Machine Learning-based Global Lightning Prediction from Convective Parameters

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Motivation

Prediction of lightning

- In the past: Global lightning climatology (before the 90s)
- In the coming days and weeks: Lightning forecast from NWP or AIWP storm environment
- In the future: Lightning projection in different climate scenarios

Problem

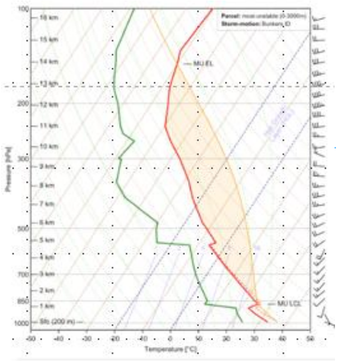
Lightning prediction over land in mid-latitudes is well established, but it is less so in the tropics or over the oceans.

Proposed solution

Interpretable AI (ensemble decision trees) applied on a massive dataset.

Training:

ERA5



thundeR
rawinsonde package

compute

convective parameters

	MIXR [g/kg]	CAPE [J/kg]	CAPE03 [J/kg]	CAPEHGL [J/kg]	CIN [J/kg]	LI [K]	LCL [m]	LFC [m]	EL [m]	WMAXSHEAR [m2/s2]
SB	19.1	5995	181	1522	-10	-14	1155	1480	13900	1644 (E 1914)
MU	19.1	5995	181	1522	-10	-14	1155	1480	13900	1644 (E 1914)
ML	17.7	5030	122	1356	-30	-13	1240	1760	13530	1506 (E 1721)

Bulk wind shear [m/s]	
Sfc - 1 km:	7.1
Sfc - 3 km:	11.8
Sfc - 6 km:	15.0
Sfc - 8 km:	19.0
Sfc - HGL:	13.7
Effec. (SB):	17.5
Effec. (MU):	17.5
Effec. (ML):	17.2

	SRH RM [m2/s2]	SRH LM [m2/s2]
Sfc - 100 m:	21	16
Sfc - 500 m:	35	12
Sfc - 1 km:	73	-15
Sfc - 3 km:	94	-63

Mean wind [m/s]	
Sfc - 1 km:	4.8
Sfc - 2 km:	4.9
1 - 3 km:	8.4
Sfc - 6 km:	8.0

Lapse rate [K/km]	
Sfc - 1 km:	9.1
Sfc - 3 km:	7.9
3 - 6 km:	7.6
500700 hPa:	7.4

Precip. water [mm]:	34
2 - 5 km RH [%]:	42
Sfc - 2 km RH [%]:	50

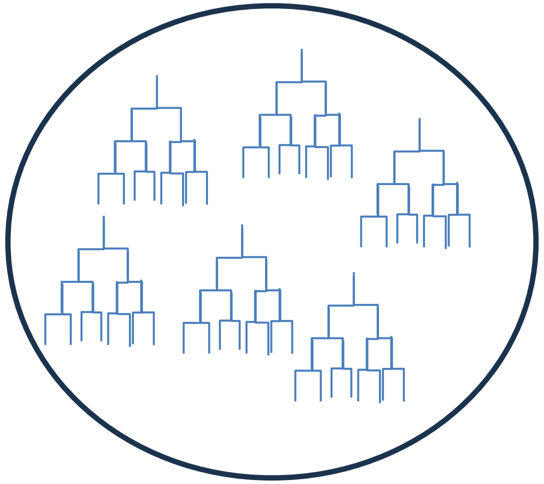
Moisture flux [g/s/m2]:	57
4 km DCAPE [J/kg]:	1359
4 km delta theta-e [K]:	40

SHIP:	2.4
SCP:	9.8
STP:	1.0

DMLC XGBoost

X: features

Ensemble Decision Trees (EDT)

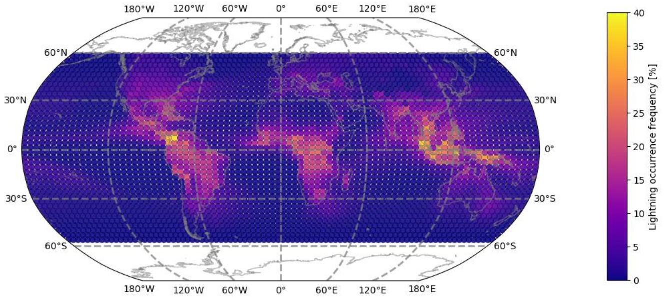


ENGLN

EARTH NETWORKS

detect

lightning occurrence

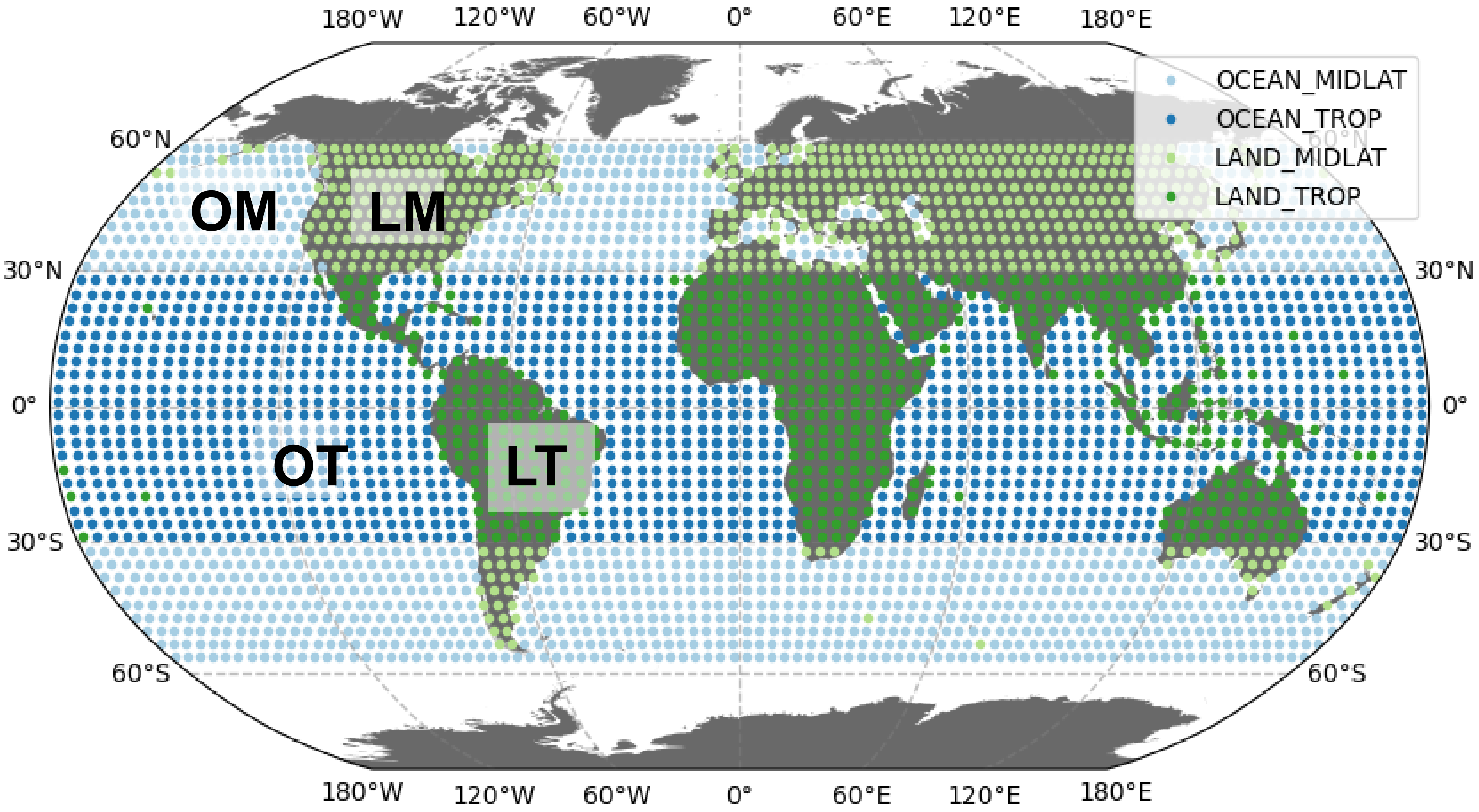


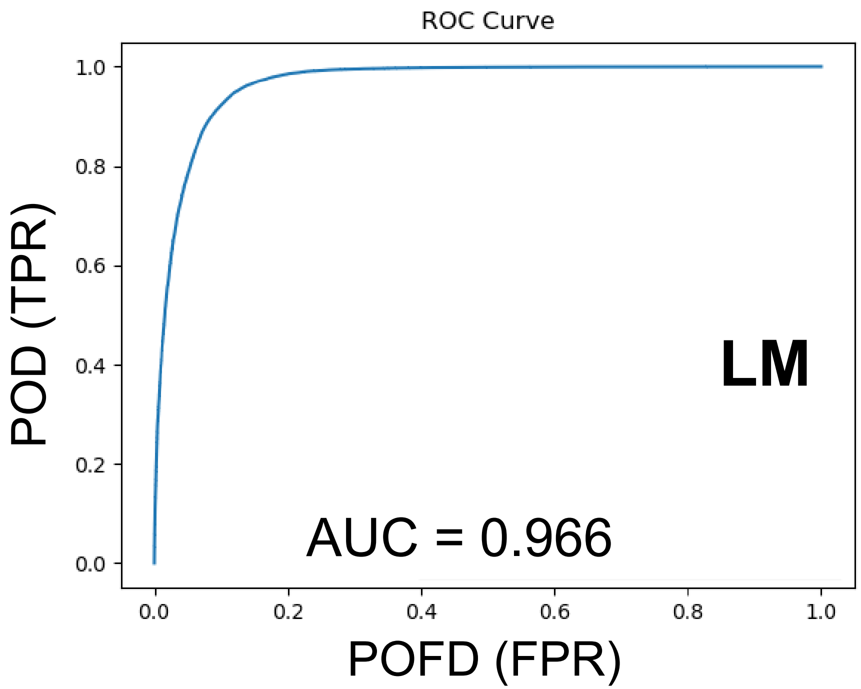
y: predicted classes

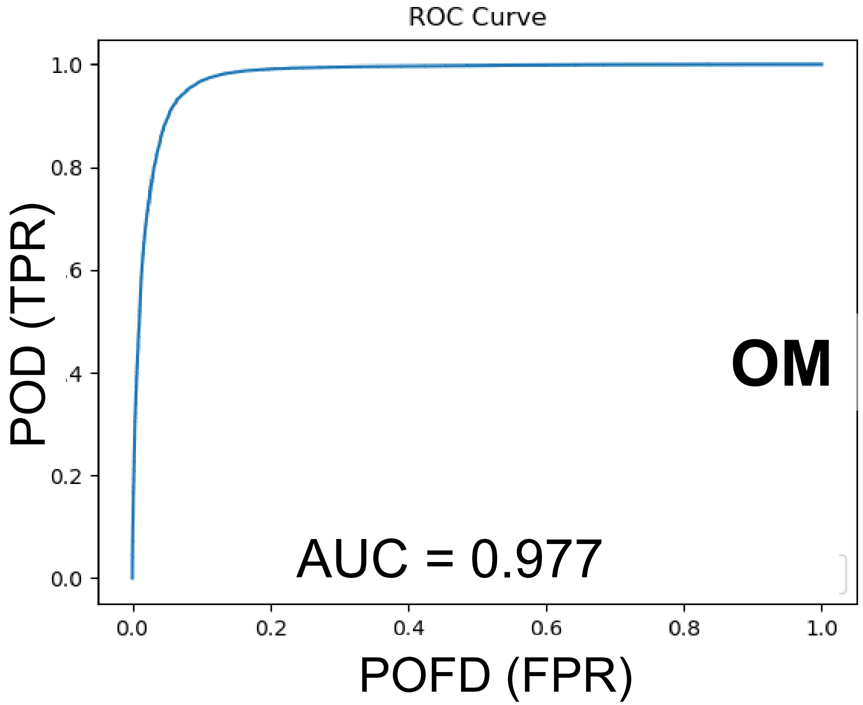
Inference: Apply EDT on ERA5-like data to predict lightning occurrence

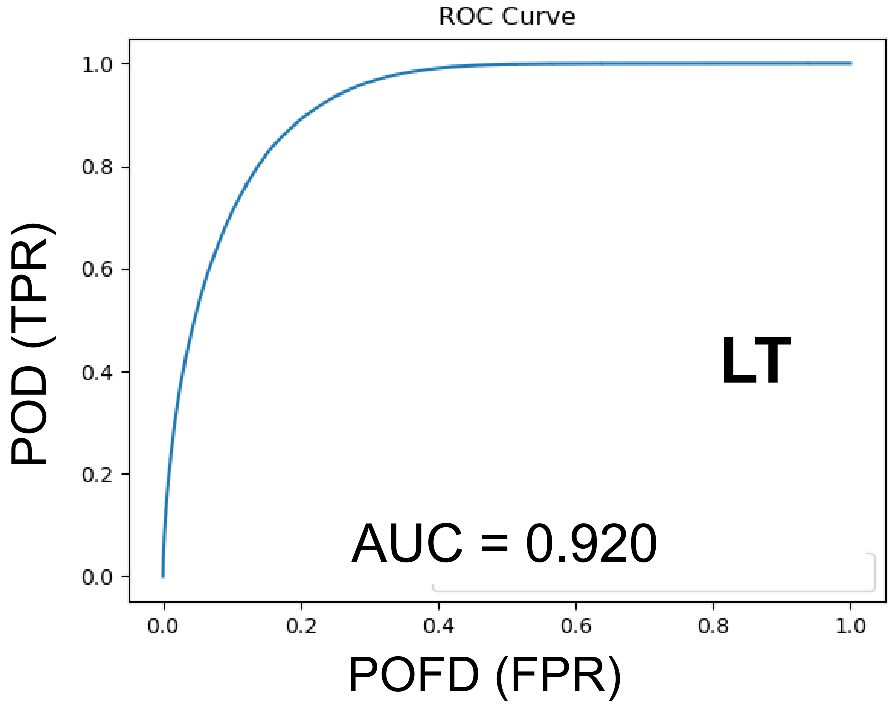
Experiment

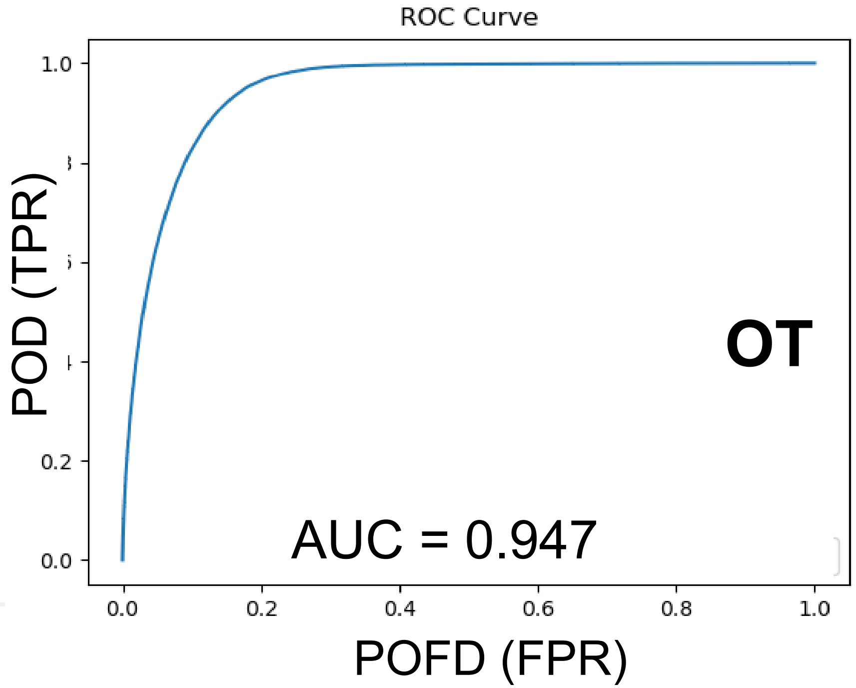
- 153 convective parameters tested
- 51,000,000 cases
- 3,500,000 cases after QC and data balancing
- Split:
  - Train: 2019-2021
  - Validation: 2022
  - Test: 2023







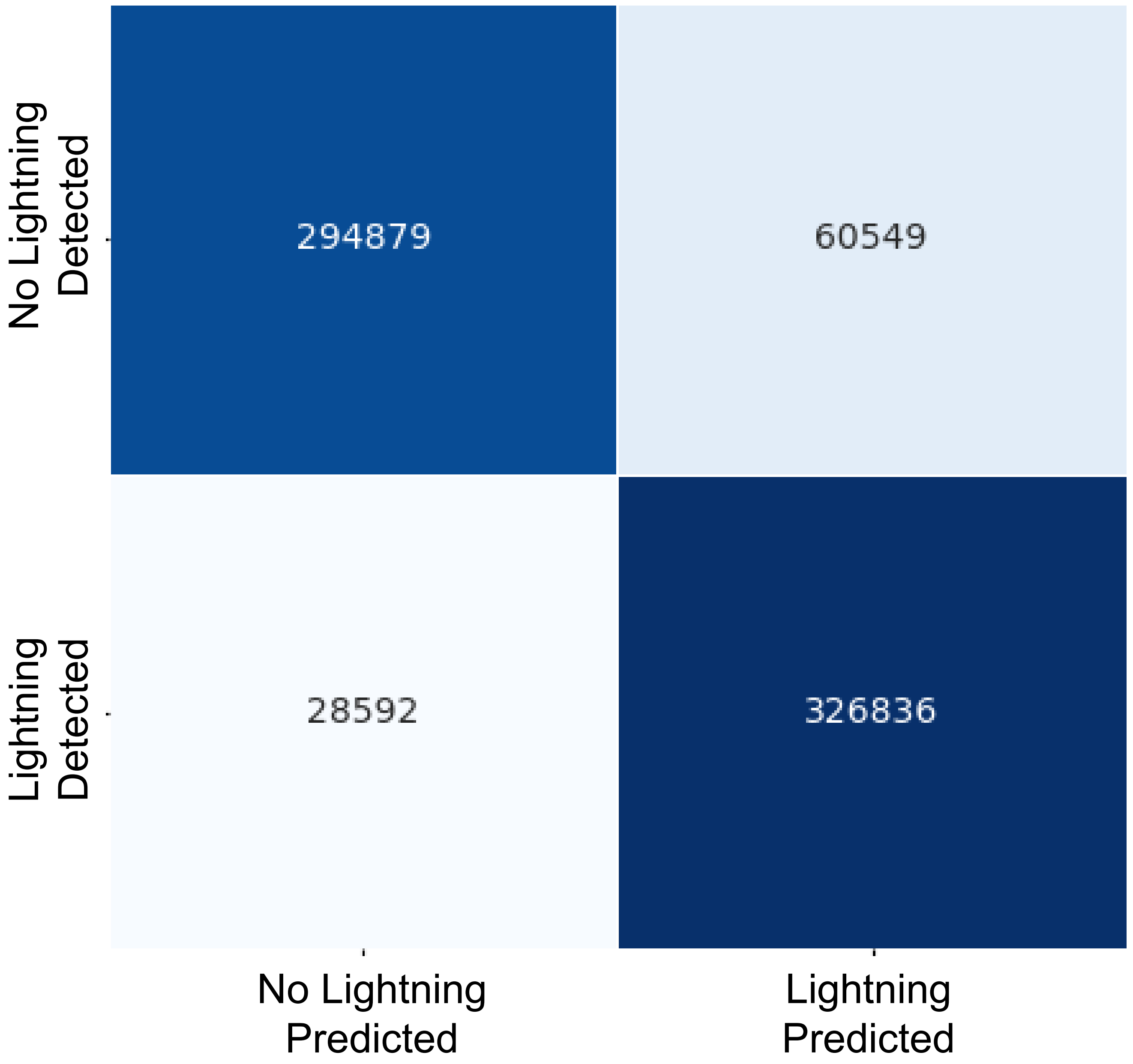




Results

Trained globally

Global ROC-AUC = 0.938



Test dataset (2023)

Global domain

Threshold: 50% (default)

POD = 92%

POFD = 17%

SR = 84%

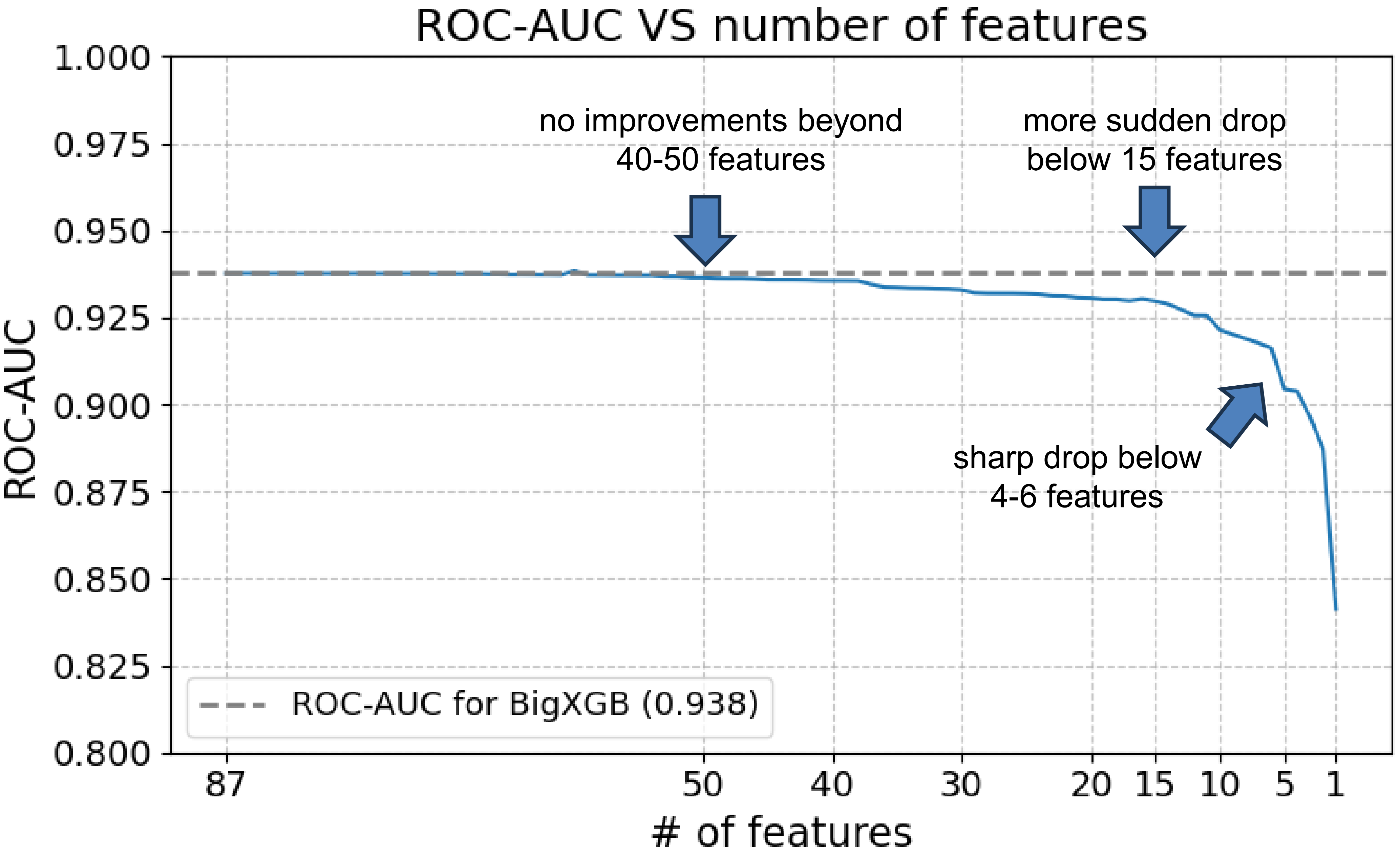
CSI = 79%

(balanced 50-50)

SR = 15%

CSI = 15%

(true climatology of lightning: 3.2%)



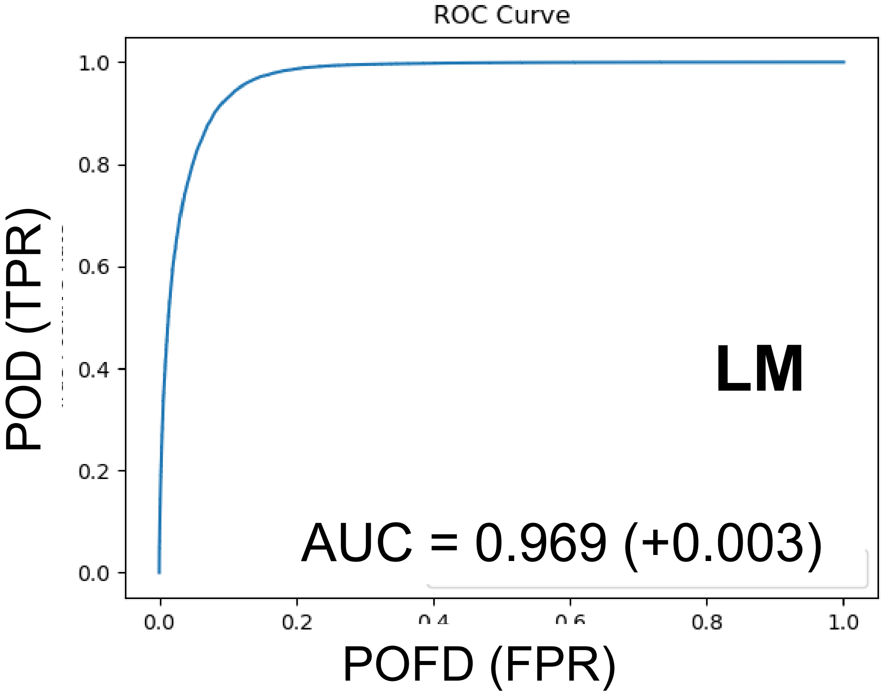
(convective parameters)

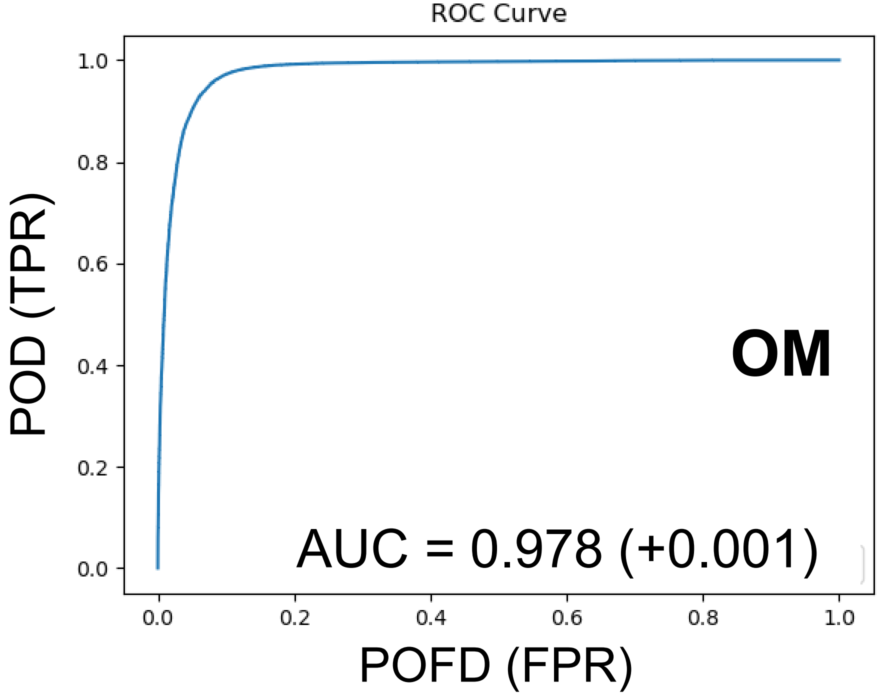
Experiment: Training by regions

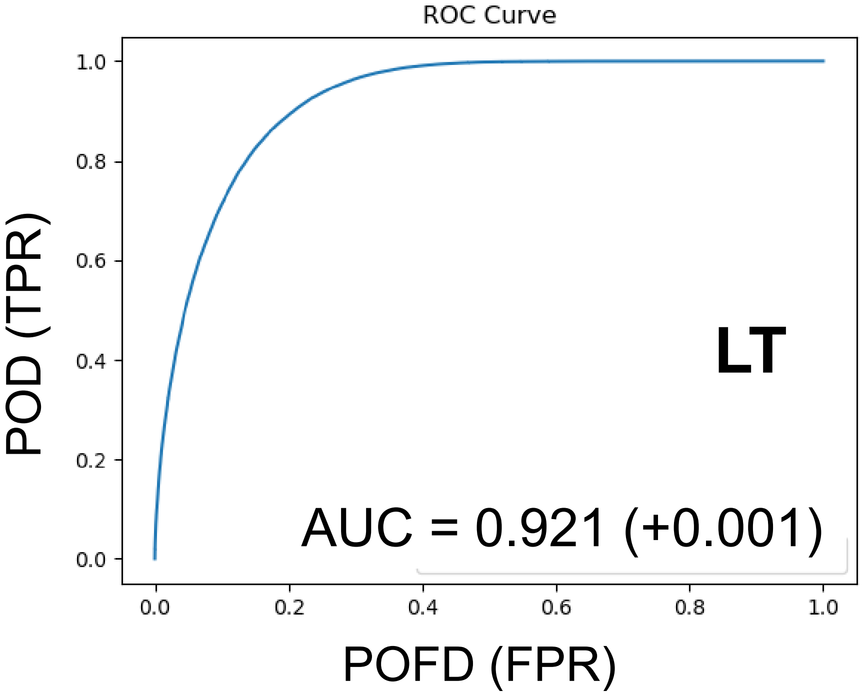
- Are the scores the same for universal VS specialized training?
- What are the best convective parameters for each region?

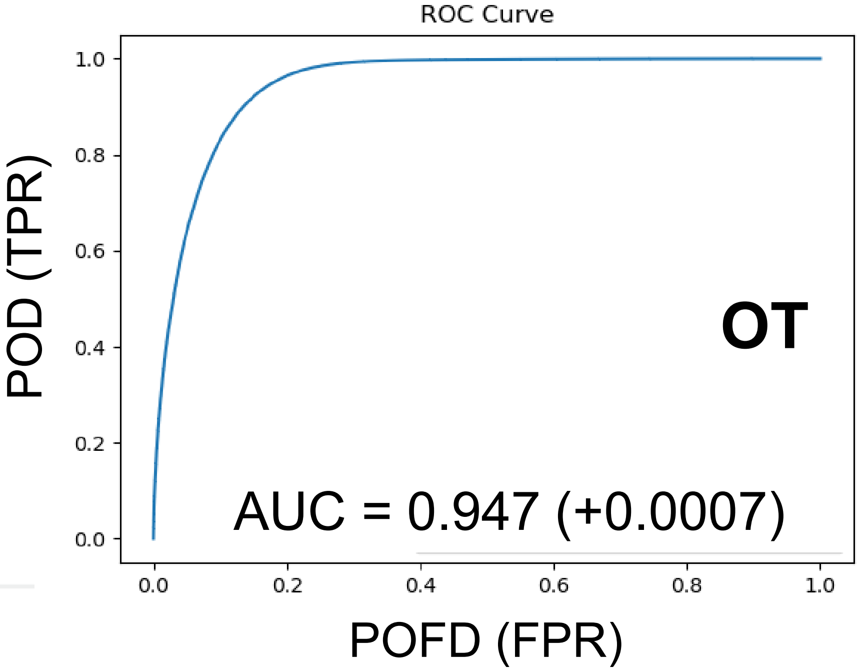
Results

Trained by regions









	Global	LM	OM	LT	OT
1.	**MU5_CIN_4km**	MUML_LI_eff	MUML_LI_eff	**MU5_CIN_4km**	RH_500850
2.	MU5_LI_eff	MU_LI_eff	MU5_LI_eff	MUML_LI	MU5_LI
3.	tciw	MUML_equal_layer	MUML_CAPE_HGL	MU5_LI	tciw
4.	tcslw	MUML_CAPE_HGL	MU_LI_eff	tciw	MUML_LI
5.	MUML_LI_eff	tciw	MU_CAPE_HGL	MUML_LI_eff	tcslw
6.	MU5_CAPE_HGL	MU5_LI_eff	**MU_CIN_4km**	tcslw	MU5_CAPE_HGL
7.	MUML_CAPE_HGL	**MU5_CIN_4km**	tciw	THETAE_02km	RH_14km
8.	MUML_LI				ML_CAPE_HGL
9.	LR_06km	tcslw	ML_LCL_hgt	ML_LI_eff	MU5_LI_eff
10.	MU_LI_eff	Moisture_Flux_SR	vigd	LR_06km	RH_ML_LCL_3km

MU5_CIN_4km: Convective inhibition for lifted parcel (MU5: most-unstable above 500 m AGL) in 4 km layer with the bottom of that layer at the parcel lifting height.

	Global	**LM**	**OM**	**LT**	**OT**
1.	MU5_CIN_4km	**MUML_LI_eff**	**MUML_LI_eff**	MU5_CIN_4km	RH_500850
2.	**MU5_LI_eff**	**MU_LI_eff**	**MU5_LI_eff**	**MUML_LI**	**MU5_LI**
3.	tciw	MUML_equal_layer	MUML_CAPE_HGL	**MU5_LI**	tciw
4.	tcslw	MUML_CAPE_HGL	**MU_LI_eff**	tciw	**MUML_LI**
5.	**MUML_LI_eff**	tciw	MU_CAPE_HGL	**MUML_LI_eff**	tcslw
6.	MU5_CAPE_HGL	**MU5_LI_eff**	MU_CIN_4km	tcslw	MU5_CAPE_HGL
7.	MUML_CAPE				km
8.	**MUML_LI**	**MU_LI**	BS_eff_MU	MU5_CAPE_HGL	MUML_CAPE_HGL
9.	LR_06km	tcslw	ML_LCL_hgt	**ML_LI_eff**	**MU5_LI_eff**
10.	**MU_LI_eff**	Moisture_Flux_SR	vigd	LR_06km	RH_ML_LCL_3km

MU5_LI_eff: The largest difference *between* lifted parcel (MU5) *and* ambient temperature found in the entire profile assuming environmental temperature is below -10 °C and the height is at least 2 km above lifted condensation level.

	Global	LM	OM	LT	OT
1.	MU5_CIN_4km	MUML_LI_eff	MUML_LI_eff	MU5_CIN_4km	RH_500850
2.	MU5_LI_eff	MU_LI_eff	MU5_LI_eff	MUML_LI	MU5_LI
3.	**tciw**	MUML_equal_layer	MUML_CAPE_HGL	MU5_LI	**tciw**
4.	**tcslw**	MUML_CAPE_HGL	MU_LI_eff	**tciw**	MUML_LI
5.	MUML_LI_eff	**tciw**	MU_CAPE_HGL	MUML_LI_eff	**tcslw**
6.	MU5_CAPE_HGL	MU5_LI_eff	MU_CIN_4km	**tcslw**	MU5_CAPE_HGL
7.	MUML_CAPE_HGL	MU5_CIN_4km	**tciw**	THETAE_02km	RH_14km
8.	MUML_LI	[illegible]	[illegible]	[illegible]	_CAPE_HGL
9.	LR_06km	**tcslw**	ML_LCL_hgt	ML_LI_eff	MU5_LI_eff
10.	MU_LI_eff	Moisture_Flux_SR	vigd	LR_06km	RH_ML_LCL_3km

tciw: Total column cloud ice water (ERA5).
tcslw: Total column supercooled liquid water (ERA5).

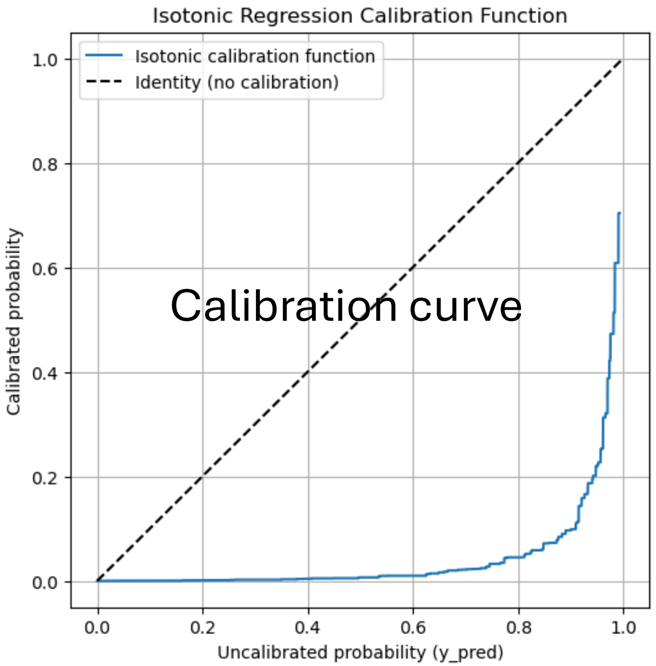
	Global	LM	OM	LT	OT
1.	MU5_CIN_4km	MUML_LI_eff	MUML_LI_eff	MU5_CIN_4km	RH_500850
2.	MU5_LI_eff	MU_LI_eff	MU5_LI_eff	MUML_LI	MU5_LI
3.	tciw	MUML_equal_layer	**MUML_CAPE_HGL**	MU5_LI	tciw
4.	tcslw	**MUML_CAPE_HGL**	MU_LI_eff	tciw	MUML_LI
5.	MUML_LI_eff	tciw	**MU_CAPE_HGL**	MUML_LI_eff	tcslw
6.	**MU5_CAPE_HGL**	MU5_LI_eff	MU_CIN_4km	tcslw	**MU5_CAPE_HGL**
7.	**MUML_CAPE_HGL**	MU5_CIN_4km	tciw	THETAE_02km	RH_14km
8.	MUML_LI	MU_LI	BS_eff_MU	**MU5_CAPE_HGL**	**MUML_CAPE_HGL**
9.	LR_06km	[illegible]	[illegible]	[illegible]	MU5_LI_eff
10.	MU_LI_eff	[illegible]	[illegible]	[illegible]	RH_ML_LCL_3km

MU5_CAPE_HGL : Convective Available Potential Energy *for* lifted parcel (MU5) in the Hail Growth Layer (-10 °C to -40 °C).

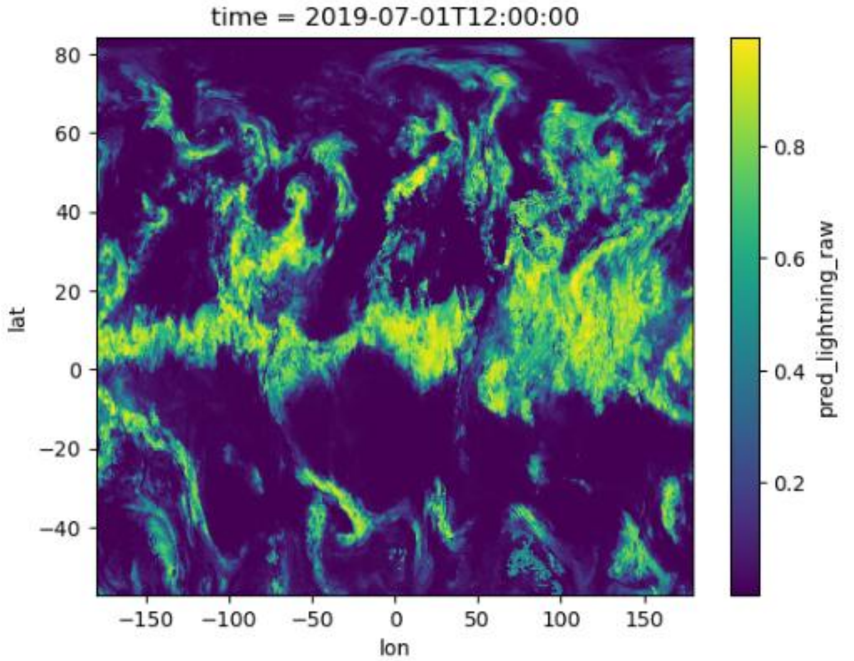
	Global	LM	OM	LT	OT
1.	MU5_CIN_4km	MUML_LI_eff	MUML_LI_eff	MU5_CIN_4km	**RH_500850**
2.	MU5_LI_eff	MU_LI_eff	MU5_LI_eff	MUML_LI	MU5_LI
3.	tciw	MUML_equal_layer	MUML_CAPE_HGL	MU5_LI	tciw
4.	tcslw	MUML_CAPE_HGL	MU_LI_eff	tciw	MUML_LI
5.	MUML_LI_eff	tciw	MU_CAPE_HGL	MUML_LI_eff	tcslw
6.	MU5_CAPE_HGL	MU5_LI_eff	MU_CIN_4km	tcslw	MU5_CAPE_HGL
7.	MUML_CAPE_HGL	MU5_CIN_4km	tciw	THETAE_02km	**RH_14km**
8.	MUML_LI	MU_LI	[illegible]	[illegible]E_HGL	MUML_CAPE_HGL
9.	LR_06km	tcslw	ML_LCL_hgt	ML_LI_eff	MU5_LI_eff
10.	MU_LI_eff	Moisture_Flux_SR	vigd	LR_06km	**RH_ML_LCL_3km**

RH_500850: Mean Relative Humidity *between* 500 hPa and 850 hPa.

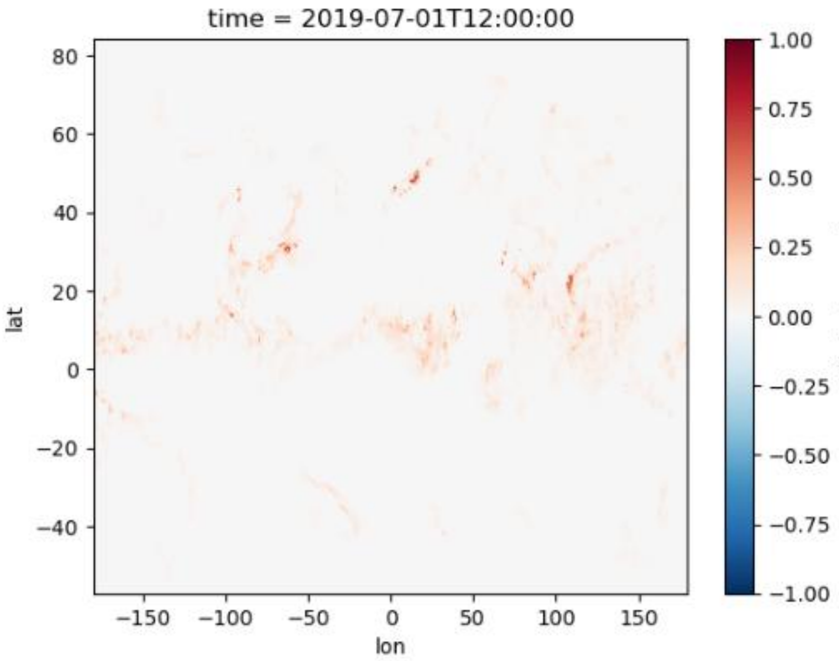
Calibrated lightning probability



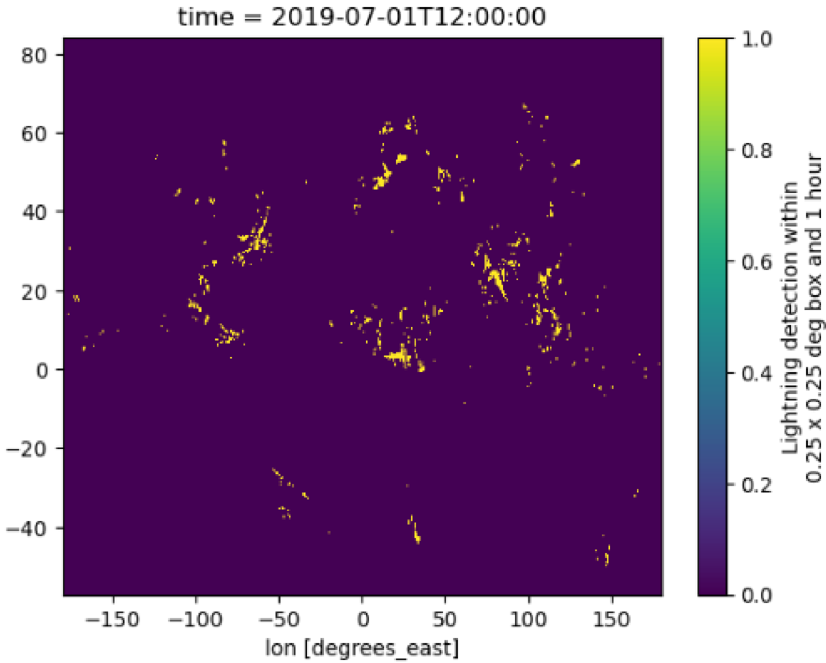
Raw XGBoost output



Calibrated lightning probability



Detected lightning



Concluding remarks

- *State-of-the-art prediction of lightning occurrence*; recommended number of convective parameters to use depend on desired trade-off between computational cost, interpretability and discriminative power.
- Different flavors of the same convective parameter help to boost performance. Open question: *why is it the case?*
- Small performance gap between regionalized and global model: *could new predictors close that gap?*
- Final calibrated model needs to be verified and benchmarked against baselines on full test year, then potential to deploy the model for climatology, forecasts and climate change studies.

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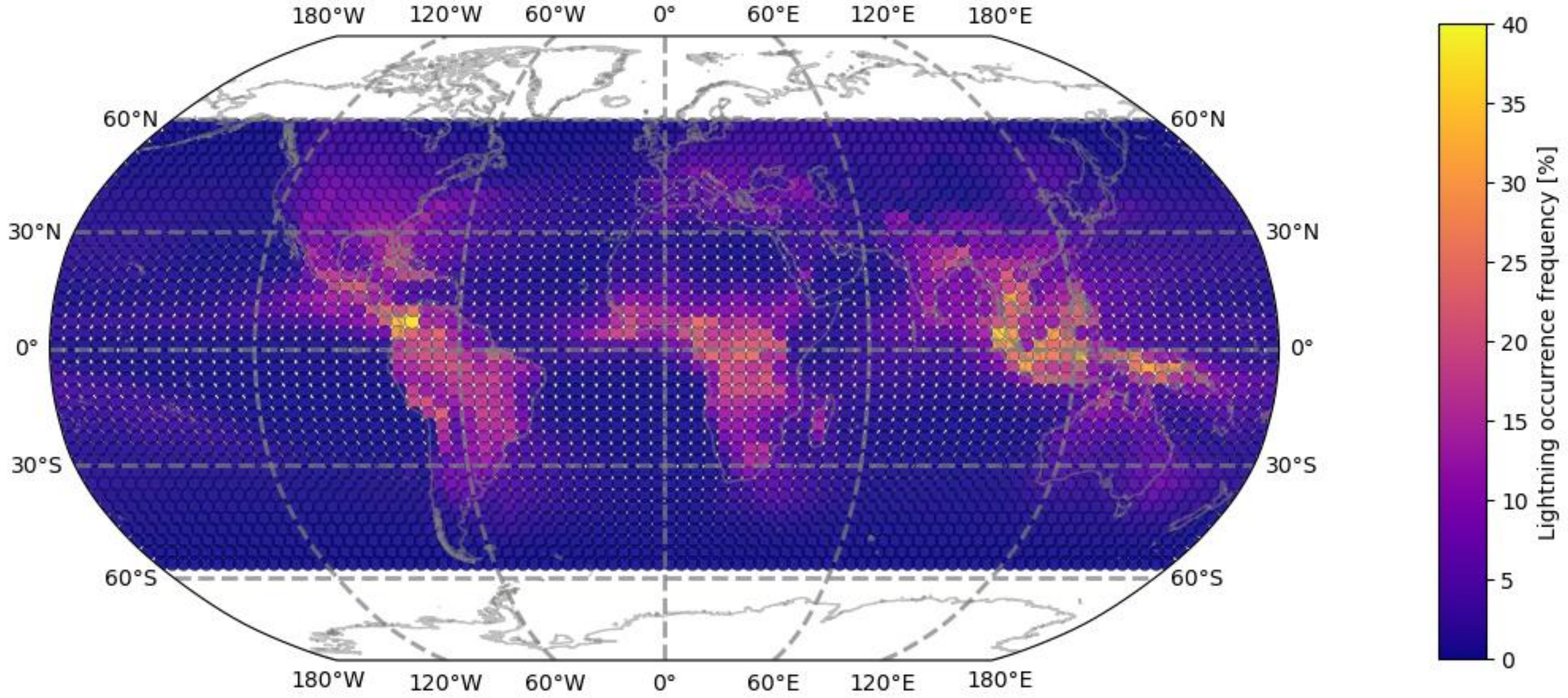
EXTRAS

Convective Parameters Count

Convective parameter type	Prefix	Count
Most-unstable parcel (CAPE, CIN, LI, buoy, etc.)	MU	25
Most-unstable-mean-layer parcel (CAPE, CIN, LI, buoy, etc.)	MUML	25
Most-unstable above 500 m parcel (CAPE, CIN, LI, buoy, etc.)	MU5	16
Mixed-layer parcel (CAPE, CIN, LI, buoy, etc.)	ML	7
Bulk wind shear (from level X to Y)	BS	19
Wind speed (mean or max between level X and Y)	MW, WS	6
Storm-relative winds, storm-motion vectors	SRW, CBV	9
Moisture parameters (mean between level X and Y, flux)	RH, Moisture, PRCP	21
Temperature lapse rates (between level X and Y)	LR	10
Theta-e and downdraft parameters	THETAE, Cold_Pool	9
Height of specific levels (isotherms, parcel)	HGT	6
Direct ERA5 fields (precipitation, total column water)		13
Static features (angle, mask)	Sun, Land	3
Lightning climatology	Climatology	1
Total (no composite or SB parameters)		**170**

Earth Networks Global Lightning Detection Network (ENGLN)

Lightning occurrence: lightning detection +/-1h and +/-0.25deg around ERA5 grid

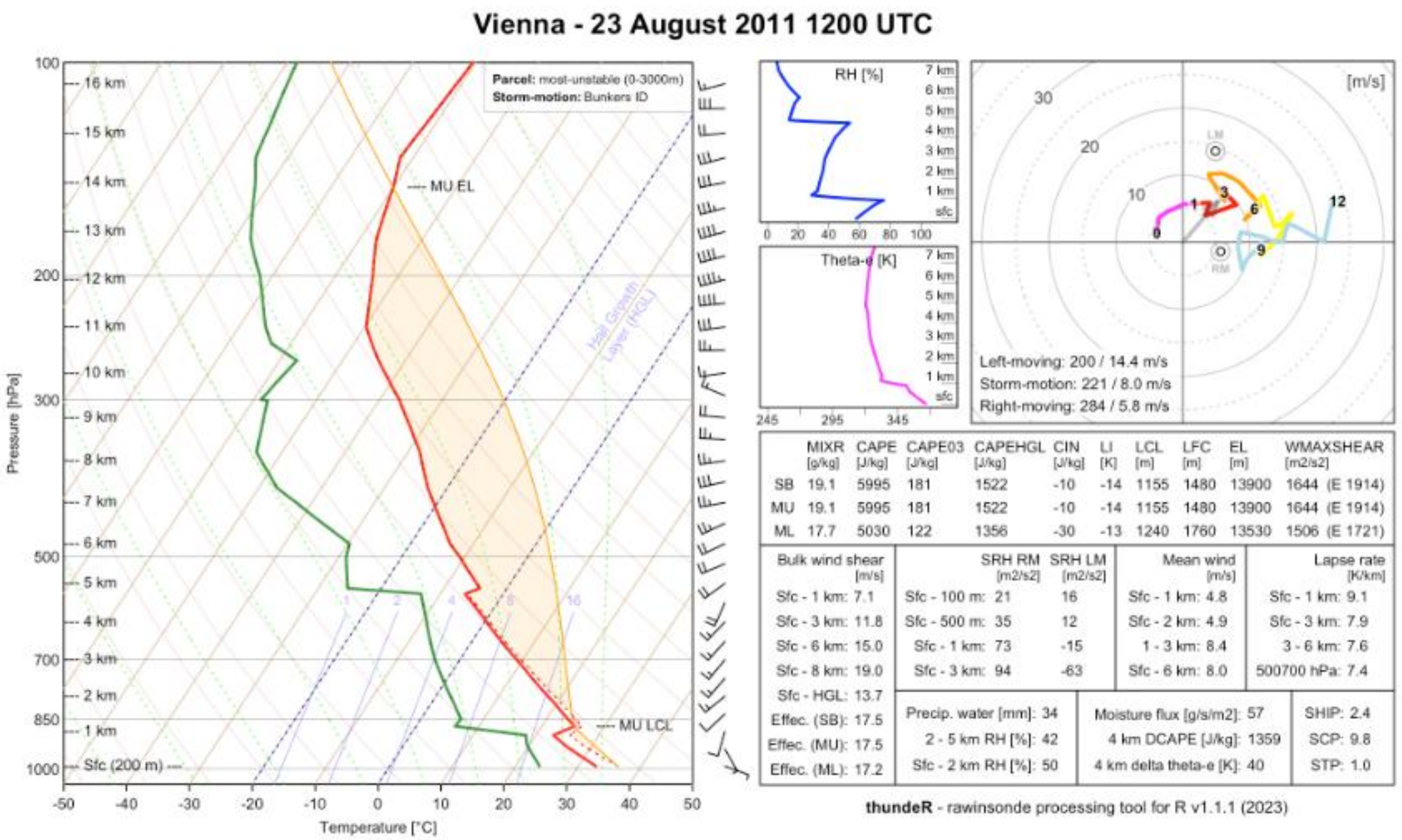


Period: 2019-2023

ThundeR

v.1.5 (pre-release)

```
data("sounding_vienna") # load example dataset (Vienna rawinsonde profile for 23 Aug 2011 12UTC):
pressure = sounding_vienna$pressure # vector of pressure [hPa]
altitude = sounding_vienna$altitude # vector of altitude [meters]
temp = sounding_vienna$temp  # vector of temperature [degree Celsius]
dpt = sounding_vienna$dpt # vector of dew point temperature [degree Celsius]
wd = sounding_vienna$wd # vector of wind direction [azimuth in degrees]
ws = sounding_vienna$ws # vector of wind speed [knots]
sounding_save(filename = "Vienna.png", title = "Vienna - 23 August 2011 1200 UTC", pressure, altitude, tem
p, dpt, wd, ws)
```



- Computation and visualisation of an extensive suite of convective parameters for severe weather forecasting
- Efficient computation in C++
- R interface and Python calls via rpy2 library: https://bczernecki.github.io/thundeR/
- Web interface: www.rawinsonde.com

XGBoost

XGBoost is an optimized distributed gradient boosting library designed to be highly **efficient**, **flexible** and **portable**.

- Type of **Ensemble Decision Trees**
- **Gradient Boosting**: Alternative training method to **Random Forests**
- Can handle **billions** of examples

```python
# Model Parameters
params = {
    'max_depth': 10,
    'learning_rate': 0.003,
    'eval_metric': 'logloss',
    'tree_method': 'hist',
    'objective': 'binary:logistic',
    'verbosity': 1,
}
n_boosting_rounds = 3500
```

Hyperparameters optimized with GridSearchCV

Data pre-processing

- #features: 170 (153 after removing features with # Nans > 1%)
- #samples:
  - LM = 8M
  - OM = 17M
  - LT = 8M
  - OT = 19M

  Total: 51M
- Data split:
  - Train = 2019-2021
  - Validation = 2022
  - Test = 2023
- Data balancing (random under-sampling):
  - LM = 3.1% => train = 0.3M, validation = 0.1M, test = 0.1M
  - OM = 0.8% => train = 0.2M, validation = 0.1M, test = 0.1M
  - LT = 10.7% => train = 1M, validation = 0.3M, test = 0.3M
  - OT = 2.7% => train = 0.6M, validation = 0.2M, test = 0.2M

Rank	Convective parameters	Normalized information gain
1	MU5_CIN_4km	100.0%
2	MU5_LI_eff	95.9%
3	tciw	32.8%
4	tcslw	16.9%
5	MUML_LI_eff	10.0%
6	MU5_CAPE_HGL	8.2%
7	MUML_CAPE_HGL	7.7%
8	MUML_LI	7.3%
9	LR_06km	6.6%
10	MU_LI_eff	4.8%
11	LR_16km	4.4%
12	vigd	3.4%
13	RH_500850	3.0%
14	MU5_buoy_HGL	3.2%
15	MU_CAPE_HGL	3.0%
16	LR_03km	2.8%
17	HGT_ISO_M10	2.8%
18	RH_14km	2.5%
19	THETAE_02km	2.5%
20	MU_LI	2.4%
21	MU5_LI	2.4%
22	RH_ML_LCL_3km	2.4%
23	RH_25km	2.3%
24	MU5_CAPE_M10	2.2%
25	THETAE_01km	2.1%
26	tcrw	2.0%
27	LR_04km	1.8%
28	cp	1.8%
29	vimd	1.7%
30	tp	1.7%
31	MU_CIN_4km	1.7%
32	MU5_CAPE	1.6%
33	MU_cold_cloud	1.6%
34	SRW_0500m_MW	1.6%
35	tclw	1.5%
36	LR_26km	1.5%
37	BS_18km	1.5%
38	Cold_Pool_Strength	1.4%
39	MUML_CAPE	1.4%
40	HGT_ISO_0	1.4%

Explanation of “features”

1. **MU5_CIN_4km** : Convective inhibition for lifted parcel (MU5) in 4 km layer with the bottom of that layer at the parcel lifting height.
2. **MU5_LI_eff** : The largest difference *between* lifted parcel (MU5) *and* ambient temperature found in the entire profile assuming environmental temperature is below -10 °C and the height is at least 2 km above lifted condensation level.
3. **tciw** : Total column cloud ice water (ERA5).
4. **tcslw** : Total column supercooled liquid water (ERA5).
5. **MUML_LI_eff** : Same as 2., but the lifted parcel (MUML) is the most-unstable parcel after mixing 500 m layers (moving window), up to 3 km AGL.
6. **MU5_CAPE_HGL** : Convective Available Potential Energy *for* the most-unstable parcel after excluding lowest 500m from the profile *and* in the Hail Growth Layer (-10 °C to -40 °C).

Interpretation of “features”

- **CIN** - highlights convective initiation failure modes when there is too much inhibition
- **CAPE_HGL** - measure of buoyancy in a lightning-favorable charge separation zone
- **LI** - measure of atmospheric instability, supplements CAPE in marginal situations when CAPE is zero, but lightning can still form
- **tciw / tcslw** - proxy for lift, indicative of presence of hail/graupel
- Both **MU5** and **MUML** parcels are worth to use simultaneously and they supplements each other and account for different atmospheric scenarios