Assimilation of satellite-derived rainfall estimates to improve numerical simulations of medicanes

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ABSTRACT

Medicanes are Mediterranean cyclones displaying tropical-like cyclone characteristics. Their development and intensification occur primarily over the sea, where conventional observations are scarce, triggered and enhanced by diabatic processes. Therefore, the assimilation of satellite-derived rainfall estimates into a high-resolution, convection-permitting meteorological model, is expected to improve the simulation of their evolution. The aim of this study is to assess the capability of assimilating precipitation data through a latent heat nudging procedure, to improve the simulated evolution of medicanes Ianos (2020) and Apollo (2021). This work is conducted in the framework of the ESA-funded project "MEDICANES - Earth Observation as a cornerstone to the understanding and prediction of tropical-like cyclone risk in the Mediterranean" (https://medicanes.isac.cnr.it).

Data, Models and Methods

Rainfall estimates from CMORPH Climate Data Record were ingested into the MOLOCH model (2 km horizontal resolution) using a nudging scheme, an assimilation scheme continuous over time that progressively modifies the model prognostic humidity profiles to correct the simulated rainfall toward observed precipitation estimates, according to equation 1: the nudging gradually forces specific humidity q(k) toward super-saturation $\epsilon^+ q^*(k)$ if the observed precipitation is higher than predicted, and toward sub-saturation $\epsilon^- q^*(k)$, otherwise. The strength of the forcing is controlled by τ, which modulates the temporal adjustment of moisture profiles, and by the vertical modulation $\nu(k)$.

$$\frac{\partial q}{\partial t} = -\frac{\nu(k)}{\tau}\left[q(k) \pm \epsilon^{\pm} q^*(k)\right] \quad (1)$$

Case studies and set-up of numerical experiments

For each case studies a control (CNTR) and two nudging runs (NUDG and NUDG24, with the same set-up of CNTR) are conducted. The set-up for the numerical experiments is summarized in Tab 1 and 2. The Initial Condition (IC) and Boundary Conditions (BC) are supplied by the 6-hourly analysis field of the Integrated Forecasting System (IFS) of the European Centre for Medium-Range Weather Forecast (ECMWF), on a 0.1-degree regular grid. Control and nudging experiments are contrasted using several diagnostics, including comparison among mean sea level pressure (MSLP) and geopotential fields, cyclone trajectory and intensity, and by analysing Hart diagrams. ECMWF-IFS analyses are taken as reference.

Medicane Ianos 15-18 Sep. 2020

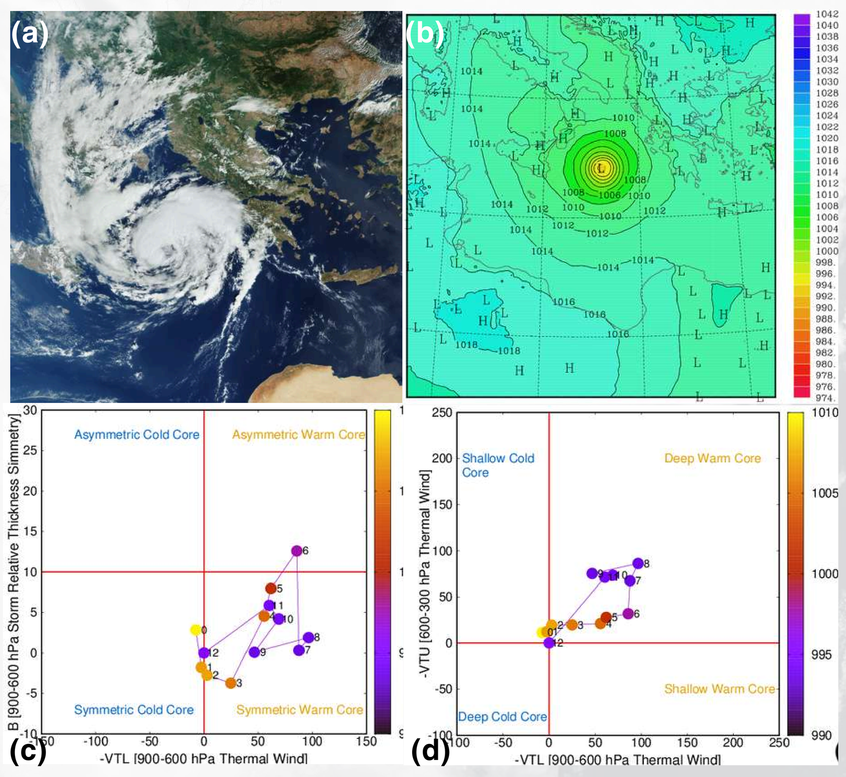


Fig. 1: (a) Satellite image (Terra/MODIS True color) of medicane Ianos on 17 Sep. 2020. (b) Mean sea level pressure (IFS-ECMWF analysis) at 06 UTC, 17 Sep. 2020. (c,d) Cyclone phase space diagrams for medicane Ianos computed from IFS-ECMWF analysis.

Ianos

	INITIAL COND.	DURATION	ASSIMILATION TIME
CNTRL	15/09/20, 00 UTC	72 h	-
NUDG	15/09/20, 00 UTC	72 h	48 h
NUDG24	15/09/20, 00 UTC	72 h	24 h

Apollo

	INITIAL COND.	DURATION	ASSIMILATION TIME
CNTRL	28/10/21, 00 UTC	48 h	-
NUDG	28/10/21, 00 UTC	48 h	48 h
NUDG24	28/10/21, 00 UTC	48 h	24 h

Medicane Apollo 28-30 Oct. 2021

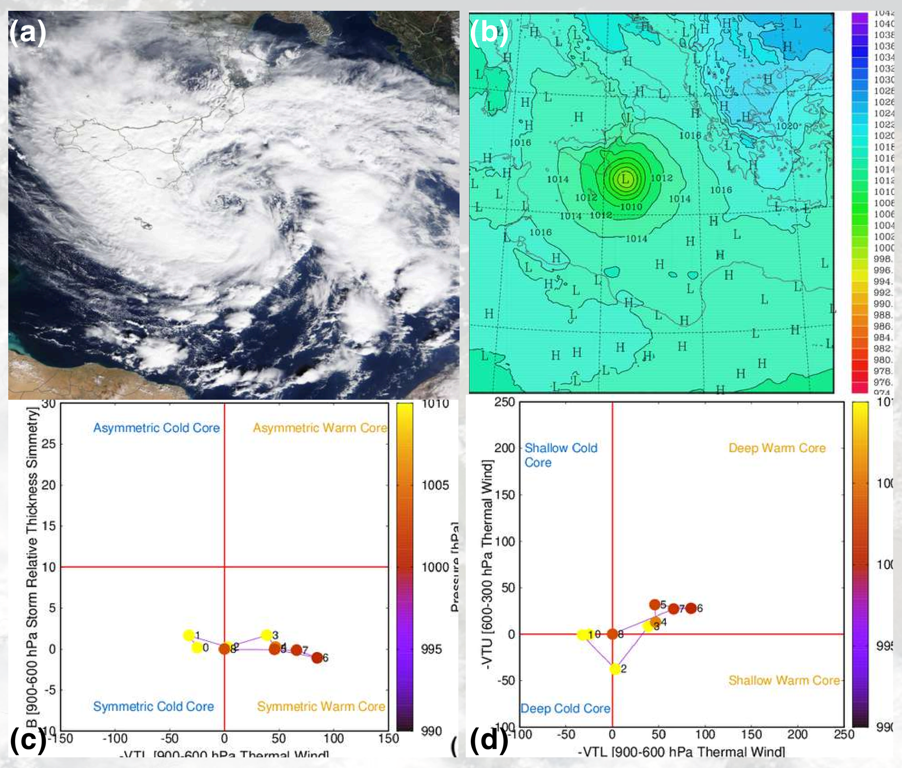


Fig.2: (a) Satellite image (Terra/MODIS True color) of medicane Apollo on 29 Oct. 2021. (b) Mean sea level pressure (IFS-ECMWF analysis) at 12 UTC, 29 Oct. 2021. (c,d) Cyclone phase space diagrams for medicane Apollo computed from IFS-ECMWF analysis.

Simulation results

Medicane Ianos 15-18 Sep. 2020

The CNTR simulation fails in reproducing the correct evolution of Ianos, depicting a weak and shallow cold-core cyclone:

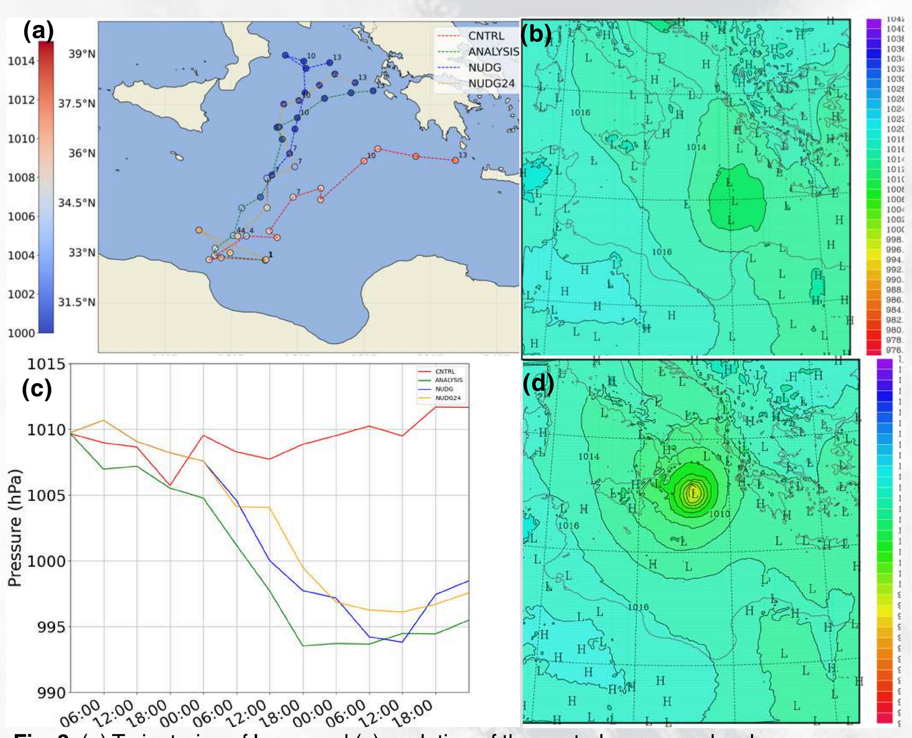


Fig. 3: (a) Trajectories of Ianos and (c) evolution of the central mean sea level pressure, computed from the IFS-ECMWF analysis (green), CNTR (red), NUDG (blue) and NUDG24 (orange) experiments. Mean sea level pressure field at 06 UTC, 17 Sep. 2020 for (b) CNTR and (d) NUDG24 experiments.

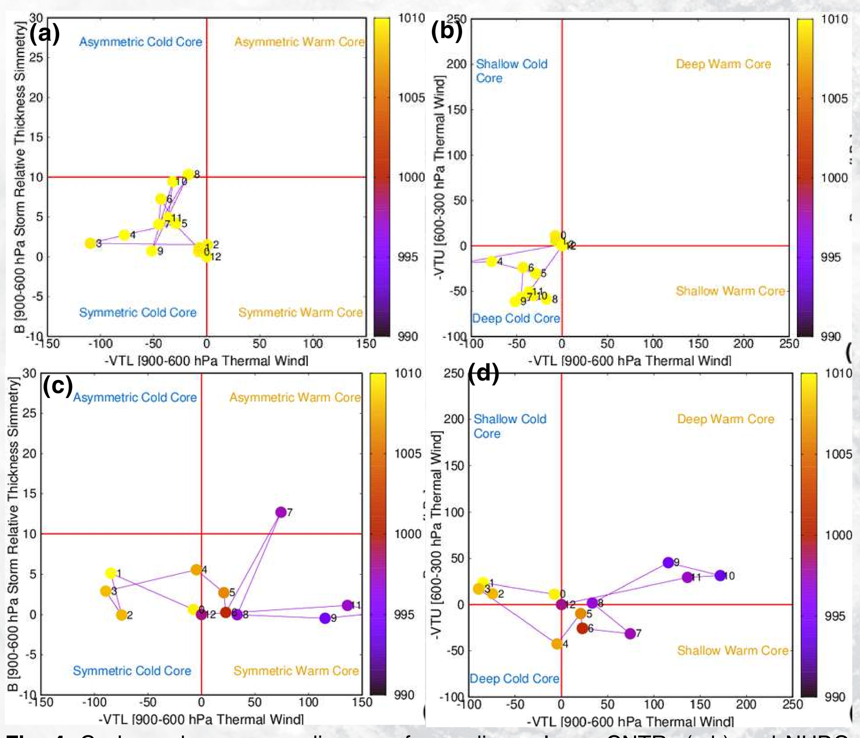


Fig. 4: Cyclone phase space diagrams for medicane Ianos CNTR (a,b) and NUDG experiments (c,d)

Both NUDG and NUDG24 closely match the observations, both in terms of trajectory and intensity (Figs: 3a,c). Indeed, Hart diagrams diagnostic highlights that nudging experiments simulate a deep and symmetric warm-core structure.

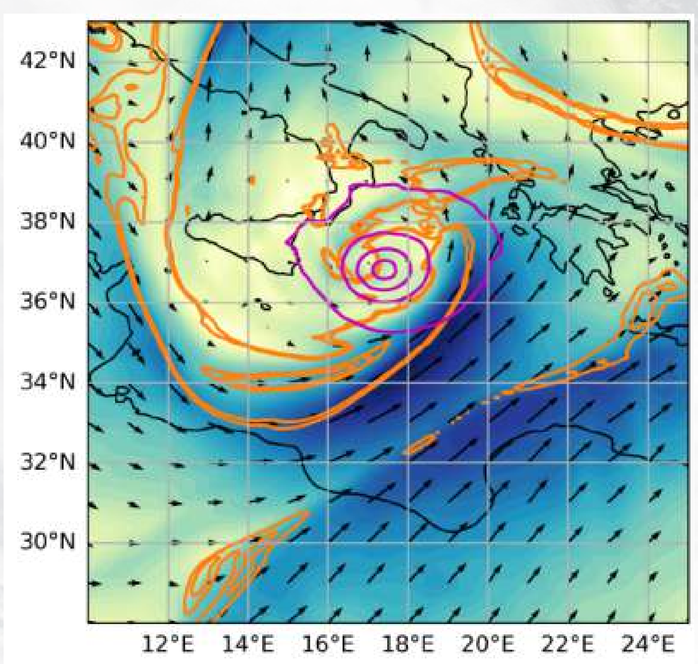


Fig. 7: 300 hPa wind (shading in m s−1 and vectors), 300 hPa potential vorticity (orange contours at 1.5 and 2 pvu) and MSLP (pink contours every 5 hPa below and including 1010 hPa). From Pantillon et al., 2024 https://doi.org/10.5194/wcd-5-1187-2024

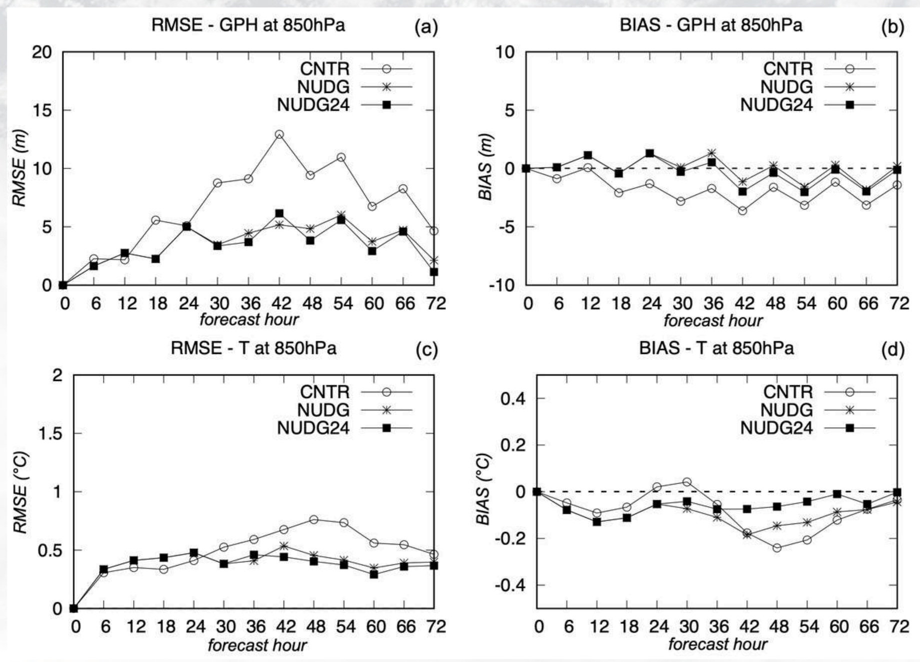
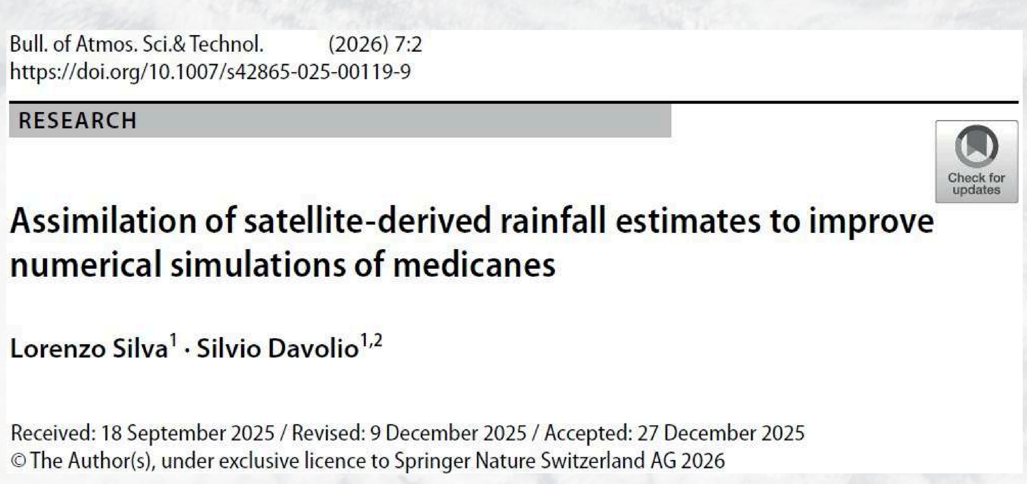


Fig. 8: RMSE and bias between IFS-ECMWF analysis and the three MOLOCH experiments (CNTR, NUDG and NUDG24) computed for geopotential height (a, b) and temperature (c, d) at 850 hPa, for Ianos case study.

Both nudging experiments reduce the RMSE of the 850 hPa geopotential field and slightly improve the BIAS (Fig. 7 a,b). Regarding temperature at the same isobaric level, the improvement introduced by nudging is weaker (Fig. 7 c,d). In this case the improvements result particularly pronounced due to the existing feedback between deep convection and large scale dynamic, as highlighted by Pantillon et al. (2024).



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RESEARCH

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Medicane Apollo 28-30 Oct. 2021

Apollo CNTR simulation underestimates the cyclone intensity and misrepresent the trajectory and the thermodynamic structure of the cyclone:

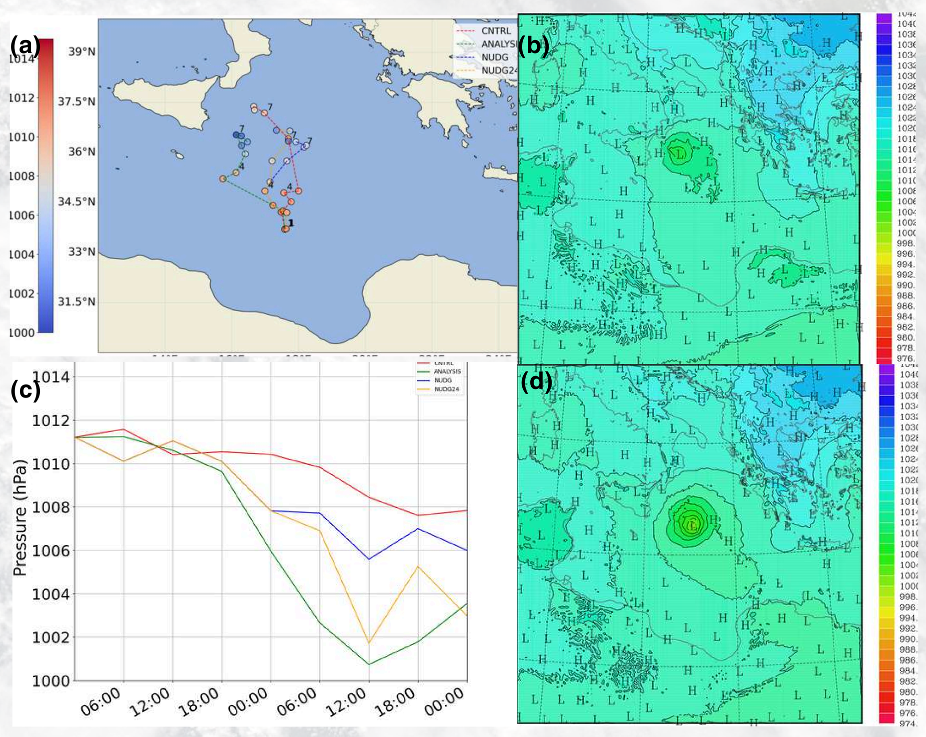

Fig. 5: (a) Trajectories of Apollo and (c) evolution of the central mean sea level pressure, computed from the IFS-ECMWF analysis (green), CNTR (red), NUDG (blue) and NUDG24 (orange) experiments. Mean sea level pressure field at 12 UTC, 29 Oct. 2021 for (b) CNTR and (d) NUDG24 experiments.

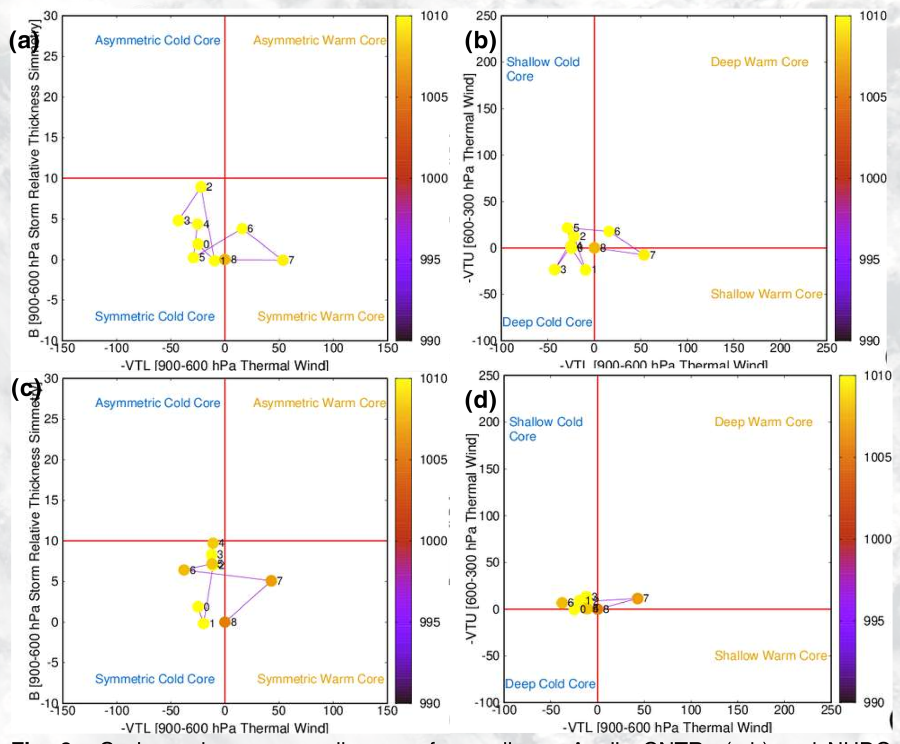

Fig. 6: Cyclone phase space diagrams for medicane Apollo CNTR (a,b) and NUDG experiments (c,d)

In this case the impact of rainfall assimilation is more limited: overall the nudging experiments simulate a warm-core cyclone more realistic than CNTR whilst the trajectory aligns to the observed path only during the initial phase (Figs: 5-6).

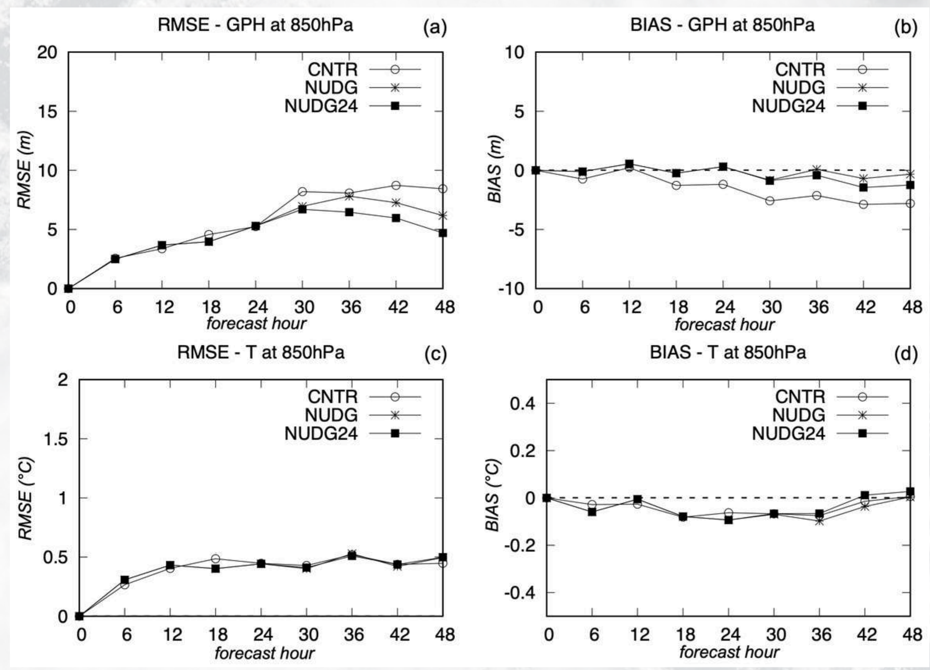

Fig. 9: RMSE and bias between IFS-ECMWF analysis and the three MOLOCH experiments (CNTR, NUDG and NUDG24) computed for geopotential height (a, b) and temperature (c, d) at 850 hPa, for Apollo case study.

This is confirmed by RMSE and BIAS computed against IFS-ECMWF analysis: regarding the 850 hPa geopotential significant improvements appear only the second day of simulation, while are negligible for temperature.

In this case, the reduced impact of nudging can likely be attributed to the less prominent role of large-scale forcing in the cyclone's dynamic.

Conclusion

- A rainfall assimilation scheme (based on latent-heat nudging) was implemented and tuned in the convection-permitting model MOLOCH.
- Assimilation of satellite-derived precipitation improves the representation of medicane structure, intensity, and evolution, with a marked event-to-event variability.
- For the Ianos case, nudging substantially corrects both cyclone intensity and track, while for medicane Apollo the track shows limited improvement.
- Results suggest that nudging can effectively modify diabatic processes, and these corrections become particularly relevant when propagate on the large-scale dynamic (upscaling).
- Although based on a limited number of cases, these findings highlight the potential of satellite rainfall assimilation and motivate further studies including additional events and observational datasets.