

UEF2026



Medium-Range Temperature Regime Transitions over Montenegro's Complex Terrain

A Comparison of AI and NWP Forecasts

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Presentation Outline

01 **Model specifications and observational data**
(models and stations selection, data sources, and resolution)

02 **Methodology**

03 **Results**
AI models vs. NWP for 2-metre temperature forecasts
(verification metrics)
AI models vs. NWP for 850 hPa temperature forecasts
(verification metrics)

04 **Conslusions and recommendations for future work**

Early detection of significant temperature changes over the following 15 days is important for:

- **Issuing timely public warnings** related to abrupt temperature variations
- **Supporting flood preparedness** during springtime warming episodes in the presence of snow cover
- **Providing input for the energy sector**, particularly for temperature-driven energy consumption forecasts

Although IHMS does not provide operational forecast bulletins beyond a three-day range, extended weather outlooks and public forecast broadcasts are used to communicate potential abrupt changes in weather regimes up to about 10 days ahead.

Model Specifications

- PanguWeather:** aifs_model Python package; **0-360 h**, 6-hourly output, daily 00 UTC initialization during the 2024 - 2025 period
- GraphCast:** aifs_model Python package; **0-120 h**, 6-hourly output, daily 00 UTC initialization during the 2024 - 2025 period
- FourCastNet:** aifs_model Python package; **0-360 h**, 6-hourly output, daily 00 UTC initialization during the 2024 - 2025 period
- AIFS Single:** MARS archive; **0-360 h**, 6-hourly output, daily 00 UTC initialization during the March 2024 - 2025 period
- IFS Single:** MARS archive; **0-240 / 360 h**, 6-hourly output, daily 00 UTC initialization during the 2024 - 2025 period

Observation Stations

Bar – coastal station, located very close to the shoreline

Žabljak – mountain station in northern Montenegro, at approximately 1,500 m a.s.l.

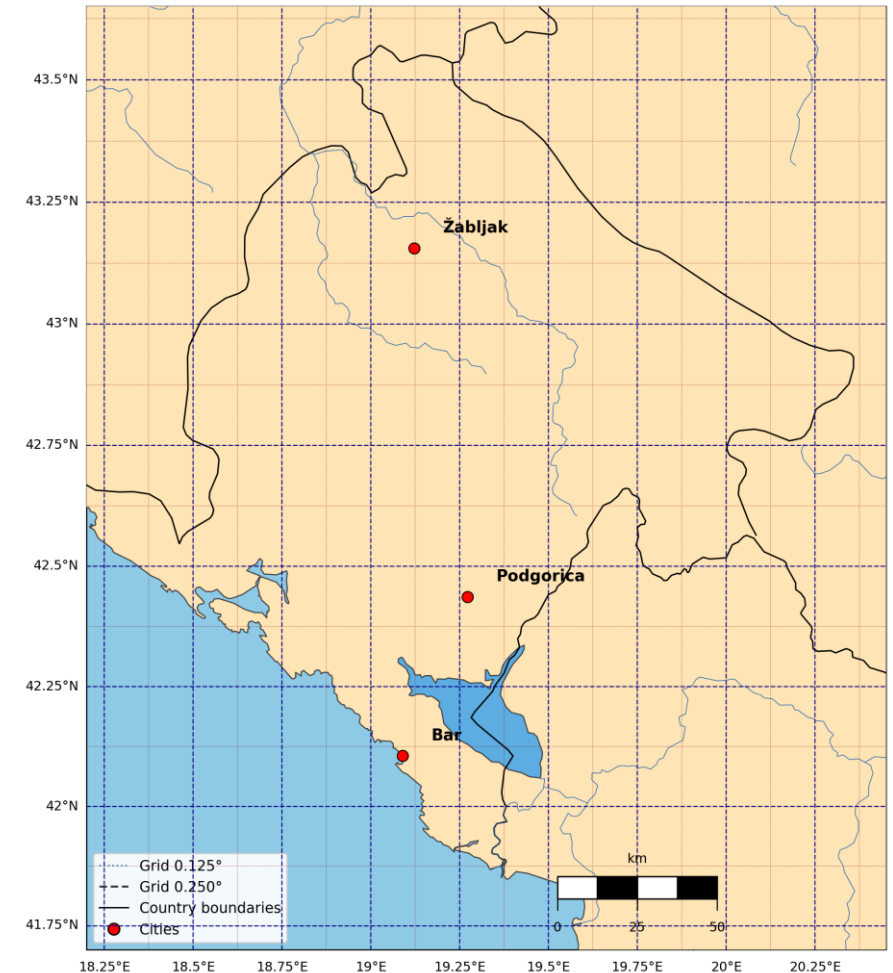
Podgorica – lowland station situated on flat, uniform terrain within the largest plain in Montenegro.

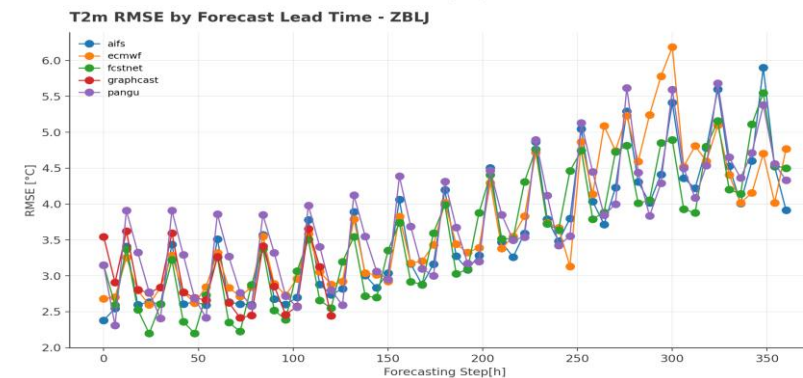
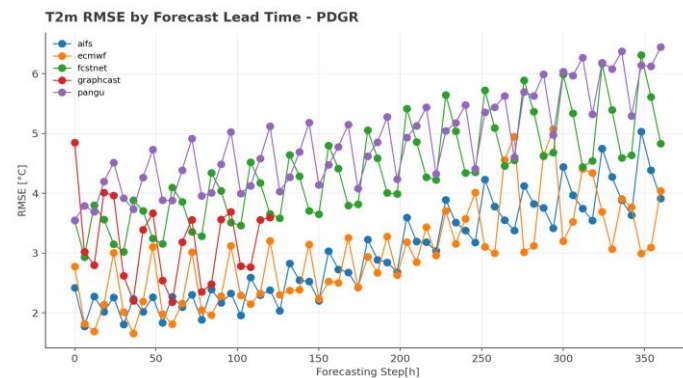
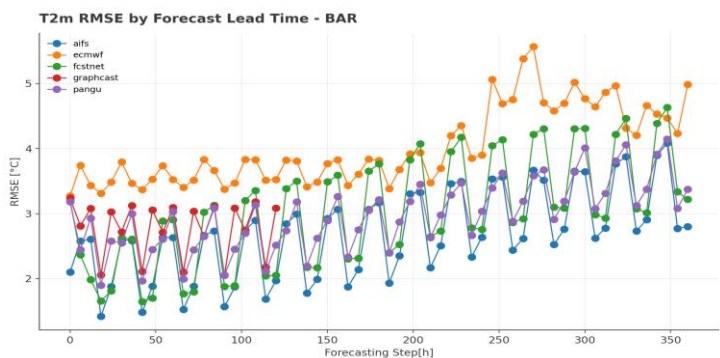
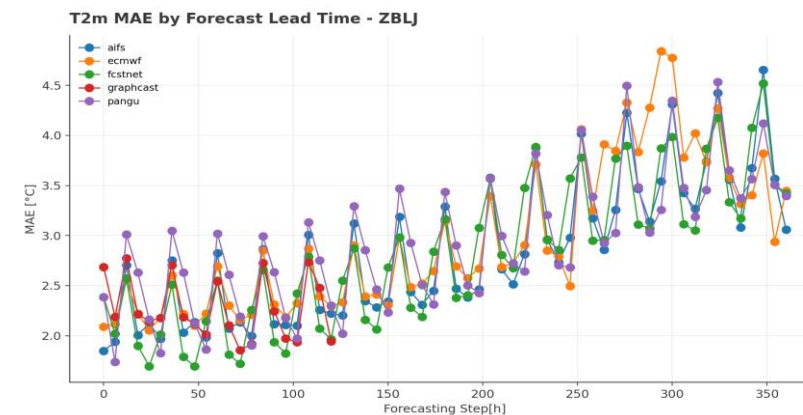
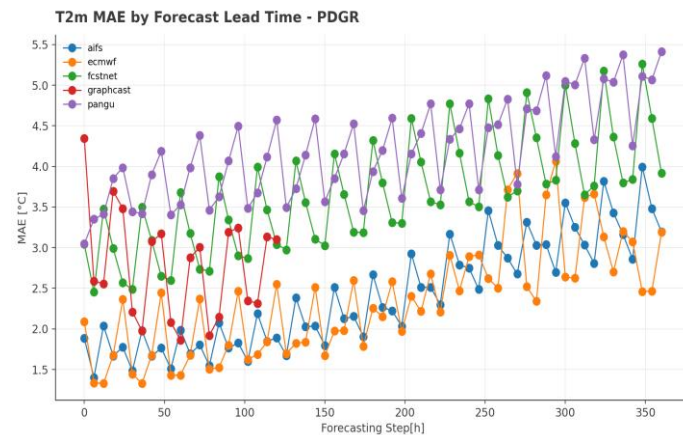
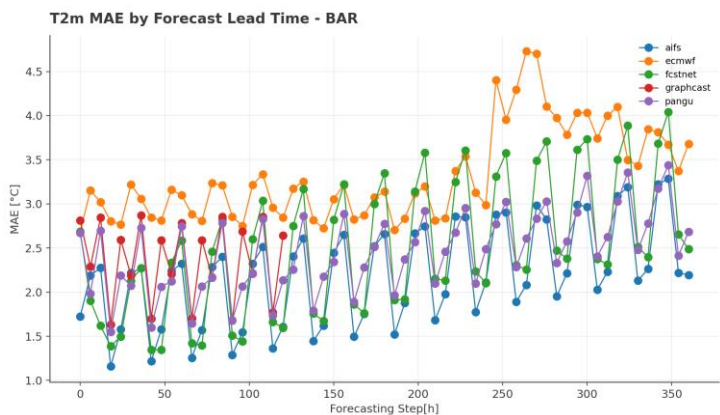
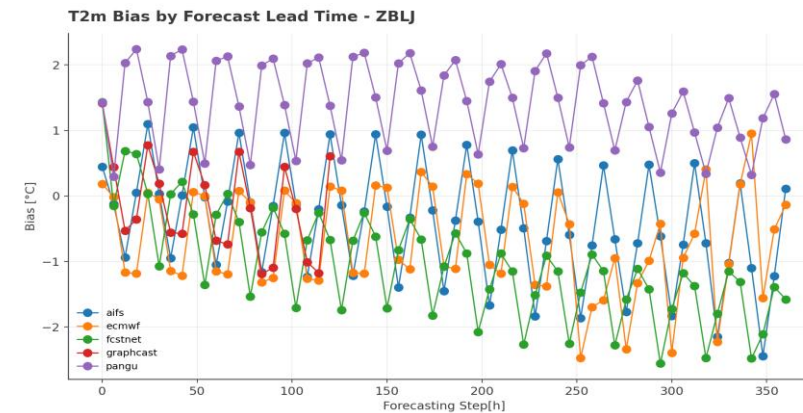
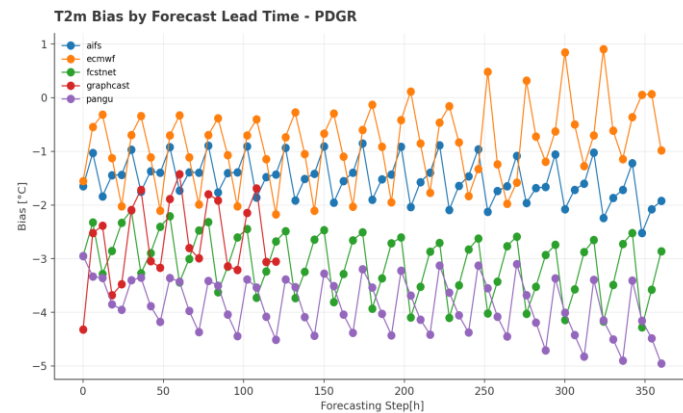
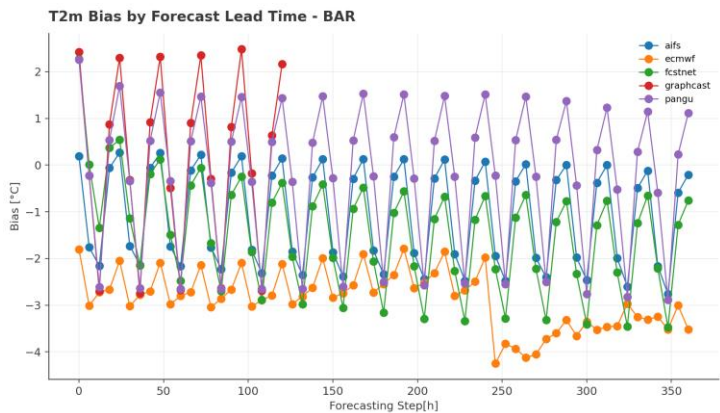
*For the verification of 850 hPa temperature forecasts, observational data were obtained from the University of Wyoming upper-air sounding archive, using **Sjenica** and **Belgrade** as the nearest available radiosonde stations.*

Forecasts from the **nearest model grid point** were used without any post-processing or interpolation.

Python packages were primarily used for reading GRIB files, data processing and filtering, and visualization.

Montenegro — Cities with 0.125° and 0.250° Model Grids





Bias and RMSE

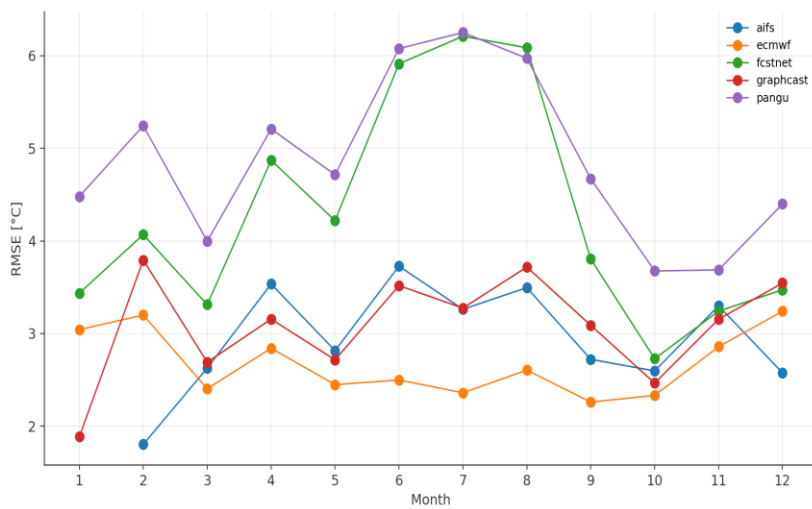
Bias = Tfcst - Tobs shows a clear **diurnal cycle** for all models and stations, which is also reflected in **RMSE**.

Bar: *nighttime underestimation and daytime overestimation by most models; IFS shows persistent underestimation.
The newer IFS version shows higher bias and RMSE, both increasing with lead time after November 2024, when the forecast range was extended from 240 h to 360 h.*

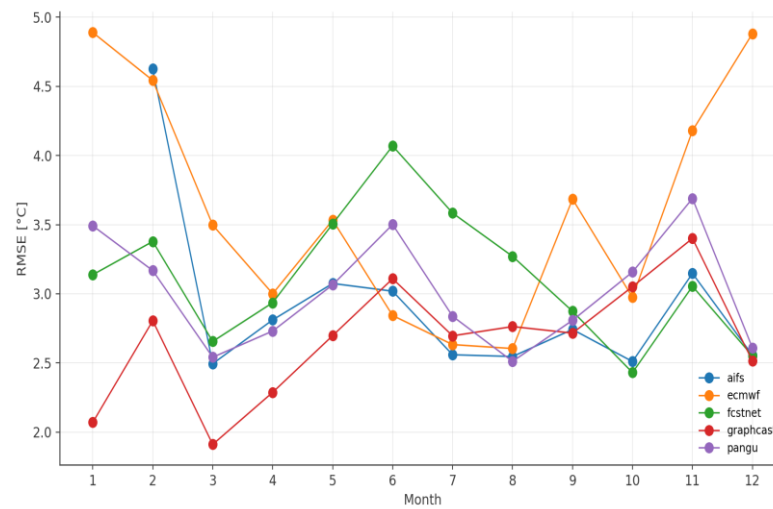
Podgorica: *underestimation throughout the day, stronger for FourCastNet and PanguWeather than for AIFS and IFS.*

Žabljak: *PanguWeather tends to overestimate, while the other models generally underestimate temperature.*

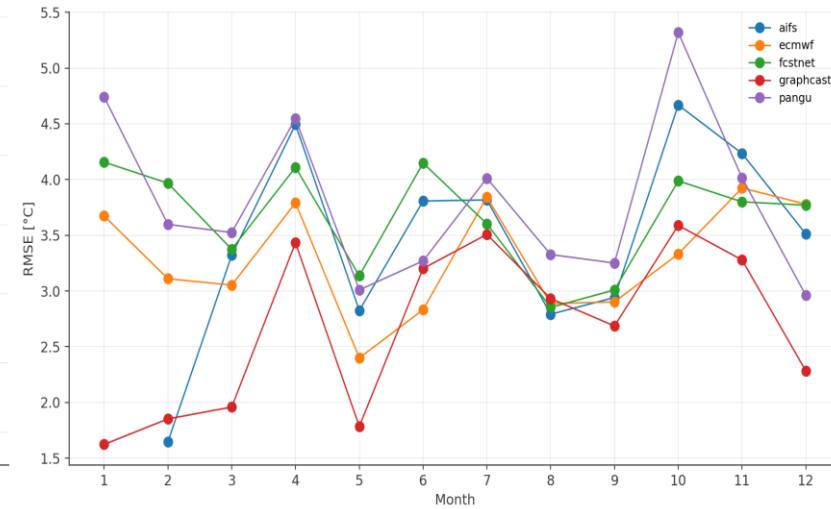
RMSE T2m by Month - Podgorica



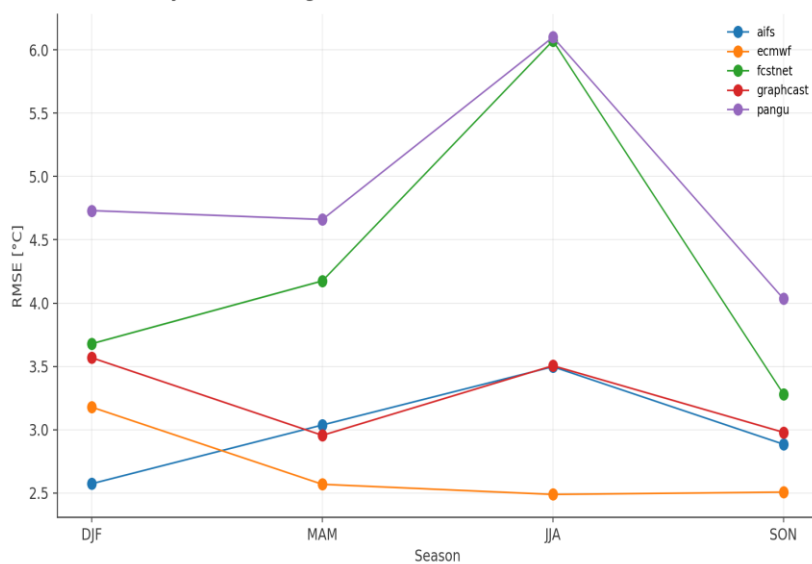
RMSE T2m by Month - Bar



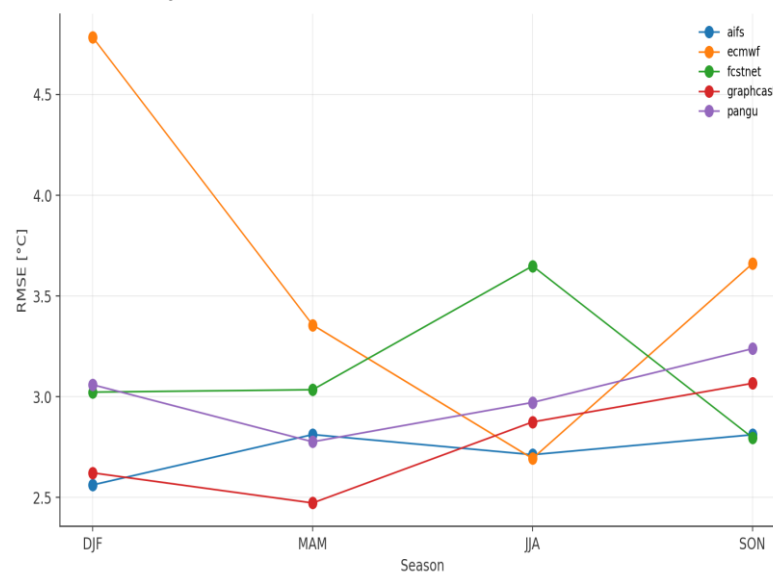
RMSE T2m by Month - Zabljak



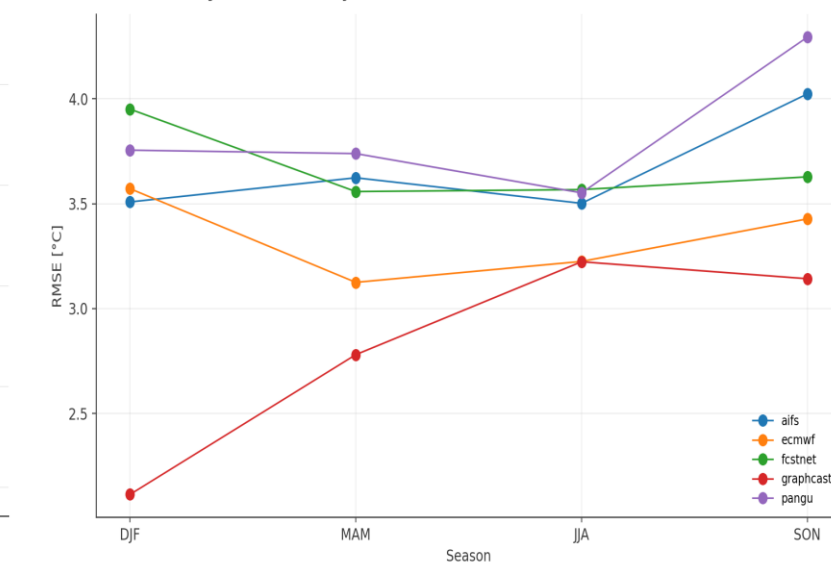
RMSE T2m by Season - Podgorica



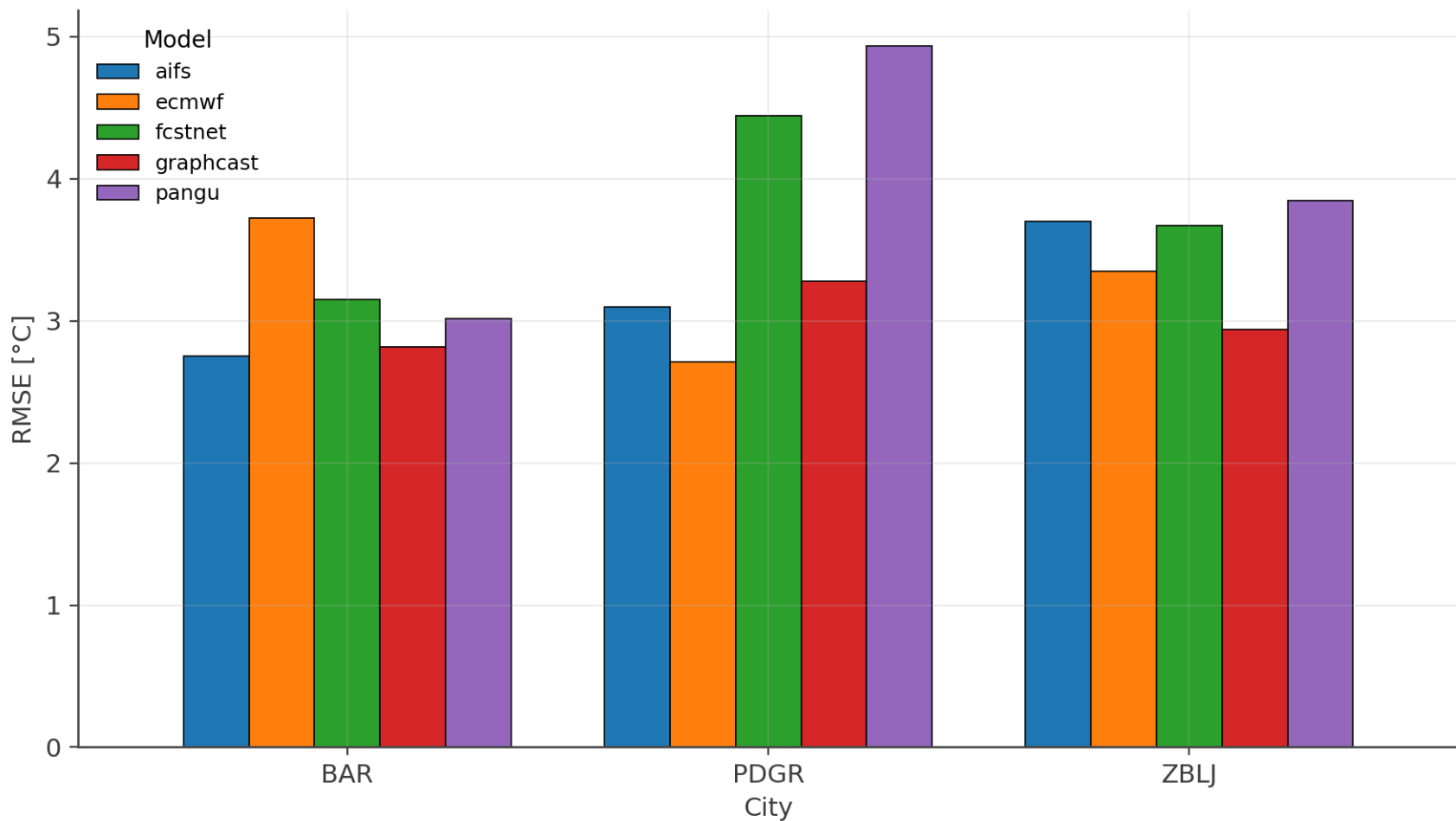
RMSE T2m by Season - Bar



RMSE T2m by Season - Zabljak



Total RMSE T2m by city



- POD (Probability of Detection)** measures the ability to detect observed events; higher values indicate fewer missed events.
- FAR (False Alarm Ratio)** measures the proportion of false alarms among forecast events; lower values indicate fewer false alarms.
- CSI (Critical Success Index)** combines hits, misses, and false alarms, making it suitable for evaluating relatively rare events.
- Accuracy** measures the overall fraction of correct forecasts, but may be misleading when non-events dominate.
- Frequency Bias** shows whether the model forecasts events too frequently or too rarely; the ideal value is 1.

Warming event

- TP = warming forecast and warming observed
- TN = no warming forecast and no warming observed
- FP = warming forecast but no warming observed
- FN = warming observed but no warming forecast

Cooling event

- TP = cooling forecast and cooling observed
- TN = no cooling forecast and no cooling observed
- FP = cooling forecast but no cooling observed
- FN = cooling observed but no cooling forecast

Zabljak (ZBLJ) | Event type: **Warming** | ΔT24h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.23	0.70	0.15	0.87	0.77
ECMWF	0.36	0.65	0.22	0.85	1.02
FourCastNet	0.19	0.57	0.15	0.88	0.44
GraphCast	0.39	0.56	0.26	0.89	0.90
PanguWeather	0.30	0.63	0.20	0.86	0.81

Zabljak (ZBLJ) | Event type: **Warming** | ΔT24h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.10	0.78	0.07	0.95	0.47
ECMWF	0.17	0.76	0.11	0.93	0.69
FourCastNet	0.08	0.67	0.07	0.95	0.24
GraphCast	0.22	0.61	0.16	0.96	0.56
PanguWeather	0.14	0.73	0.10	0.94	0.52

Zabljak (ZBLJ) | Event type: **Warming** | ΔT48h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.34	0.65	0.21	0.78	0.96
ECMWF	0.46	0.56	0.29	0.79	1.04
FourCastNet	0.28	0.57	0.21	0.80	0.66
GraphCast	0.47	0.52	0.31	0.82	1.00
PanguWeather	0.37	0.60	0.24	0.78	0.92

Zabljak (ZBLJ) | Event type: **Warming** | ΔT48h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.23	0.79	0.12	0.91	1.06
ECMWF	0.37	0.68	0.21	0.90	1.17
FourCastNet	0.19	0.64	0.14	0.92	0.54
GraphCast	0.41	0.69	0.21	0.92	1.34
PanguWeather	0.26	0.73	0.15	0.89	0.97

Zabljak (ZBLJ) | Event type: **Cooling** | ΔT24h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.28	0.66	0.18	0.84	0.81
ECMWF	0.37	0.59	0.24	0.84	0.91
FourCastNet	0.25	0.62	0.18	0.84	0.67
GraphCast	0.43	0.49	0.31	0.88	0.85
PanguWeather	0.31	0.62	0.21	0.84	0.81

Zabljak (ZBLJ) | Event type: **Cooling** | ΔT24h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.24	0.72	0.15	0.94	0.87
ECMWF	0.39	0.60	0.24	0.94	0.98
FourCastNet	0.22	0.65	0.16	0.94	0.63
GraphCast	0.46	0.54	0.30	0.96	0.99
PanguWeather	0.26	0.71	0.16	0.93	0.89

Zabljak (ZBLJ) | Event type: **Cooling** | ΔT48h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.34	0.67	0.20	0.76	1.02
ECMWF	0.45	0.56	0.29	0.79	1.01
FourCastNet	0.33	0.62	0.21	0.77	0.85
GraphCast	0.51	0.51	0.33	0.82	1.03
PanguWeather	0.37	0.61	0.24	0.77	0.94

Zabljak (ZBLJ) | Event type: **Cooling** | ΔT48h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.31	0.73	0.17	0.88	1.14
ECMWF	0.44	0.60	0.27	0.90	1.11
FourCastNet	0.32	0.67	0.19	0.90	0.97
GraphCast	0.47	0.62	0.27	0.91	1.25
PanguWeather	0.37	0.67	0.21	0.89	1.13

Bar (BAR) | Event type: Cooling | ΔT24h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.15	0.54	0.13	0.90	0.32
ECMWF	0.25	0.61	0.18	0.87	0.64
FourCastNet	0.12	0.53	0.11	0.89	0.26
GraphCast	0.19	0.20	0.18	0.91	0.24
PanguWeather	0.12	0.50	0.11	0.89	0.24

Bar (BAR) | Event type: Cooling | ΔT24h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.04	0.72	0.04	0.96	0.16
ECMWF	0.15	0.69	0.11	0.96	0.47
FourCastNet	0.07	0.60	0.07	0.96	0.18
GraphCast	0.08	0.38	0.07	0.96	0.12
PanguWeather	0.06	0.56	0.06	0.96	0.14

Bar (BAR) | Event type: Cooling | ΔT48h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.23	0.52	0.19	0.85	0.48
ECMWF	0.36	0.55	0.25	0.84	0.80
FourCastNet	0.23	0.52	0.18	0.85	0.47
GraphCast	0.31	0.31	0.27	0.87	0.45
PanguWeather	0.21	0.51	0.17	0.85	0.43

Bar (BAR) | Event type: Cooling | ΔT48h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.11	0.65	0.09	0.94	0.32
ECMWF	0.28	0.62	0.19	0.93	0.73
FourCastNet	0.16	0.55	0.13	0.94	0.36
GraphCast	0.09	0.43	0.08	0.95	0.16
PanguWeather	0.12	0.57	0.10	0.94	0.27

Bar (BAR) | Event type: Warming | ΔT24h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.05	0.55	0.05	0.91	0.11
ECMWF	0.11	0.78	0.08	0.87	0.52
FourCastNet	0.05	0.47	0.04	0.90	0.09
GraphCast	0.05	0.12	0.05	0.91	0.06
PanguWeather	0.02	0.62	0.02	0.89	0.06

Bar (BAR) | Event type: Warming | ΔT24h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.01	0.70	0.01	0.97	0.02
ECMWF	0.02	0.89	0.02	0.96	0.21
FourCastNet	0.00	0.78	0.00	0.96	0.01
GraphCast	0.00	1.00	0.00	0.97	0.03
PanguWeather	0.00	0.93	0.00	0.96	0.02

Bar (BAR) | Event type: Warming | ΔT48h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.13	0.59	0.11	0.87	0.31
ECMWF	0.30	0.67	0.19	0.82	0.90
FourCastNet	0.12	0.52	0.11	0.86	0.26
GraphCast	0.12	0.41	0.11	0.88	0.21
PanguWeather	0.10	0.52	0.09	0.86	0.21

Bar (BAR) | Event type: Warming | ΔT48h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.00	0.98	0.00	0.96	0.11
ECMWF	0.10	0.81	0.07	0.94	0.56
FourCastNet	0.04	0.58	0.04	0.95	0.10
GraphCast	0.00	1.00	0.00	0.96	0.01
PanguWeather	0.01	0.79	0.01	0.95	0.06

Podgorica (PDGR) | Event type: Cooling | ΔT24h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.21	0.57	0.17	0.87	0.50
ECMWF	0.28	0.61	0.20	0.85	0.73
FourCastNet	0.16	0.55	0.14	0.87	0.36
GraphCast	0.34	0.36	0.28	0.90	0.53
PanguWeather	0.22	0.64	0.16	0.86	0.61

Podgorica (PDGR) | Event type: Cooling | ΔT24h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.15	0.66	0.12	0.96	0.45
ECMWF	0.19	0.69	0.13	0.95	0.60
FourCastNet	0.08	0.74	0.07	0.95	0.33
GraphCast	0.25	0.54	0.19	0.96	0.54
PanguWeather	0.14	0.76	0.10	0.95	0.60

Podgorica (PDGR) | Event type: Cooling | ΔT48h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.34	0.50	0.26	0.83	0.69
ECMWF	0.42	0.48	0.30	0.83	0.81
FourCastNet	0.28	0.51	0.22	0.83	0.57
GraphCast	0.49	0.30	0.40	0.88	0.70
PanguWeather	0.38	0.54	0.26	0.82	0.84

Podgorica (PDGR) | Event type: Cooling | ΔT48h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.26	0.56	0.20	0.93	0.58
ECMWF	0.35	0.52	0.25	0.92	0.73
FourCastNet	0.21	0.59	0.16	0.92	0.50
GraphCast	0.44	0.27	0.38	0.95	0.61
PanguWeather	0.29	0.65	0.19	0.91	0.81

Podgorica (PDGR) | Event type: Warming | ΔT24h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.14	0.63	0.11	0.89	0.37
ECMWF	0.23	0.69	0.15	0.87	0.74
FourCastNet	0.09	0.64	0.08	0.89	0.24
GraphCast	0.31	0.52	0.23	0.90	0.63
PanguWeather	0.16	0.65	0.13	0.88	0.47

Podgorica (PDGR) | Event type: Warming | ΔT24h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.06	0.65	0.05	0.98	0.16
ECMWF	0.08	0.87	0.05	0.96	0.64
FourCastNet	0.02	0.85	0.02	0.97	0.14
GraphCast	0.12	0.70	0.09	0.97	0.40
PanguWeather	0.08	0.76	0.06	0.97	0.32

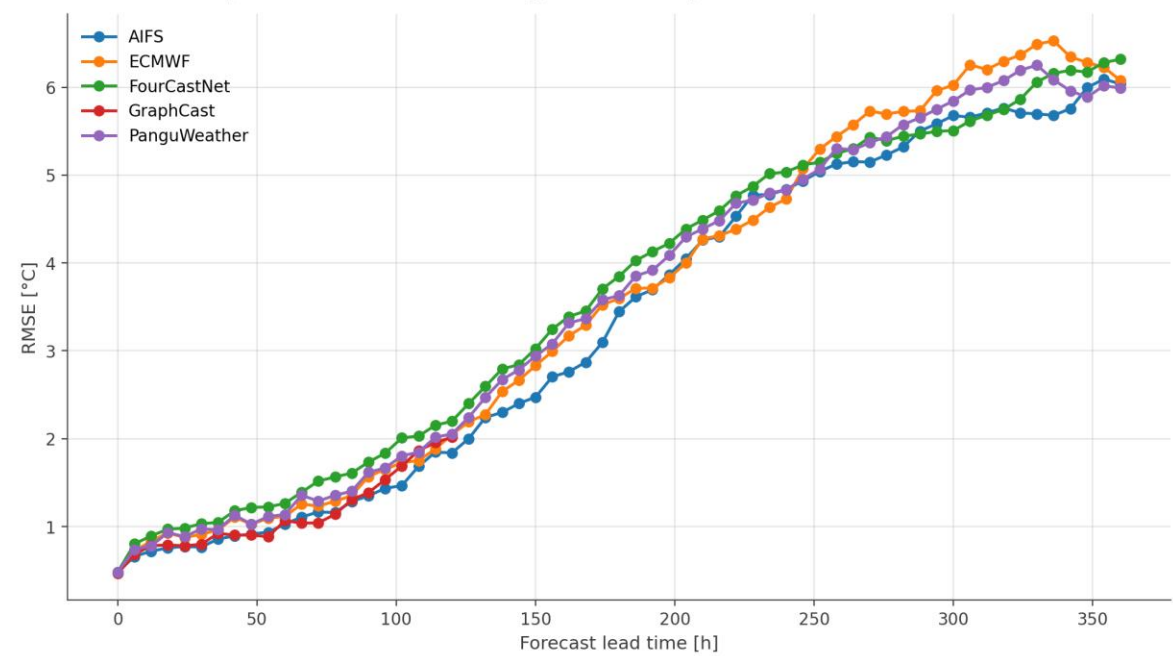
Podgorica (PDGR) | Event type: Warming | ΔT48h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.28	0.51	0.22	0.84	0.58
ECMWF	0.38	0.54	0.26	0.82	0.82
FourCastNet	0.22	0.53	0.18	0.83	0.47
GraphCast	0.49	0.49	0.34	0.84	0.97
PanguWeather	0.32	0.56	0.23	0.82	0.73

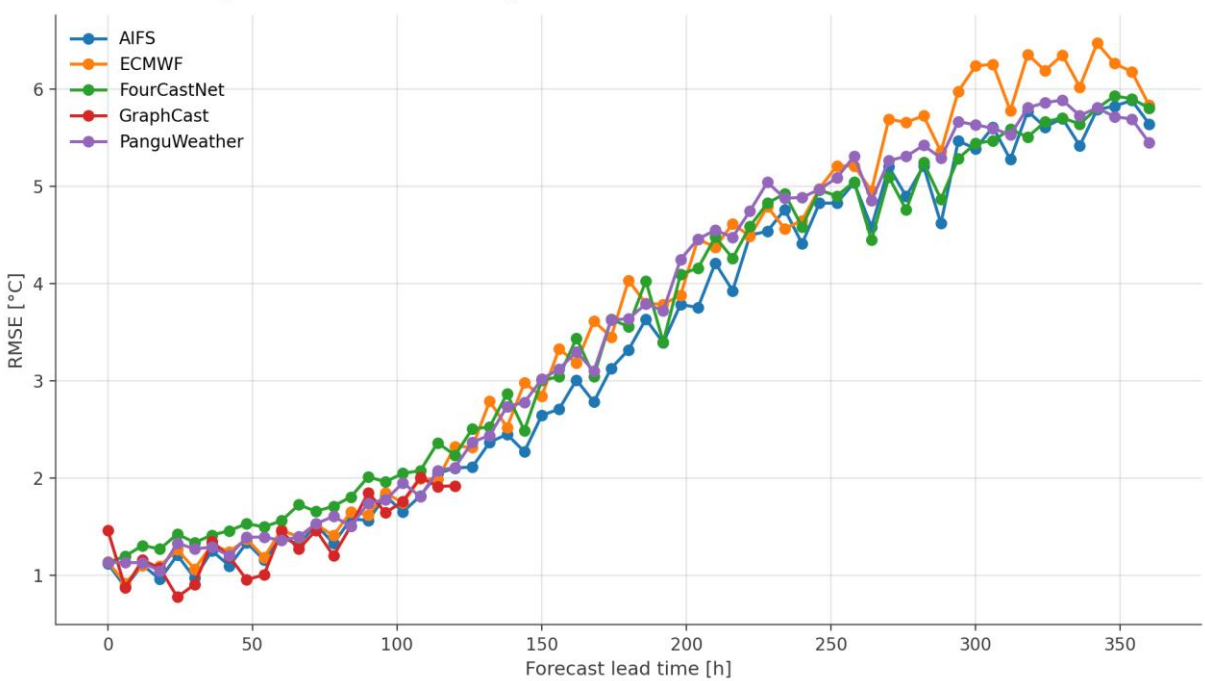
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ECMWF	0.21	0.76	0.12	0.93	0.87
FourCastNet	0.09	0.74	0.07	0.94	0.34
GraphCast	0.34	0.60	0.22	0.95	0.84
PanguWeather	0.23	0.67	0.16	0.94	0.70

RMSE T850 by forecast lead time - Belgrade Košutnjak



RMSE T850 by forecast lead time - Sjenica



Belgrade Košutnjak (Belgrade_Kosutnjak) | Event type: Cooling | ΔT24h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.46	0.50	0.32	0.84	0.93
ECMWF	0.48	0.50	0.33	0.84	0.95
FourCastNet	0.41	0.53	0.28	0.83	0.86
GraphCast	0.71	0.15	0.63	0.93	0.83
PanguWeather	0.44	0.54	0.29	0.83	0.96

Belgrade Košutnjak (Belgrade_Kosutnjak) | Event type: Cooling | ΔT24h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.41	0.54	0.28	0.91	0.88
ECMWF	0.41	0.52	0.29	0.91	0.85
FourCastNet	0.33	0.56	0.23	0.91	0.75
GraphCast	0.69	0.15	0.61	0.96	0.81
PanguWeather	0.36	0.59	0.24	0.90	0.88

Belgrade Košutnjak (Belgrade_Kosutnjak) | Event type: Cooling | ΔT48h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.55	0.42	0.39	0.79	0.96
ECMWF	0.56	0.40	0.41	0.80	0.93
FourCastNet	0.50	0.45	0.36	0.77	0.91
GraphCast	0.80	0.14	0.71	0.92	0.92
PanguWeather	0.53	0.45	0.37	0.77	0.97

Belgrade Košutnjak (Belgrade_Kosutnjak) | Event type: Cooling | ΔT48h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.48	0.48	0.33	0.86	0.94
ECMWF	0.49	0.44	0.35	0.87	0.88
FourCastNet	0.42	0.52	0.29	0.85	0.86
GraphCast	0.77	0.09	0.72	0.96	0.84
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ECMWF	0.45	0.48	0.32	0.83	0.85
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GraphCast	0.67	0.17	0.59	0.92	0.81
PanguWeather	0.42	0.51	0.29	0.82	0.85

Belgrade Košutnjak (Belgrade_Kosutnjak) | Event type: Warming | ΔT24h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.33	0.56	0.23	0.94	0.74
ECMWF	0.38	0.58	0.25	0.94	0.90
FourCastNet	0.26	0.55	0.20	0.93	0.59
GraphCast	0.55	0.15	0.50	0.97	0.64
PanguWeather	0.34	0.61	0.22	0.93	0.86

Belgrade Košutnjak (Belgrade_Kosutnjak) | Event type: Warming | ΔT48h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.54	0.40	0.40	0.78	0.90
ECMWF	0.59	0.38	0.44	0.79	0.94
FourCastNet	0.50	0.41	0.37	0.77	0.86
GraphCast	0.79	0.14	0.70	0.91	0.93
PanguWeather	0.53	0.42	0.38	0.77	0.90

Belgrade Košutnjak (Belgrade_Kosutnjak) | Event type: Warming | ΔT48h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.46	0.46	0.33	0.87	0.85
ECMWF	0.50	0.45	0.36	0.87	0.91
FourCastNet	0.41	0.47	0.30	0.86	0.77
GraphCast	0.72	0.10	0.67	0.95	0.80
PanguWeather	0.44	0.49	0.31	0.86	0.87

Sjenica (Sjenica) | Event type: Warming | ΔT24h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.37	0.48	0.28	0.83	0.72
ECMWF	0.40	0.53	0.28	0.81	0.85
FourCastNet	0.29	0.48	0.23	0.83	0.56
GraphCast	0.60	0.25	0.50	0.91	0.80
PanguWeather	0.37	0.53	0.26	0.81	0.79

Sjenica (Sjenica) | Event type: Warming | ΔT24h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.25	0.56	0.19	0.94	0.57
ECMWF	0.28	0.66	0.18	0.93	0.83
FourCastNet	0.16	0.55	0.13	0.94	0.35
GraphCast	0.49	0.22	0.43	0.96	0.63
PanguWeather	0.25	0.62	0.18	0.93	0.67

Sjenica (Sjenica) | Event type: Warming | ΔT48h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.52	0.39	0.39	0.78	0.86
ECMWF	0.55	0.41	0.40	0.76	0.93
FourCastNet	0.45	0.42	0.34	0.76	0.77
GraphCast	0.76	0.14	0.67	0.91	0.89
PanguWeather	0.51	0.43	0.37	0.76	0.89

Sjenica (Sjenica) | Event type: Warming | ΔT48h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.39	0.45	0.30	0.86	0.72
ECMWF	0.43	0.50	0.30	0.85	0.86
FourCastNet	0.30	0.46	0.24	0.85	0.56
GraphCast	0.64	0.17	0.57	0.93	0.78
PanguWeather	0.40	0.50	0.29	0.85	0.80

Sjenica (Sjenica) | Event type: Cooling | ΔT24h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.39	0.51	0.28	0.83	0.81
ECMWF	0.41	0.51	0.29	0.83	0.83
FourCastNet	0.35	0.52	0.25	0.83	0.72
GraphCast	0.69	0.17	0.60	0.92	0.83
PanguWeather	0.39	0.54	0.27	0.82	0.86

Sjenica (Sjenica) | Event type: Cooling | ΔT24h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.36	0.53	0.26	0.91	0.77
ECMWF	0.35	0.58	0.24	0.91	0.84
FourCastNet	0.30	0.53	0.22	0.92	0.64
GraphCast	0.70	0.17	0.61	0.96	0.84
PanguWeather	0.33	0.61	0.22	0.90	0.84

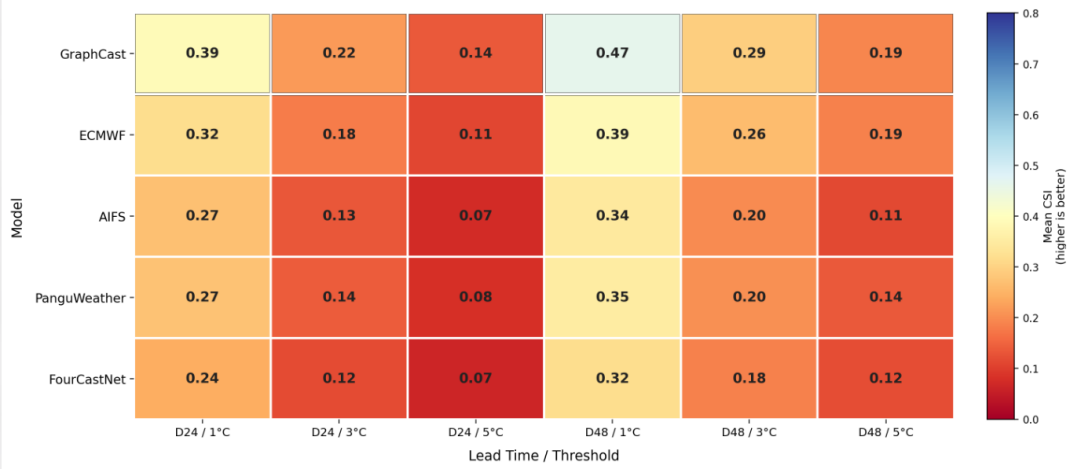
Sjenica (Sjenica) | Event type: Cooling | ΔT48h | Threshold: 3°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.51	0.42	0.37	0.77	0.87
ECMWF	0.50	0.42	0.37	0.77	0.86
FourCastNet	0.44	0.46	0.32	0.76	0.82
GraphCast	0.79	0.14	0.70	0.91	0.92
PanguWeather	0.50	0.46	0.35	0.76	0.91

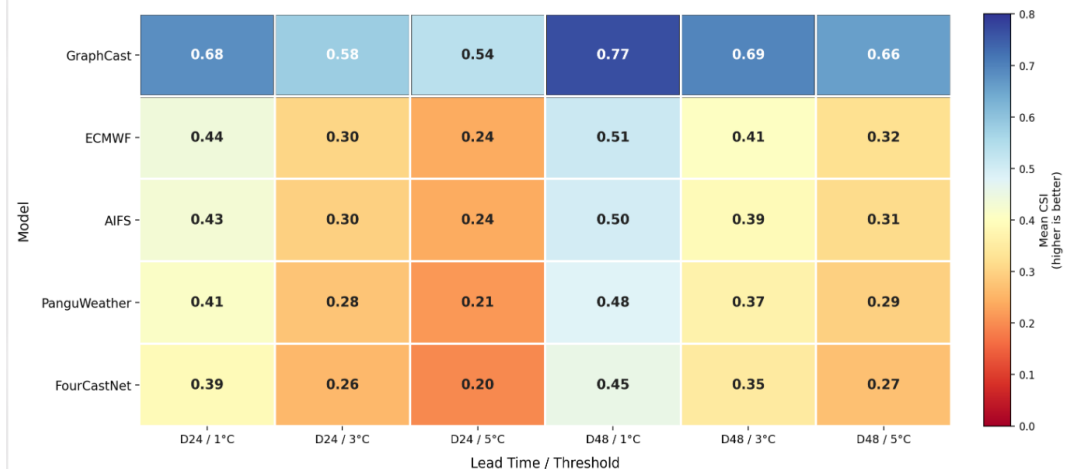
Sjenica (Sjenica) | Event type: Cooling | ΔT48h | Threshold: 5°C

Model	POD	FAR	CSI	Accuracy	Freq. Bias
AIFS	0.42	0.51	0.29	0.85	0.86
ECMWF	0.43	0.52	0.29	0.85	0.90
FourCastNet	0.35	0.53	0.25	0.85	0.74
GraphCast	0.73	0.11	0.67	0.94	0.82
PanguWeather	0.42	0.55	0.27	0.84	0.93

2 m Temperature (T2m) — Mean CSI by Model, Lead Time and Threshold

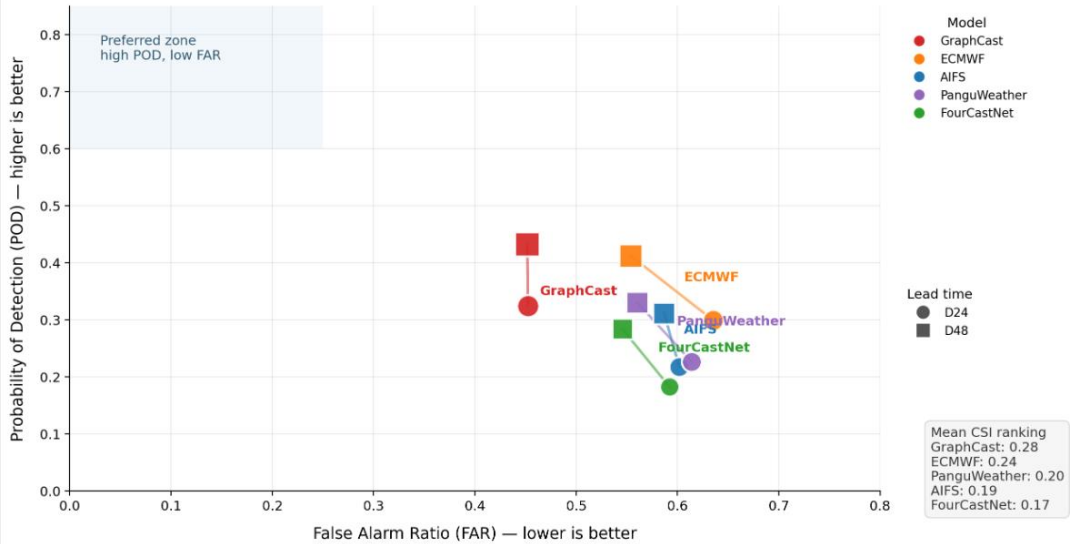


850 hPa Temperature (T850) — Mean CSI by Model, Lead Time and Threshold



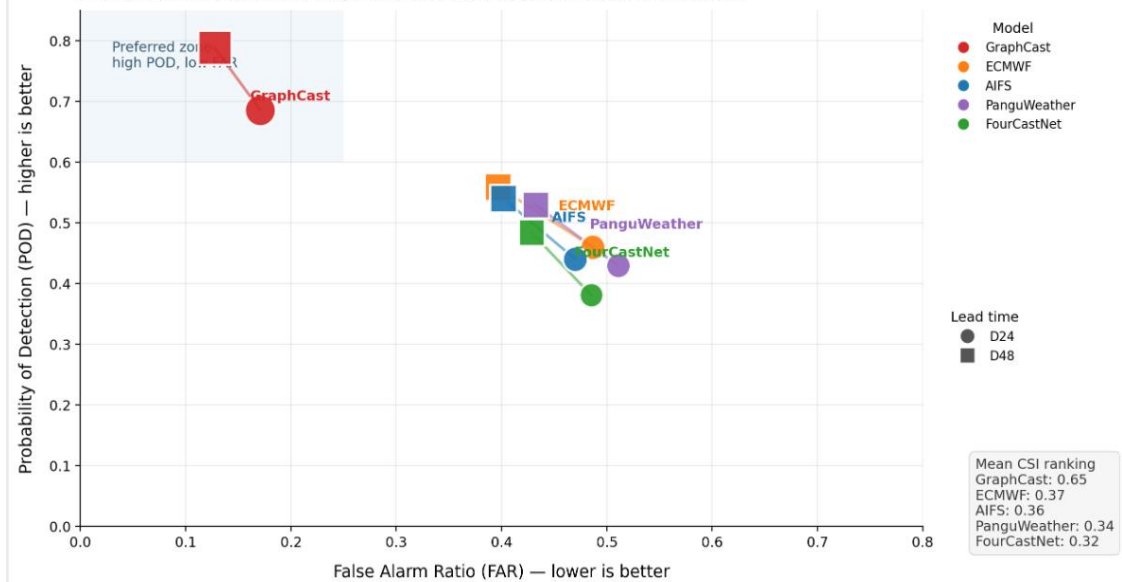
2 m Temperature (T2m) — POD vs FAR Trade-off

Averaged across stations, event types and thresholds. Bubble size represents mean CSI.



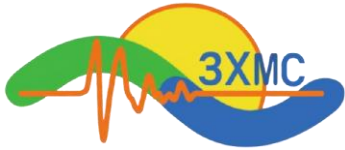
850 hPa Temperature (T850) — POD vs FAR Trade-off

Averaged across stations, event types and thresholds. Bubble size represents mean CSI.



Conclusion

- **GraphCast** gives the strongest scores, but its advantage is partly influenced by the shorter 120 h verification range.
- When GraphCast is excluded, **IFS** is the most consistent model overall, with AIFS close behind, especially for T850.
- T850 provides a more robust event-warning signal than T2m, while the **IFS degradation after 240 h** for Bar is confirmed by RMSE, MAE and ME diagnostics.
- Additional verification is required over a broader part of Montenegro, taking into account how **changes in model cycles** may affect forecast performance for our region



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Thank You

For Your Attention

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