Evaluating the performance of Climate Models over the North Sea region for the estimation of offshore wind energy changes due to climate change

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1. MOTIVATION

Marine wind changes may affect offshore wind farms through different cycles (e.g. design phase, operability and maintenance activities, life span of the structure). The aim of this study is to analyze the climate change impact on offshore wind energy resource over the North Sea. The **phase I of this study therefore focused on evaluating the performance of climate models to simulate surface atmospheric circulation**. The behavior of different climate model products to simulate present climate conditions and future changes under several climate change scenarios is analyzed by developing a **weather type classification** for the study area. Results indicate that spatial resolution of RCMs better reproduce meso-scale features and related wind climate changes, and a **ranking of the performance of the RCMs** is provided. Outcomes will help to reduce uncertainty in future wind climate change estimations at regional scale.

Several works aim to assess changes in atmospheric characteristics during the XXI century, as **small modifications of large circulation patterns can affect the availability of renewable sources at mid-to-long term.** As it regards North Sea region:

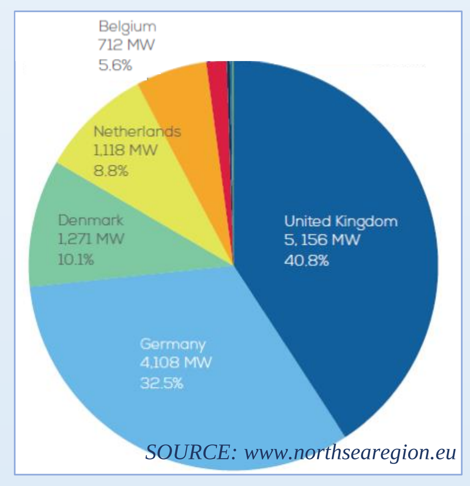
- Carvalho et al. (2017) simulated a **decrease in Wind Energy Density** (10% to 30%) by the end of the century.
- **Distribution of projected changes varies considerably** between models, both in sign and in strength, as found also in Kjellström et al. (2011), McInnes et al. (2011) and De Winter et al. (2013).
- McInnes et al. (2011) found an overall increase up to 5% of the 99th percentile daily mean wind speed in winter and a similar decrease in summer, consistent with Scaife et al. (2008) prevision of **climate extremes occurrence variation as a consequence of NAO** oscillations.

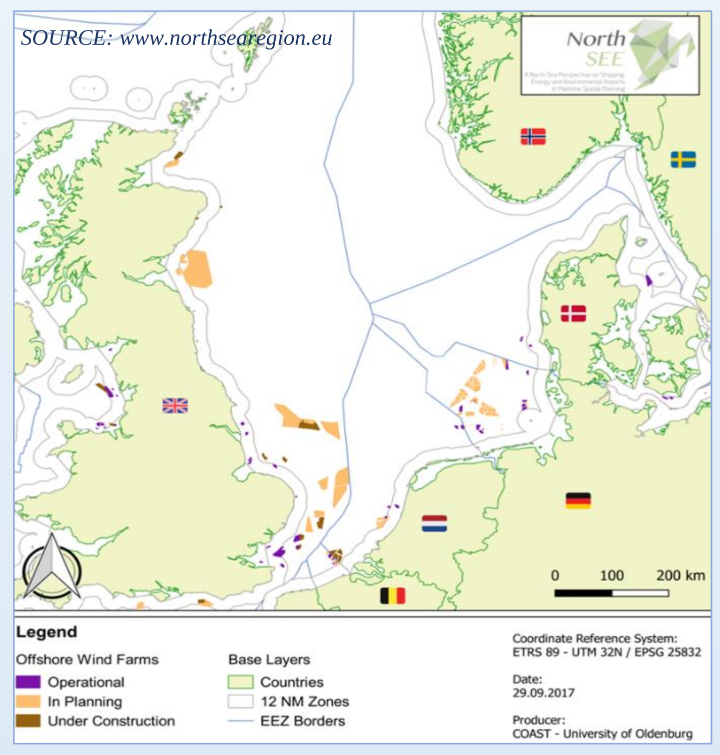
A ranking method for climate models could guide the selection of the most skilled ones in a specific study area, thus increasing significance and reliability of ensemble results.

2. STUDY AREA

According to "Offshore renewable energy developments - Offshore Wind" (https://northsearegion.eu), by the end of 2016 in Europe:

- Offshore wind farms: 81
- Installed turbines: 3.589
- Nominal Power: 12.631 GW





North Sea region has been selected for this study as all top 5 European countries (**UK, DE, DK, NL, BE**) for the largest amount of installed offshore wind capacity are bordering it, representing combined **97% of all grid-connected offshore turbines in Europe.**

3. DATA

ECMWF ReAnalysis-5 (ERA5)

Past conditions are characterized through reanalysis product ERA5 (released by the European Center for Medium Range Weather Forecast in 2019), which combines vast amounts of historical observations into global estimates using advanced modelling and data assimilation systems.

In this way "quasi-real" hourly estimates of a large number of atmospheric, land and oceanic climate variables are provided:

- Spatial Domain: whole Earth
- Time coverage: 1950 onward
- Grid dimension: 30 km (0.25°)
- Levels number: 137 (up to z = 80 km)

General Circulation Models (GCMs) and Regional Climate Models (RCMs)

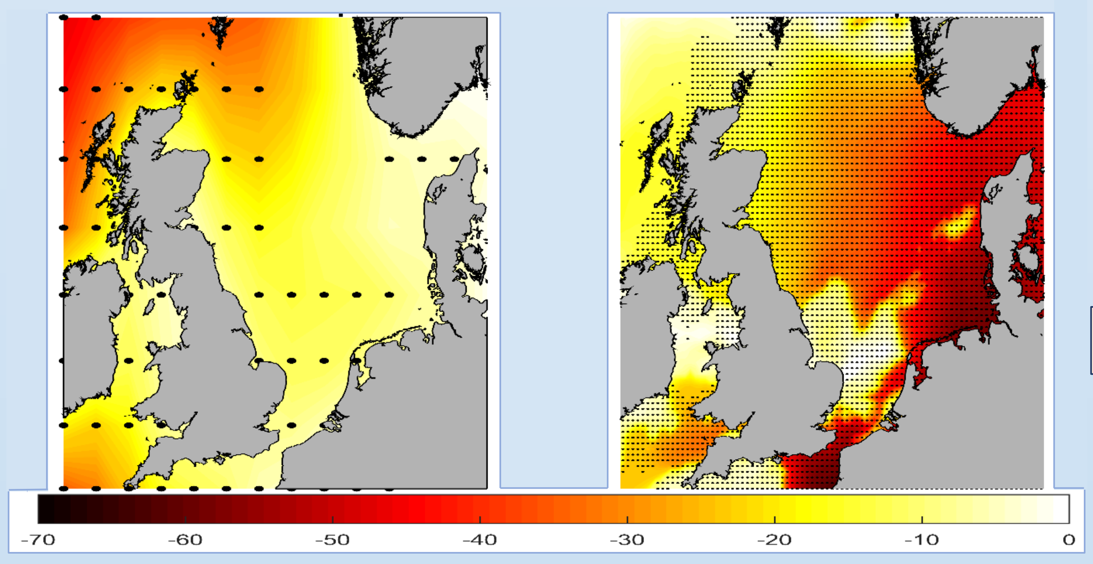
- 7 GCMs and 7 RCMs considered
- RCP scenarios: 4.5 (peak in 2040) and 8.5 (steady increase)
- Spatial definition: LON: (48 : 63), LAT: (-11 : 14)
- Spatial resolution: GCM ≈ 10^2 Km, RCM ≈ 10 Km
- Time periods: historical: 1985-2005, future: 2081-2100

Table 1: Analyzed CMIP5 GCMs names, institutions, countries and atmospheric resolution

GCM Model	Modelling Center	Country	Resolution
ACCESS1	CSIRO-BOM	Australia	1.25° x 1.90°, L38
CMCC-CM	Centro Euro-Mediterraneo per i Cambiamenti Climatici	Italy	0.75° x 0.75°, L31
CNRM-CM5	Centre National de Recherches Meteorologiques	France	1.40° x 1.40°, L31
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory	USA	2.00° x 2.50°, L48
HadGEM2-ES	Met Office Hadley Centre	UK	1.25° x 1.90°, L38
IPSL-CM5A-MR	Institut Pierre-Simon Laplace	France	1.25° x 2.50°, L39
MIROC5	MIROC	Japan	1.40 °x 1.40°, L40

Table 2: Analyzed EuroCORDEX RCMs names, parent GCMs, institutions and atmospheric resolution

RCM Model	Parent GCM	Modelling Center	Resolution
CCLM4-8-17	MIROC5	MIROC5	0.11° x 0.11°
CCLM4-8-17	CanESM2	Canadian Centre for Climate Modelling and Analysis	0.11° x 0.11°
RCA4	CNRM-CM5	Centre National de Recherches Me´te´orologiques	0.11° x 0.11°
RCA4	EC-EARTH	EC-EARTH consortium	0.11° x 0.11°
RCA4	HadGEM2-ES	Met Office Hadley Centre	0.11° x 0.11°
RCA4	IPSL-CM5A-MR	Institute Pierre-Simon Laplace	0.11° x 0.11°
RCA4	MPI-ESM-LR	Max-Planck-Institut fur Meteorologie	0.11° x 0.11°



GCMs and RCMs Wind Power Density **(WPD) changes estimated by the end of XXI** century for RCP8.5 climate scenario

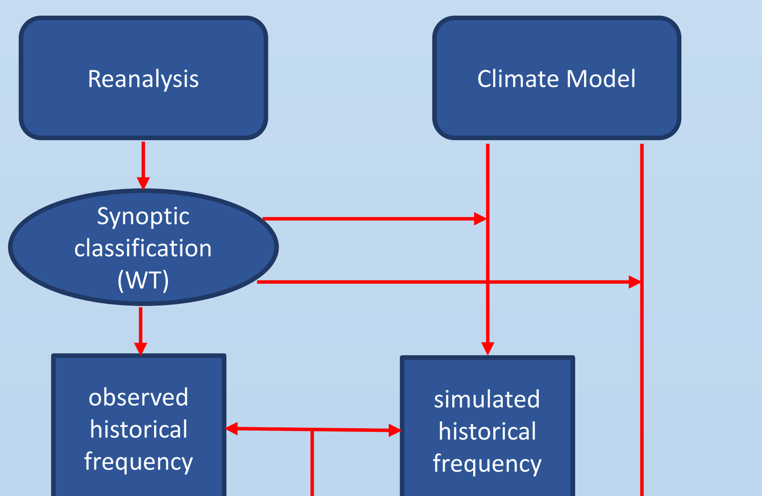
$$WPD = \frac{1}{2} * \rho * w^3 \; [kg/m^3]$$

The ensemble mean of Wind Power Density (WPD) changes are estimated. Points in which at least 80% of models considered show sign agreement are identified by black dots. The wider area covered by dots in the right panel justify the choice to use only RCMs for the present work, although a higher computational cost must be sustained.

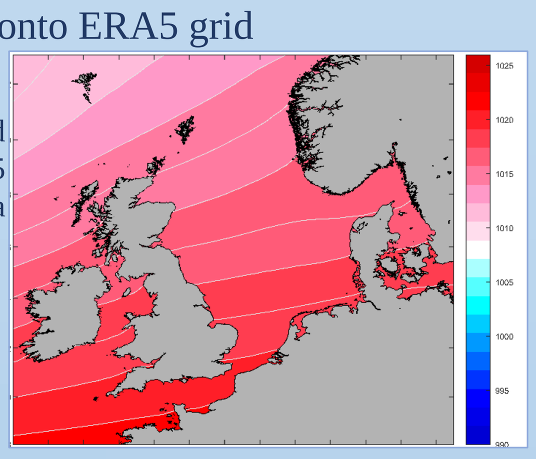
4. METHODOLOGY

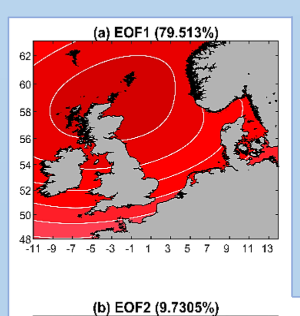
A synoptic classification based on sea level pressure (slp) data for successive wind analysis purposes is well motivated by the fact that **in the Atlantic region several surface variables are highly correlated with pressure fields**, such as wind waves and precipitation:

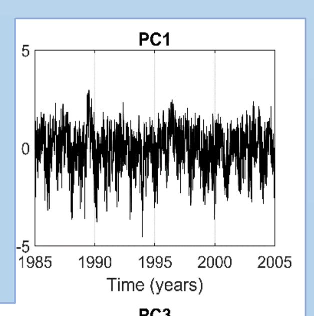
- **slp daily mean from ERA5's** and **7 RCM's** (1985-2005)
- **RCMs data re-gridded** onto ERA5 grid



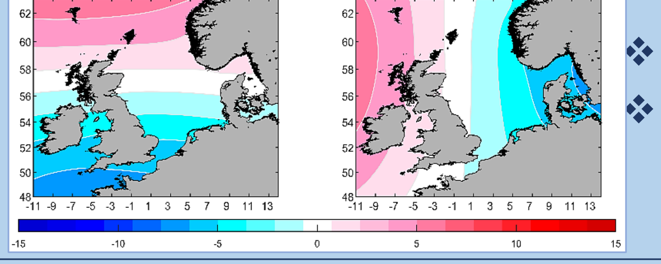
Mean SLP during the period 1985-2005 based on ERA5 hourly data



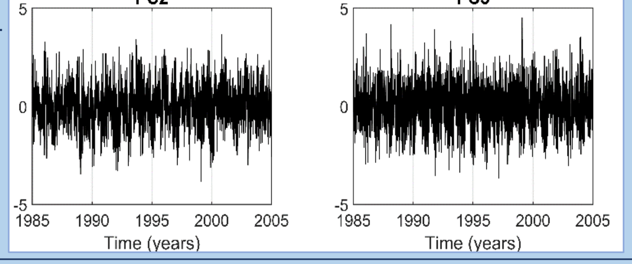




Principal Component Analysis (PCA) is used in order to apply the clustering technique on a reduced virtual space whilst conserving the maximum original data variance. (Perez et al. 2014), through a representation of anomalies in **space** and **time**

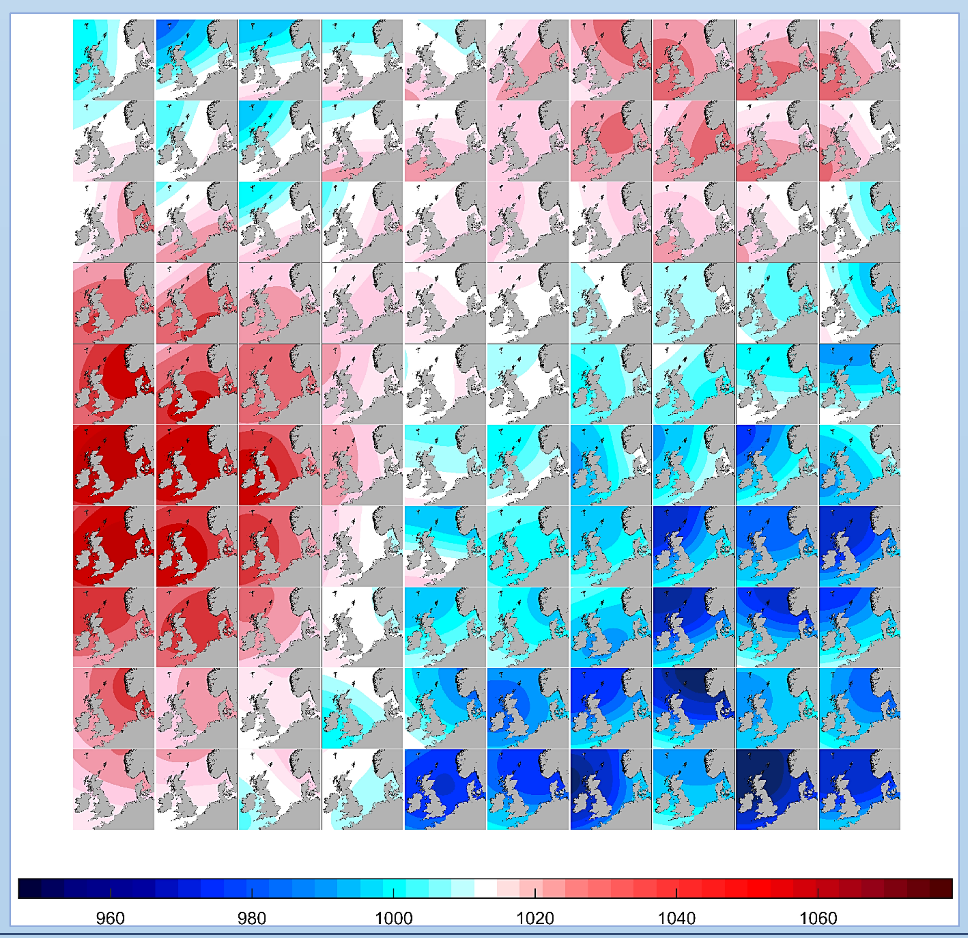


- $SLP'(x,t) = SLP(x,t) - \overline{SLP(t)}$
- **3 modes** for 95% of variance



The Weather Type classification is obtained by applying the non-hierarchical **clustering technique K-means** over the previously identified components:

- **100 classes** in order to preserve results significance and accurately reproduce extreme situations
- **Dissimilarity-based compound selection** (Snarey et al. 1997) as algorithm forcing:
- **Proximity criterion** to minimize the sum of Euclidean distances between each centroid and its neighbors

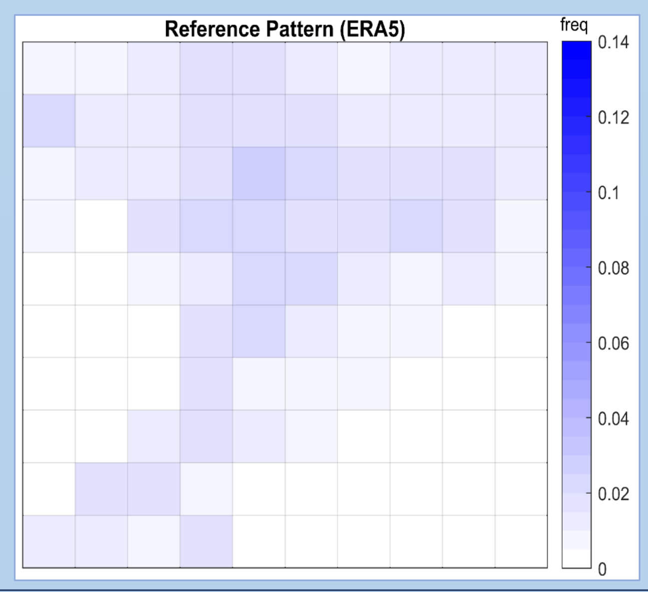


$$SI = \sqrt{\frac{\sum_{i=1}^{N}(p_i - p_i')^2}{N}} \Big/ \frac{\sum_{i=1}^{N} p_i}{N}$$

$$Re = \sum_{i=1}^{N} p_i \left| log \frac{p_i}{p_i'} \right|$$

$$std(SI) = \sqrt{\frac{\sum_{i=1}^{N}(std(p_i) - std(p_i'))^2}{N}} \Big/ \frac{\sum_{i=1}^{N} std(p_i)}{N}$$

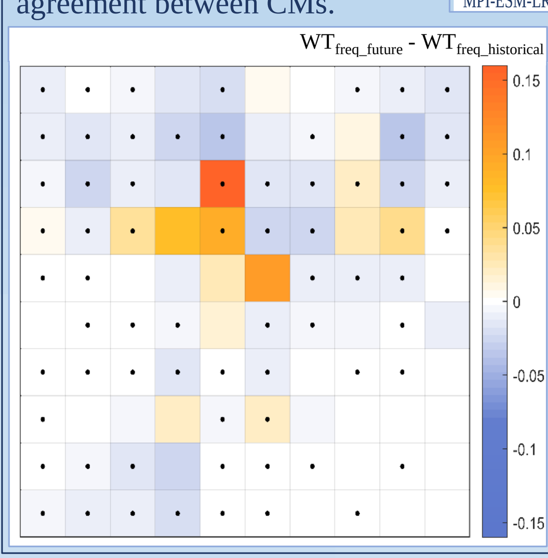
N=1:100 (WT) p_i = ERA5 frequency p'_i = CM frequency

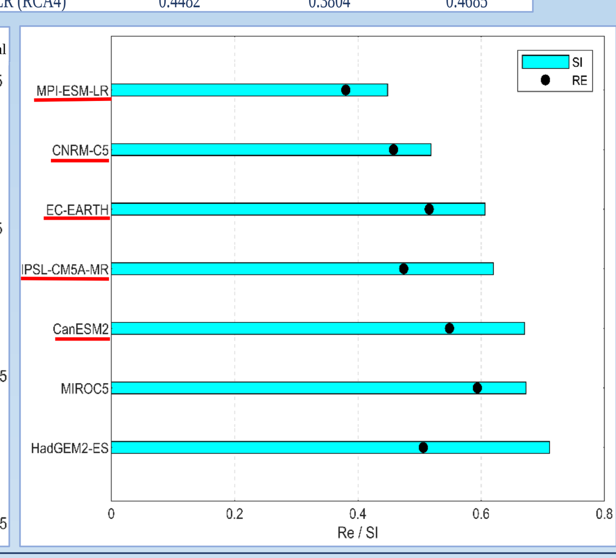


5. RESULTS

Five best RCMs (underlined in red) have been ensembled to investigate **variations in the occurrence of each WT between future and historic** period considered. Black dots indicate at least 80% of sign agreement between CMs.

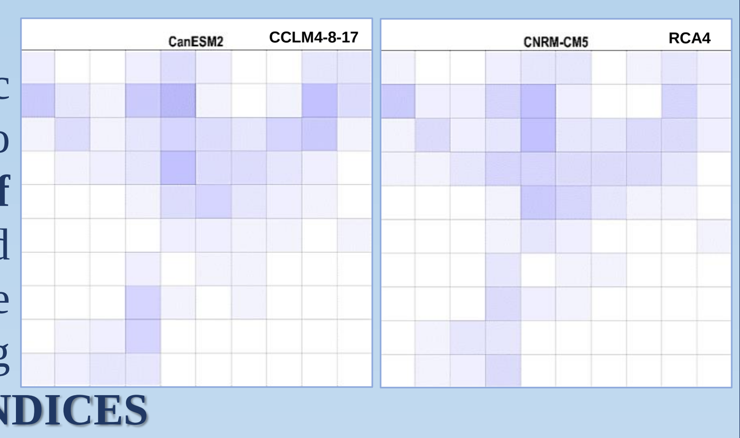
RCM	Scatter Index (SI)	Relative Entropy (Re)	SI std deviation std(SI)
CanESM2 (CCLM4-8-17)	0.6700	0.5485	0.5276
CNRM-CM5 (RCA4)	0.5185	0.4577	0.5081
EC-EARTH (RCA4)	0.6058	0.5157	0.5320
HadGEM2-ES (RCA4)	0.7112	0.5061	0.5334
IPSL-CM5A-MR (RCA4)	0.6196	0.4743	0.5291
MIROC5 (CCLM4-8-17)	0.6727	0.5938	0.5318
MPI-ESM-LR (RCA4)	0.4482	0.3804	0.4685

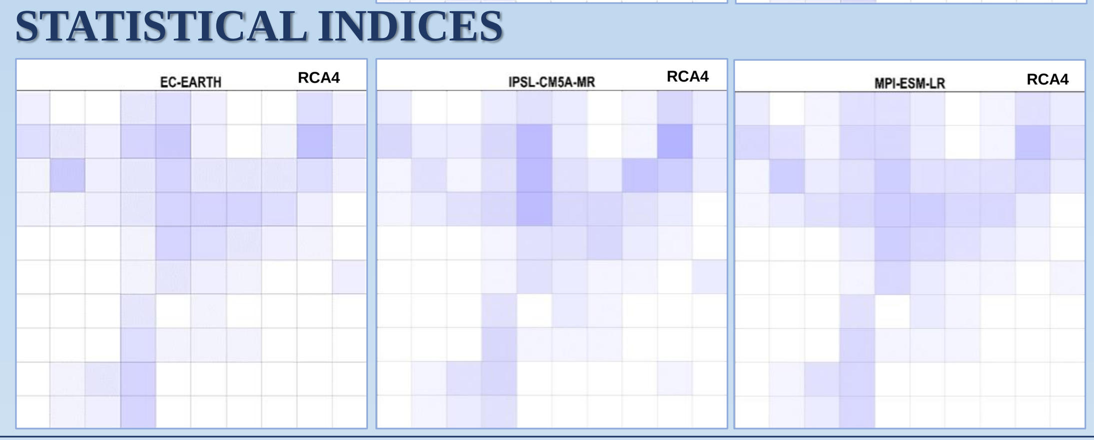




Weather Types synoptic classification is applied to RCMs and **frequency of occurrence** is compared with ERA5 reference pattern, obtaining

STATISTICAL INDICES





6. CONCLUSIONS

- A Weather Type classification over the North Sea region is obtained using a **machine learning approach, allowing objective offshore wind climate conditions analysis.**
- **MPI results to be the best performing model.** Low values of std(SI) (0.4685), SI (0.4482) and RE (0.3804) mean good skills in reproducing interannual variability, frequent and unusual synoptic situations.
- **Variations in the occurrence of specific WT have been highlighted for the end of the century through ensemble approach**, showing a strong increase in the frequency of a limited number of synoptic situations and a less intense decrease for a number of weather types.

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