Prediction of large scale atmospheric processes on decadal timescales with INM-CM5 and INM-CM6 Earth system models

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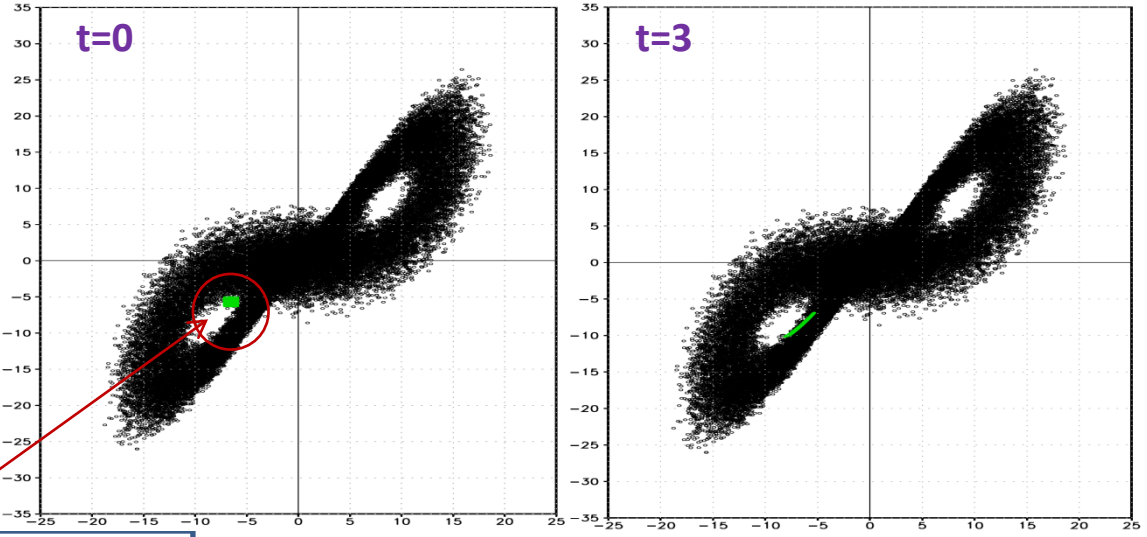
Ensemble of 40000 trajectories of Lorenz system

$$\frac{dx}{dt} = \sigma(y - x)$$

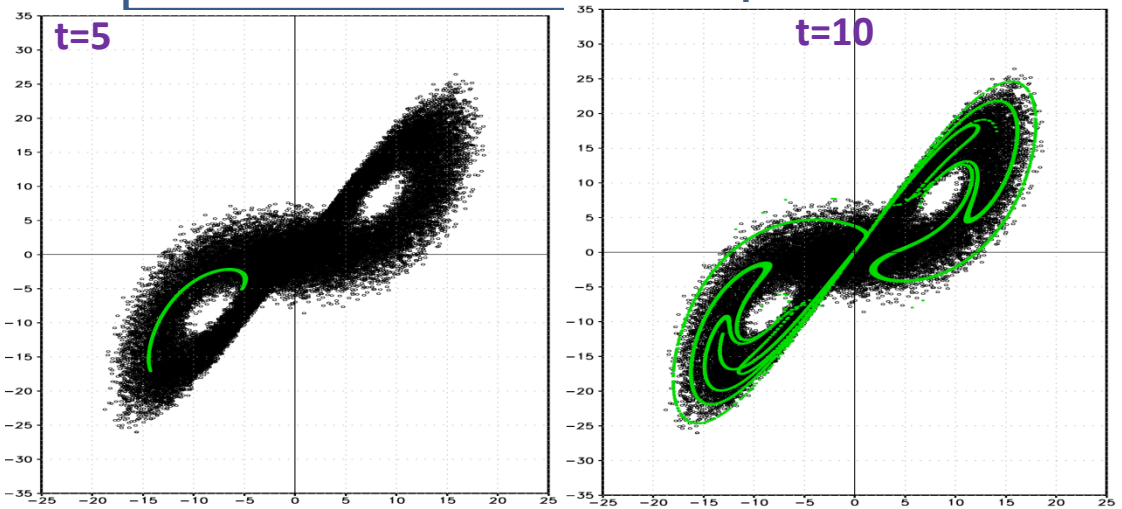
$$\frac{dy}{dt} = x(\rho - z) - y$$

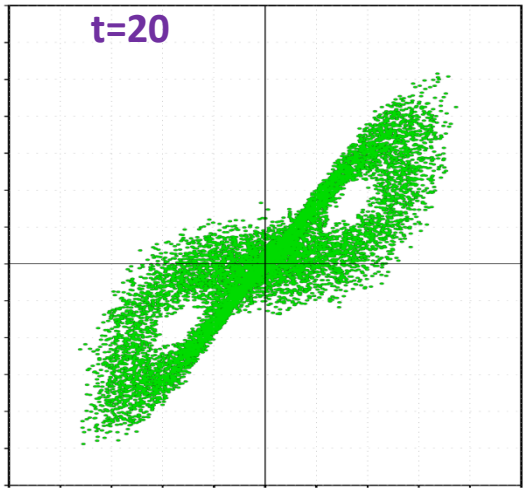
$$\frac{dz}{dt} = xy - \beta z$$

$$\sigma = 10, \beta = 8/3, \rho = 28$$



Ensemble of initial conditions





Deterministic forecast fails, but probabilistic category forecast for large areas makes sense

All information from initial condition is lost

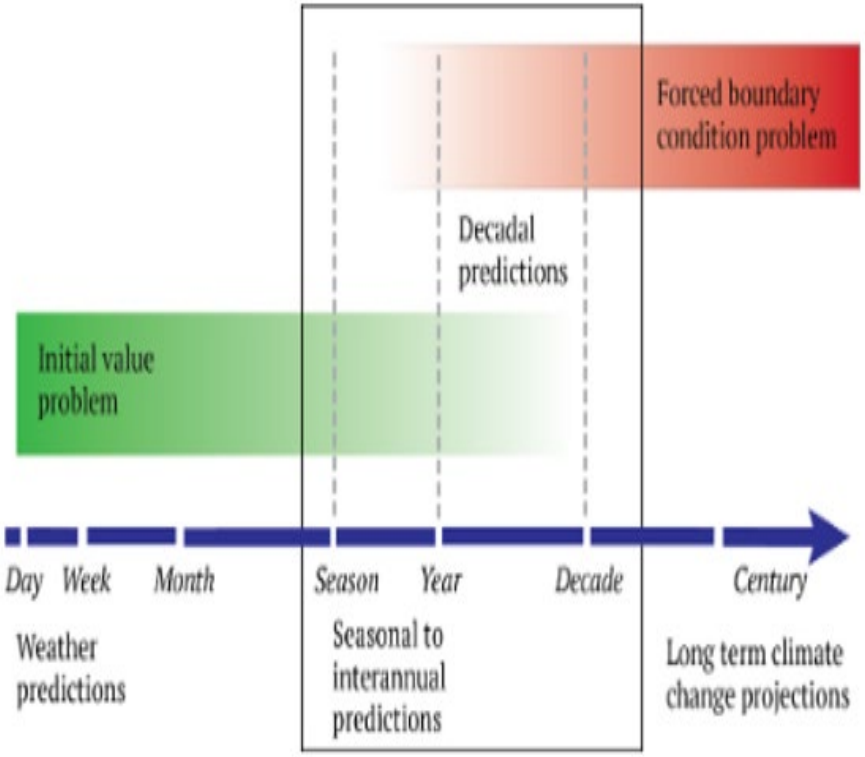
Seasonal to Decadal forecasts: sources of predictability

- **Initial conditions**

Quasi periodic processes: long period mode of atmospheric, oceanic and coupled dynam (MJO, Sudden stratospheric warming, Quasi biannual oscillation, El Nino Southern oscillation, AMOC changes, PDO, AMO etc)

- **Changes of external forcings:**

Changes of Earth orbital parameters, Variations of Solar activity, anthropogenic forcings (GHG, land use), volcanic activity.



Major components of Earth system models INM-CM5

Atmospheric model

Land surface and vegetation

- horizontal resolution 2° × 1,5°
- 73 vertical σ-levels (~60km)
- regular lon-lat grid
- finite difference approximations
- physical parameterizations:
  - deep and shallow covections
  - gravity wave grad
  - cloud microphysics
  - atmospheric radiation
  - land surface and vegetation

Aerosols

- evolution of 10 atmospheric aerosols are calculated on atmospheric grid including large and small sea salt particles, mineral dust, SO2, sulphate aerosol, black carbon, organic aerosols

Ocean dynamics and sea ice

- horizontal resolution 0.5°×0.25°
- 40 vertical σ-levels
- generalized spherical grid with two displaced poles
- finite difference approximations
- Морской лед. Упруго-вязко-пластичная реология. Одна категория льда.

E. Volodin , et al. 2017, Simulation of the present-day climate with the climate model INMCM5, Climate dynamics, 49, Issue 11–12, 3715–3734;

Володин Е.М., Галин В.Я., Грицун А.С. и др., 2016, Математическое моделирование Земной системы М.: МАКС Пресс. — 328 с. ISBN 978-5-317-05435-9

Volodin E.M. et. Al. Computational framework for the Earth system modelling and the INM-CM6 climate model implemented on its base. Russ. J. Of Numerical Analysis and Math. Modelling. 2024, no. 39(6), pp. 379–392.

Procedure of forecast technology

Reanalysis data for atmosphere, soil, land surface (ERA5)
Reanalysis data for ocean and sea ice (SODA 3.4.2./HMC-NEMO)

Model climatology
Results of historic +SSP3-7.0 experiment from CMIP6 scenario experiment

Initial conditions in terms of anomalies against the climate

$$W_{22\,NOV\,1991} = \overline{W^{m}_{22\,NOV}} + \left(W^{r}_{22\,NOV\,1991} - \overline{W^{r}_{22\,NOV}} \right)$$

INM-CM5 – ensemble of 15 members

5 year hindcasts (1961-2023)

Starting date – 01 November
Duration – 5-15 years
Output – daily and monthly data

Initialization

ERA 5

U, V-components of the wind speed
Air temperature
Specic humidity
Surface pressure
Surface temperature
Snow thickness
Soil temperature
Soil humidity

SODA 3.4.2

U, V - climate
salt - practical salinity
temp - potential temperature
ssh - sea level
mi - ice mass
hs - ice thickness
nc1, nc2, nc3, nc4, nc5 ice concentration in 5 gradations of thickness

Verification

- **Forecast ensemble (hindcasts) for 1960-2023**
- **Historic ensemble (no initialization, start from i.c. of 1850) for 1960-2023**
- **Era5 and Soda 3.4.2.**
- **Difference in quality between the two sets of forecasts**

gives added value from initialization with real initial conditions.

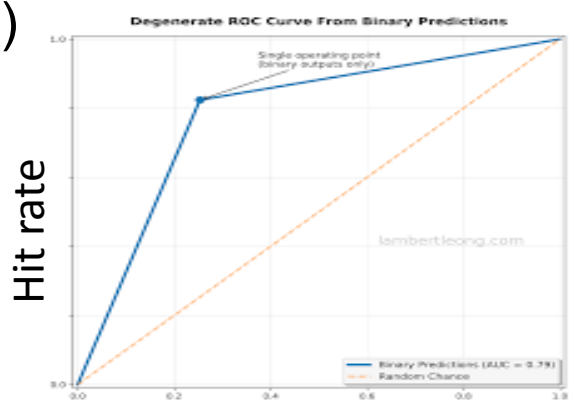
Metrics

- **Anomaly correlation coefficient (ACC) with Reanalysis**
- **Deterministic ROC (**Hanssen and Kuipers score)

		Observations		
		occurrences	non-occurrences	
forecasts	Occurrences	O_1	NO_1	$O_1 + NO_1$
	non-occurrences	O_2	NO_2	$O_2 + NO_2$
		$O_1 + O_2$	$NO_1 + NO_2$	T

$$HR = O_1 / (O_1 + O_2) \qquad FAR = NO_1 / (NO_1 + NO_2) \qquad KS = (HR - FAR + 1)/2$$

Hit rate False alarm rate



- **Probabilistic ROC**

bin number	member distribution	observed occurrences	observed non-occurrences
1	F=0, NF=N	O_1	NO_1
2	F=1, NF=N-1	O_2	NO_2
3	F=2, NF=N-2	O_3	NO_3
•••		•••	•••
n	F=n-1, NF=N-n+1	O_n	NO_n
•••		•••	•••
N+1	F=N, NF=0	O_{N+1}	NO_{N+1}

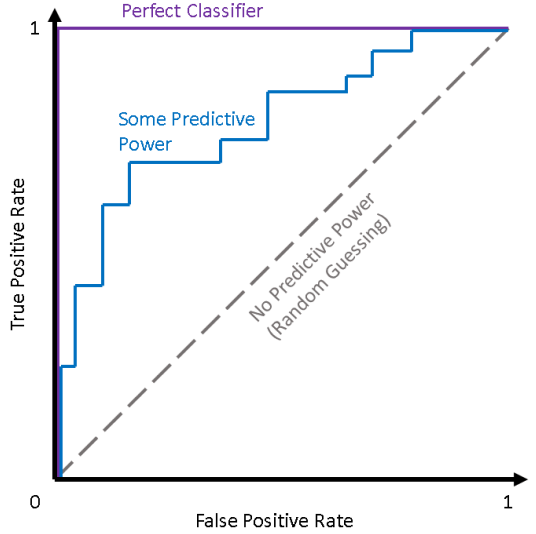
$$HR_n = \sum_{i=n}^{N} O_i \Big/ \sum_{i=1}^{N} O_i \qquad FAR_n = \sum_{i=n}^{N} NO_i \Big/ \sum_{i=1}^{N} NO_i$$

Hit rate False alarm rate

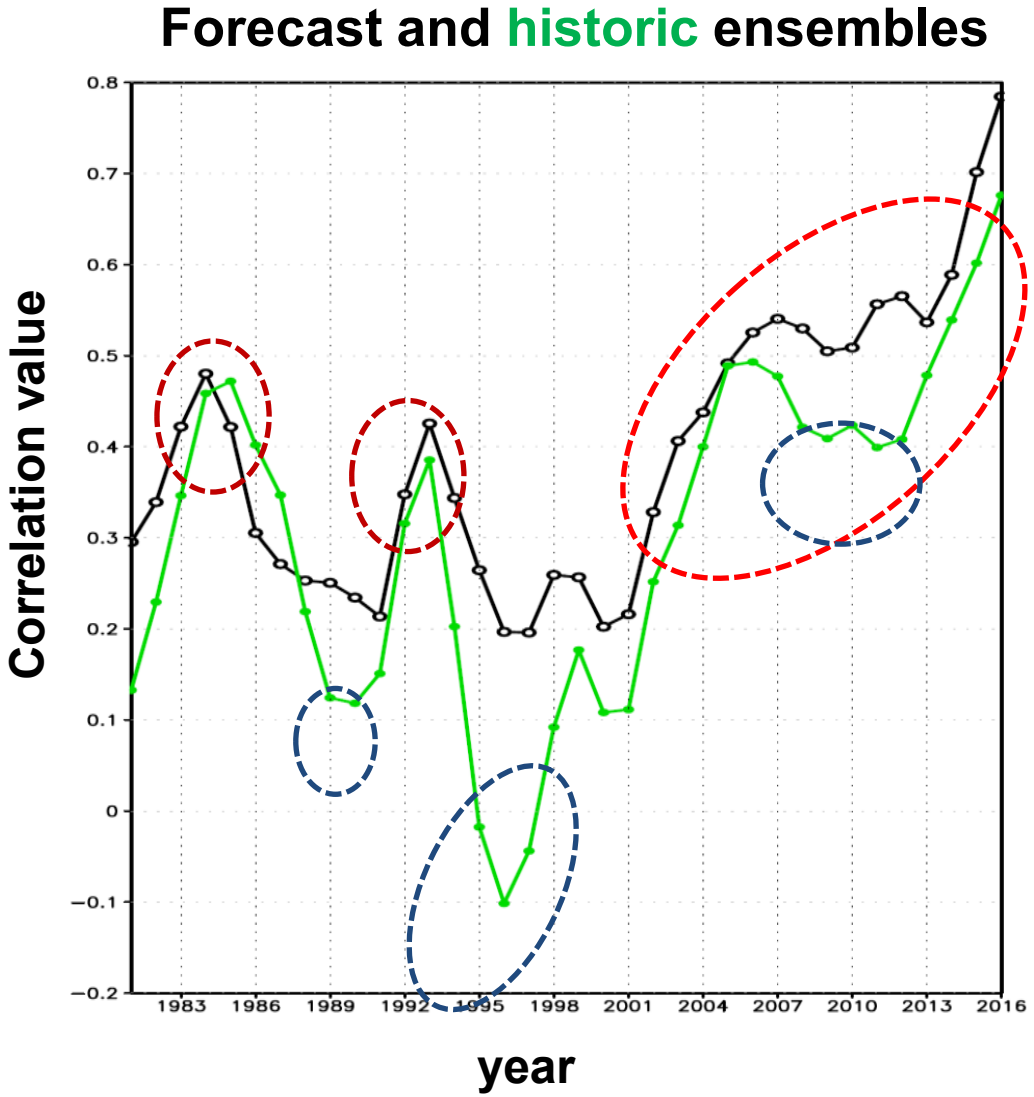
Below/Above average

N – number of ens. members

T – number of forecasts



Globally and annually averaged T2m anomaly correlations predictions



Influence on predictability from:

Natural variability

- **strong LA/El Nino**

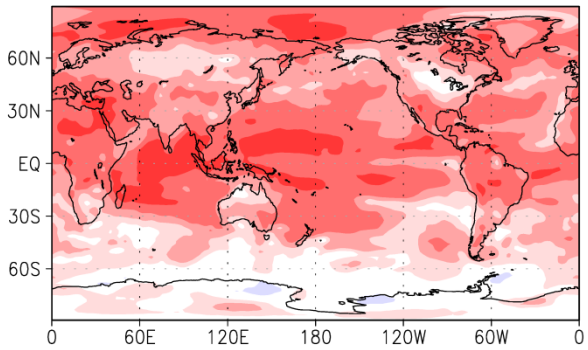
External forcings:

- **volcanic eruptions,**
- **Global anthropogenic warm trend of T2m**

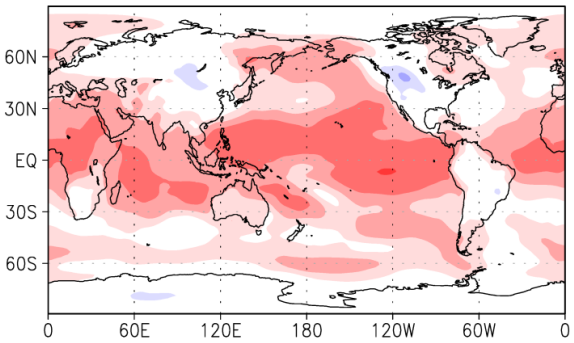
ACC of predicted and observed (ERA5) next year anomalies for 1960-2020 period

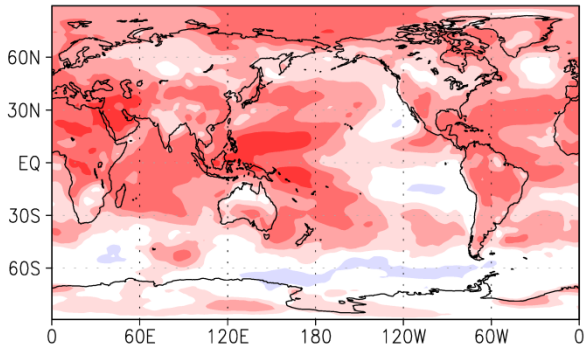
T2m

SLP

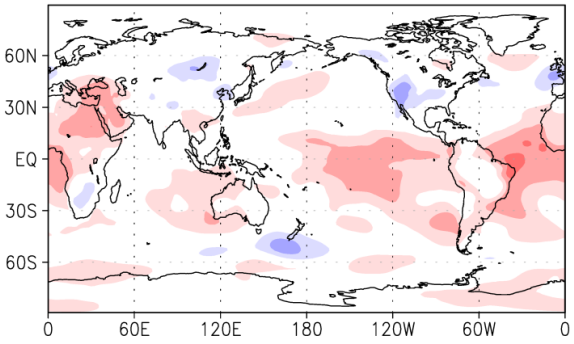


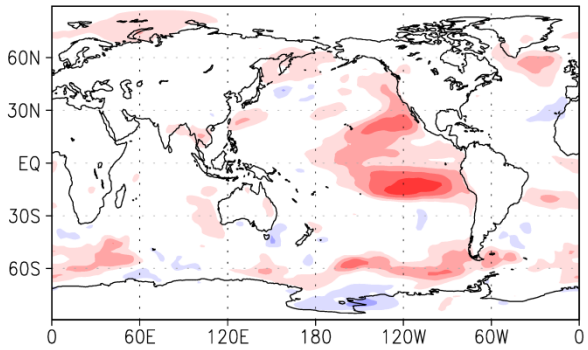
Forecast ensemble INM-CM5 (FA)

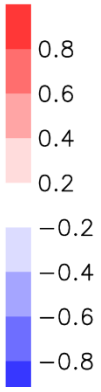




Historic ensemble INM-CM5 (HA)

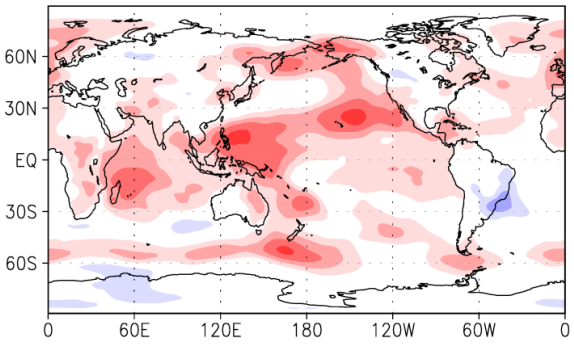






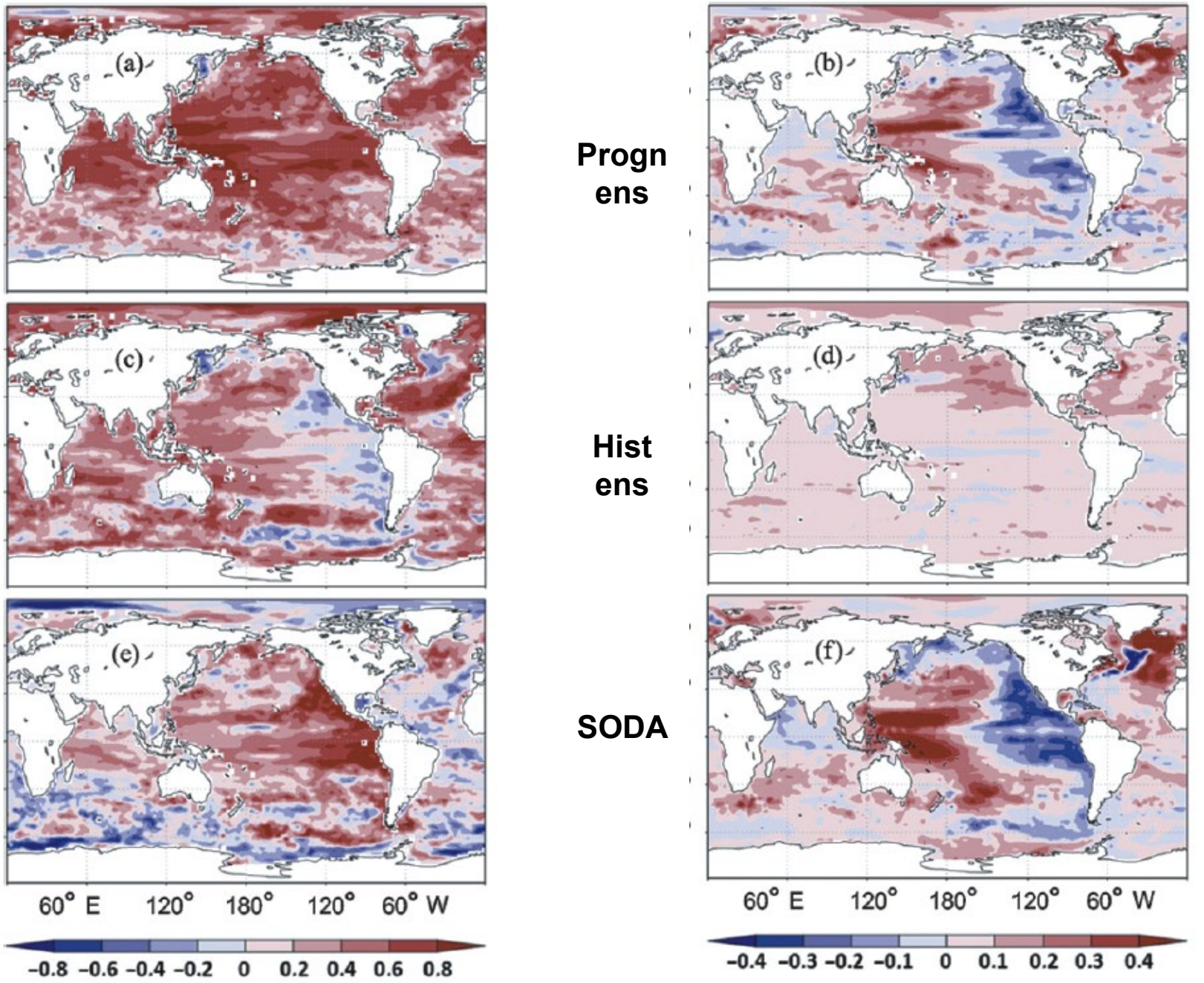
Added value from i.c. («FA» - «HA»)

ACC improvement 0.1/0.2



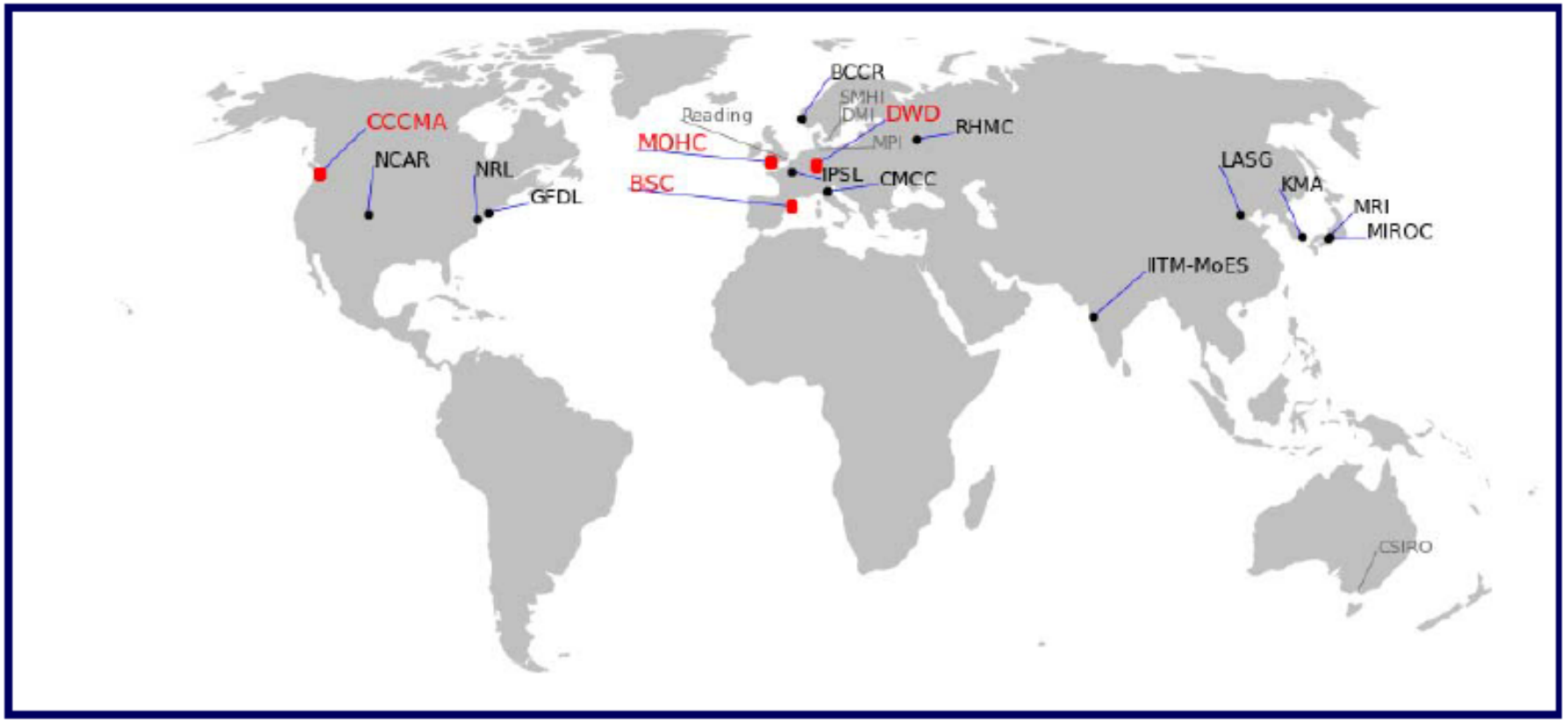
ACC for the ocean heat content 0-300m layer

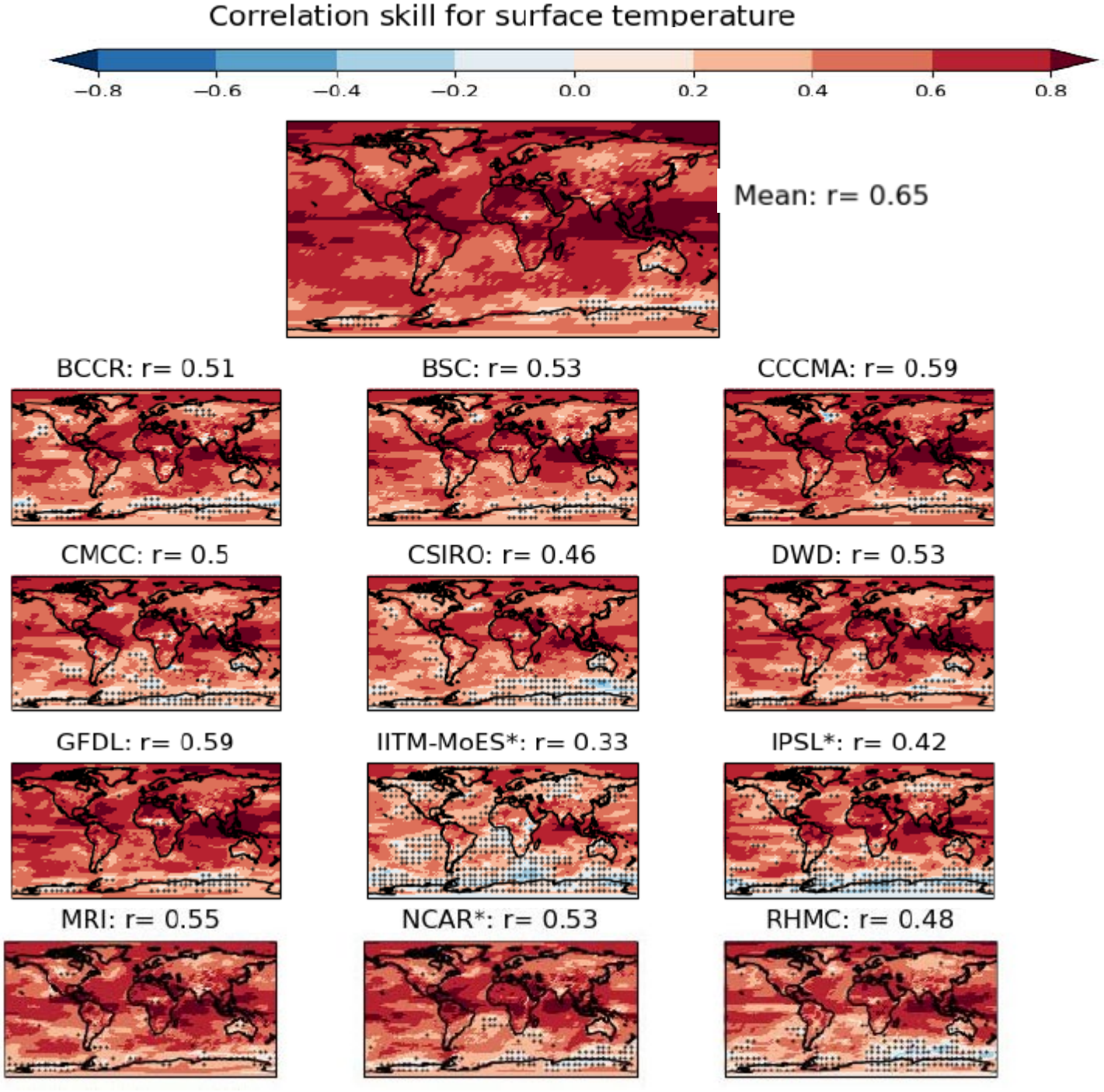
Heat content anomaly in i.c. for 2001-13

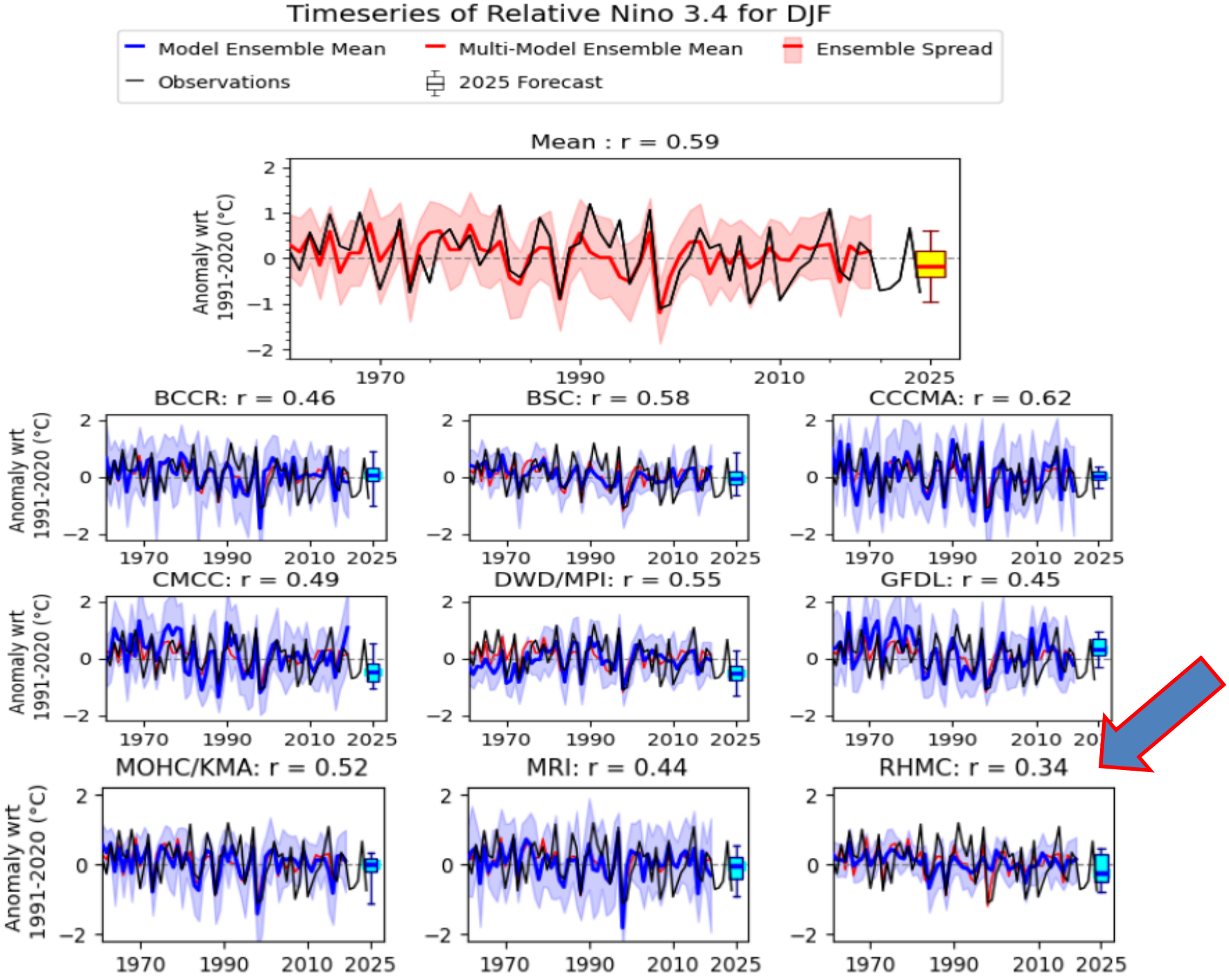


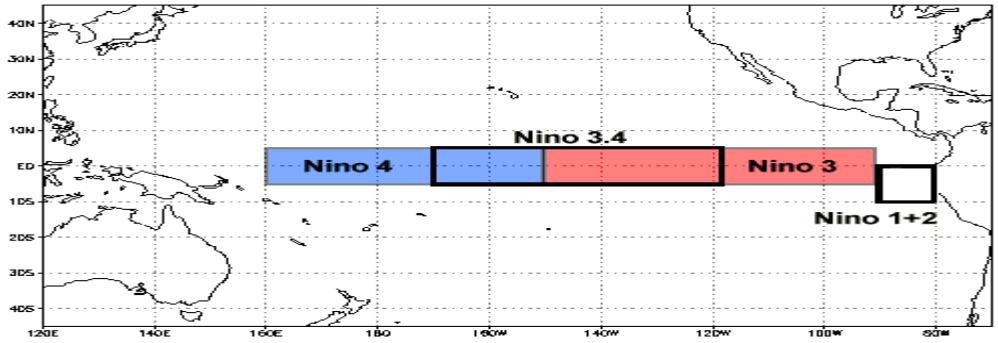
WMO Lead Centre for Annual-to-Decadal Climate Prediction

The Lead Centre for Annual-to-Decadal Climate Prediction collects and provides hindcasts, forecasts and verification data from a number of contributing centres worldwide.

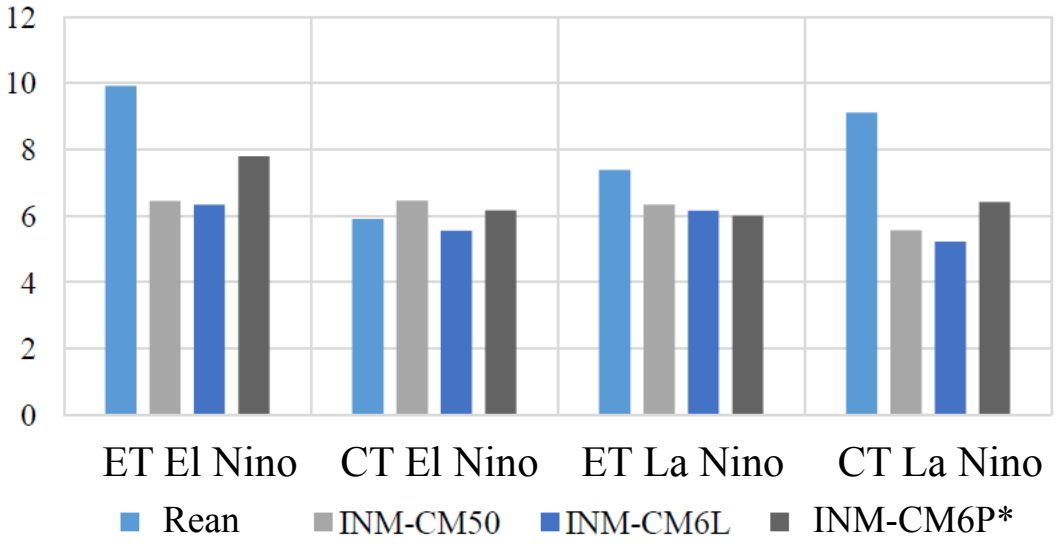



Correlation skill for surface temperature
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
Mean: r= 0.65
BCCR: r= 0.51
BSC: r= 0.53
CCCMA: r= 0.59
CMCC: r= 0.5
CSIRO: r= 0.46
DWD: r= 0.53
GFDL: r= 0.59
IITM-MoES*: r= 0.33
IPSL*: r= 0.42
MRI: r= 0.55
NCAR*: r= 0.53
RHMC: r= 0.48


Timeseries of Relative Nino 3.4 for DJF
Model Ensemble Mean
Multi-Model Ensemble Mean
Ensemble Spread
Observations
2025 Forecast
Mean : r = 0.59
BCCR: r = 0.46
BSC: r = 0.58
CCCMA: r = 0.62
CMCC: r = 0.49
DWD/MPI: r = 0.55
GFDL: r = 0.45
MOHC/KMA: r = 0.52
MRI: r = 0.44
RHMC: r = 0.34
Anomaly wrt 1991-2020 (°C)
1970
1990
2010
2025

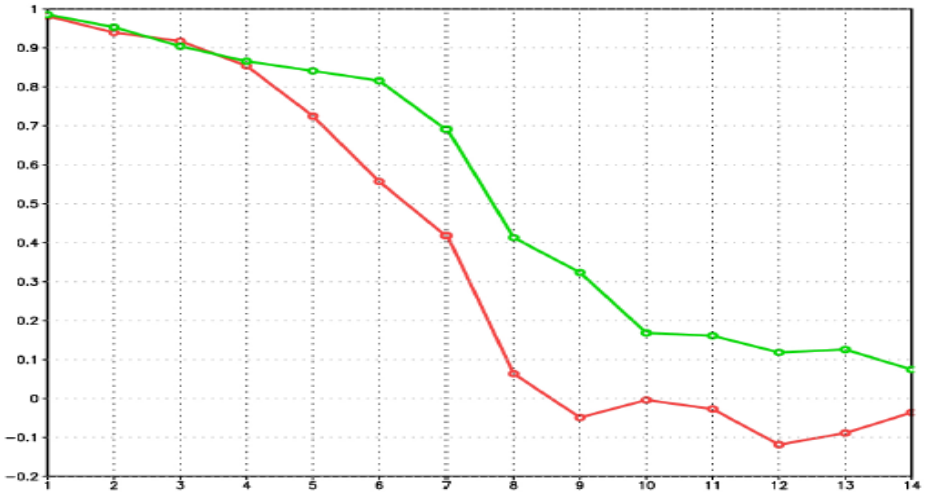


Insufficient duration of El Nino/ La Nino in INMCM models

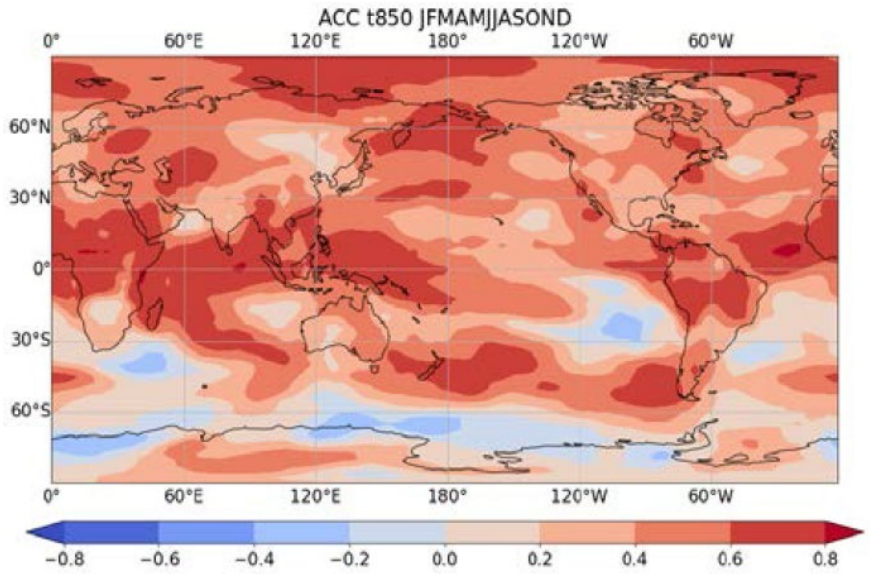


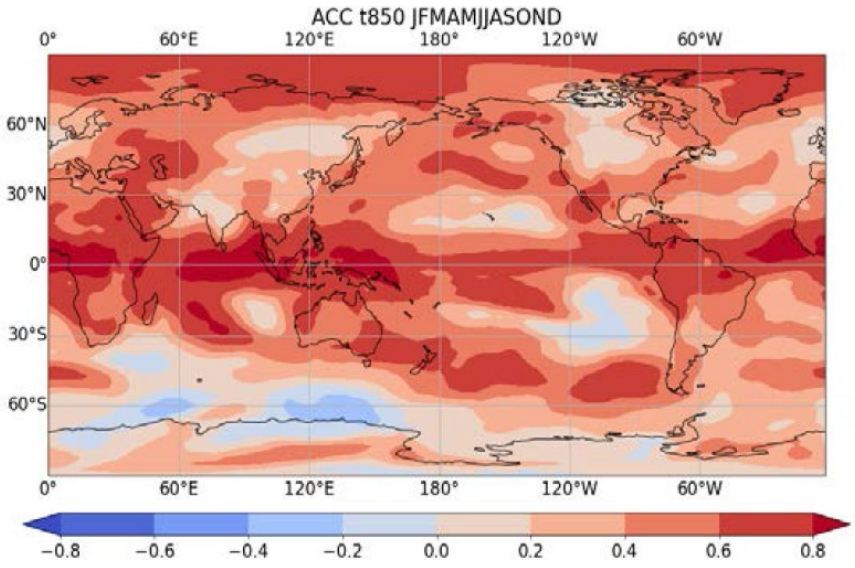
Average duration of El Nino/La Nino
(when indices Nino3 or Nino 4 exceed cutoff value) of two types (Eastern and Central) calculated for Reanalysis/INM-CM5/INMCM-6L/INM-CM6P*

Improvement of El Nino forecast for INM CM6P*



ACC for Nino 3.4 index for INM-CM5 (red) and INM-CM6P* (green)





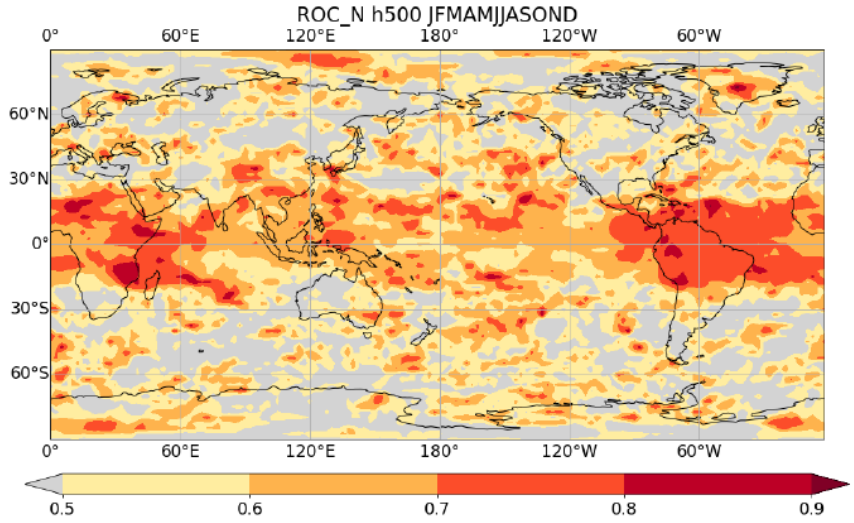
ACC for H850 temperature for INM-CM5 (left) and INM-CM6P* (right)

Improvement of the forecasts with data assimilation

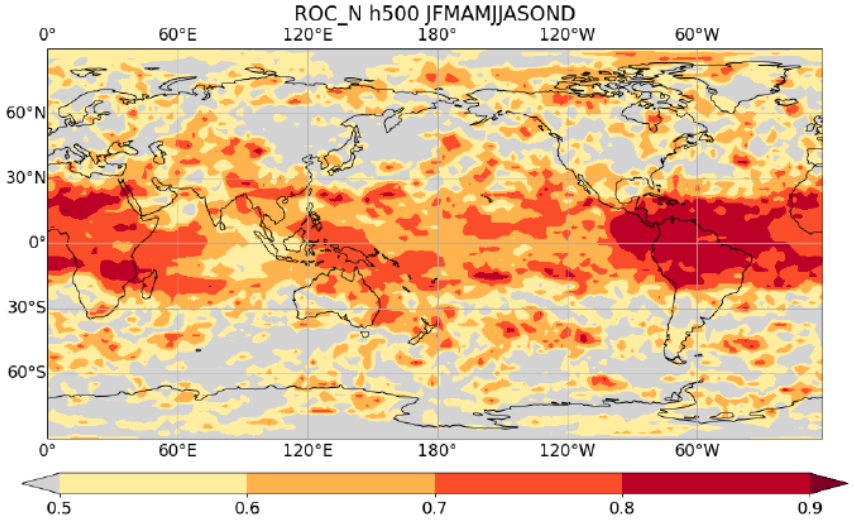
nudging to reanalysis

$$\frac{dx}{dt} = \cdots \quad \rightarrow \quad \frac{dx}{dt} = \cdots + {(x_{data} - x)}/{\tau}$$

- ERA5 data for air temperature, u- v- wind components, *τ_atm = 6 days*
- No nudging for 5 lower model levels in the atmospheric model
- SODA3.4.2 data for ocean temperature and salinity, *τ_oc = 7 days*
- Model run for 01.01.1990 – 31.12.2020, keep initial conditions for the forecasts.



INMCM5A, ROC_N=0.59



INMCM5N, ROC_N=0.61

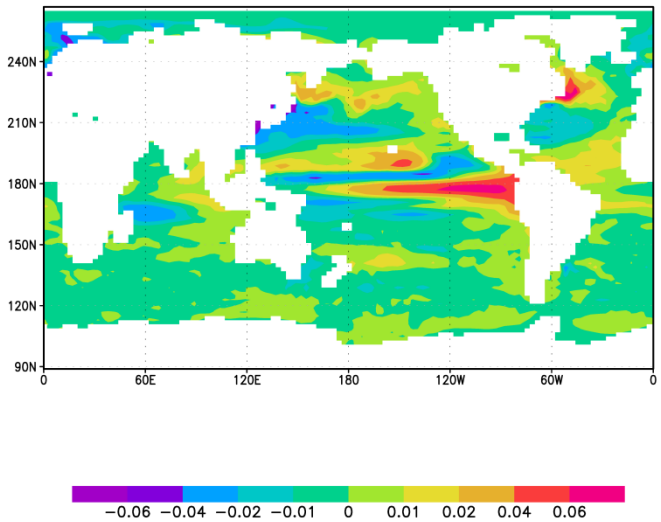
Improvement of the forecasts with initialization methods

perturbation of oceanic i.c. along unstable directions calculated for LIM/XDS model “analogues”

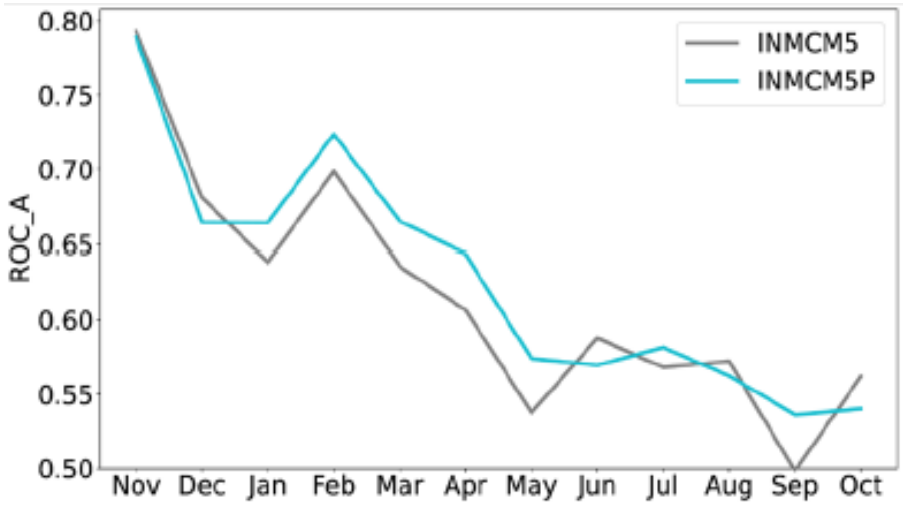
$$x(t+\Delta) = S(\Delta, x(t)) \longrightarrow x(t+\Delta) = Lx(t) + \zeta$$

$$L = \min_L \|x(t+\Delta) - Lx(t)\| \quad \text{(LIM)}$$

$$< x(t+\Delta)\, x(t+\Delta)^T >= L < x(t)x(t)^T > L^T \quad \text{(XDS)} \qquad L = U\Lambda V^T$$



Optimal perturbation used for perturbation of i.c.



ROCa characteristic for surface pressure forecast in the tropics depending on the lead time (INMCM5 и INMCM5 with perturbation of i.c. in the ocean).

Results

- Decadal prediction system is now used in operational pipeline of Russian Hydrometcenter (yearly 1-5 year forecasts)
- System participates in ADCP WMO Center

Further plans

- Move to ART-ESM(M) with1x1.25 resolution in the atmosphere
- Decadal predictions in CMIP7 project
- Assimilation (nudging) of “model-reanalysis” anomalies
- Ensemble with LIM-based perturbations in the ocean
- Statistic correction
- Further analysis of the predictability sources