From prescribed to interactive aerosols: implications for decadal prediction

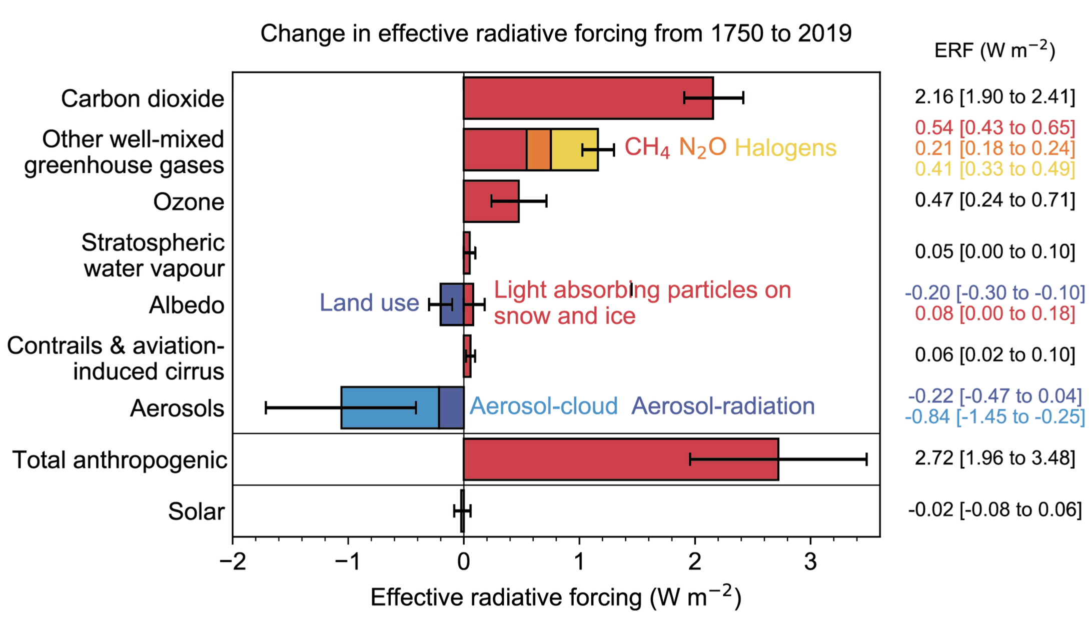
Lilian Garcia-Oliva[1], Pablo Ortega[1], Roberto Bilbao[1], María Gonçalves Ageitos[1,2], Carlos Pérez García-Pando[1,3], Montserrat Costa-Surós[1], and Marios Chatziparaschos[1]

[1]Barcelona Supercomputing Center, Earth Sciences Department, Barcelona, Spain [2]Universitat Politècnica de Catalunya, Barcelona, Spain [3]Institució Catalana de Recerca i Estudis Avançats, Barcelona, Spain

How do aerosols affect prediction skill?

Aerosols are among the largest climate forcers, producing a strong net cooling through direct radiative effects and indirect aerosol–cloud interactions (Fig. 1), with the latter being the most uncertain. By altering the mean state and internal variability of the climate system, aerosols influence modes of variability such as the monsoons, Atlantic Multidecadal Variability (AMV), and North Pacific Decadal Variability (NPDV). **Here, we aim to assess the impact of (interactive) aerosols on the predictability of climate on decadal timescales.**

Figure 1. Change in effective radiative forcing (ERF) from 1750 to 2019 by contributing forcing agents. *Source: IPCC, 2021.*



An experimental setup to isolate the effects of aerosols on decadal prediction

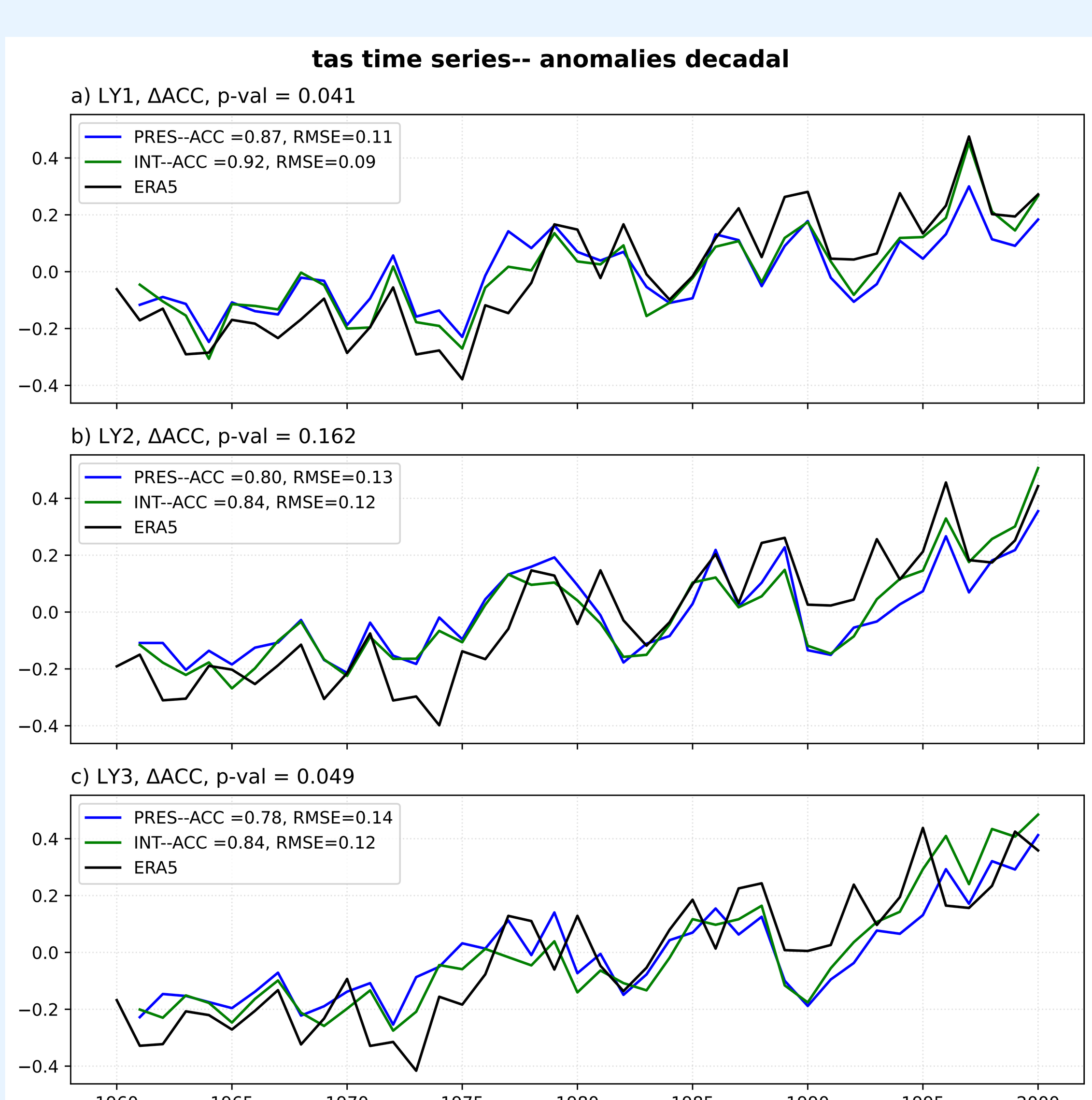
We evaluate the performance of two prediction systems for the 1960–2000 period, based on two different configurations of the EC-Earth3 Earth System Model:

Exp name	Model	Aerosol treatment	Initial conditions
PRES	EC-Earth3 (atmosphere-ocean)	prescribed	ERA5 Nud: ORAS5 (SST) + EN4 (S, T) ERA5 forcing
INT	EC-Earth3-AerChem (atmosphere-ocean-chemistry)	interactive	AMIP-like EC-Earth-AerChem Nud: ORAS5 (SST) + EN4 (S, T) ERA5 forcing

Anomalies are computed by removing the lead-time-dependent climatology computed over the longest common period, 1963–2000. The ensemble size is 10. We launch multi-year predictions (3 years). Both experiments follow anthropogenic emission trajectories as defined for the CMIP6 historical period. These are embedded in the time-varying prescribed aerosol properties from MACv2-SP used in `PRES` and as input to the `INT` simulations, which also compute natural aerosol emissions online (e.g., dust, sea salt).

Results I: Skill for Global mean surface air temperature

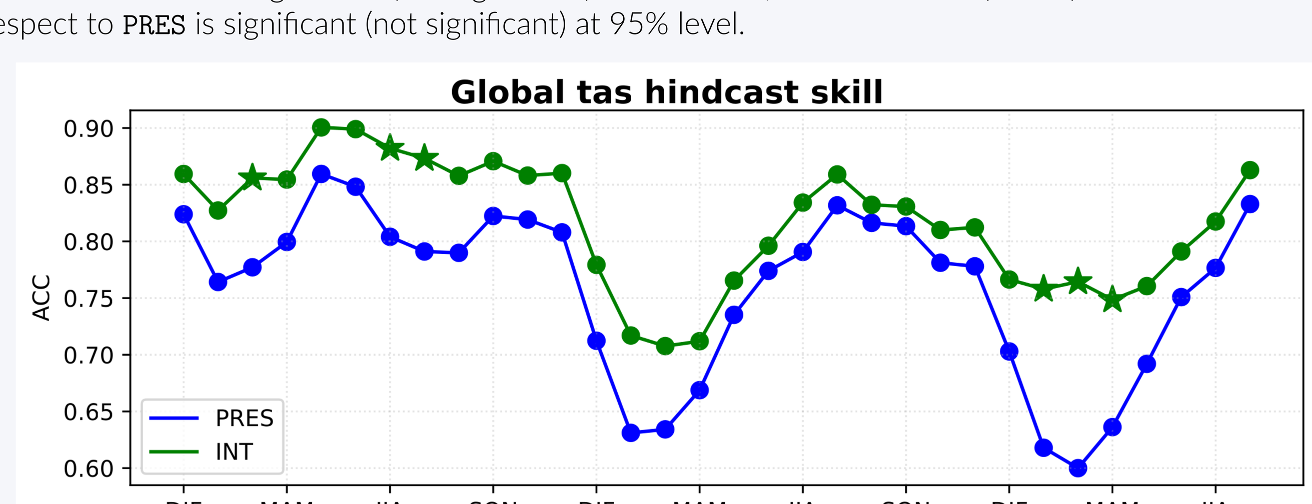
Figure 2. Global mean surface air temperature (tas) time series for each lead year. `PRES` in blue and `INT` in green. We include the anomaly correlation coefficient (ACC) and root-mean-square error (RMSE) for each system relative to observations (ERA5). We add the legend "ΔACC, p-val", indicating the p-value of the difference in skill between `PRES` and `INT`.



- Both systems present high skill over the three prediction years, largely due to the representation of the warming trends (Fig. 2). The `INT` experiment has, overall, greater predictive skill.
- The introduction of interactive aerosols improves representation of the observed warming trend, especially after 1990, which leads to enhanced skill values.
- Skill differences in LY1 and LY3 are statistically significant, indicating a real predictive added value of the interactive aerosols.

Surface air temperature skill has seasonally dependent improvements

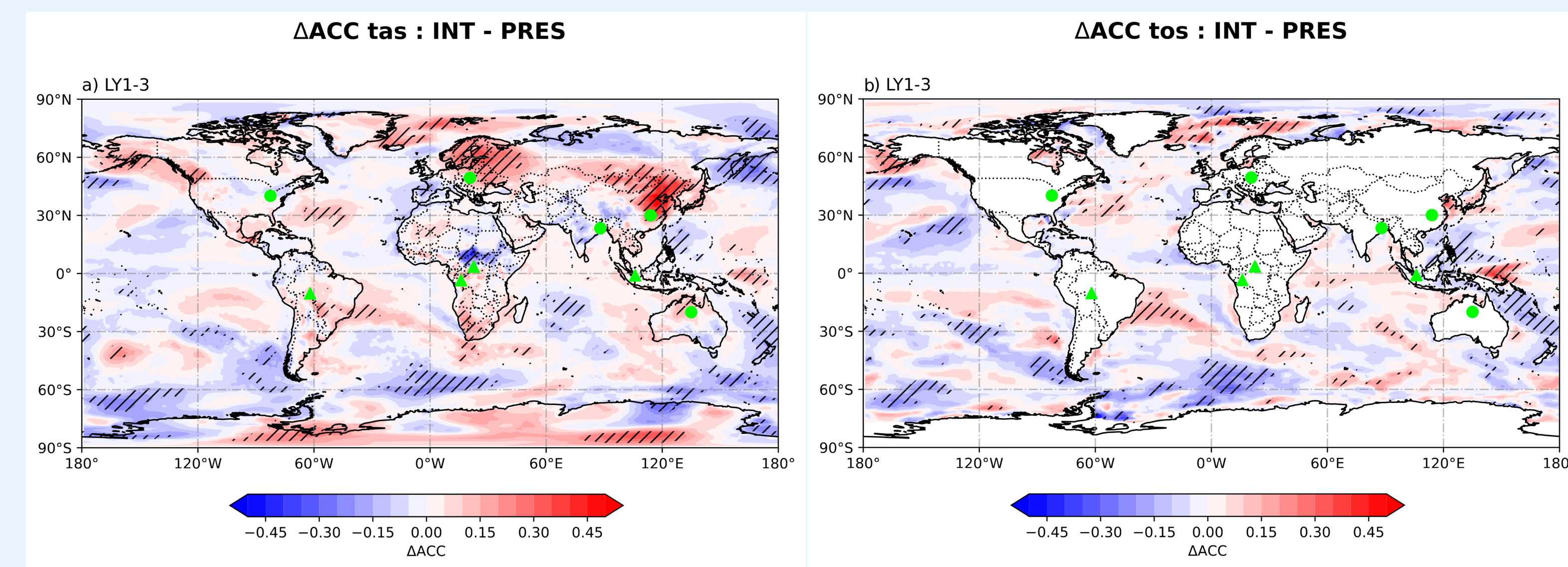
Figure 3. Global mean surface air temperature (tas) time series for each lead month. `PRES` in blue and `INT` in green. Full (empty) symbols indicate that the skill is significant (not significant) at 95% level; while the stars (circles) indicate that the skill difference of `INT` with respect to `PRES` is significant (not significant) at 95% level.



- `INT` prediction skill is consistently higher along the complete prediction period (36 months).
- Introducing interactive aerosols in `INT` ameliorates the systematic skill loss during the DJF-JJA seasons.

Results II: Differences in skill at the regional level are linked to anthropogenic emission sources

Figure 4. ΔACC, between `INT` and `PRES` for a) near-surface temperature (tas) and b) sea surface temperature (tos). The skill is measured over the entire period (LY1-3). $\Delta ACC > 0$ (< 0) in red (in blue) indicates that `INT` improves (degrades) skill, compared to `PRES`. Hashing indicates ΔACC is significant at the 95% level. In green symbols: locations of MACv2-SP plume emission centers. Industrial and biomass plumes are distinguished by the choice of symbol: circles for industrial plumes and triangles for biomass plumes.



Skill difference in tas, Fig. 4a

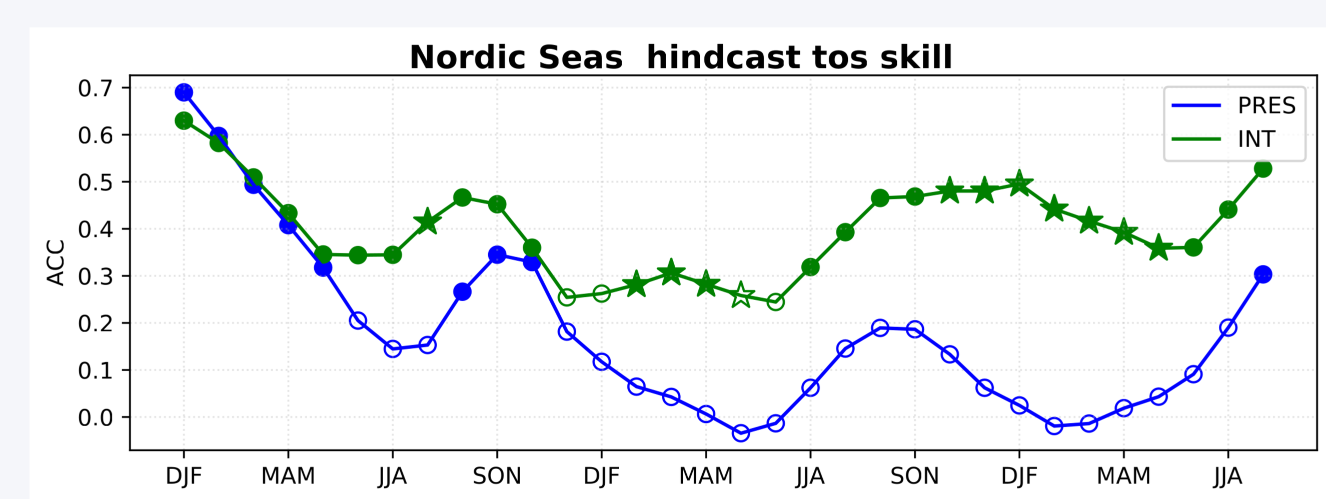
- Prediction skill shows strong sensitivity to the use of interactive aerosols in regions near anthropogenic emission sources.
- Over land, `INT` shows several regions of significant skill improvements, notably Eastern China, Central and Eastern Europe, North America, and Brazil.
- The Central Africa and India regions show a strong negative impact of the aerosols.

Skill difference in tos, Fig. 4b

- `INT` shows significant improvement in some regions in the Atlantic Ocean, eastwards of the aerosol emission regions of North America and Brazil.
- Further away from emission areas, the Nordic Seas and Agulhas regions also show added predictive value for the interactive aerosols in `INT`.
- By contrast, the Southern Ocean loses skill when aerosol interactions are considered.

Regional case: predictive skill at the Nordic Seas

Figure 5. Nordic Seas sea surface temperature (tos) time series for each lead month. `PRES` in blue and `INT` in green. Full (empty) symbols indicate that the skill is significant (not significant) at 95% level; while the stars (circles) indicate that the skill difference of `INT` with respect to `PRES` is significant (not significant) at 95% level.

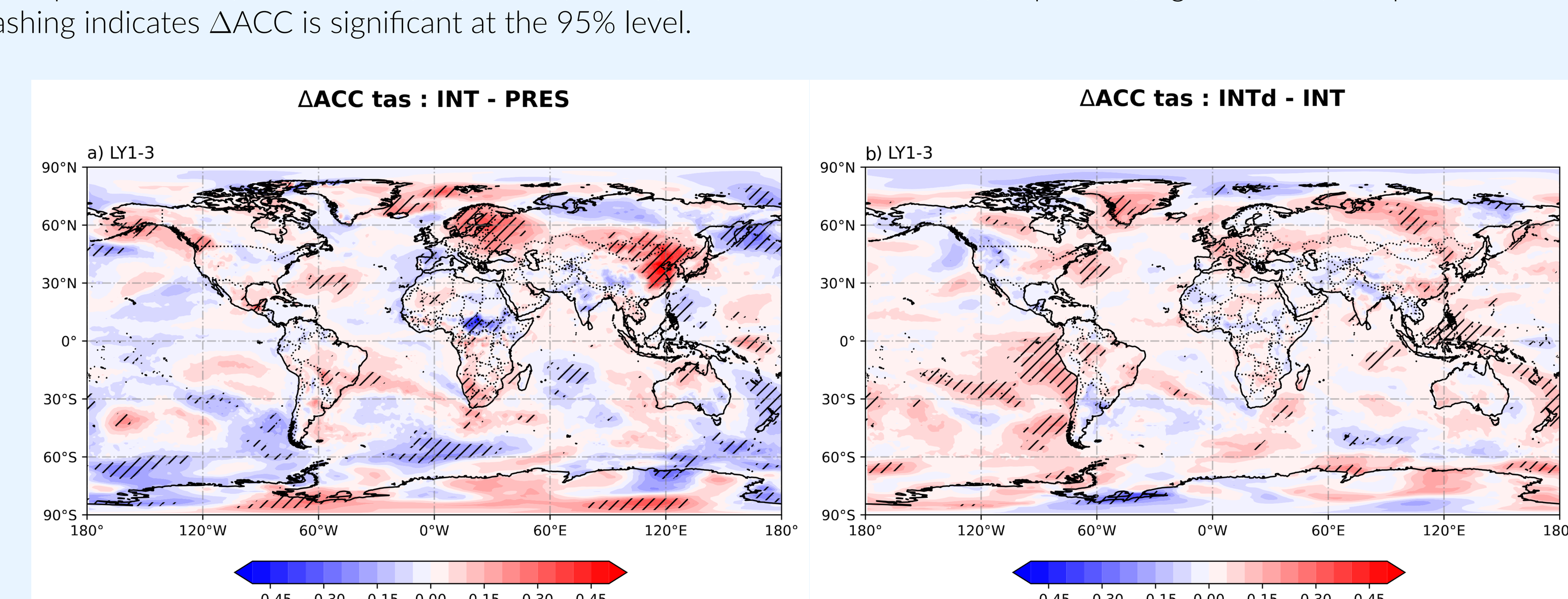


- Both systems have similar prediction skill during the first six months of prediction.
- `INT` shows significant skill for most of the prediction period, while `PRES` skill becomes insignificant after the first year. The differences in skill remain statistically significant for most of the second and third predicted years, particularly during winter and spring.
- This improved skill in `INT` is important for predicting the climate of northwestern Europe and Arctic sea ice extent.

A sensitivity test: How dust impacts predictive skill?

We conducted a new experiment `INTd`. With the same configuration as `INT`, but reducing the dust emission.

Figure 6. ΔACC, between a) `INT` and `PRES`, and b) `INTd` and `INT` for surface air temperature (tas). The skill is measured over the entire period (LY1-3). $\Delta ACC > 0$ (< 0) in red (in blue) indicates that `INT` (`INTd`) improves (degrades) skill, compared to `PRES` (`INT`). Hashing indicates ΔACC is significant at the 95% level.



- Dust has a strong impact on predictive skill in surface temperatures: reducing it enhances prediction skill compared to `INT` (Fig. 6b), suggesting that correctly capturing dust variability and properties could be key to enhancing prediction skills.

Next steps...

- Extend the prediction period (2000–2020).
- Analysis for the source of prediction skill: expand the analysis of skill in forced/internal variability signal and explore the impact on regional/large-scale dynamics, in terms of the interactions of aerosols with radiation and clouds (ARIs, ACIs).
- What is the impact of better representing dust changes? Sensitivity experiments show that the skill is strongly sensitive to this.

Acknowledgments

This research was supported by CERTAINTY, under Grant Agreement No. 101137680. We acknowledge the resources obtained in the Marenostrum5 supercomputer at BSC, granted through the RES project AECT-2025-3-0044.

lilian.garcia@bsc.es