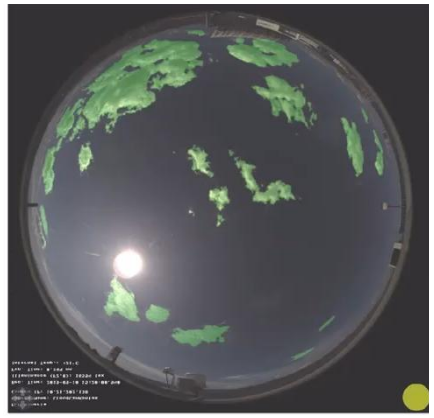
ENHANCING INTRA-HOUR SOLAR IRRADIANCE FORECASTING USING A HYBRID MODEL OF SATELLITE, SKY IMAGER AND PERSISTENCE

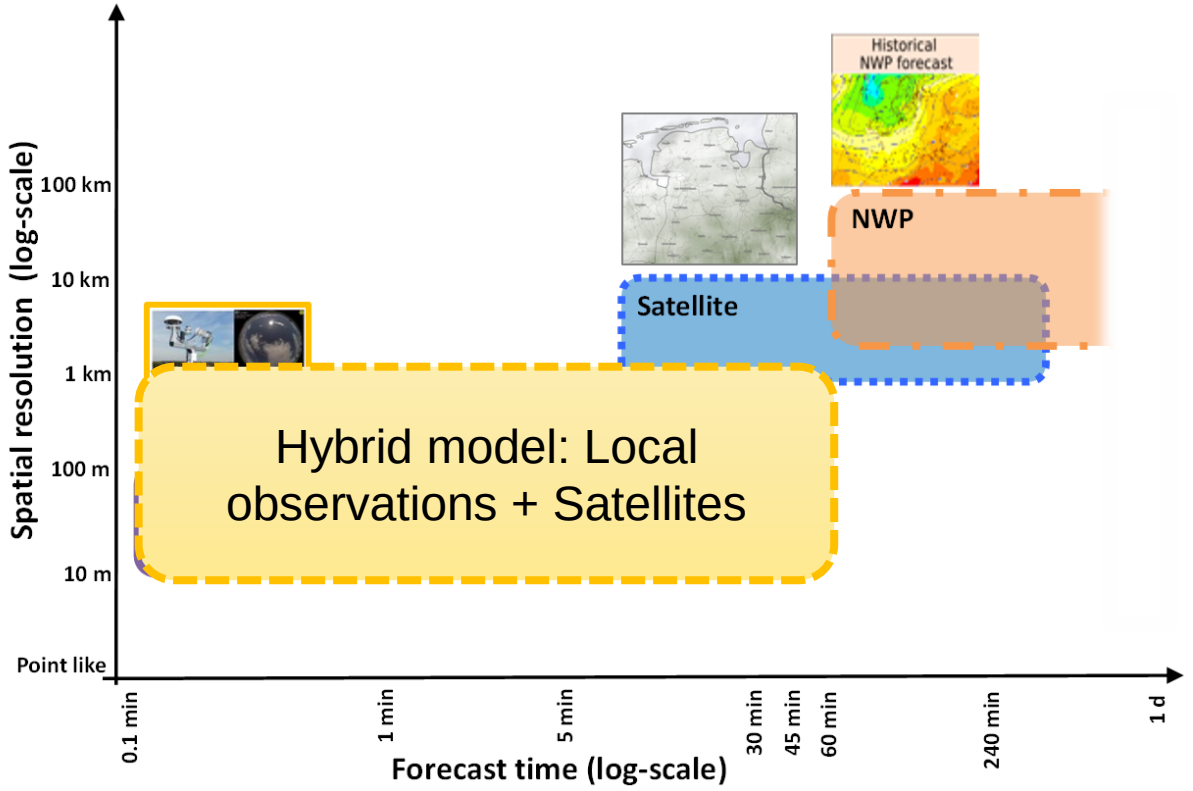
- Bijan Nouri [1], Jorge Lezaca [2], Yann Fabel[1], Annette Hammer[2], Niklas Blum[1], Stefan Wilbert[1]
- [1] DLR SF (Institut für Solarforschung)
- [2] DLR VE (Institut für Vernetzte Energiesysteme)

Motivation

- Solar irradiance **variability in space and time** on the **local scale** occur due to cloud passing by
- The anticipation of this changes is achieved through forecasting
- The accuracy of the forecast could play a crucial role on the different solar applications (monitoring, trading, storage management, …)
- Complementary Methods
  - Local observations (e.g. sky cameras and radiometers) offer high temporal and spatial resolution, but have limited spatial coverage and a short forecast horizon.
  - Satellites provide broad coverage and an extended forecast horizon, but have a coarser resolution.

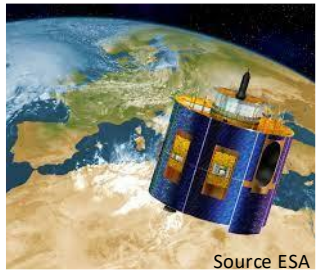
A hybrid model that blends local and satellite forecasts to produce robust, high-resolution, intra-hour local forecasts.



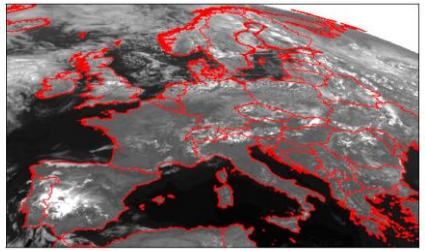


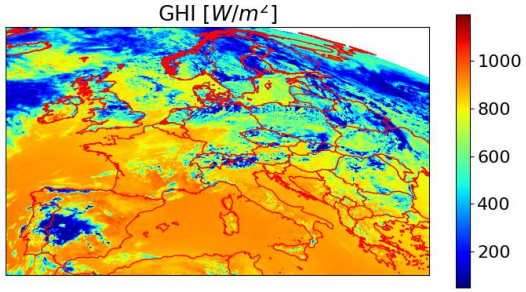
Forecasting systems

Meteosat based forecasts



Heliosat method [1]



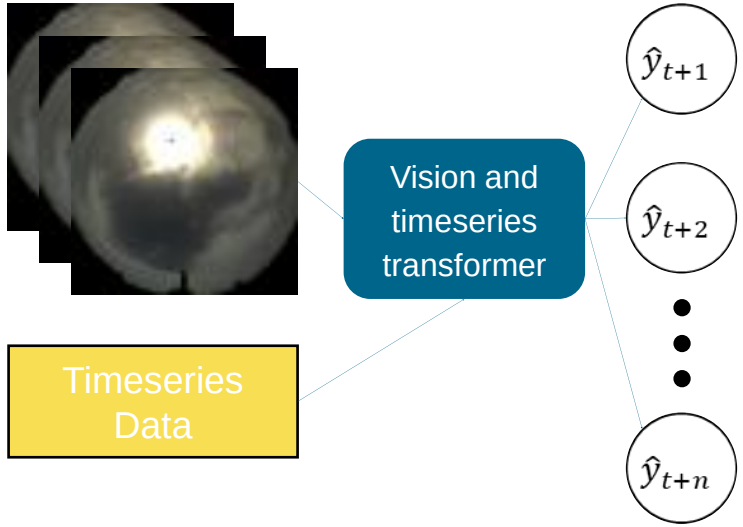


- Horizon ~6h
- Spatial resolution ~ 2km
- Temporal resolution and update rate 15 min

All sky imager (ASI) based forecast



Deep learning transformer method [2]

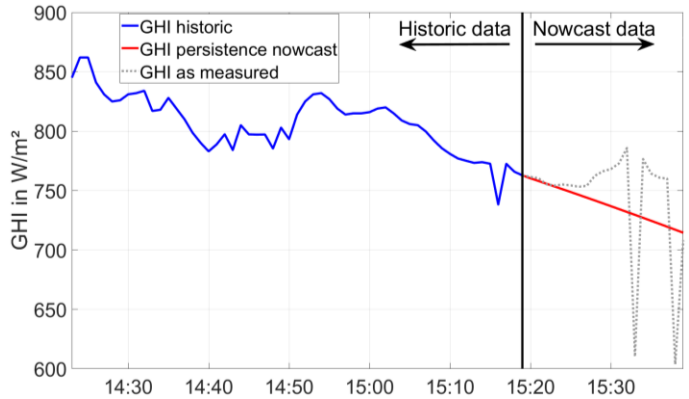


- Horizon 1h
- Temporal resolution 1 min
- Update rate 30 s
- Model trained on data set in southern Spain
- >3000000 data points distributed over 7 years

Persistence forecast



Scaled persistence method [3]



- Update rate 1 min

Blending methods



Nouri et al., 2025
https://doi.org/10.1002/solr.202500486

Ground truth

Forecast

Training data

Testing data

Homogenization

Blending
- Linear regression
- XGBoost
- LSTM
- Transformer

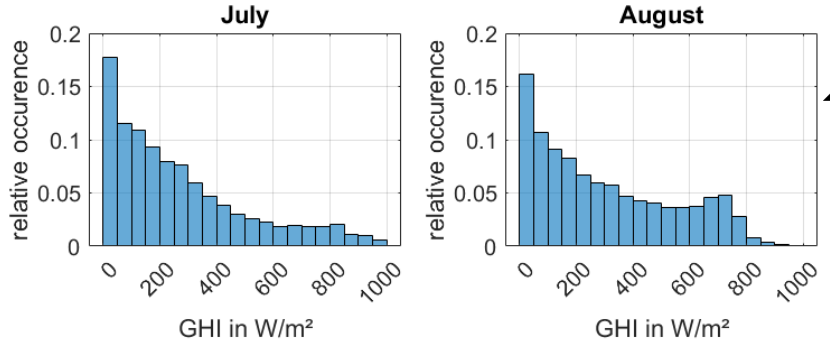
Hyperparameter tuning is performed (Optuna [6])

Inference blending

Blended forecasts
- Satellite+Persistence
- Satellite+ASI+Persistence

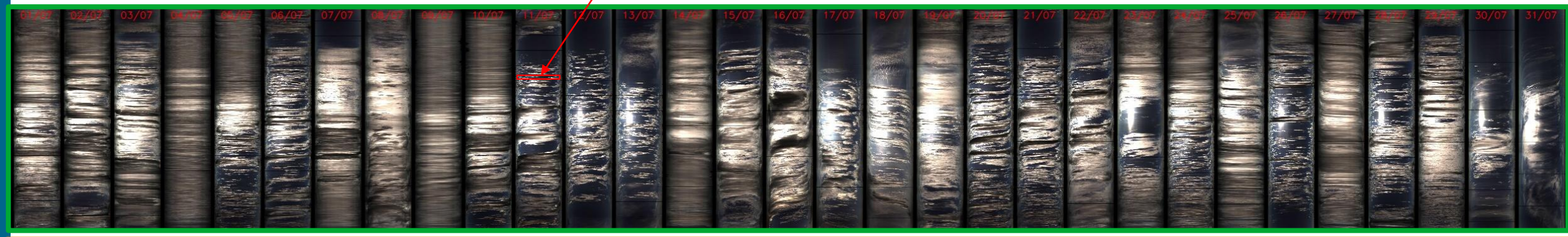
Used datasets

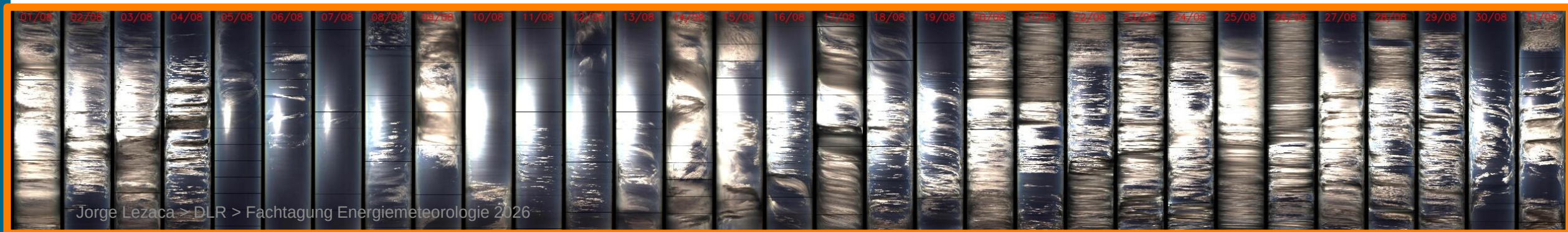
- Site: Oldenburg (Germany)
  - OLDON station of Eye2Sky Network [4]
  - 53°8´46.96´´N / 8°13´2.41´´E
- Used data
  - Training/Validation: **July 2020 (50373 datapoints)**
  - Testing: **August 2020 (45163 datapoints)**



keogram

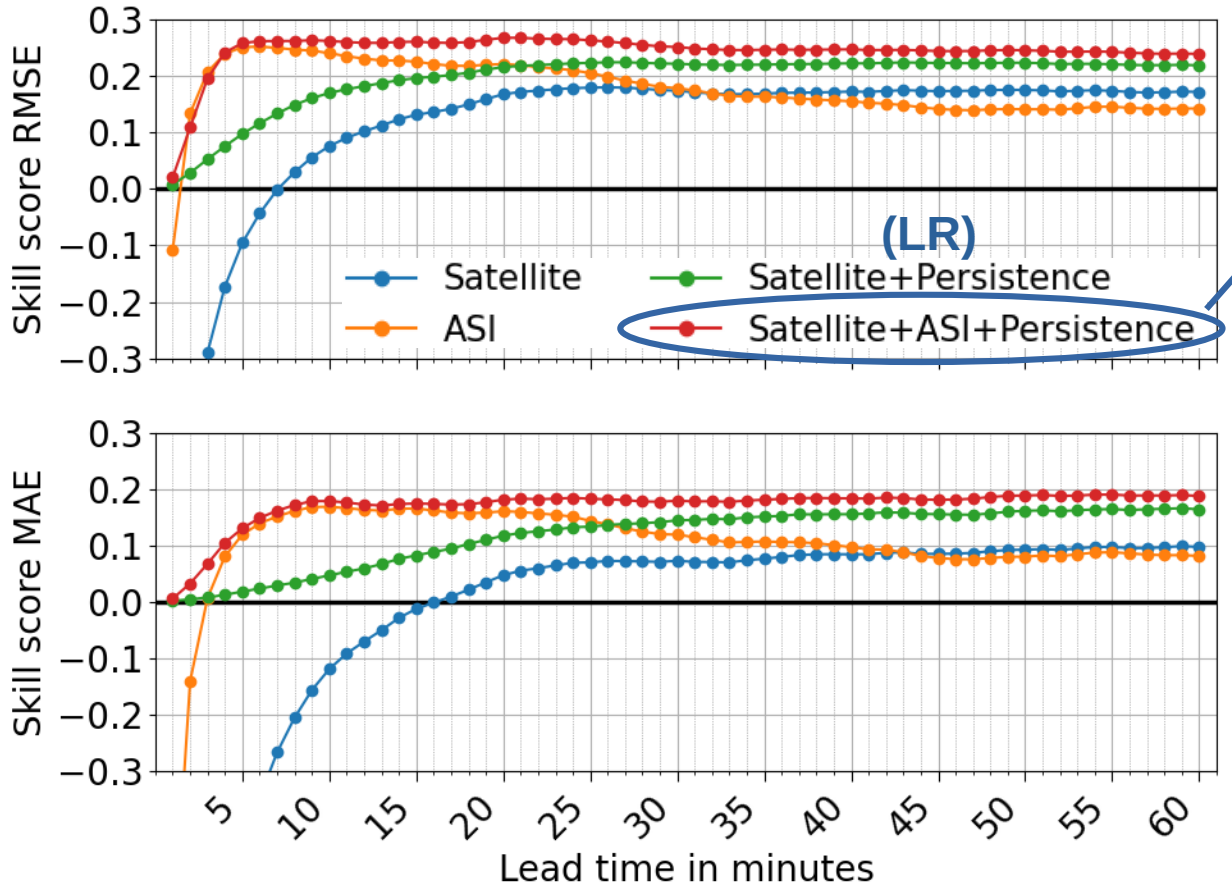






General benchmark forecasts

$$RMSE = \sqrt{{}^{1}/_{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)^2} \qquad MAE = {}^{1}/_{n}\sum_{i=1}^{n}|\hat{y}_i - y_i| \qquad Skill\ score = 1 - \frac{error_{model}}{error_{persistence}}$$



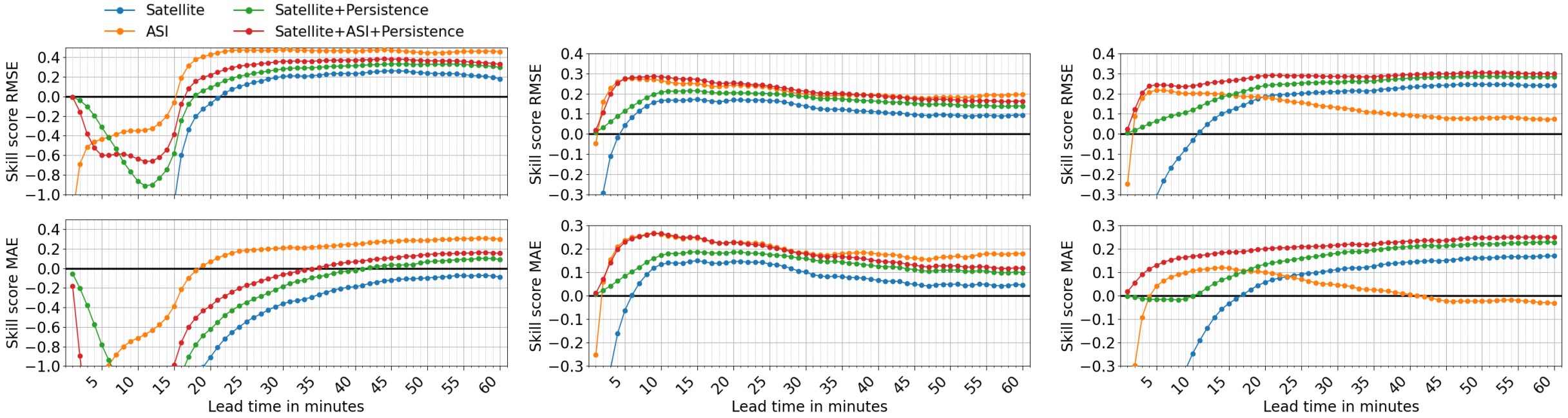
Satellite+ASI+Persistence

Error metric	LR	XGBoost	LSTM	Transfor-mer
RMSE [W/m²] ↓	121.8 ±16.9	120.8 ±17.2	119.7 ±17.4	120.4 ±17.2
MAE [W/m²] ↓	77.6 ±14.2	80.3 ±14.9	78.1 ±14.5	79.5 ±14.6
MBE [W/m²] ↓	-1.7 ±1.6	-5.5 ±1.5	-2.8 ±3.0	-1.8 ±5.1
Skill Score (RMSE) ↑	0.24 ±0.04	0.25 ±0.02	0.26 ±0.01	0.26 ±0.02
Skill Score (MAE) ↑	0.17 ±0.03	0.14 ±0.04	0.17 ±0.03	0.15 ±0.05

Averaged results over all lead times (± std)

Influence of prevailing sky conditions

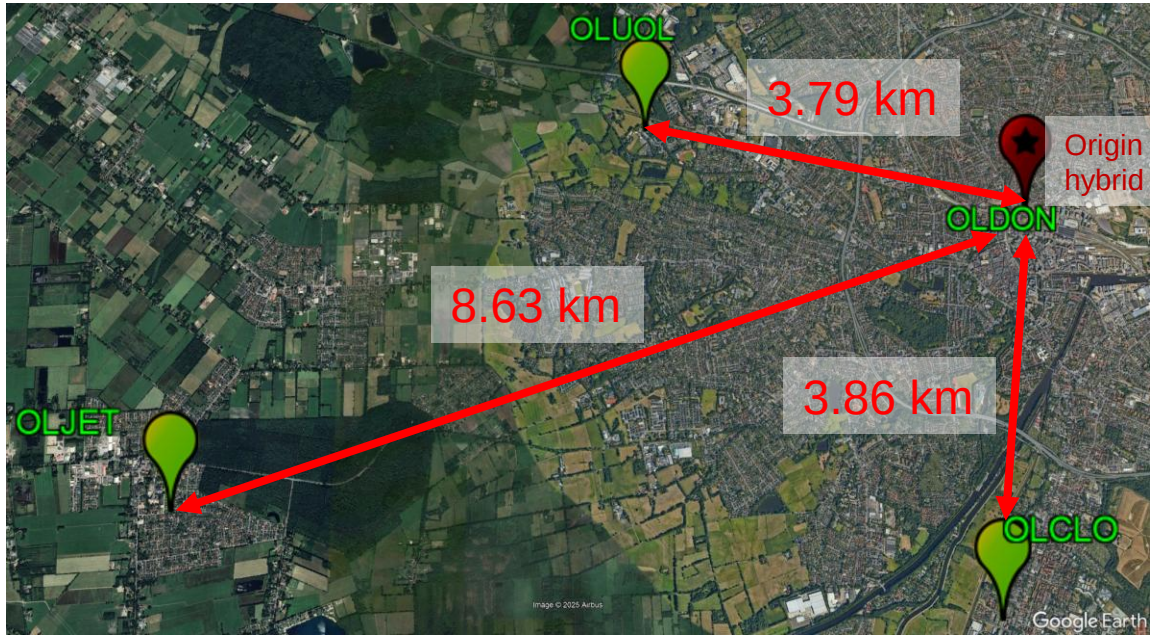
- Mostly/almost clear sky with high clear sky index
  - 27% of the dataset
  - Low variability
  - Average cloud coverage ≈ 11%
  - Average clear sky index ≈ 0.94
- Partly cloudy with intermediate clear sky index
  - 25% of the dataset
  - High/intermediate variability
  - average cloud coverage ≈ 53%
  - average clear sky index ≈ 0.57
- Almost/mostly overcast with low clear sky index
  - 48% of the dataset
  - Intermediate/low variability
  - average cloud coverage ≈ 85%
  - average clear sky index ≈ 0.08



Spatial influence

- Benchmark OLDON hybrid forecast against satellite forecasts at 3 additional sites
  - OLDON hybrid forecast remains unchanged.
  - Use site-specific satellite forecasts for comparison.
  - Sites are part of the Eye2Sky network with reference sensors.

$$Skill\ score = 1 - \frac{error_{Hybrid_{OLDON}@site(n)}}{error_{Satellite_{site(n)}}}$$



	Hybrid OLDON@OLCLO (Baseline: Satellite OLCLO)	Hybrid OLDON@OLUOL (Baseline: Satellite OLUOL)	Hybrid OLDON@OLJET (Baseline: Satellite OLJET)
Skill Score (RMSE) ↑	0.09±0.04	0.04±0.02	-0.01±0.06
Skill Score (MAE) ↑	0.14±0.03	0.07±0.02	0.05±0.03

Averaged results over all lead times (± std)

Conclusion

- Intra-Hour Boost: Local observations significantly enhance site-specific satellite forecasts in the intra-hour range.
- Hybrid Superiority: Satellite+ASI+Persistence model delivers lowest error metrics with top skill scores (RMSE: 0.24±0.04, MAE: 0.17±0.03).
- Cross-Climate Success: ASI, trained in desert climate, performs well in temperate oceanic climate.
- Short-Term Strength: ASI excels in short lead times and partly cloudy conditions, enhancing hybrid performance.
- Spatial Reach: Hybrid forecast shows a positive impact up to ~4 km away from the origin.
- Future Focus: Strong for overall irradiance, less for ramp events; generative ASI models to be explored.

References

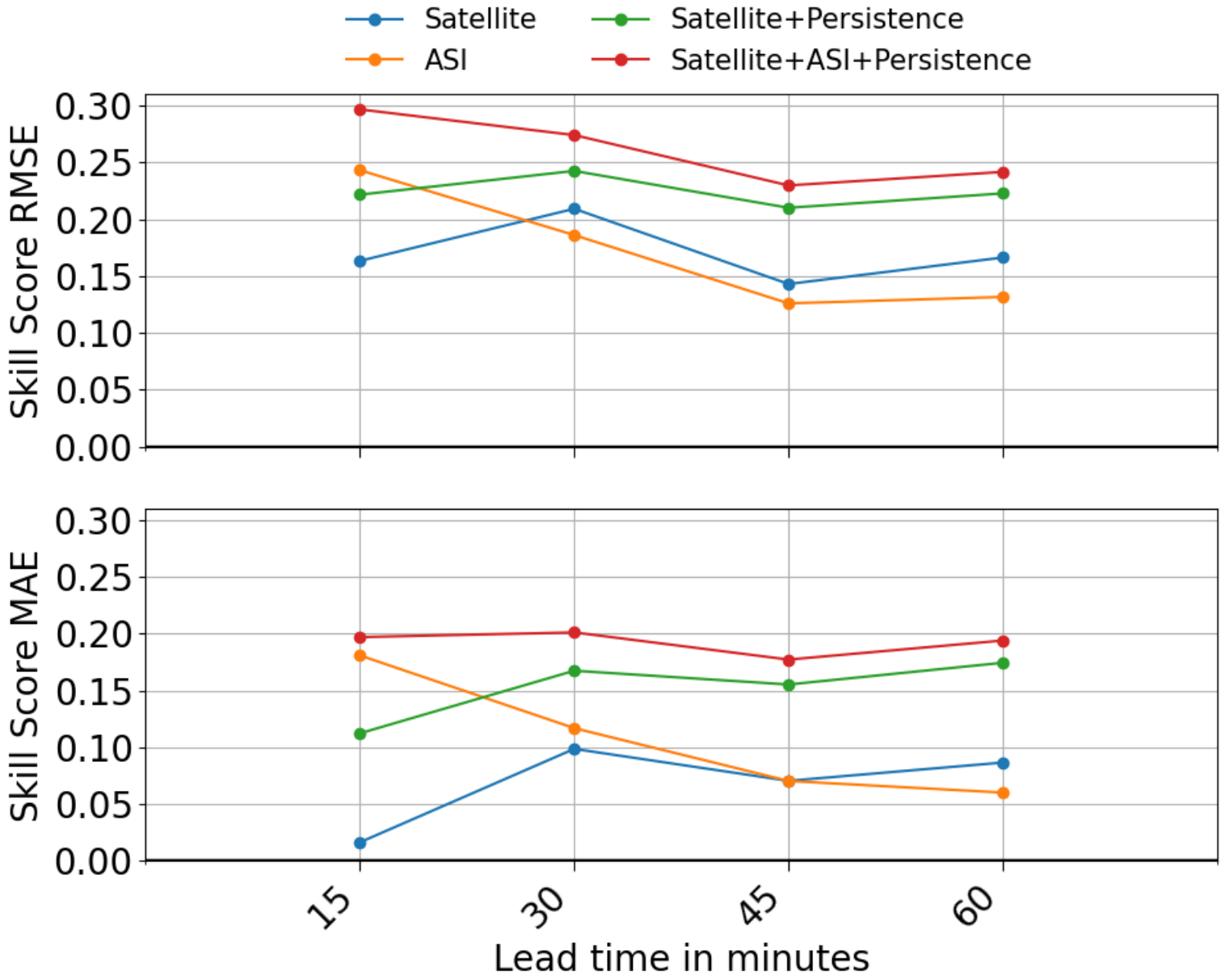
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2. Fabel, Y., Nouri, B., Wilbert, S., Blum, N., Schnaus, D., Triebel, R., ... & Pitz-Paal, R. (2024). Combining Deep Learning and Physical Models: A Benchmark Study on All-Sky Imager-Based Solar Nowcasting Systems. Solar RRL, 8(4), 2300808.
3. Chu, Y., Li, M., Coimbra, C. F., Feng, D., & Wang, H. (2021). Intra-hour irradiance forecasting techniques for solar power integration: A review. Iscience, 24(10).
4. Schmidt, T., Stührenberg, J., Blum, N., Lezaca, J., Hammer, A., Wilbert, S., ... & Vogt, T. (2025). Eye2Sky–a network of all-sky imager and meteorological measurement stations for high resolution nowcasting of solar irradiance. *Meteorologische Zeitschrift*, *34*(1), 35-55.
5. Nouri, B., Lezaca, J., Fabel, Y., Hammer, A., Blum, N., Wilbert, S. (2025). Enhancing Intra-Hour Solar Irradiance Forecasting for Solar Applications: A Blended Model of Satellite, Sky Imager, and Persistence. Solar RRL, 9(24), e202500486
6. T. Akiba, S. Sano, T. Yanase, T. Ohta, and M. Koyama, “Optuna: A next-generation hyperparameter optimization framework,” in Proceeding of the 25th ACM SIGKDD International Conference on Knowledge Discovery & Data Mining (2019), 2623–2631.



THANK YOU FOR YOUR ATTENTION!
QUESTIONS?

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Satellite resolution



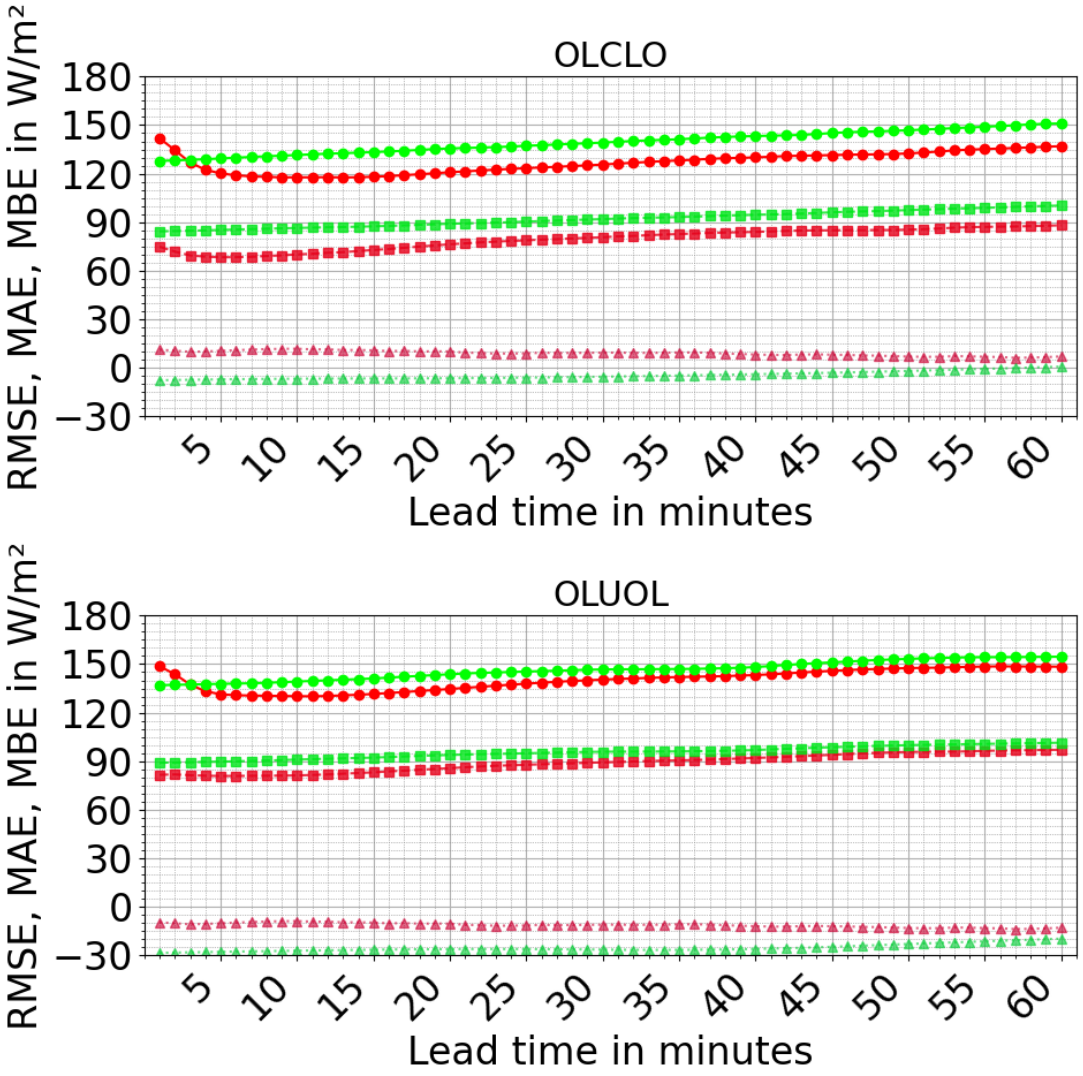
Influence of prevailing sky conditions

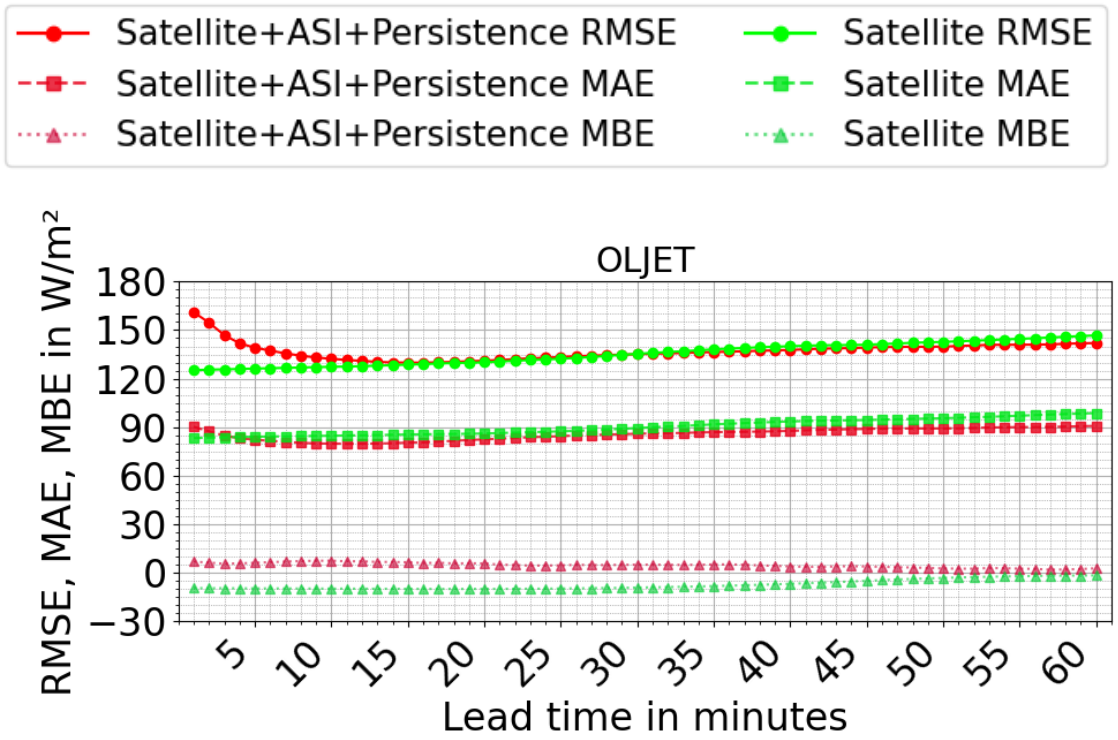
Mostly/almost clear sky with high clear sky index					
	Satellite	ASI	Satellite+ Persistence	Satellite+ASI+ Persistence	Persistence
RMSE [W/m²] ↓	59.2±3.0	35.6±7.2.	46.3±11.3	42.7±9.6	58.3±25.1
MAE [W/m²] ↓	36.5±1.3	20.2±3.9	27.8±7.3	25.6±5.5	23.4±10.7

Partly cloudy with intermediate clear sky index					
	Satellite	ASI	Satellite+ Persistence	Satellite+ASI+ Persistence	Persistence
RMSE [W/m²] ↓	196.7±6.3	174.0±17.0	183.7±14.8	173.8±17.8	220.9±22.5
MAE [W/m²] ↓	145.5±5.5	125.1±14.0	134.1±14.8	127.8±16.5	155.5±19.7

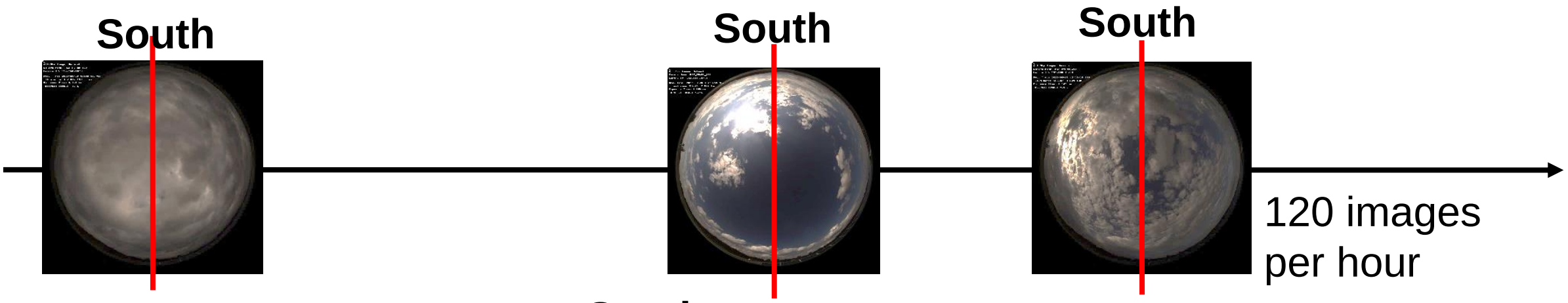
Almost/mostly overcast with low clear sky index					
	Satellite	ASI	Satellite+ Persistence	Satellite+ASI+ Persistence	Persistence
RMSE [W/m²] ↓	132.5±6.5	137.4±34.6	118.9±18.6	112.4±21.4	156.8±34.5
MAE [W/m²] ↓	93.7±5.1	94.9±26.3	81.1±16.3	76.1±17.5	97.2±25.5

Spatial influence

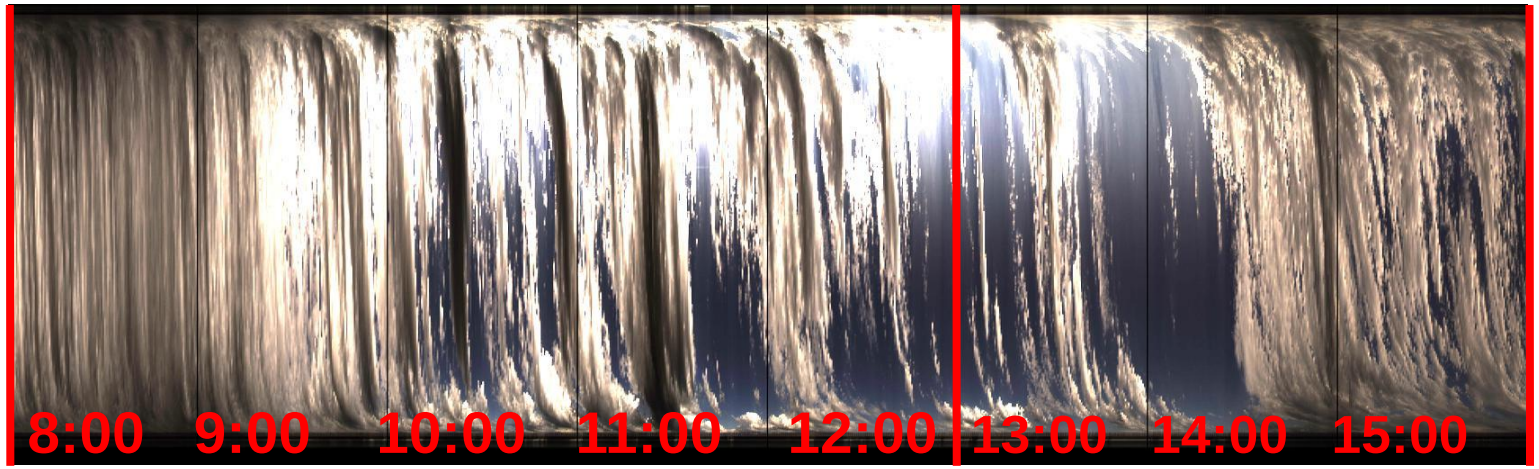




Keogram



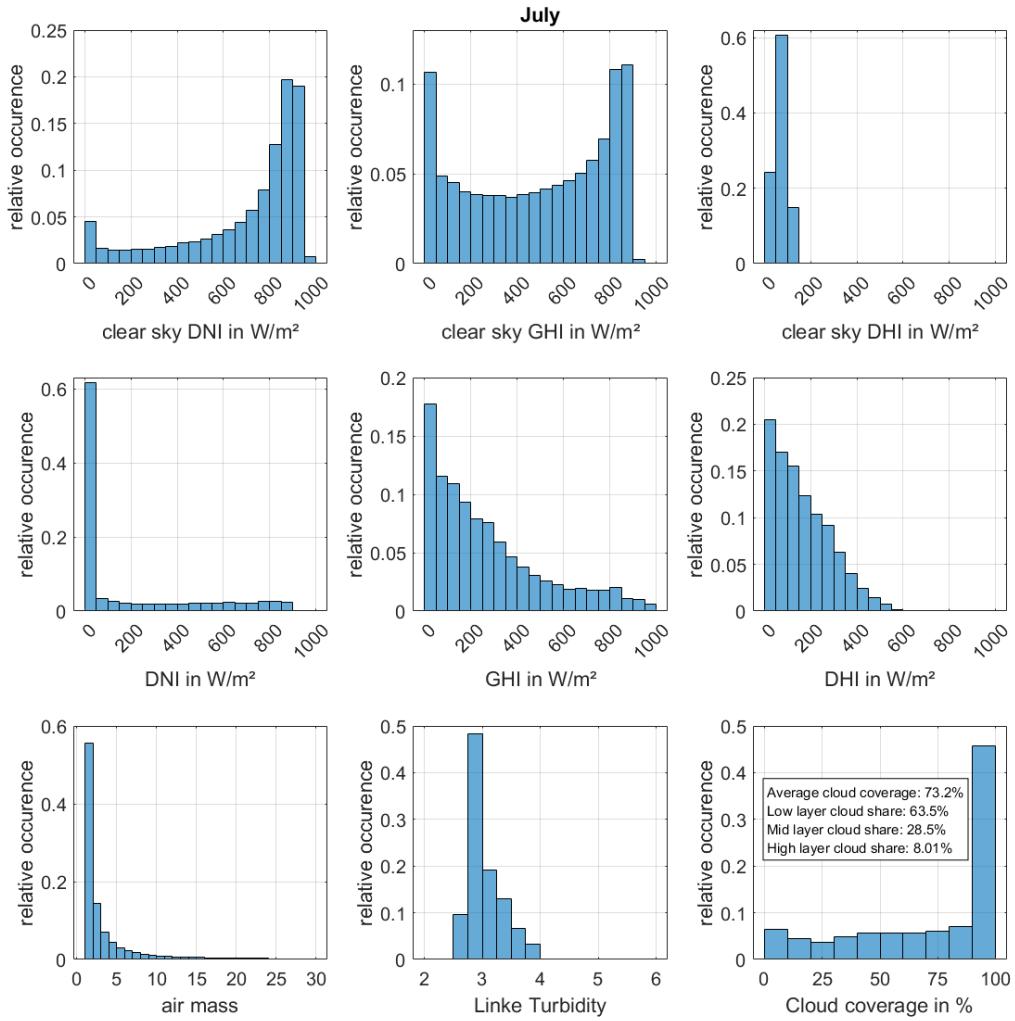
South

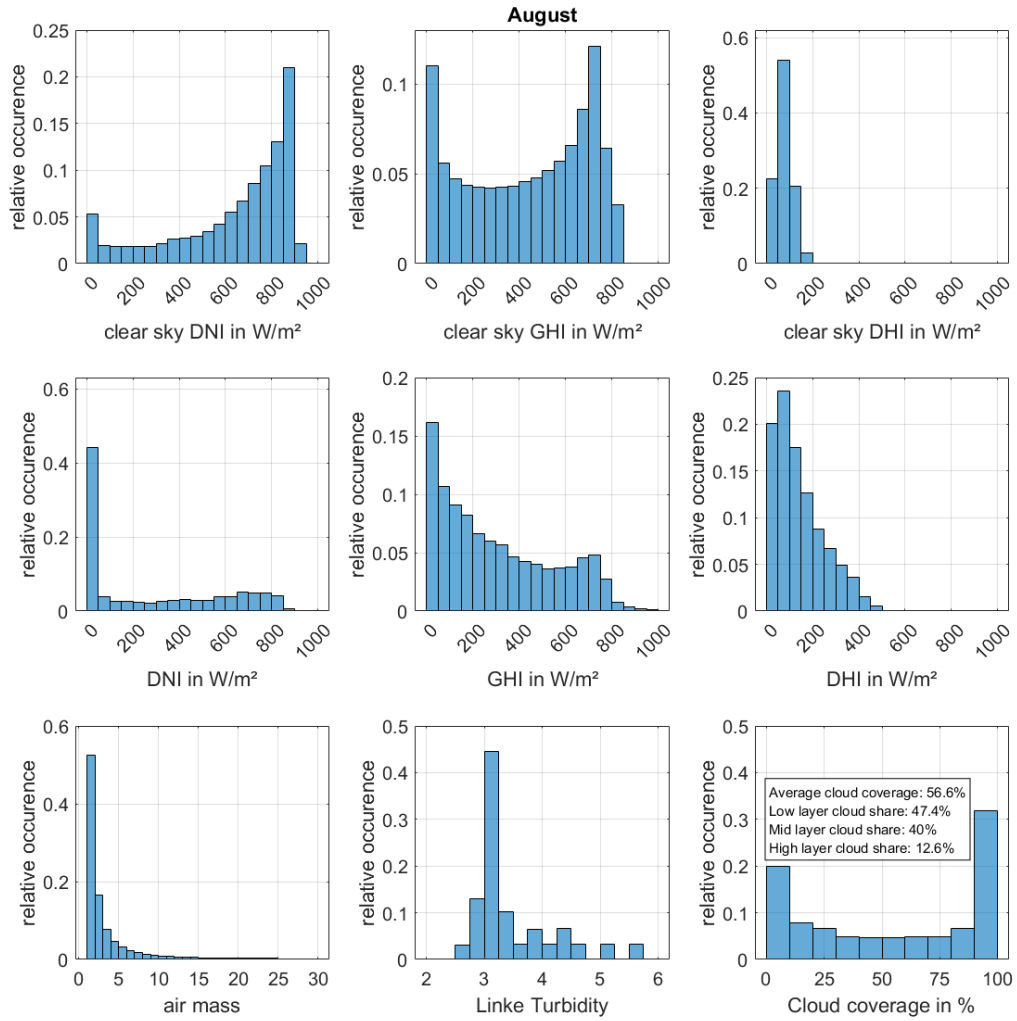


120 lines per hour

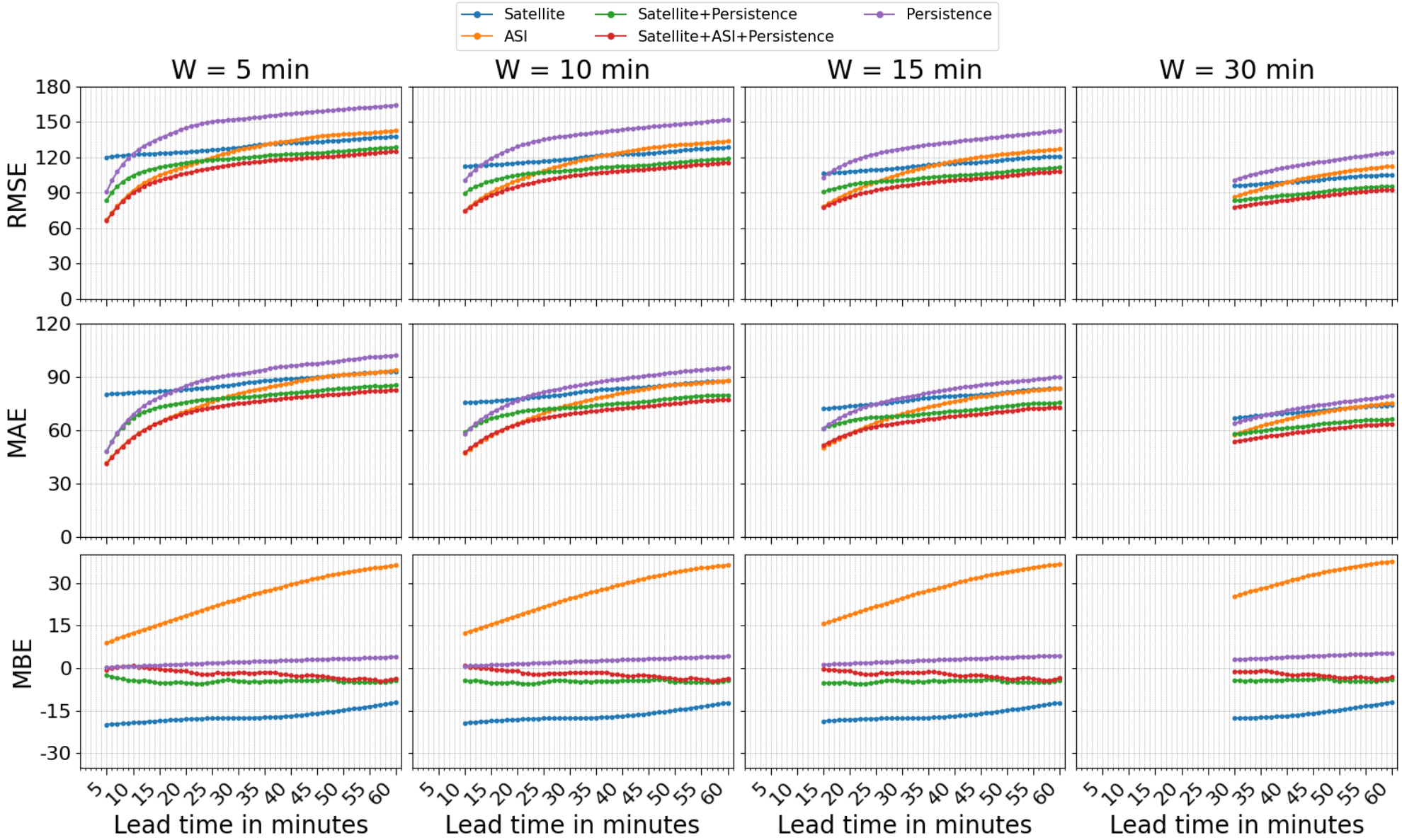
Oldenburg, 2020-08-28

Extended information on used dataset





Evaluation temporal Aggregation



Evaluation temporal Aggregation

