CNN-based forecasting of early winter NAO using sea surface temperature

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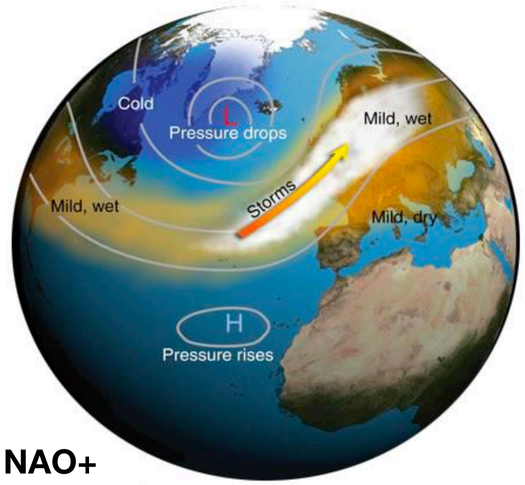
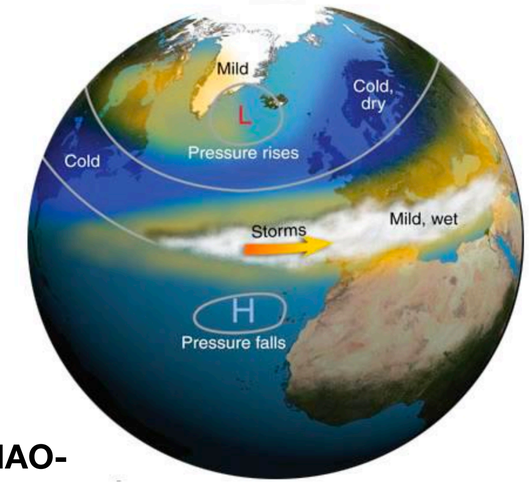
The North Atlantic Oscillation (NAO)

What is it and why forecast it?

- The **primary mode** of winter atmospheric variability in the North Atlantic (>10 days);
- A **dipole pattern** in sea-level pressure between the Icelandic Low and Azores High;



NAO+



NAO-

atmosphere is chaotic…

- Drives seasonal climate variability (Europe, North Africa, and eastern North America);
- Impacts energy, agriculture, extreme events (e.g. cold spells), and disaster preparedness.

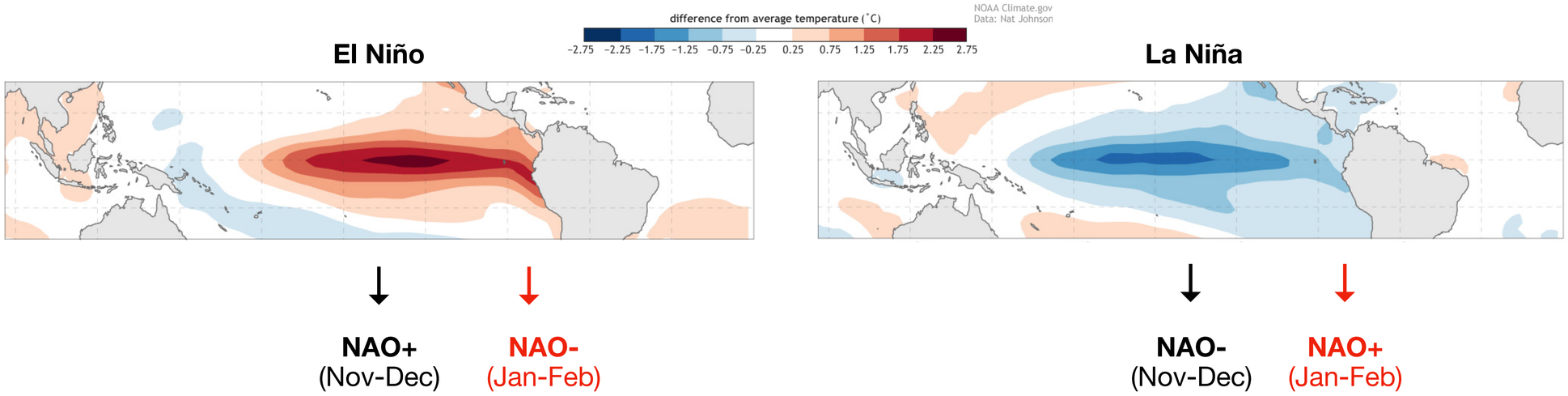
Sea Surface Temperature (SST)

How can we use it to forecast the NAO?

Sea Surface Temperatures (SST) evolve slowly and can influence the atmosphere (**weak** and **nonlinear** link).

Teleconnections: local changes in SST affect weather in remote regions

ENSO (El Niño-Southern Oscillation): SST anomalies in the central/eastern equatorial Pacific



Other key SST regions in early winter: North Atlantic, Indian Ocean

The scientific question

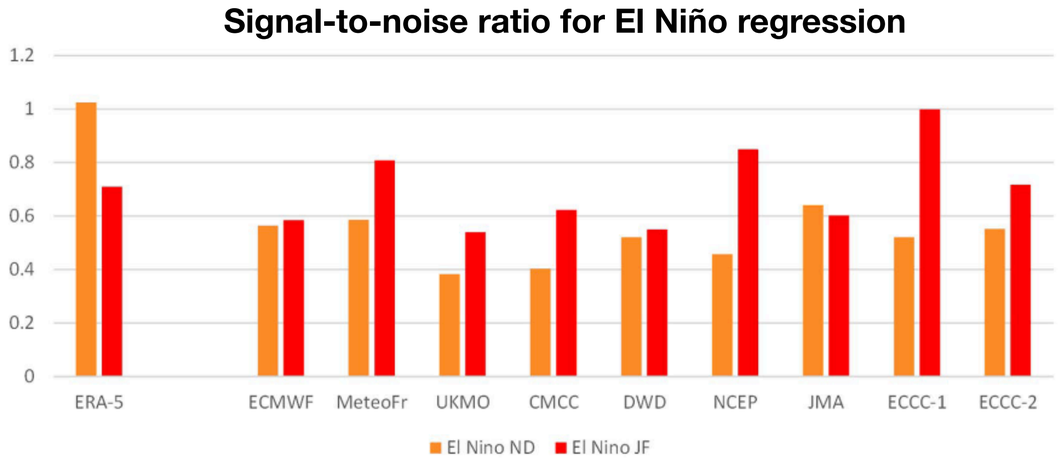
- These ocean-atmosphere interactions have been highlighted using **observations** and **linear** statistical analyses (e.g. regression, EOF, etc.) Gastineau et al. (2015)

- **Climate models** used for seasonal forecasting often struggle to capture the NAO response to SSTs, particularly during early winter.

« Signal »
Linear response to ENSO

$$S/N_{EN} = \sigma\left[s(\tau)_{EN}\right] / \sigma\left[\varepsilon(\tau)_{EN}\right]$$

« Noise »
unforced variability projecting on the same spatial patterns as the ENSO response



Molteni and Brookshaw (2023)

Can we use statistical modelling to predict early winter NAO from SSTs?

Datasets and Preprocessing

ERA5 Hourly Averaged Reanalysis
1940-2023
0.25°× 0.25° resolution

<u>Ocean (*Sea Surface Temperature*, SST)</u>

15°S-70°N region

↓

Re-gridding to 1°× 1°

↓

29-day running mean

↓

Computation of anomalies from yearly climatology

<u>Atmosphere (*Sea Level Pressure*, SLP)</u>

North Atlantic region (20°N-70°N,100°W-40°E)

↓

Re-gridding to 2°× 2°

↓

10-day running mean

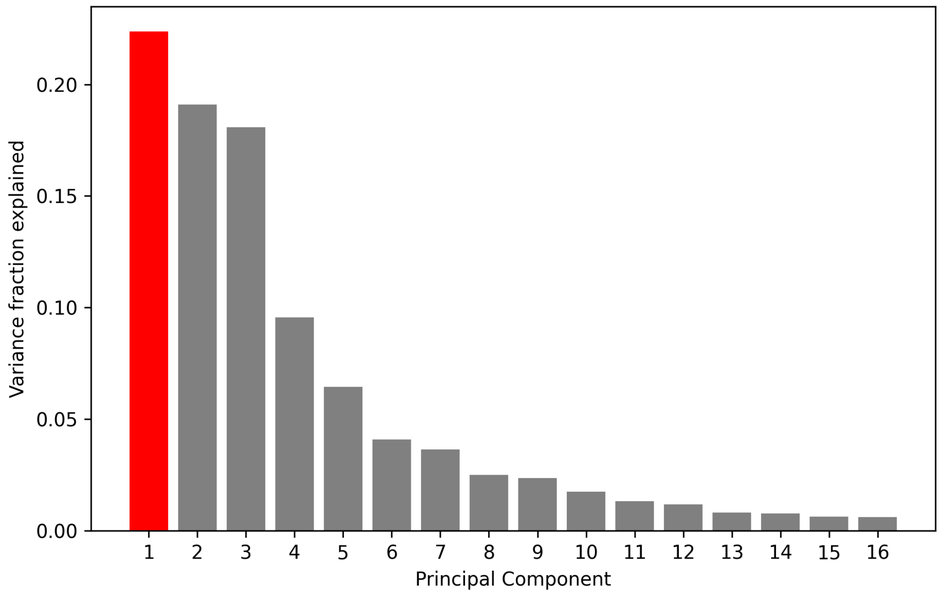
↓

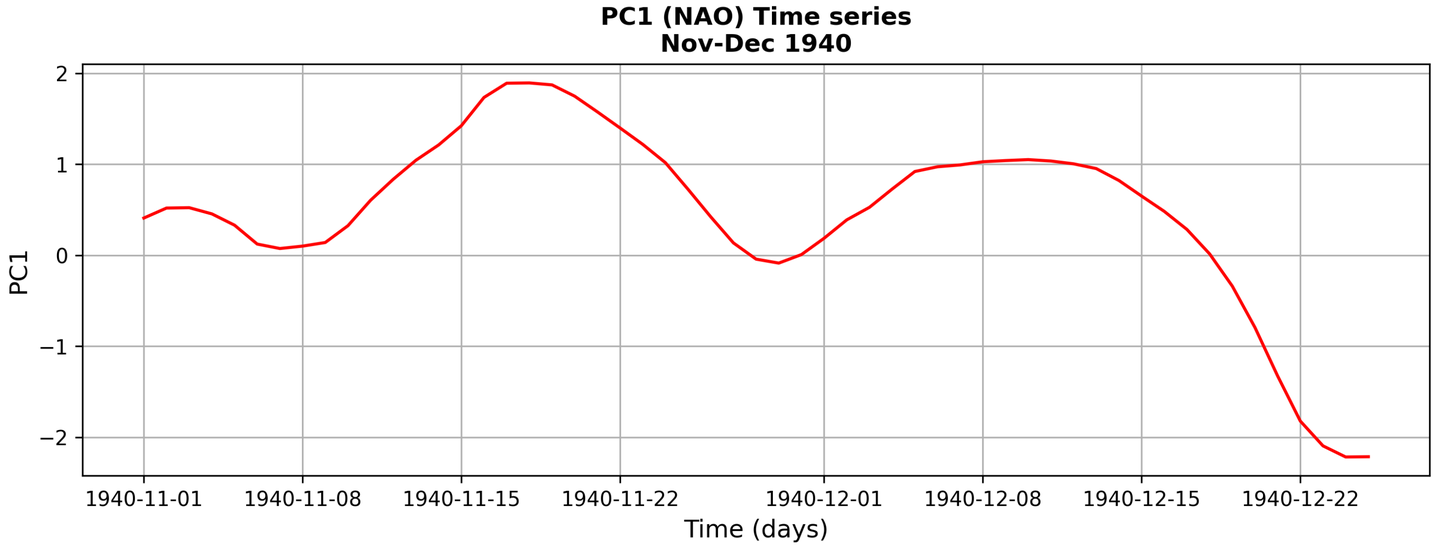
Computation of anomalies from yearly climatology
(**<u>NA ND SLP anomalies</u>**)

Dimensionality reduction

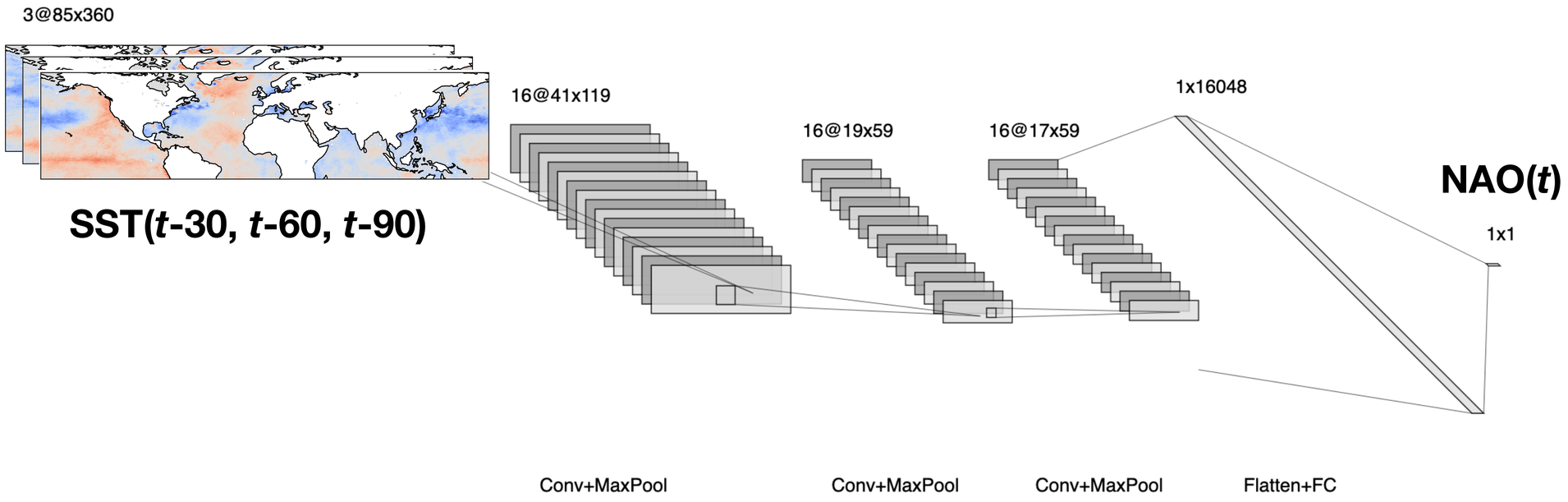
Principal Component Analysis (PCA)

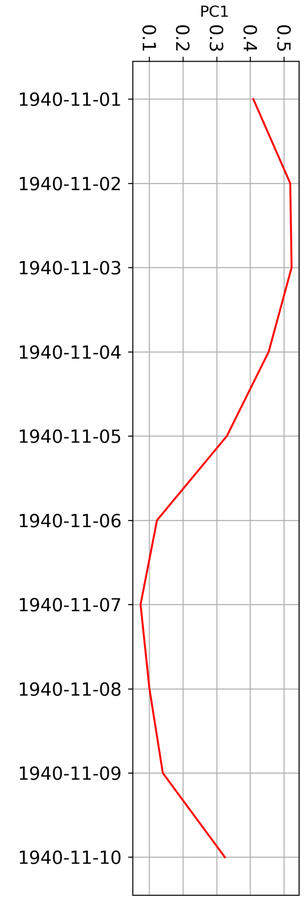
Output: <u>PC1</u> of NA ND SLP anomalies (i.e. the NAO)





Convolutional Neural Network (CNN)

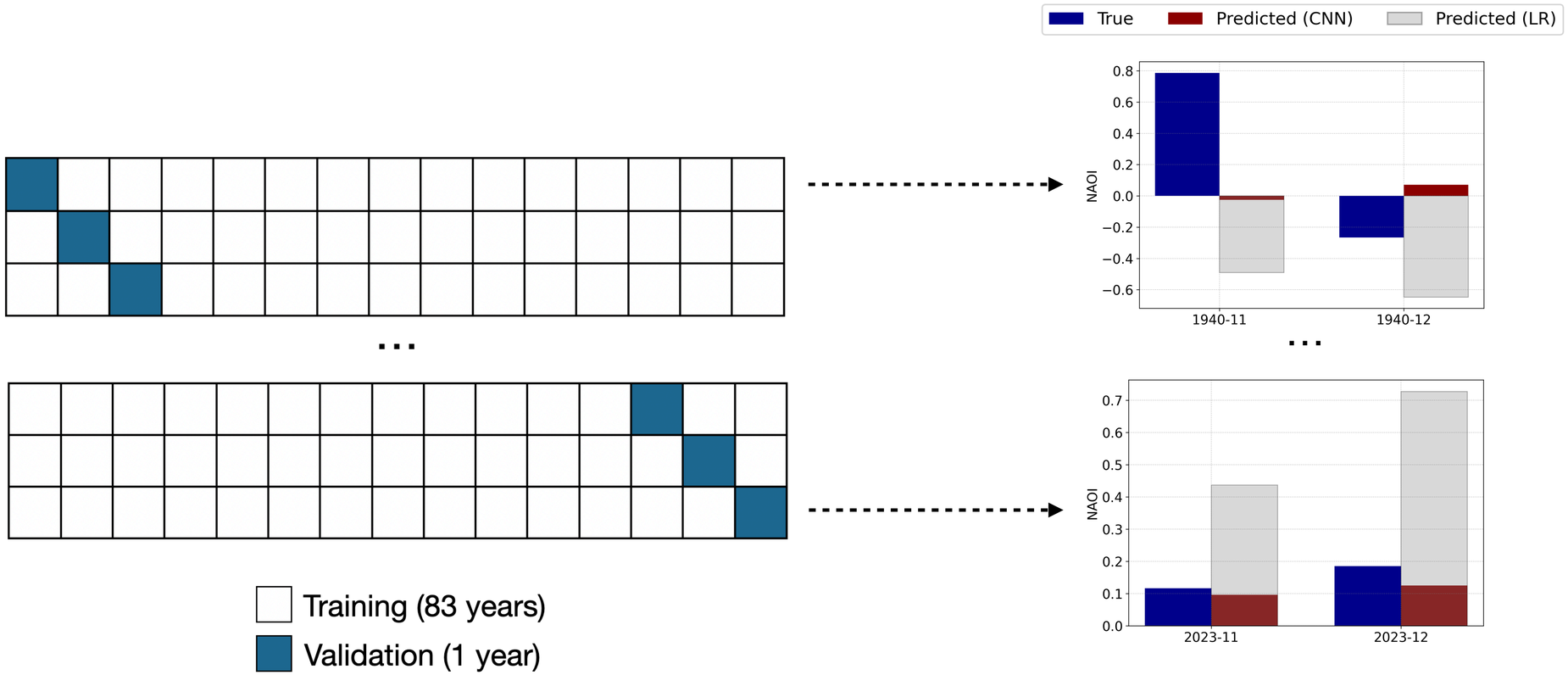




≈ 200.000 parameters

Benchmark: **Linear Regression** model (with simplified input)

Leave One Out cross-validation



➕ Robust evaluation of the model's performance

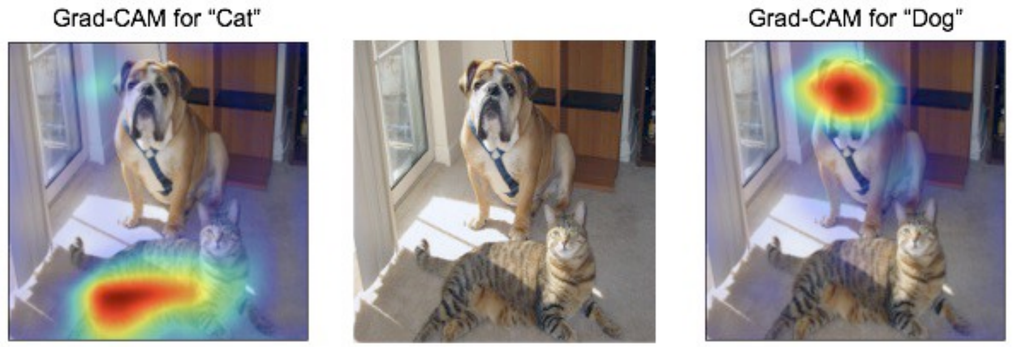
➕ Efficient use of the small dataset:

SST autocorrelation ≈ 1 month → 3 months x 83 years ≈ **250 different images**

Sensitivity analysis

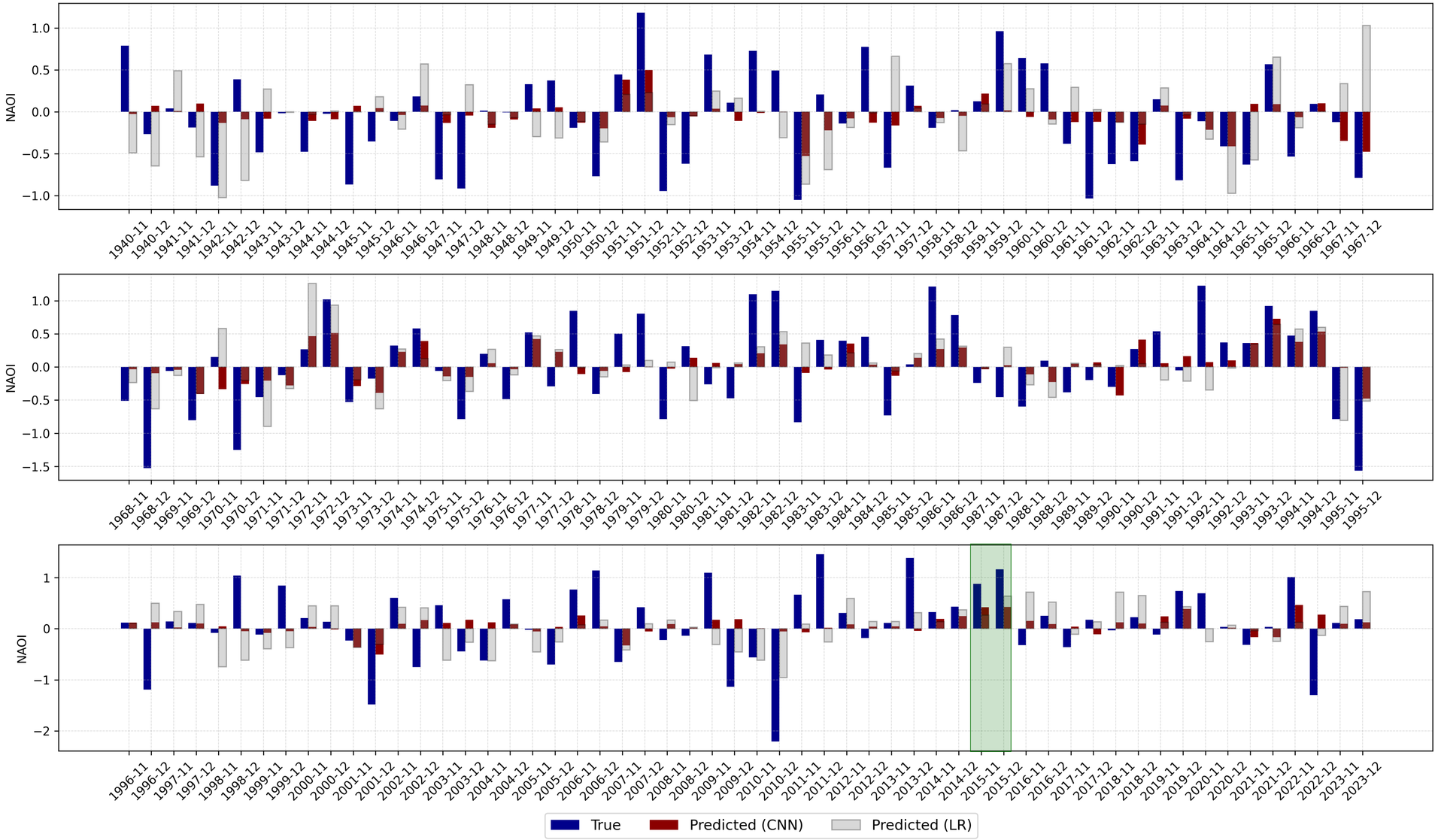
Gradient-weighted Class Activation Mapping (Grad-CAM)

- **Grad-CAM:** a technique used to visualise and understand the decisions made by the CNN
- It uses the gradients of the predicted output with respect to the final convolutional layer
- It provides a heatmap showing which areas of the image most influenced the model's regression output
  → **model interpretability**



Selvaraju et al. (2016)

CNN vs Linear Regression



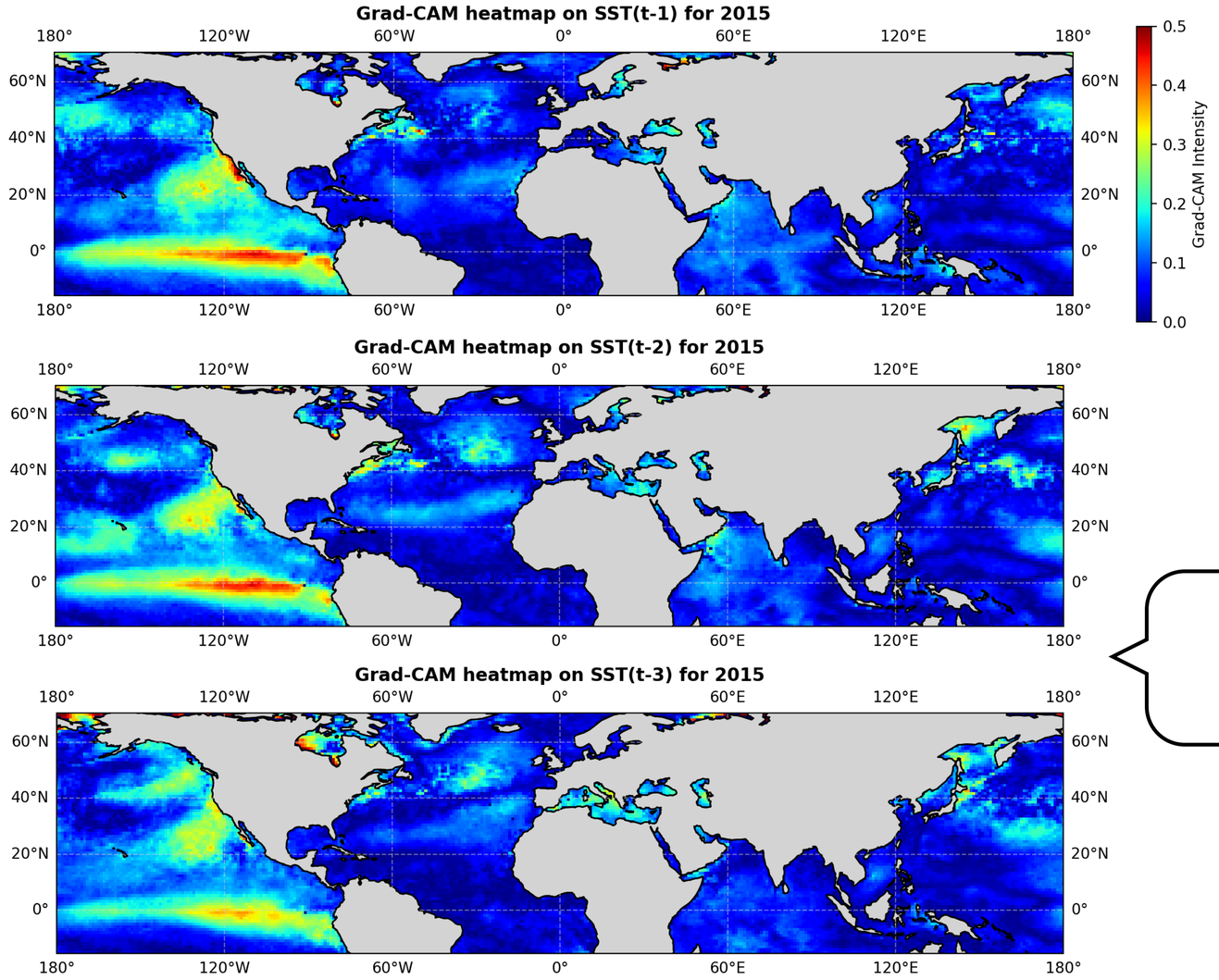
	RMSE	*r*
CNN	**0.58**	**0.49****
LR	0.65	0.34**

**significant at the 95% confidence level

$$\sigma_{NAO} = 0.66$$

Sensitivity analysis

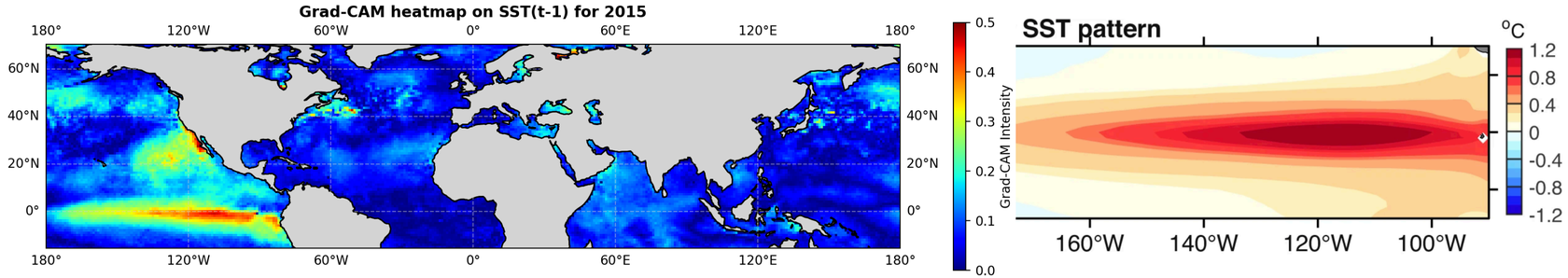
El Niño
and its teleconnections

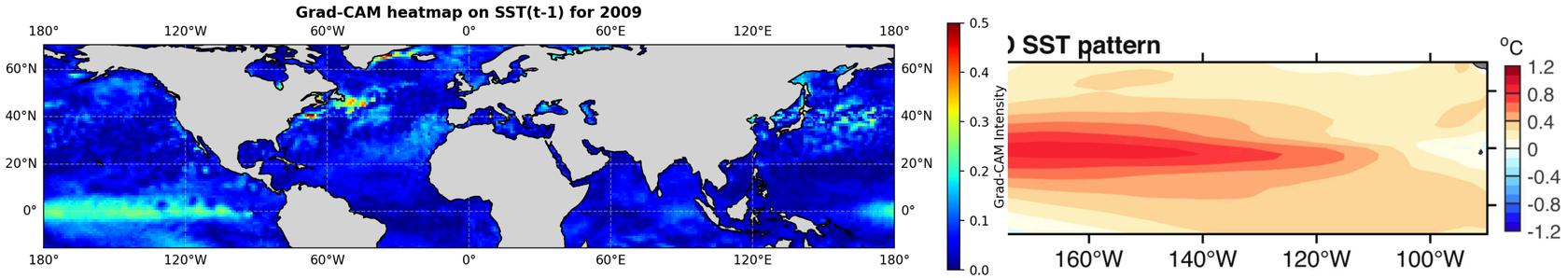


Persistence in the
North Atlantic

ENSO types and NAO predictability

Two distinct ENSO types: **Eastern-Pacific (EP-ENSO)** and **Central-Pacific (CP-ENSO)**

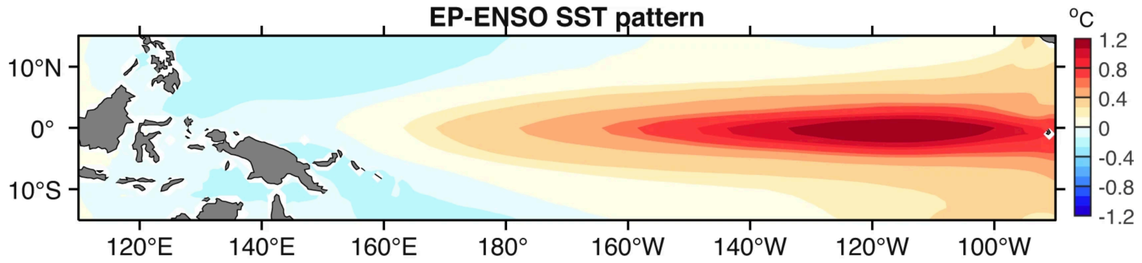




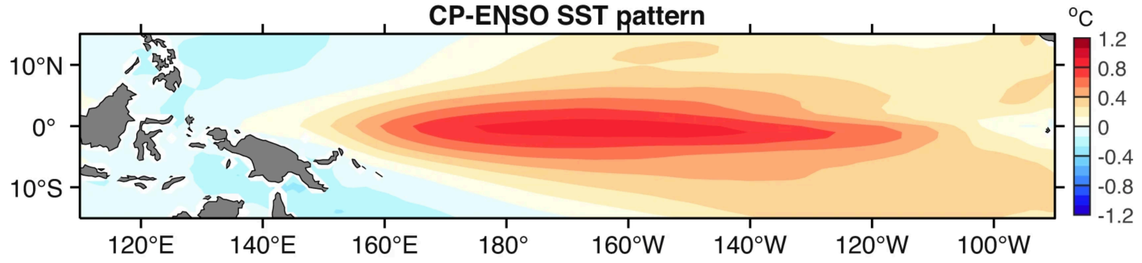
Geng et al. (2022)

ENSO types and NAO predictability

Two distinct ENSO types: **Eastern-Pacific (EP-ENSO)** and **Central-Pacific (CP-ENSO)**
= Different teleconnections



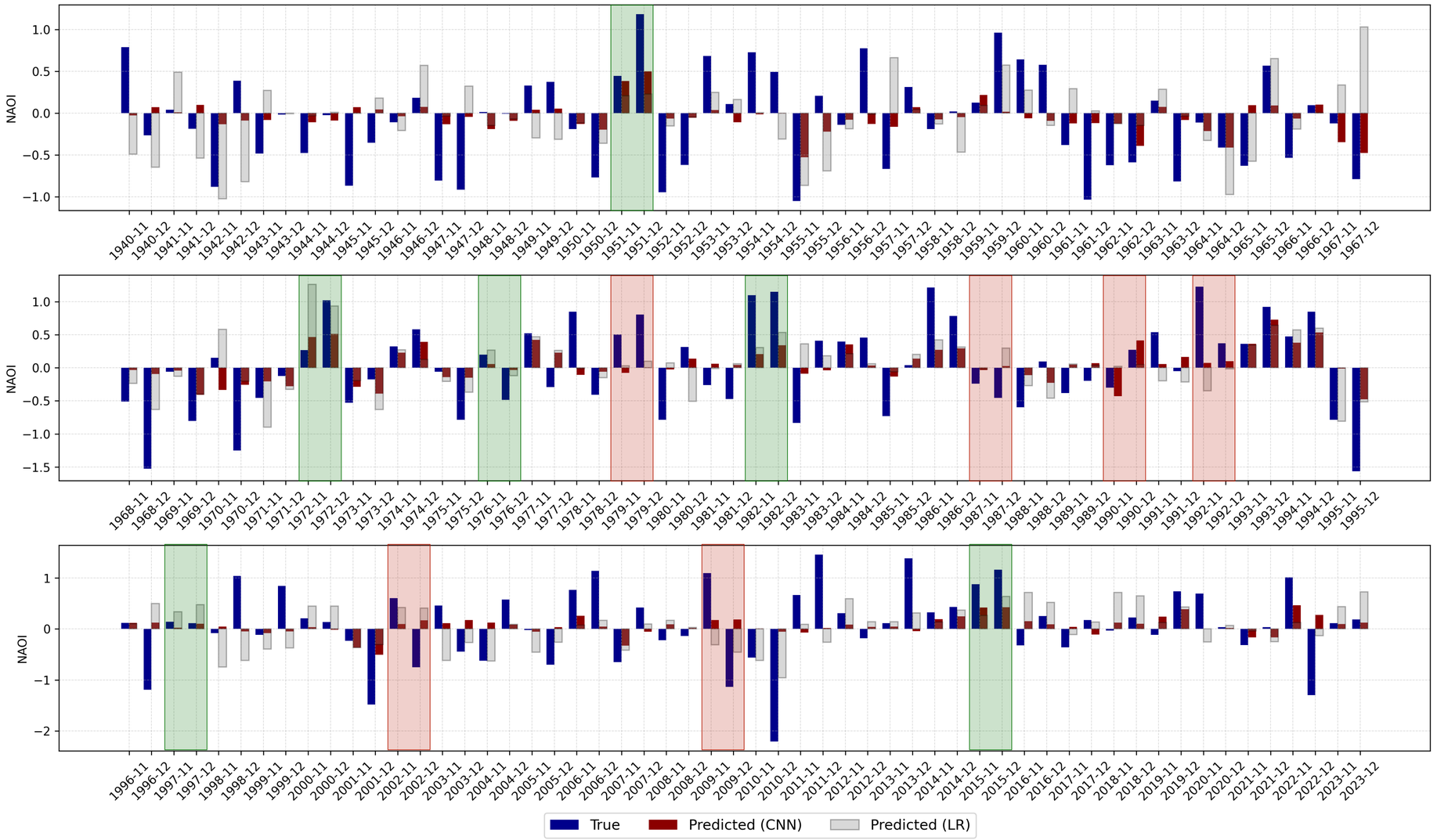
linked with enhanced stratosphere-troposphere coupling
↠ **higher NAO predictability**



weaker or mixed stratospheric impacts
↛ not consistently leading to strong NAO signals

Domeisen et al. (2019)

Year-to-year variability



(6 events) Eastern Pacific (**EP**) ENSO

(6 events) Central Pacific (**CP**) ENSO

Chen et al. (2021)

	RMSE	*r*
EP-only	**0.52**	**0.74****
CP-only	0.73	0.07

**significant at the 95% confidence level

Summary

- **CNNs outperform linear regression** in early winter NAO prediction by capturing the nonlinear SST-NAO relationship;
  This relationship may be modulated by asymmetry of teleconnections (e.g. EP- or CP- ENSO).

- **Explainable AI** techniques (e.g. Grad-CAM) can unravel how the model identifies key SST regions.

✅ **Potential of machine learning to improve climate predictions**

💭 **Ideas for further model refinement:**

- Quantile regression;
- SHAP instead of GradCAM for quantitative attribution;
- …

https://gitlab.com/provenzanoelena/cnn-based-forecasting-of-early-winter-nao-using-sst

Provenzano et al., Environmental Data Science (in prep)

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Thank you!