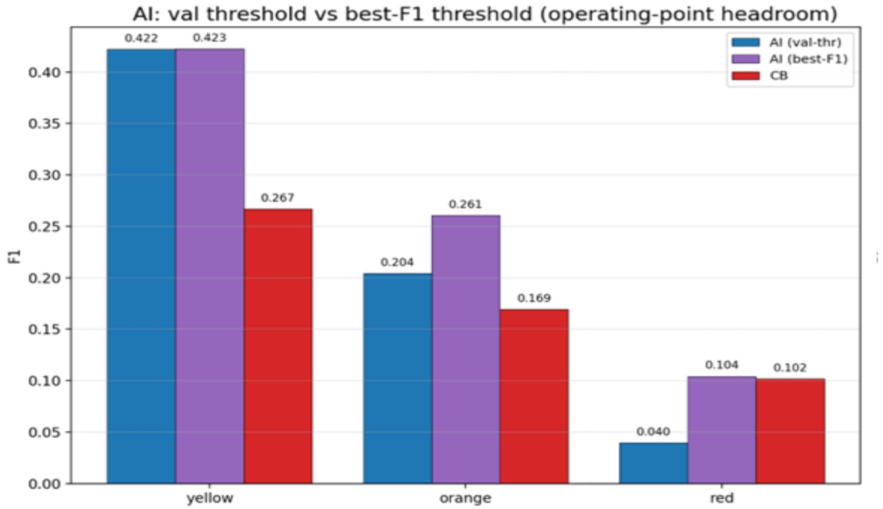
Results. Cross Border Convection Forecast Baseline Comparison



Precision — What fraction of predicted positives are correct

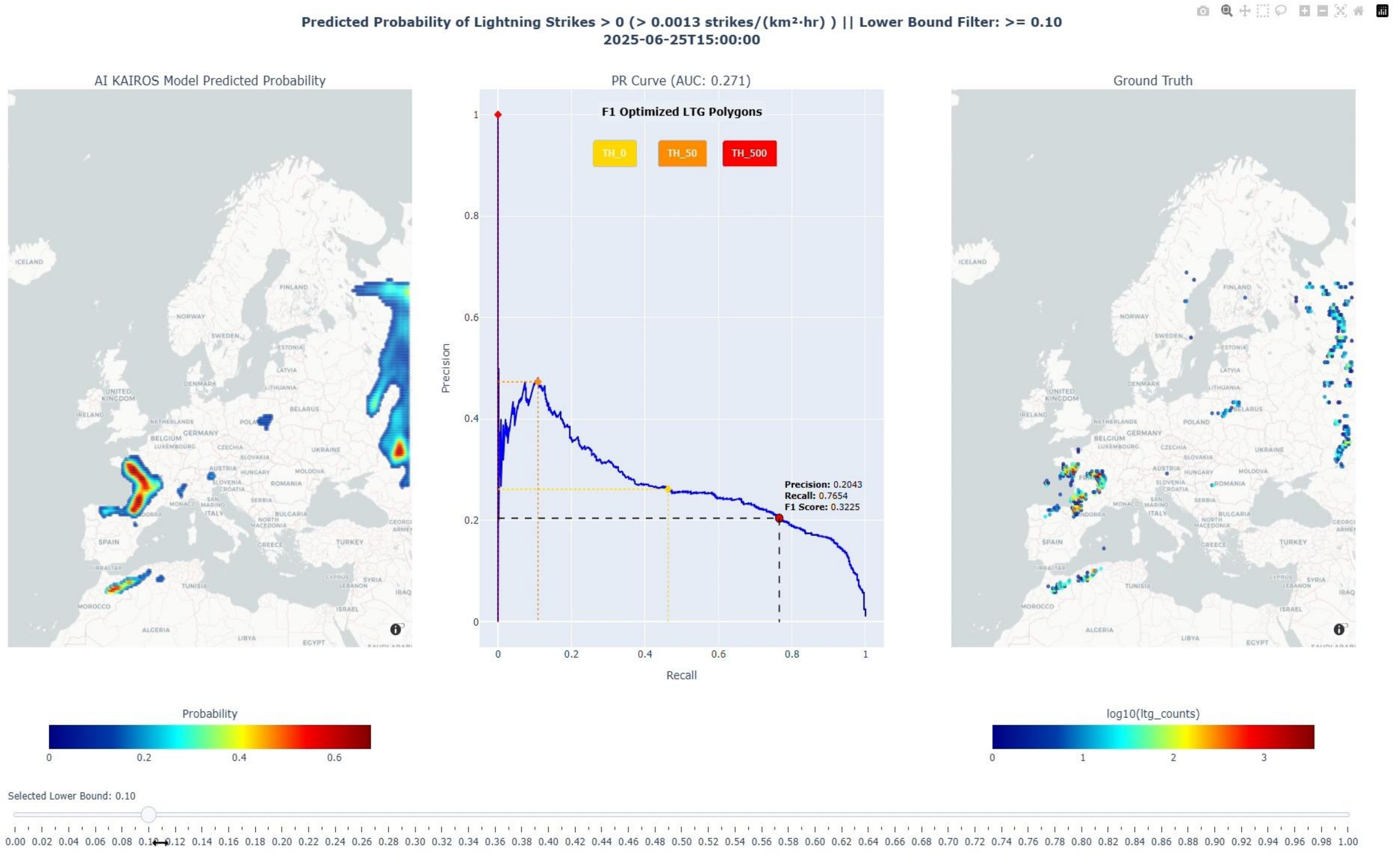
Recall — What fraction of actual positives were found





F1 — Harmonic mean of Precision and Recall

Results. Cross Border Convection Forecast Baseline Comparison



Next Steps

Short-range model · 12–72 h **Finalising journal article**

Model validated and benchmarked against EUMETNET / DWD CBCF — manuscript in preparation, submission in the coming months.

Very short-range model · 2–12 h **Next research cycle**

Hybrid AI model fusing satellite, radar, lightning and NWP — targeting the convective gap zone (2–6 h).

Nowcasting model · 0–2 h **?**

Generative / multi-source model for cell-level prediction in support of tactical ATM decisions.

Achievements

Conferences:

- Sesar Innovation Days 2025 Poster Exhibition
- Aeronautical Meteorology Scientific Conference 2024 at WMO (AeroMetSci-2024) presentation *“AI Convection Prediction”*

✓ JCR Publication (as part of the motivation of the PhD):

Predicting Air Traffic Flow Management hotspots due to weather using Convolutional Neural Networks

Martínez, I., García-Heras, J., Jardines, A., Cervantes, A., & Soler, M. (2024).

✓ 3 ECTS Complementary course on *Machine Learning in Timeseries and Data Streams*

Dirección General de Investigación e Innovación Tecnológica
CONSEJERÍA DE CIENCIA, UNIVERSIDADES E INNOVACIÓN

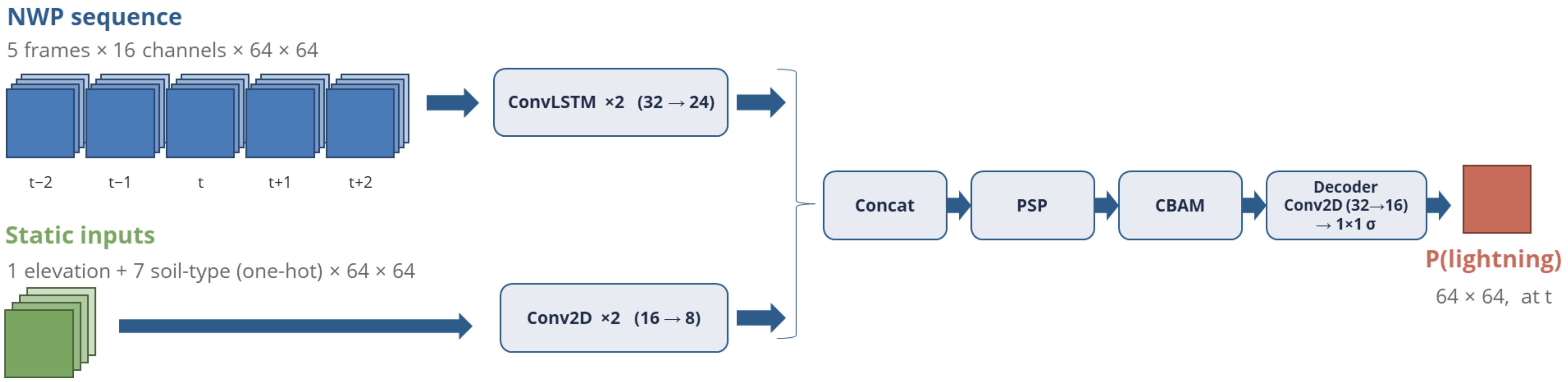
Thank you!
Questions?

Improving Thunderstorm Prediction for Aviation using Artificial Intelligence

PhD Student: Iván Martínez Vidal
Supervisor/s: Manuel Soler

Backup Slides

ConvLSTM-based lightning forecasting model



Training & forecast framing

- **Loss:** binary cross-entropy.
- Early stopping on validation AUC-PR.
- **Forecast framing** — the model ingests an IFS NWP sequence from t−2 to t+2 to predict the lightning field at t. Operationally, IFS forecasts up to D+2 from the cycle hour allow the input window to be stepped forward, producing lightning forecasts at corresponding lead times; in the historical record only the latest available cycle was retained, restricting reconstructable leads to 0–5 h.

Architecture details

- **Dynamic branch** — two stacked ConvLSTM2D layers (32 then 24 hidden channels, 3 × 3 kernels, recurrent dropout 0.2), with batch normalisation and spatial dropout.
- **Static branch** — two 2D convolutional layers (16 then 8 channels, 3 × 3 kernels), with batch normalisation and spatial dropout.
- Fusion — **concatenation**, then **PSP** module aggregating context at four pooling scales, followed by **CBAM** (channel + spatial attention).
- **Decoder** — two 3 × 3 convolutions (32 then 16 channels) and a 1 × 1 sigmoid convolution producing per-pixel lightning probability at t.

Short Range Forecast Model: Composite

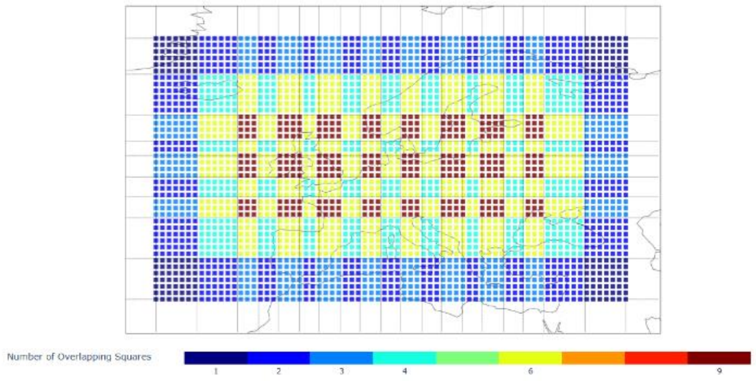
Continental-scale forecast composite through Hamming-weighted tiles

Inference scheme

Predictions are generated independently on overlapping 64 × 64 test-grid tiles and recombined into a single continental field per timestamp through weighted stitching.

Weighting

Each tile contributes its prediction multiplied by a separable 2D Hamming window $w(i, j) = w_{1D}(i) \cdot w_{1D}(j)$. Hamming is preferred over Hanning, which reaches zero at tile edges and would produce undefined values at pixels covered by only one tile.

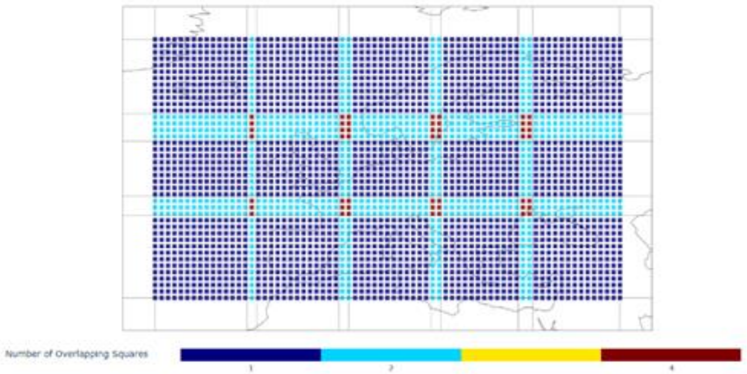


Composite construction

$$\hat{p}(r, c, t) = \Sigma_k \mathbb{1}_k(r,c) \cdot w_k(r,c) \cdot p_k(r,c,t) \ / \ \Sigma_k \mathbb{1}_k(r,c) \cdot w_k(r,c)$$

p_k — prediction from tile k; w_k — Hamming weight at the tile-local coordinate; $\mathbb{1}_k(r,c)$ — indicator that pixel (r,c) lies within tile k.

Per-pixel normalisation by the accumulated weight ensures that single-tile pixels recover the raw tile prediction, while multi-tile pixels obtain a weight-consistent blend that suppresses edge artefacts arising from the finite convolutional receptive field.



Short Range Forecast Model: Calibration

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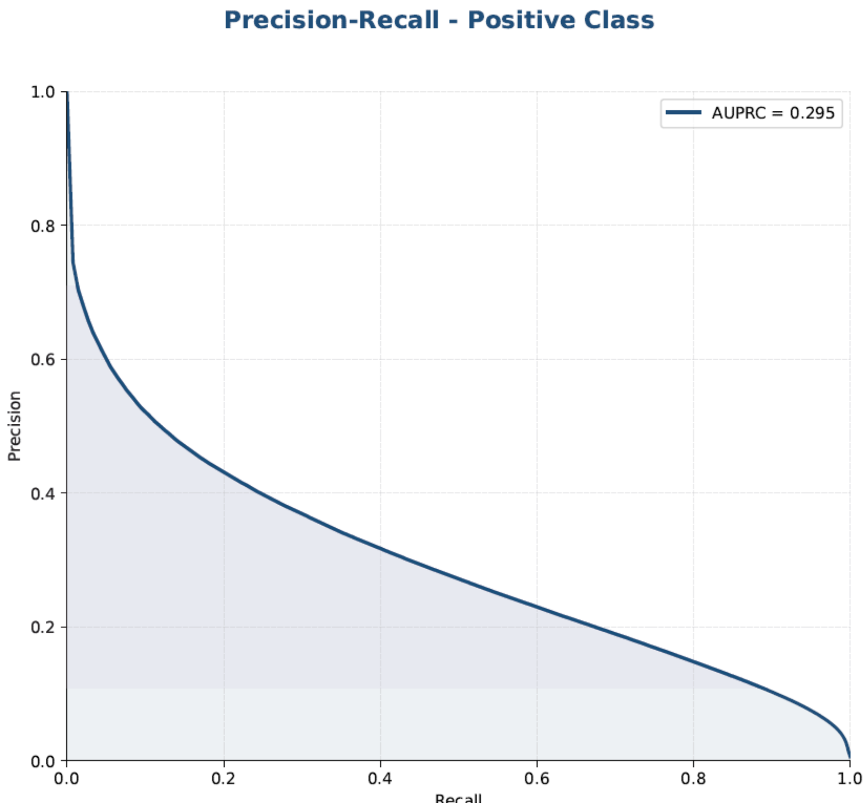

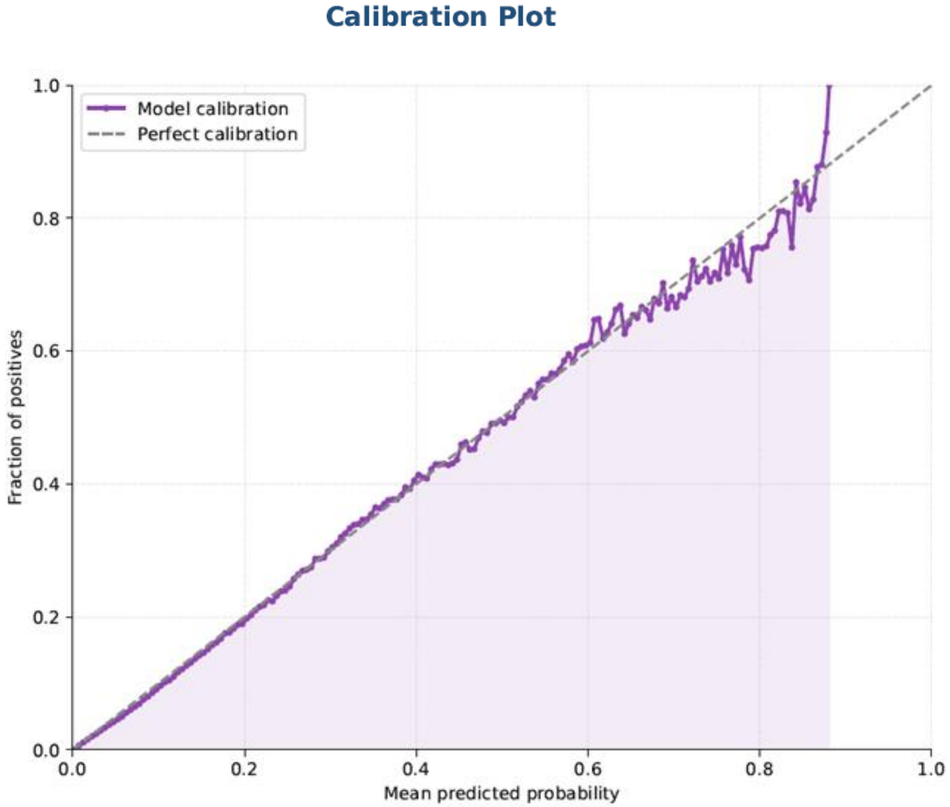

Short Range Forecast Model: Example