Comparison of the performance of PCA-NN and PCA-MRM models for TEC over the Iberian Peninsula

Anna Morozova[1], Teresa Barata[1], and Tatiana Barlyaeva[1]

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November 23, 2022

Abstract

The total electron content (TEC) over the Iberian Peninsula was modeled using a PCA-based models based on the decomposition of the observed TEC series using the principal component analysis (PCA) and reconstruction of the daily modes' amplitudes either by a multiple linear regression model (MRM) or neural networks (NN) using several types of space weather parameters as regressors/predictors: proxies for the solar UV and XR fluxes, number of the solar flares of different types, parameters of the solar wind and of the interplanetary magnetic field, and geomagnetic indices. Lags of 1 and 2 days between the TEC and space weather parameters are used. The general performance of the PCA-MRM and PCA-NN models is tested for different months and in different space weather conditions.

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COMPARISON OF THE PERFORMANCE OF PCA-NN AND PCA-MRM MODELS FOR TEC OVER THE IBERIAN PENINSULA

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Observatório Geofísico e Astronómico da Universidade de Coimbra

ia instituto de astrofísica e ciências do espaço

CONTENT

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ABSTRACT

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- Lags of 1 and 2 days between the TEC and space weather parameters are used.
- The general performance of the PCA-MRM and PCA-NN models is tested for different months and in different space weather conditions.

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PCA-BASED MODELS

- The main feature of the PCA-based models is that the TEC series is decomposed into several PCA modes which represent TEC daily variations of different types
- The amplitude of each of the mode for each day is described by the EOF coefficients
- The EOF coefficients can be modelled using space weather parameters as predictors using, e.g., multiple regression models (MRM) or neural networks (NN)
- The MRM regression coefficients or a trained NN can be used to forecast the EOF coefficients, and, consequently, to forecast TEC
- The advantage of the PCA-based models is that there is no need for any assumption on the phase and amplitude or seasonal/regional features of TEC daily variations: the daily variations of correct shapes are extracted automatically by PCA from the input TEC data.

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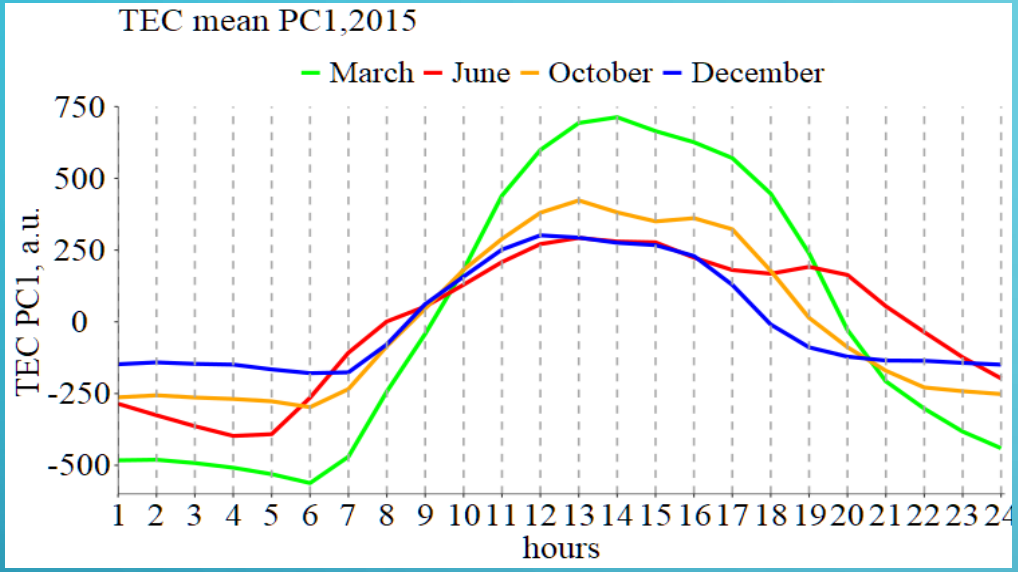
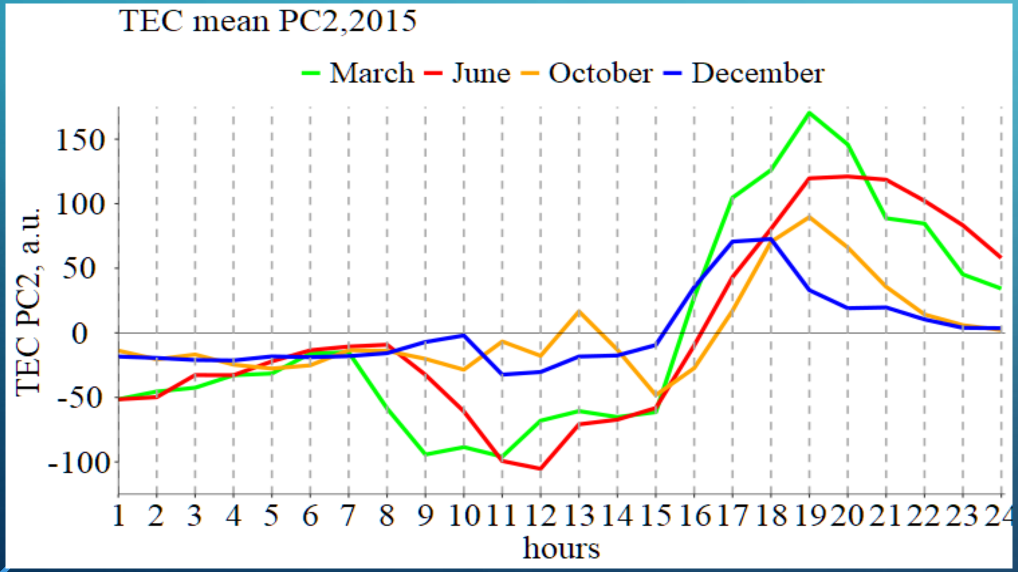
PCA MODES





Mode 1:

Explains 77-95% of the TEC variations for different months

PC1 = regular daily variation due to the changes of the insolation

Mode 2:

Explains 1.5-8.4% of the TEC variations for different months

PC2 = shallow minimum of TEC around the noon and a maximum in the late afternoon

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DATA: TEC

- Vertical TEC measured at Lisbon airport, Portugal (39° N, 9° W) by a GNSS receiver with SCINDA system
- Time interval: 01.01.2015- 31.12.2015
- Time resolution: 1h data
- Calibrated using data from Royal Observatory of Belgium (ROB) GNSS Research Group for the grid point that is very close to the location of the Lisbon airport.
  - To convert the relative TEC SCINDA data to the TEC data in TECu
  - The calibration was performed individually for each of the 12 month

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DATA: SPACE WEATHER PARAMETERS (*PREDICTORS*)

- Solar wind parameters:
  - Pressure (p), density (n), velocity (v)
- Interplanetary magnetic field:
  - Full interplanetary magnetic field (scalar B), GSM components (Bx, By, Bz)
- Geomagnetic indices:
  - Dst, ap, AE, local K_{COI}-index (Coimbra Geomagnetic Observatory, Portugal)
- Proxies for the solar UV & XR fluxes:
  - UV: Mg II composite series – a proxy for the spectral solar irradiance variability in the spectral range from UV to EUV (Snow et al., 2014);
  - F10.7 index (OMNI)
  - XR: Solar EUV Experiment (SEE) for the NASA TIMED mission at the wavelength 0.5 nm (LISIRD)
- Daily number of solar flares of classes C and M (NGDC)
- Time resolution: 1d data

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PCA-MRM MODEL

- L = 31 or 32 days
- Lag between space weather parameters and TEC = 1 & 2 days (space weather parameters lead)
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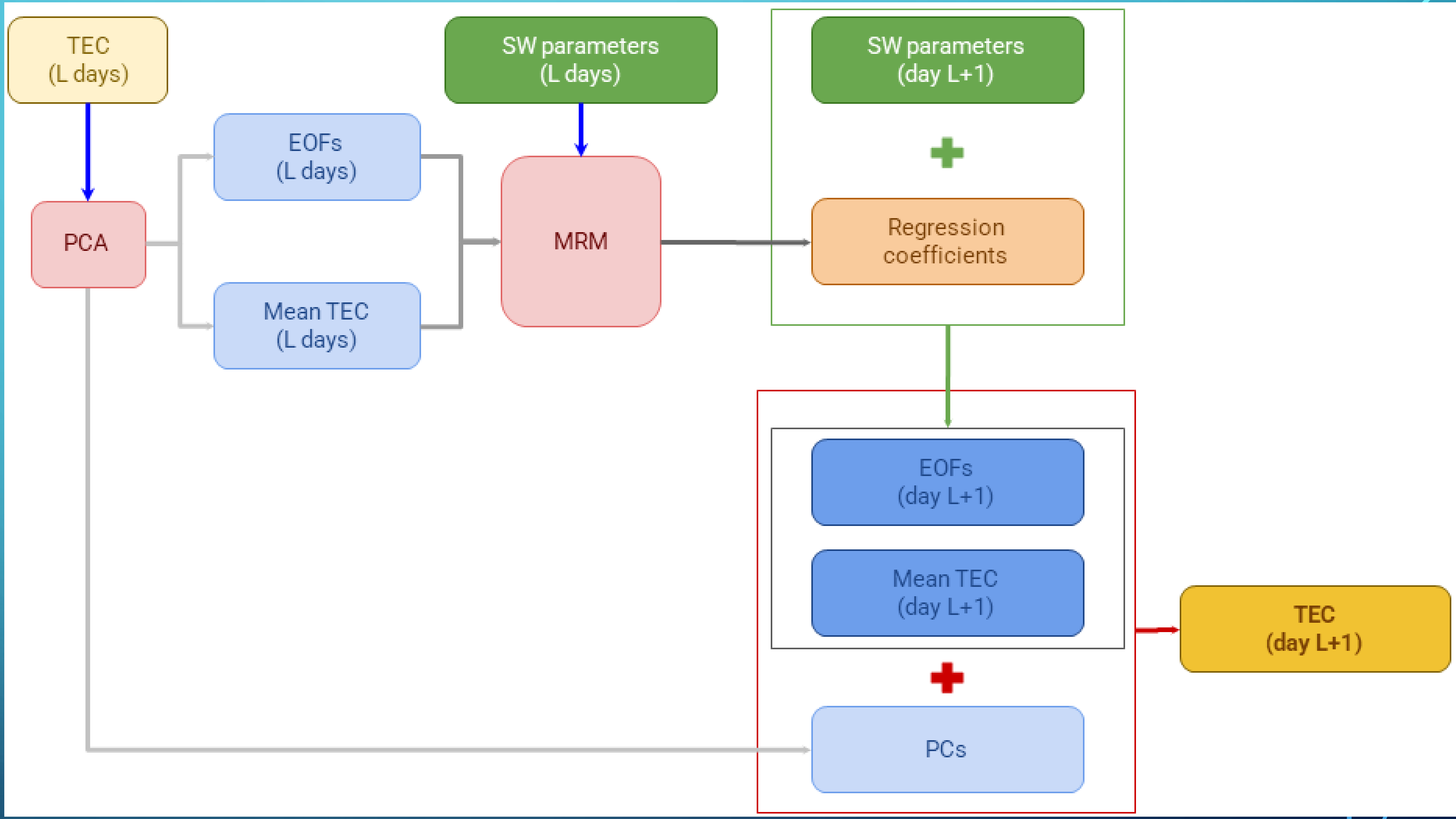

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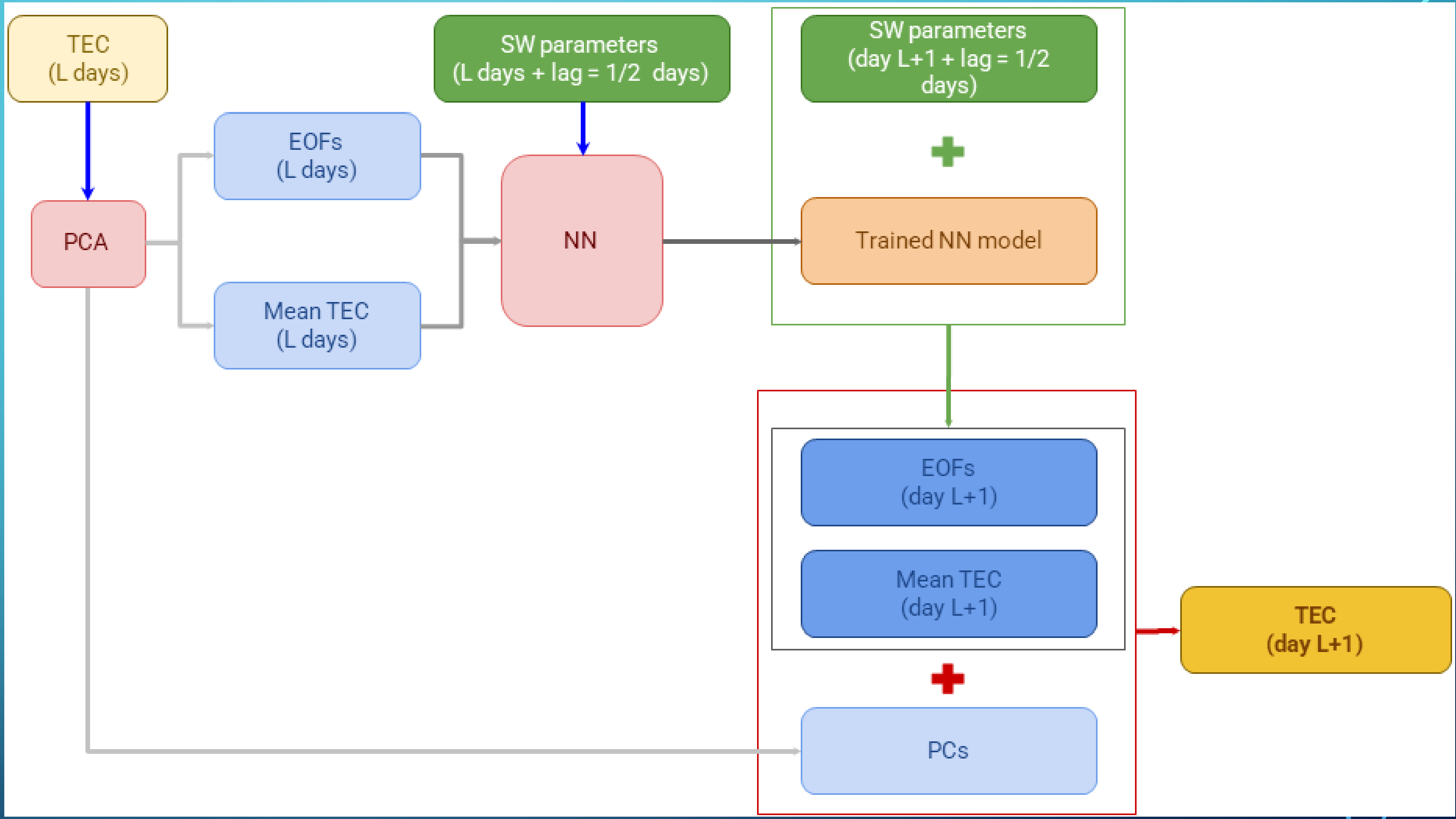
PCA-NN MODEL

- L = 31
- NN with "memory" (LSTM NN) or feedforward NN with weight backpropagation trained on the lagged series of predictors



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NEURAL NETWORK

- R package: *neuralnet*
- NN algorithm: *the resilient backpropagation with weight backtracking*
- Input dataset length = 31 days → for NN models we cannot use all 16 predictors → we selected the predictors that were used by most of the PCA-MRM models
- Tested predictors: *Mg II, Dst, By lagged by 1 and 2 days (6 input series)*
  - These space weather parameters were used in 67-83% of the tested MRM models
- Tested TEC parameter: *daily mean TEC*

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COMPARISON OF THE MRM AND NN FORECASTS

- Different NN were trained to find the best combination of the
  - Input series
  - NN depth (number of hidden layers and number of nodes)
  - Usage of an "ensemble forecast": a number (e.g., 100) of NN models of the same architecture were trained on the same input dataset and were used to make a forecast for the day L+1; the final forecast is the arithmetic average of 100 forecasts
- The forecasts of the daily mean TEC made by NN models for all available days of 2015 were compared to the forecasts of the daily mean TEC made by the (PCA)-MRM model using the following metrics:
  1. Correlation coefficient (r)
  2. Mean absolute error (MAE)
  3. Root-mean-square error (RMSE)

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COMPARISON OF THE MRM AND NN FORECASTS

	(PCA) -MRM	NN 3 predictors			NN 3 predictors "ensemble"			NN 2 predictors			NN, 1 predictor		
predictors	16 predictors & "best subset"	MgII, Dst, By			MgII, Dst, By			MgII, Dst	Dst, By	MgII, By	MgII	Dst	By
Layers & nodes		(6,4,2)	(6,4)	(6,2)	(6,4,2)	(6,4)	(6,2)	(4,2)	(4,2)	(4,2)	(2)	(2)	(2)
r	**0.88**[1]	0.88	0.88	0.88	**0.9**[2,3]	0.89	**0.9**[2,3]	**0.9**[2,3]	0.87	0.89	0.89	0.87	0.85
MAE	**2.0**[1,2]	2.21	2.16	2.17	**2.08**[3]	2.1	**2.08**[3]	**2.05**[3]	2.28	2.13	2.11	2.31	2.91
RMSE	**2.8**[1]	2.79	2.82	2.79	**2.64**[2,3]	2.7	**2.63**[2,3]	**2.61**[2,3]	2.88	2.7	2.68	2.91	3.09

[1,2,3] Notes

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COMPARISON OF THE MRM AND NN FORECASTS

1 – metrics for the (PCA)-MRM model
2 – best metrics for all kind of models
3 – best metrics for NN models

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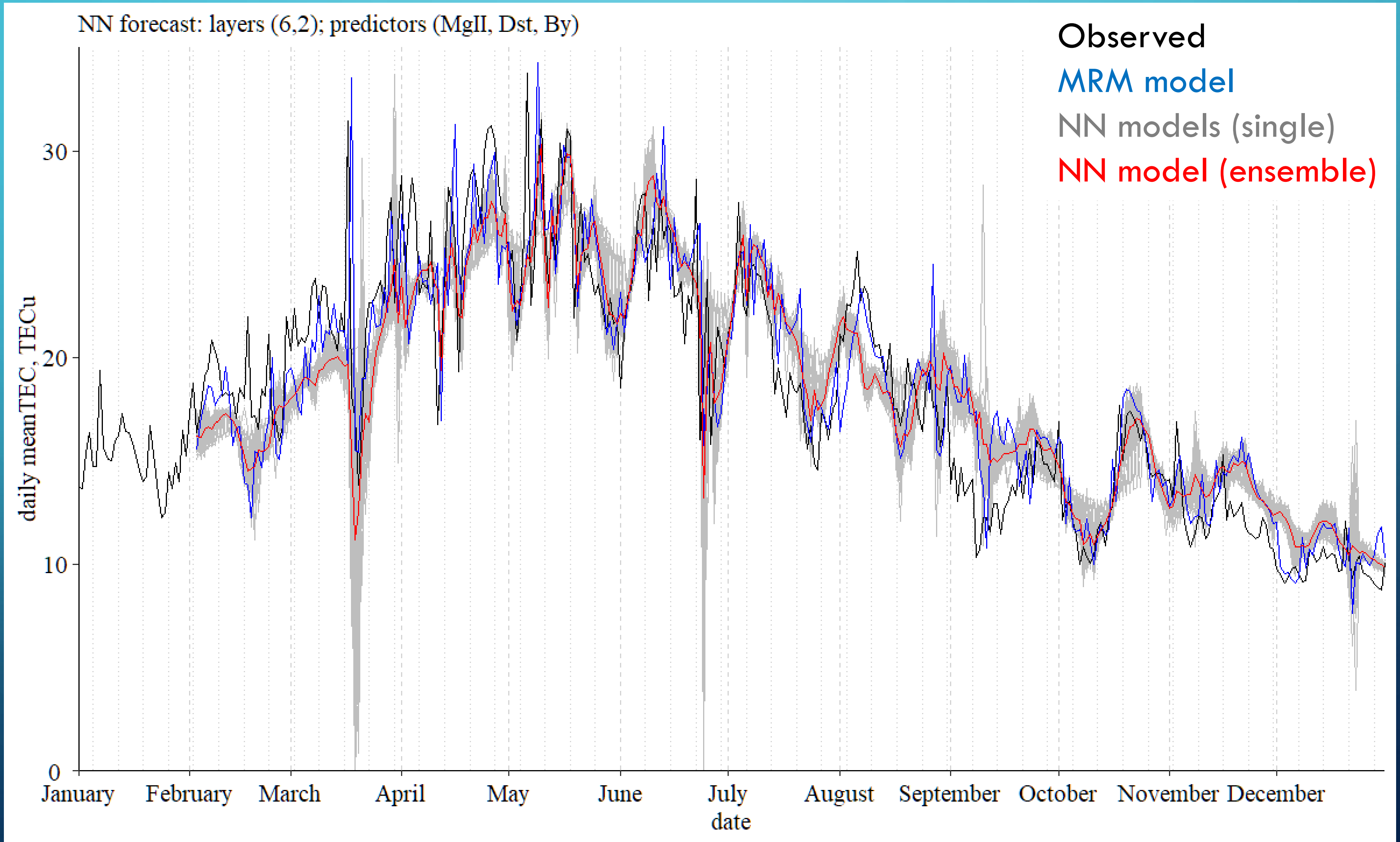
COMPARISON OF THE MRM AND NN FORECASTS

- Observations vs MRM model vs NN models with single and ensemble forecasts



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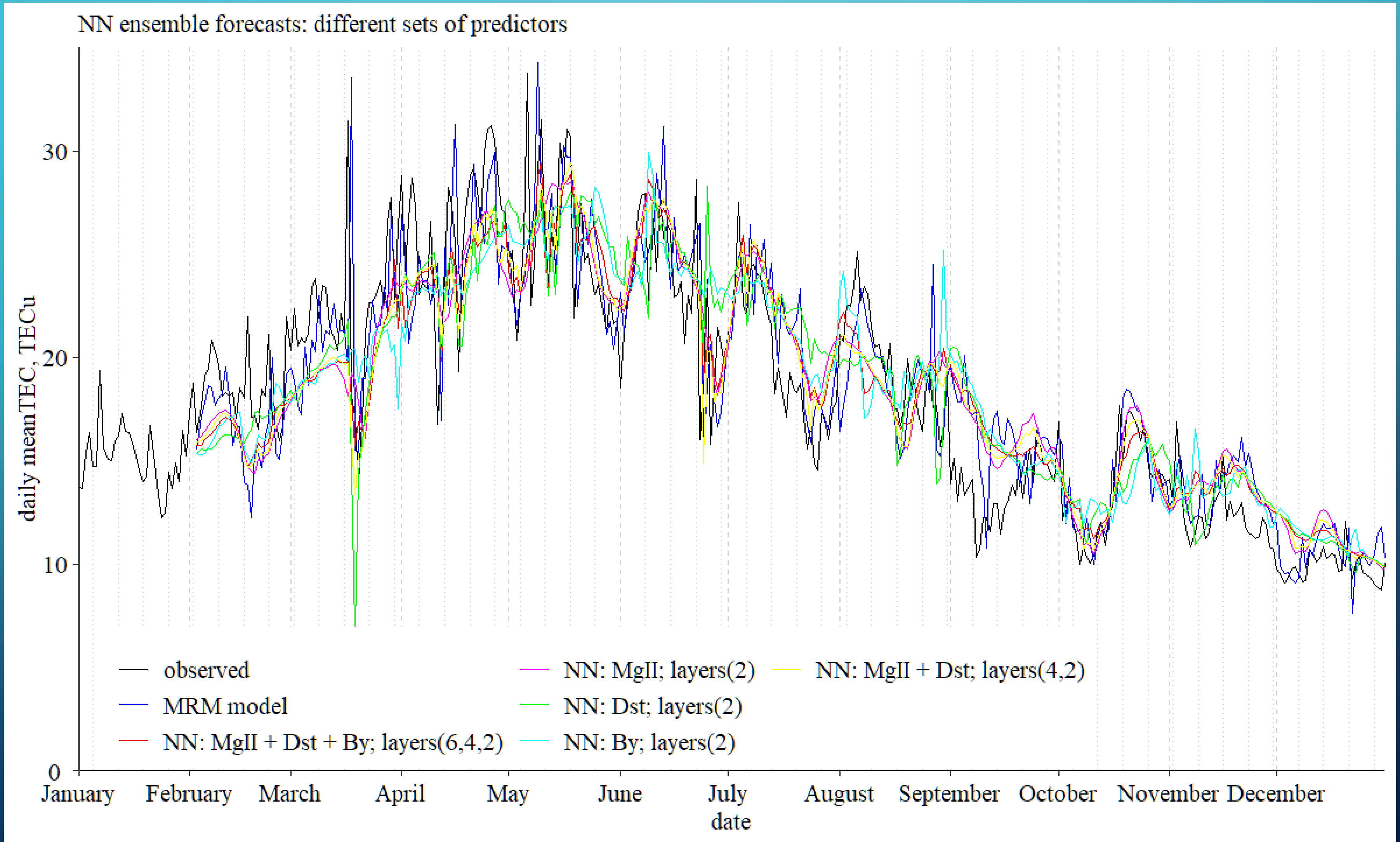
COMPARISON OF THE MRM AND NN FORECASTS

- Observations vs MRM model vs NN models with 1, 2 and 3 predictors



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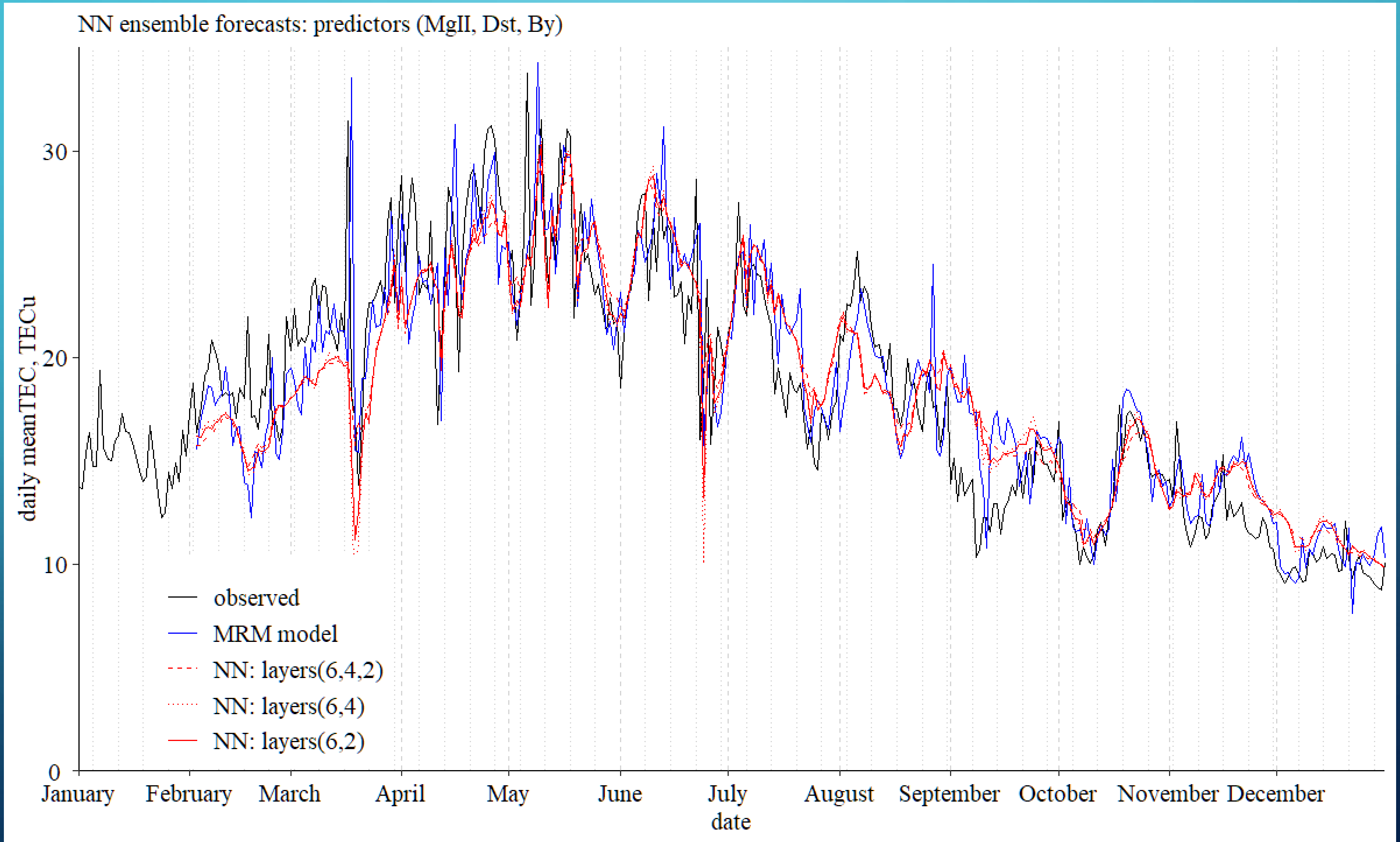
COMPARISON OF THE MRM AND NN FORECASTS

- Observations vs MRM model vs NN models with 3 predictors and different NN depth



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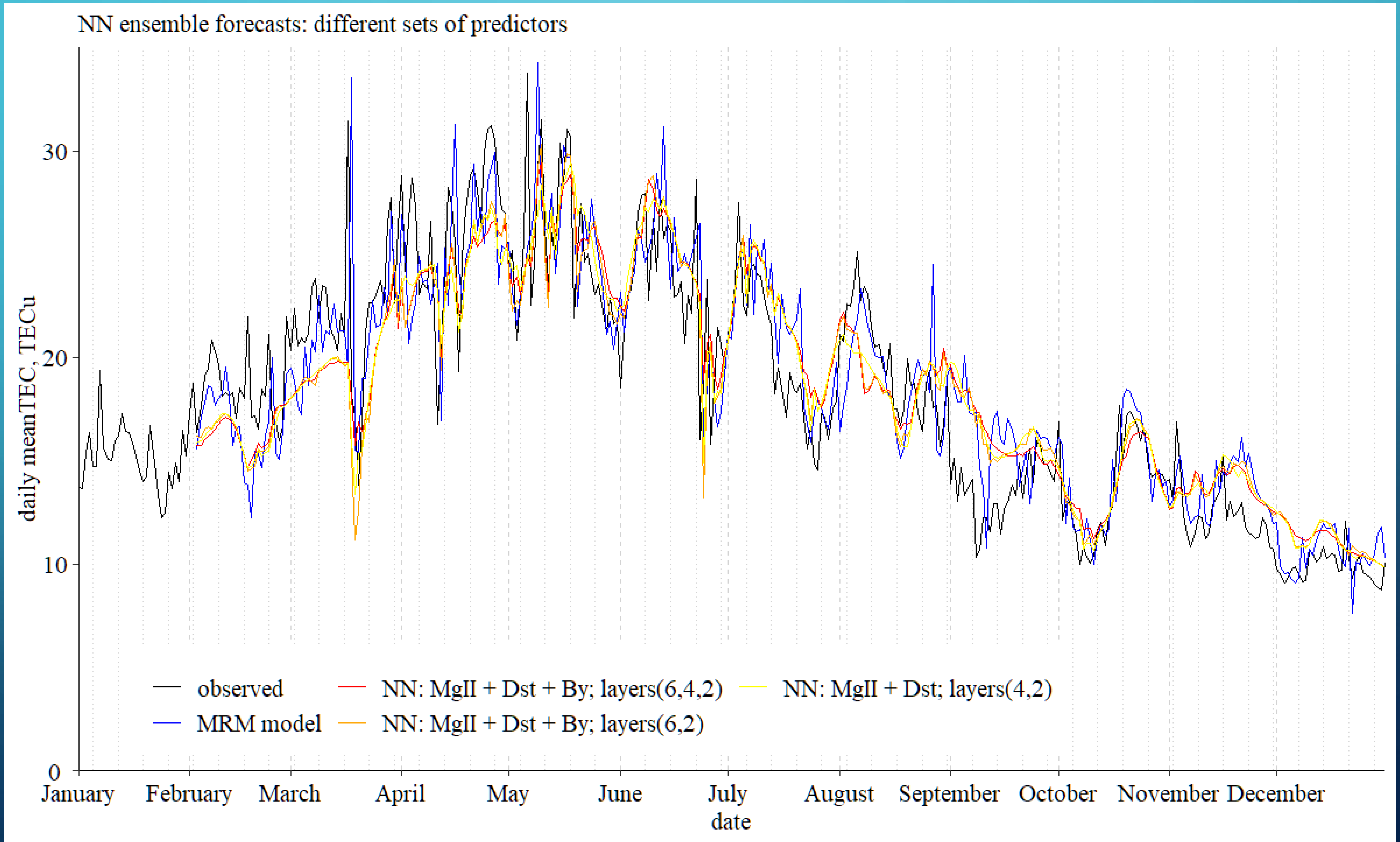
- Observations vs MRM model vs best NN models (marked in the Table)



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CONCLUSIONS

- A simple NN (feedforward NN with weight backpropagation) with just 2 or 3 predictors with time lags trained on a 31-days long input dataset can forecast the daily mean TEC series with the same or even better quality than the multiple regression model with up to 16 regressors
  - For some time intervals both the MRM and NN models give similar predictions different from observations. Hypothesis: TEC variations for that time intervals have other (non-space weather) drivers
- Ensemble NN forecast perform better than the single forecast
- As predictors the solar UV proxy (MgII) is the most important predictor (models without MgII perform worse)
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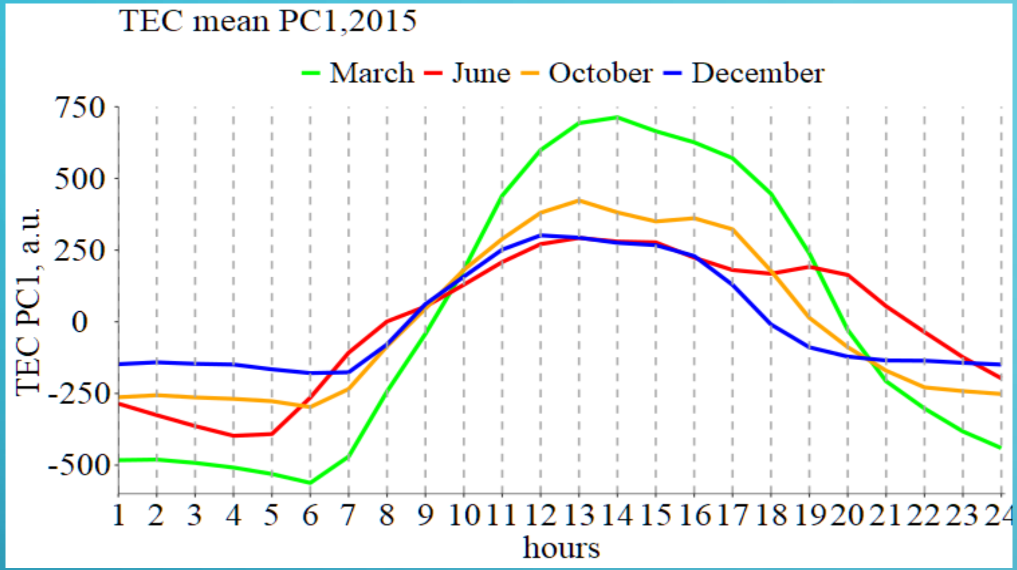

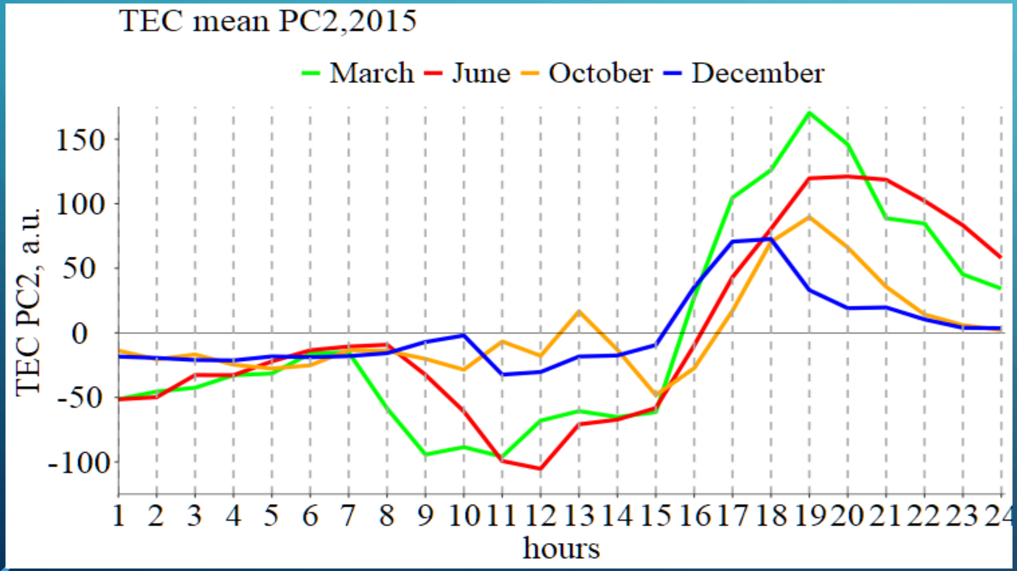

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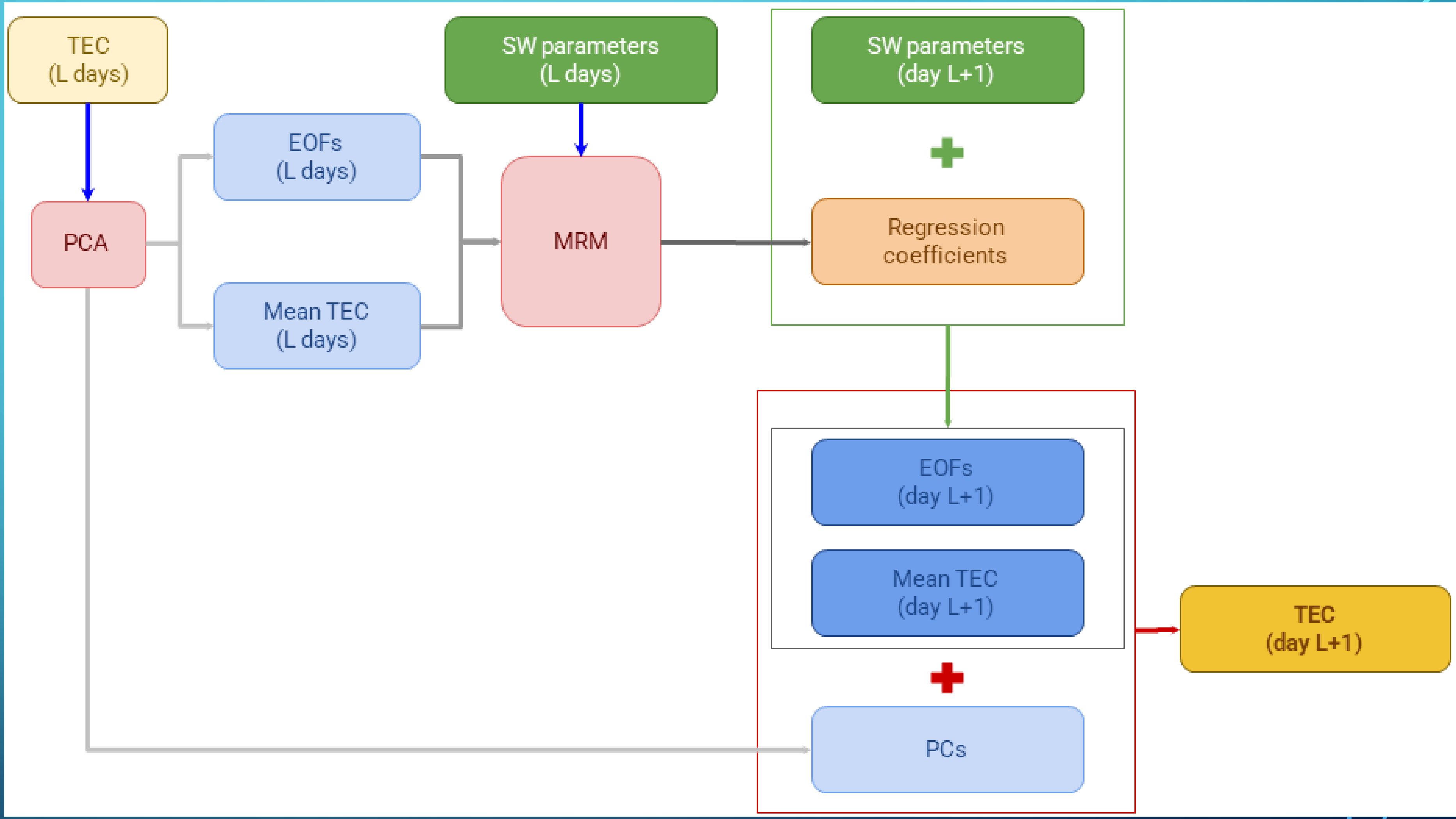

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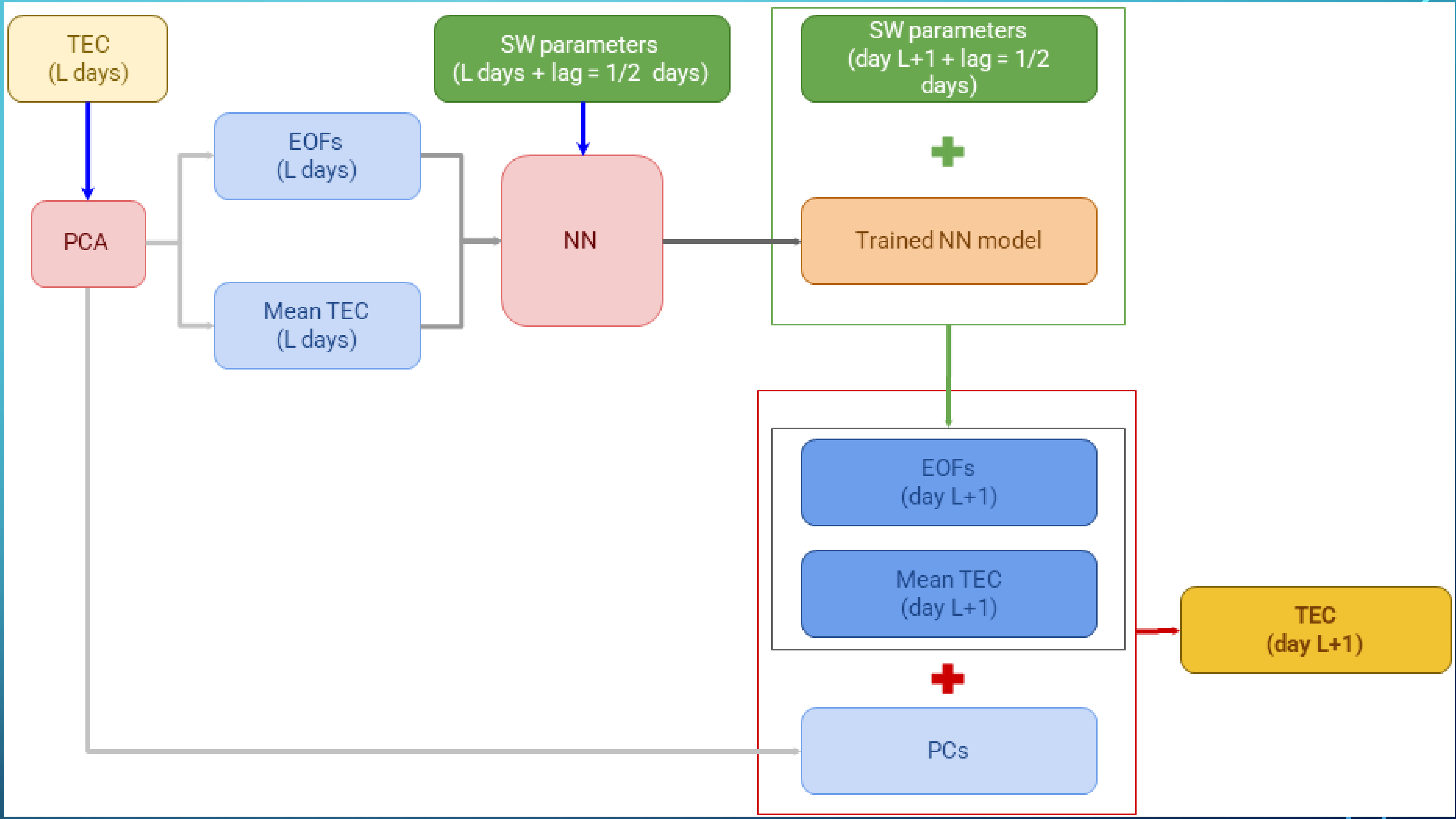

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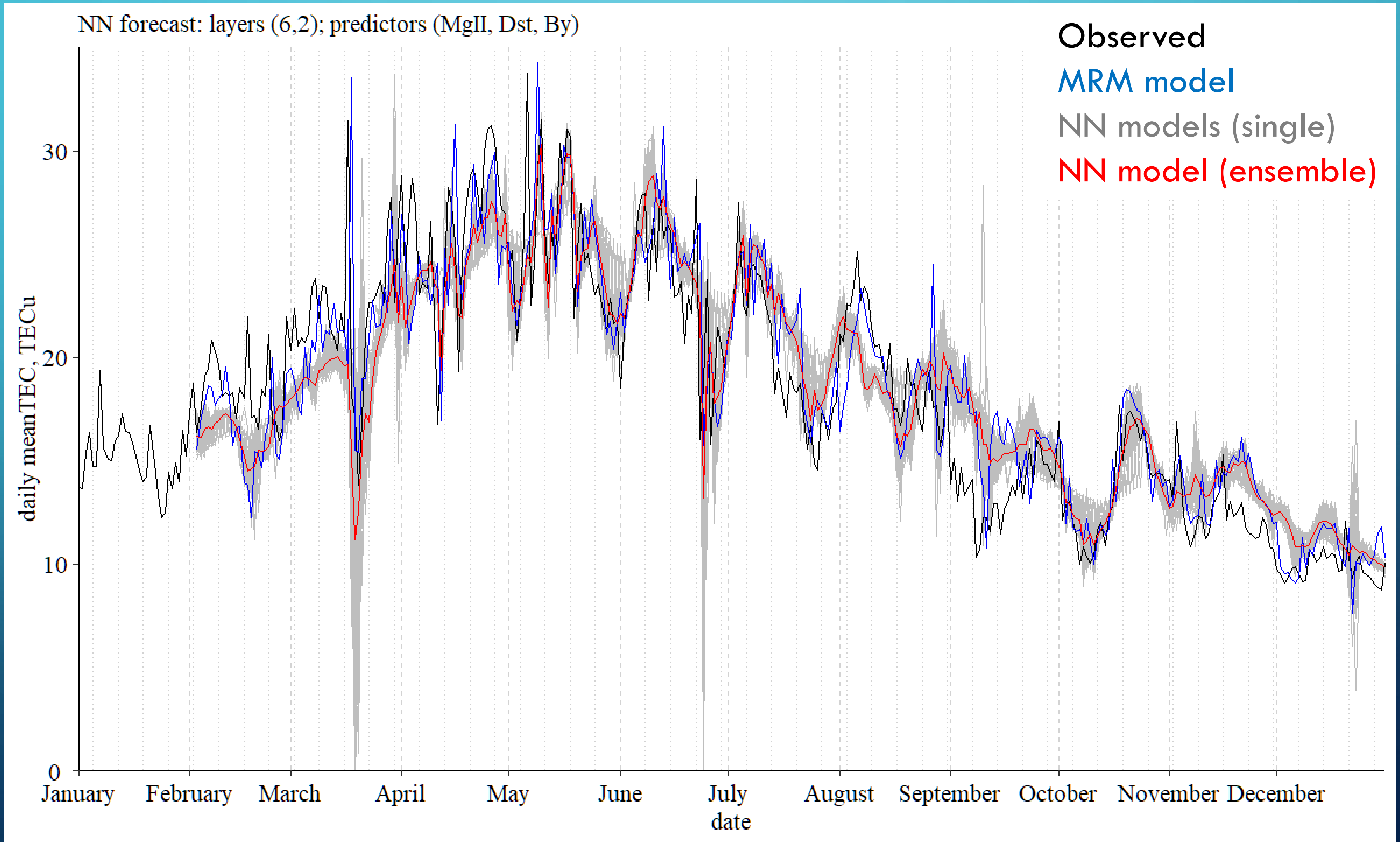

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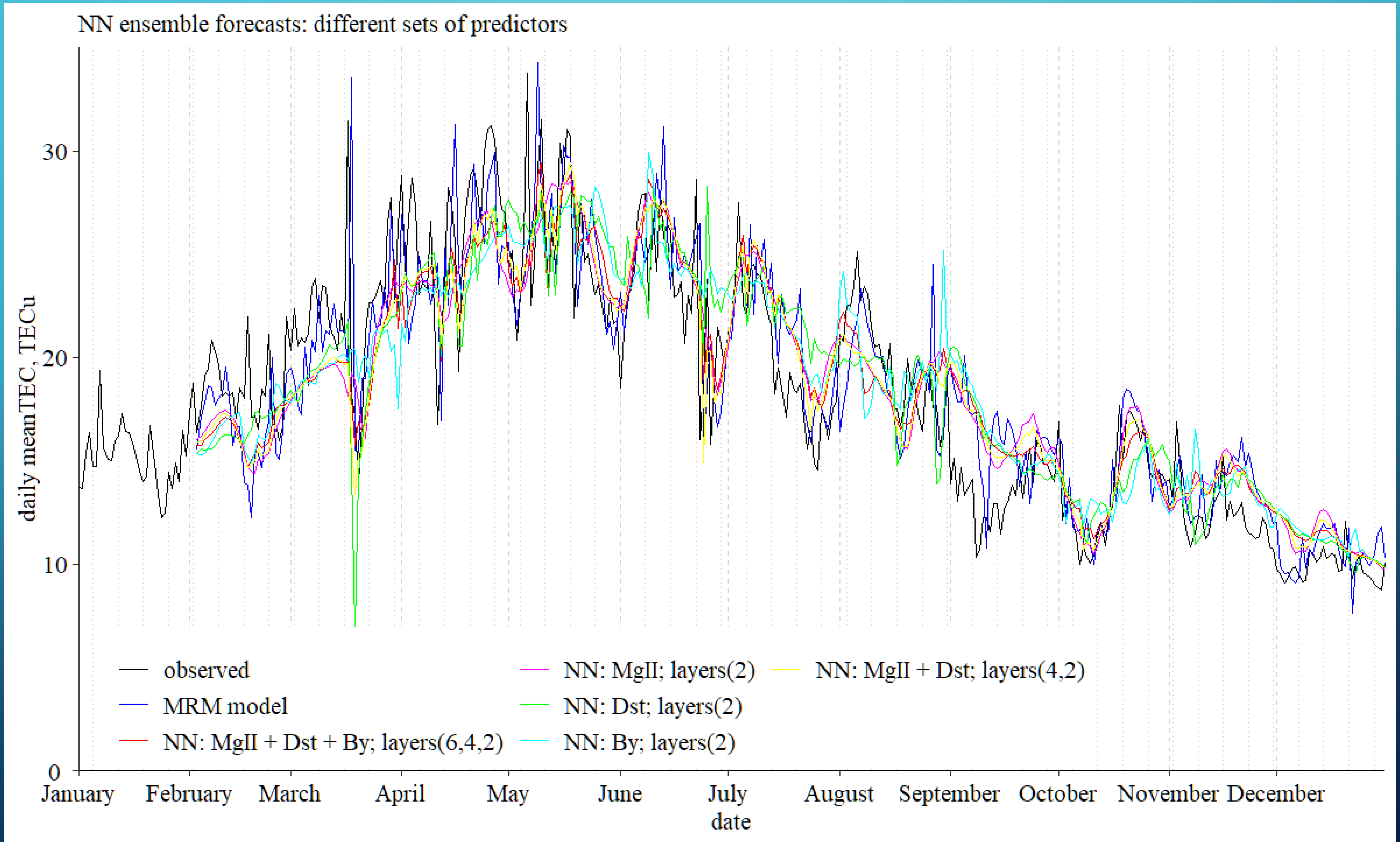

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COMPARISON OF THE MRM AND NN FORECASTS

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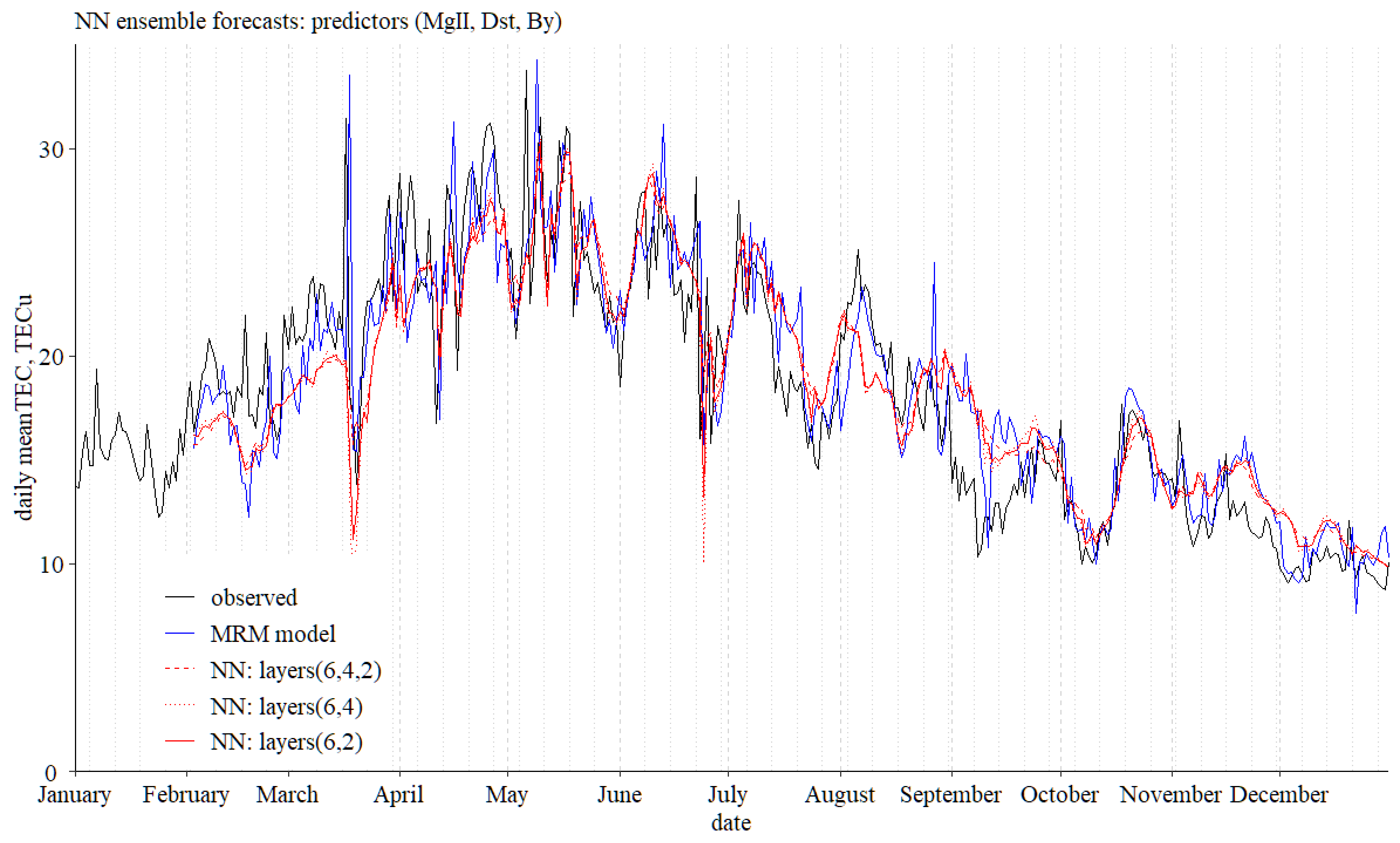

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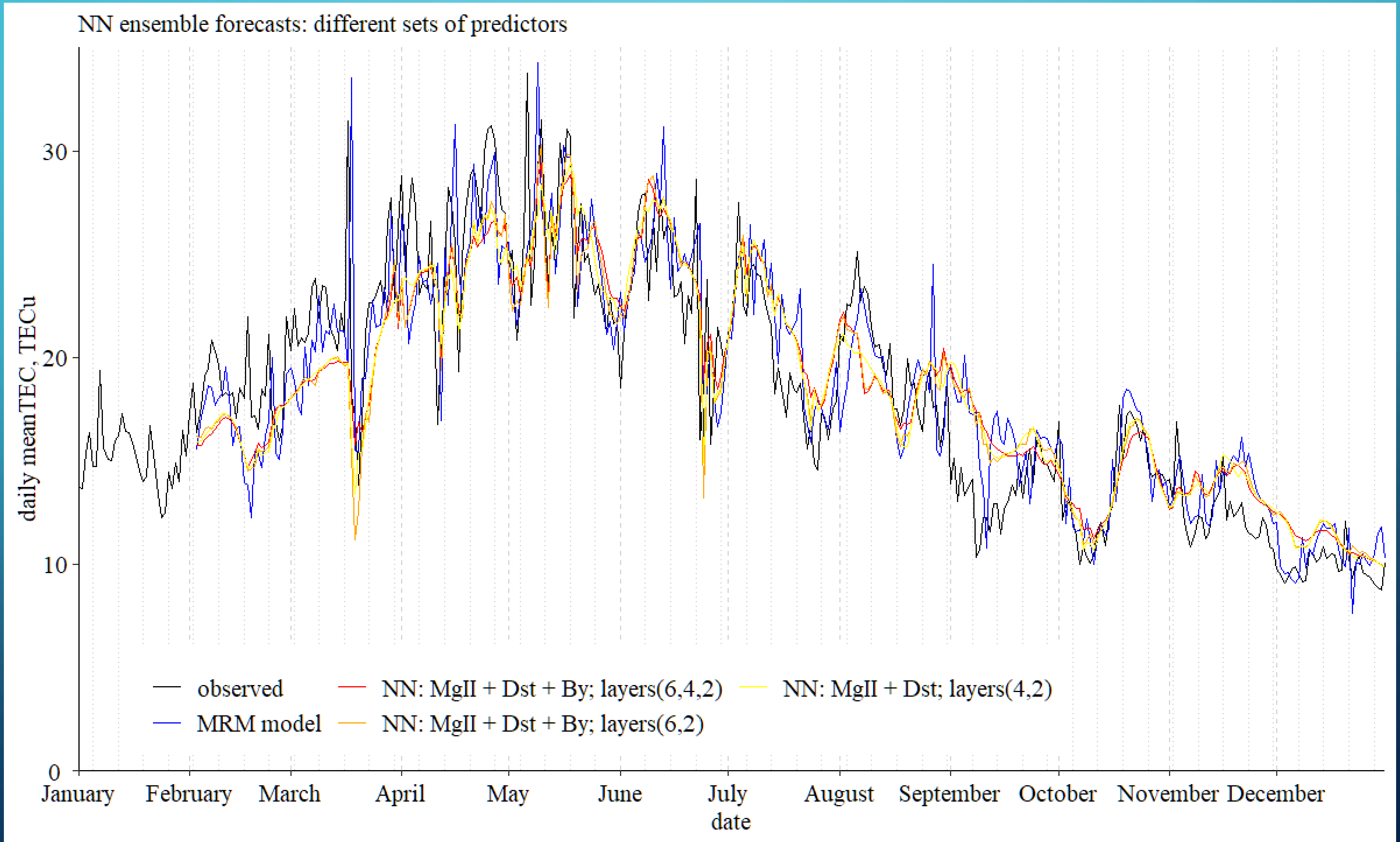

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