Advancing the global km-scale models underpinning the DestinE Digital Twins

Benoît Vannière

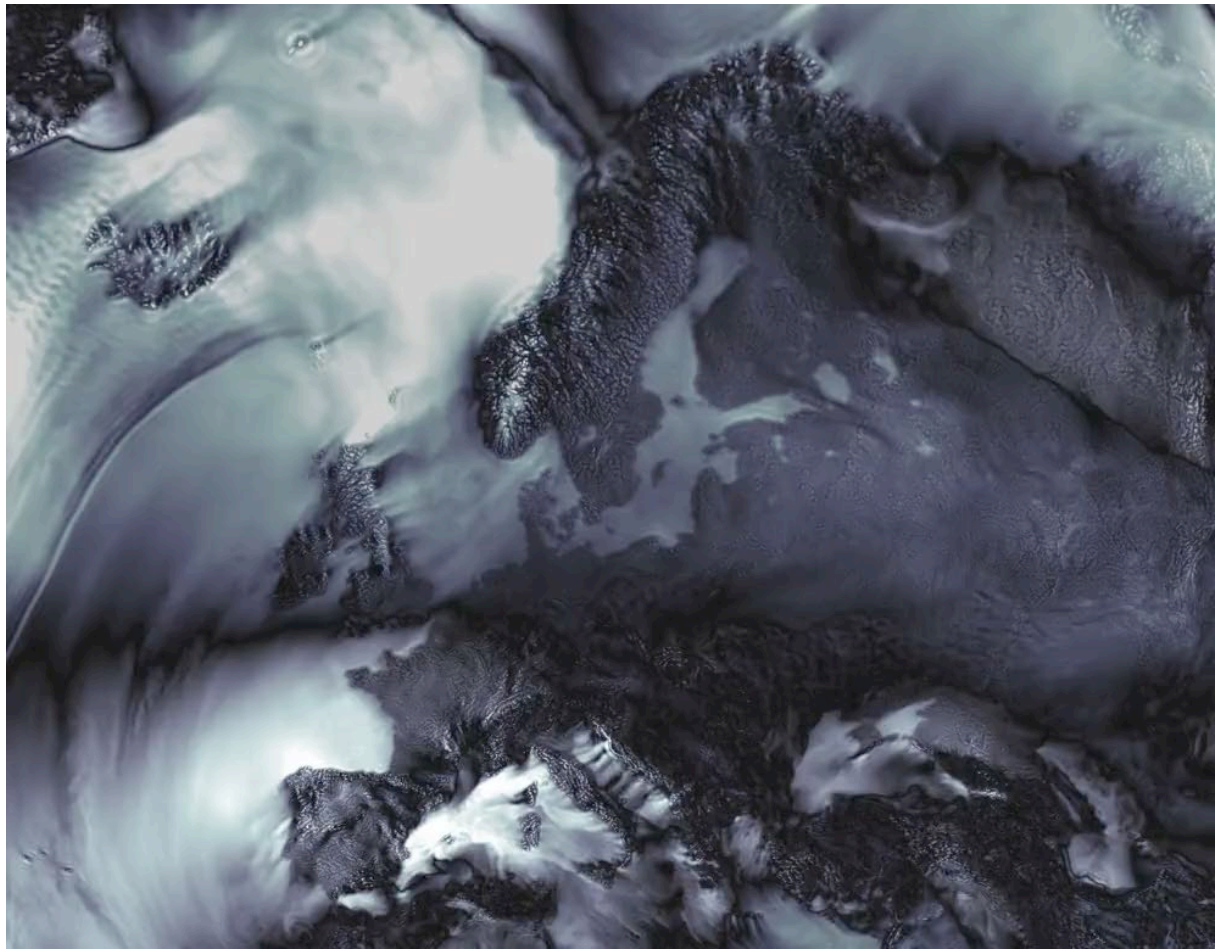
on behalf of colleagues developing the IFS at km-scale at ECMWF

in collaboration with ECMWF Member States

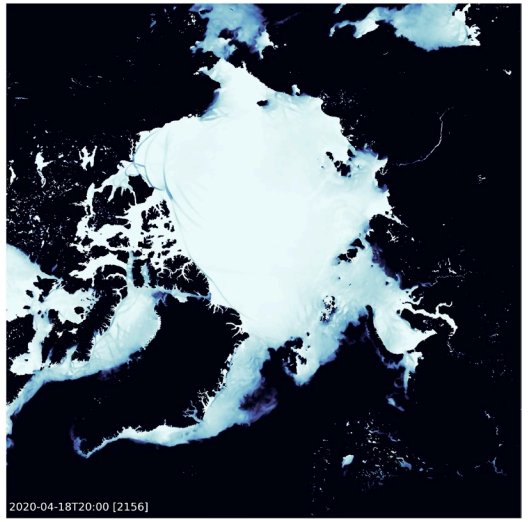
Funded by the European Union

Destination Earth implemented by ECMWF esa EUMETSAT

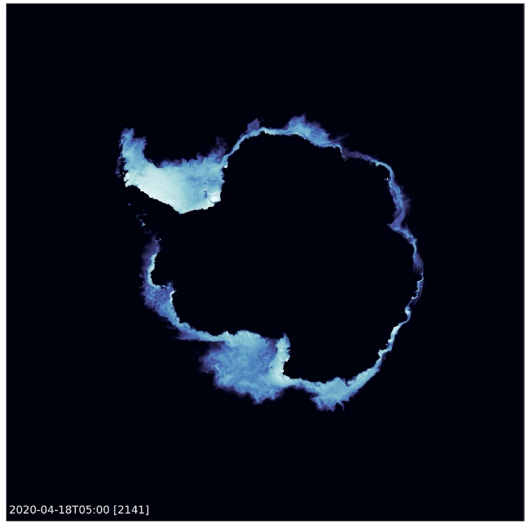
BUILDING ON PIONEERING GLOBAL KM-SCALE MODELLING



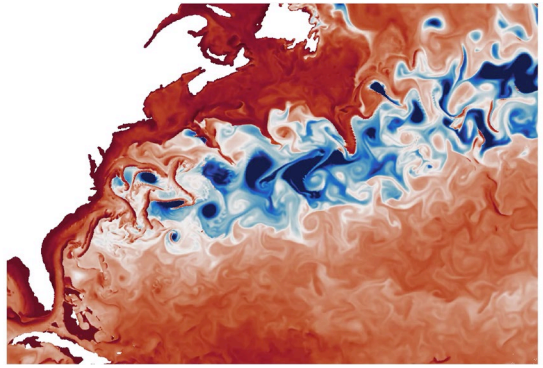
10m wind gust in IFS-FESOM (atmosphere ~5km/ ocean ~5km)



Arctic sea ice fraction



Antarctic sea ice fraction



Mixed-layer depth

next GEMS

U.S. DEPARTMENT OF ENERGY INCITE LEADERSHIP COMPUTING

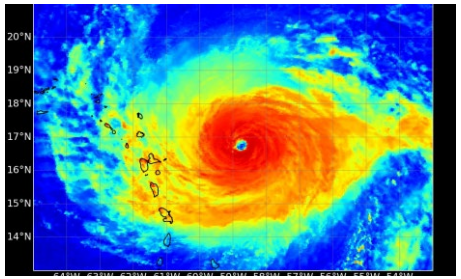
EERIE European Eddy-Rich ESMs

GLOBAL KM-SCALE MODELLING EFFORTS AT ECMWF

U.S. DEPARTMENT OF ENERGY INCITE LEADERSHIP COMPUTING

Short forecasts pioneering physics for global km-scale

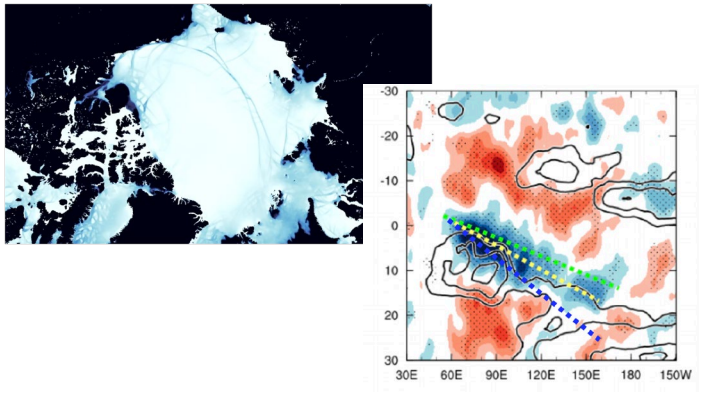
Multiple case studies up to IFS (2.8km/1.4km) + NEMO12 (9km)



next GEMS

Multidecadal coupled simulations

In 2024, 30 years of IFS (4.4km) + NEMO025 (25km) IFS (4.4km) + FESOM (5km)

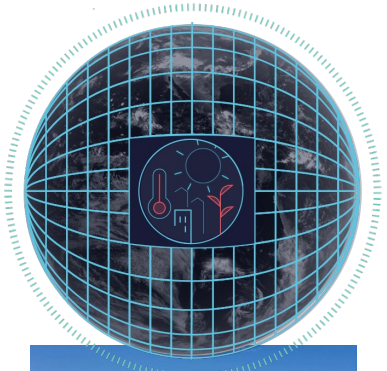


Destination Earth

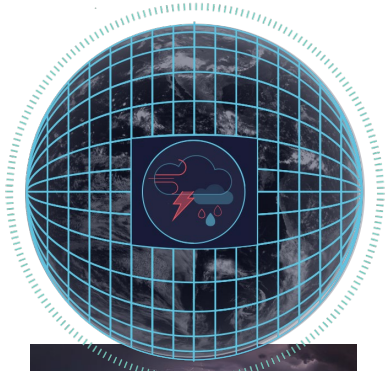
Implemented by ECMWF esa EUMETSAT

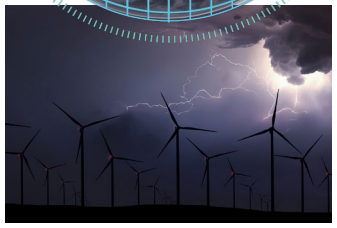
Pathway to operational use

Climate adaptation DT



Weather-Induced Extremes DT





KM-SCALE MADE POSSIBLE BY THE WORLD'S FASTEST SUPERCOMPUTERS

EuroHPC Joint Undertaking

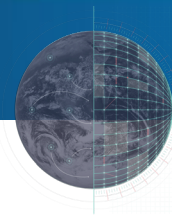
LUMI

LEONARDO CINECA

MN5 MARENOSTRUM

	SDPD	Computer	CPU nodes
IFS-FESOM 5km (Climate DT)	180	LUMI-C	201
IFS-NEMO 5km (Climate DT)	160	MareNostrum5	284
IFS-NEMO 5km (Extremes DT)	70	ECMWF Atos	128

Throughput allows for decade-long simulations and is fast enough for operational weather predictions

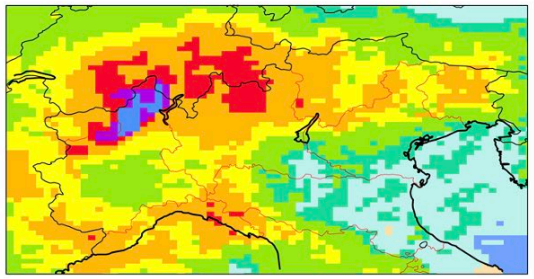


IMPROVEMENT DUE TO KM-SCALE

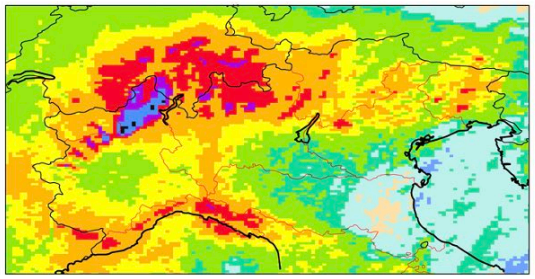
OROGRAPHIC PRECIPITATION AND NEAR-SURFACE FIELDS

Storm Alex 24h TP, 2020-10-01 T+60h

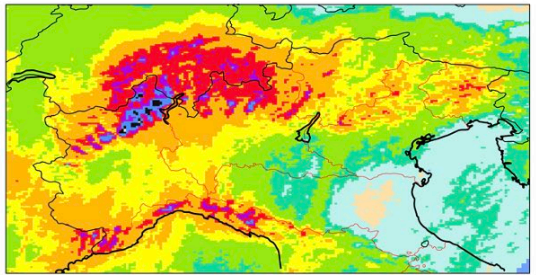
OPER (9km)



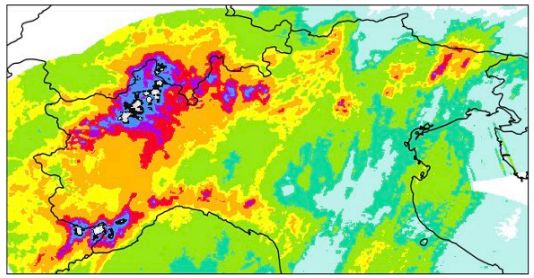
DestinE (4.4km)

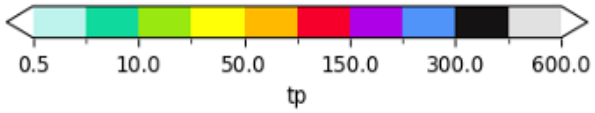


DestinE (2.8km)



Gridded radar + gauges





"Extremes score-card" (ref SYNOP)

ETS 10ff - 99th percentile

	Flat areas NH extra					Mountainous areas NH extra					Tropics
	DJF	MAM	JJA	SON	all year	DJF	MAM	JJA	SON	all year	all year
day 5	0.012	0.004	0.005	0.007	0.007	0.021	0.026	0.023	0.024	0.025	0.009
day 3	0.021	0.004	0.004	0.009	0.012	0.025	0.029	0.027	0.027	0.028	0.009
day 1	0.026	0.006	0.004	0.008	0.014	0.027	0.033	0.028	0.027	0.030	0.010

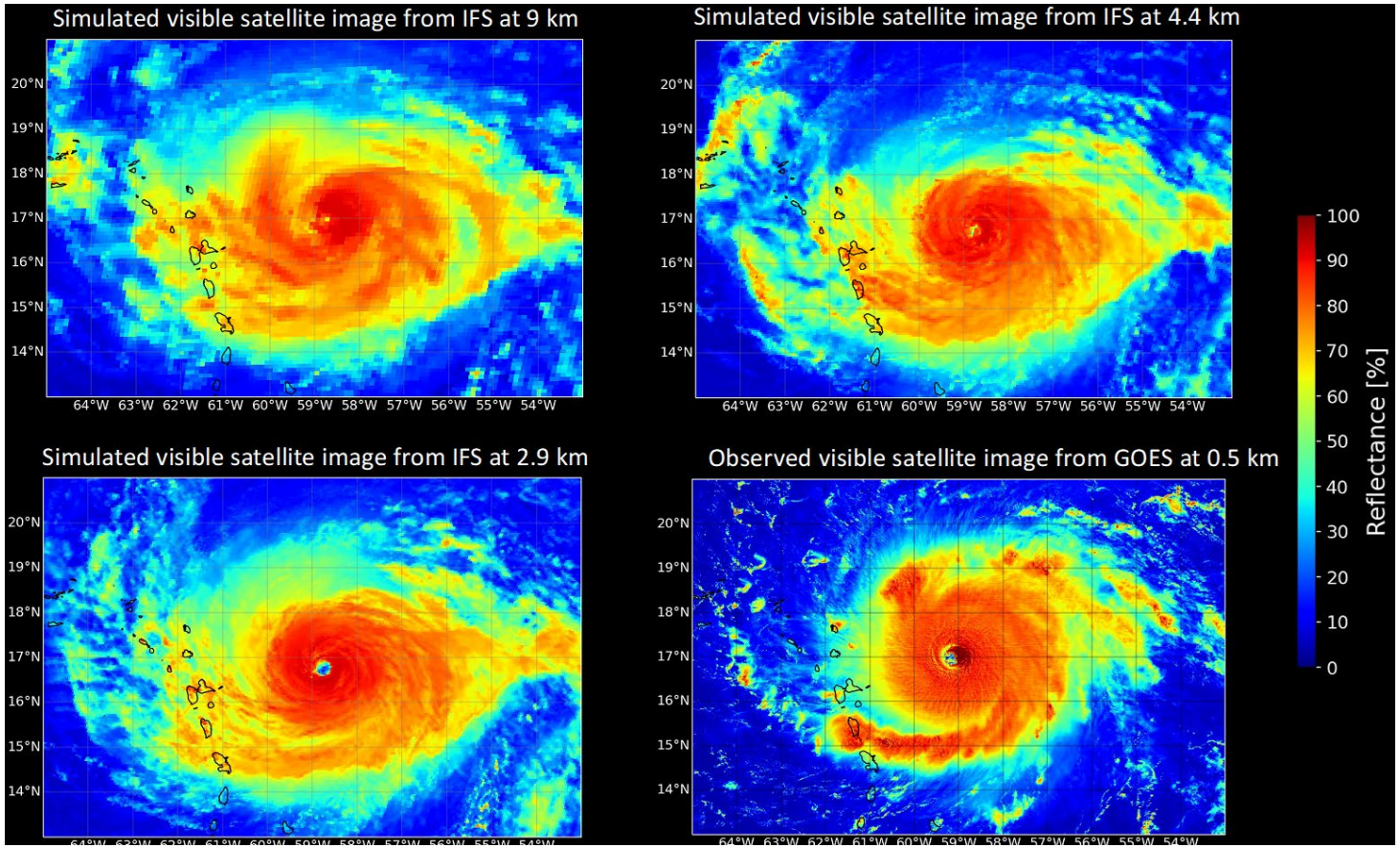
$$ETS = \frac{H - C}{H + M + F - C}$$

H: Hits
M: Misses
F: False alarms
C: Correct negatives

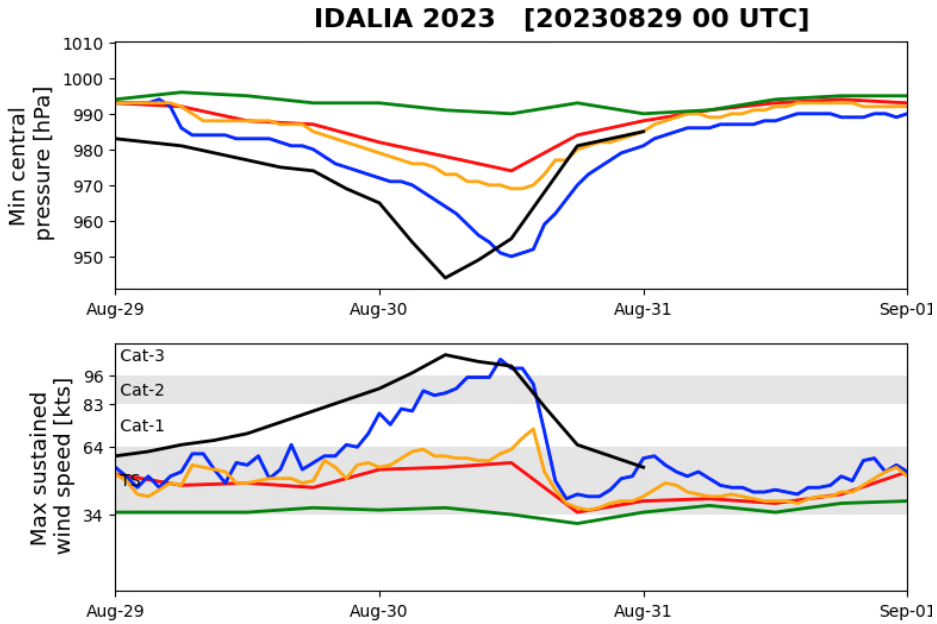
Precipitation totals and surface wind are in better agreement with the observations. But poses verification challenges because of data quality/quantity and double penalty issue

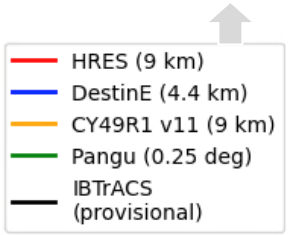
ECMWF *Estíbaliz Gascón*

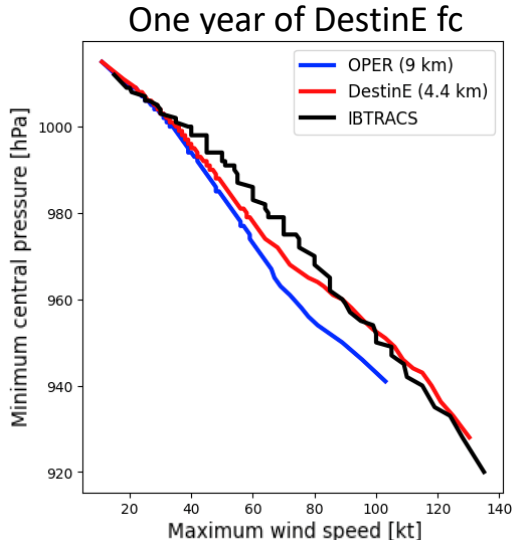
HOW DOES KM-SCALE IMPROVE TROPICAL CYCLONES?



Hurricane Irma (2017-09-05 00 UTC T+18)

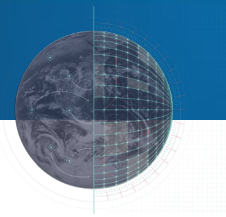






… improved mesoscale features & intensity but lingering slow propagation bias

ECMWF *I. Polichtchouk, M. Maier-Gerber*

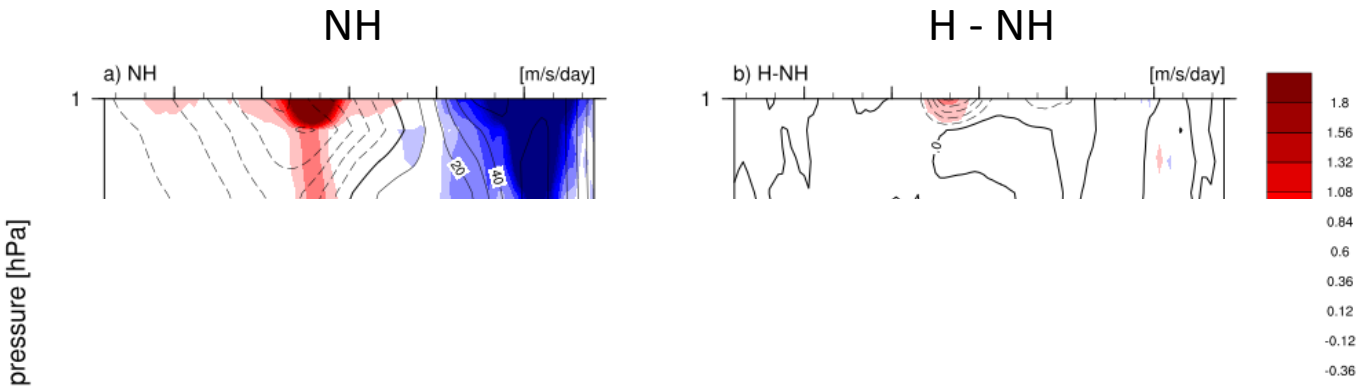


WHERE HAVE WE MADE PROGRESS?

Funded by the European Union **Destination Earth** implemented by ECMWF esa EUMETSAT

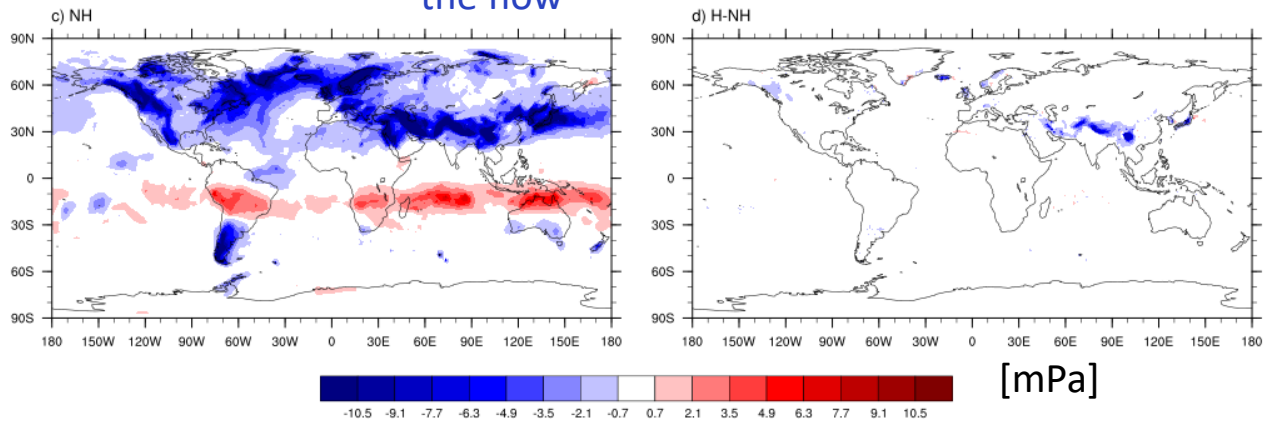
IS THE HYDROSTATIC ASSUMPTION STILL VALID AT KM-SCALE?

Zonal-mean of $\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\bar{\rho}\overline{u'w'}$



GWs decelerate the flow

$\bar{\rho}\overline{u'w'}$ @90hPa



GWs carry westward momentum

GWs carry eastward momentum

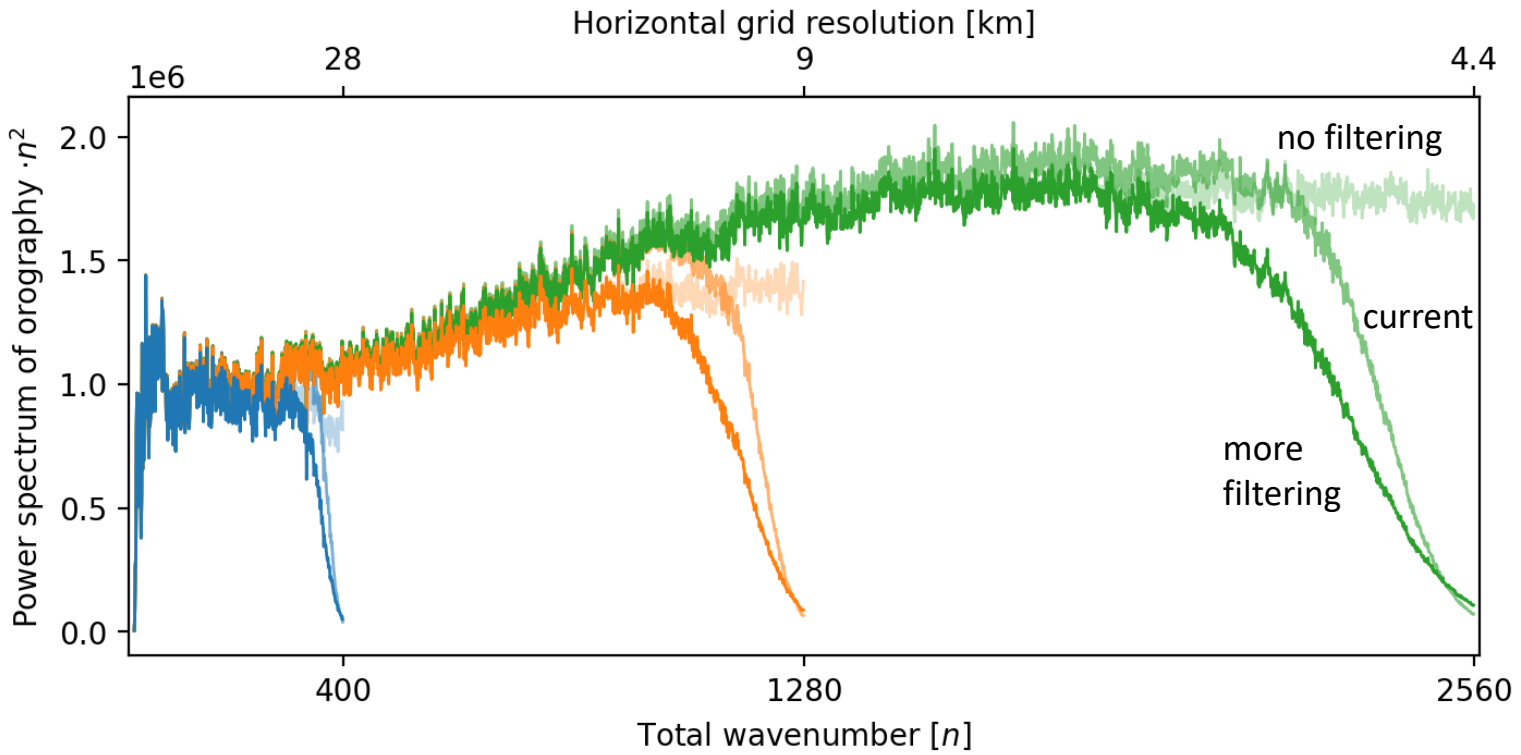
2.8 km resolution simulations for end of January 2022 (winds over Himalayas ~50 m/s)

… mostly **YES**, difference between H and NH is limited to a few specific flow situations.
Fortunately, because NH is >2 times more expensive.

Inna Polichtchouk, Jozef Vivoda

ECMWF
U.S. DEPARTMENT OF ENERGY INCITE LEADERSHIP COMPUTING

HOW TO TREAT OROGRAPHY?

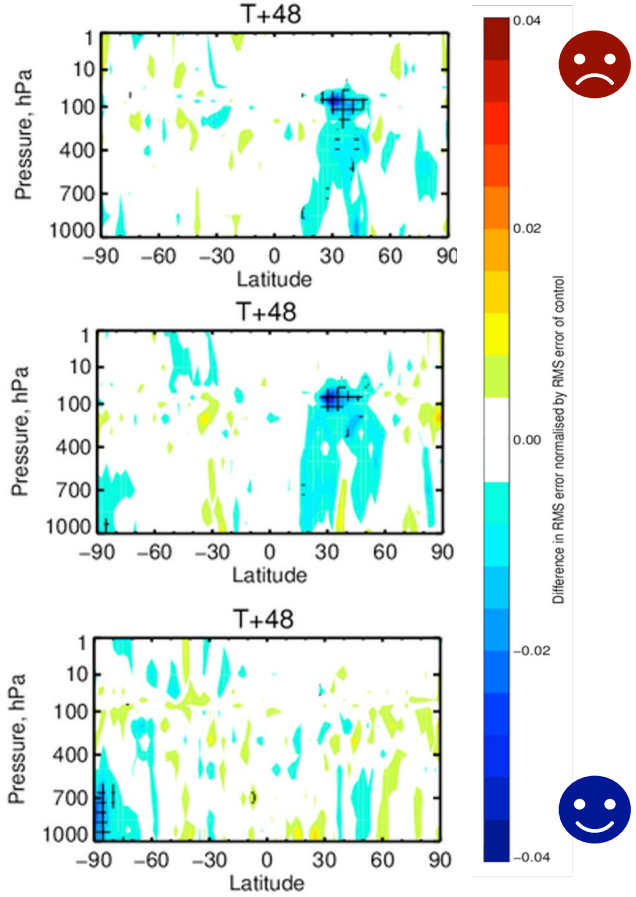


Change in RMSE of winds
More filtering vs current

4.4 km

9 km

28 km



… careful balance between filtering small scales to improve accuracy, while preserving orographic detail

Birgit Sützl, Annelize Van Niekerk

VT at 27/02/2021 05Z

PROGNOSTIC TKE TURBULENT SCHEME

T+53h

T+101h

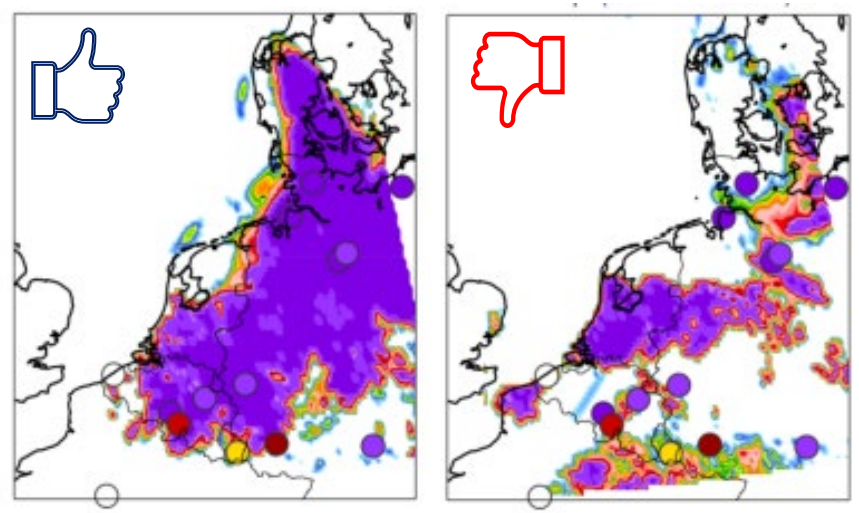
T+101h

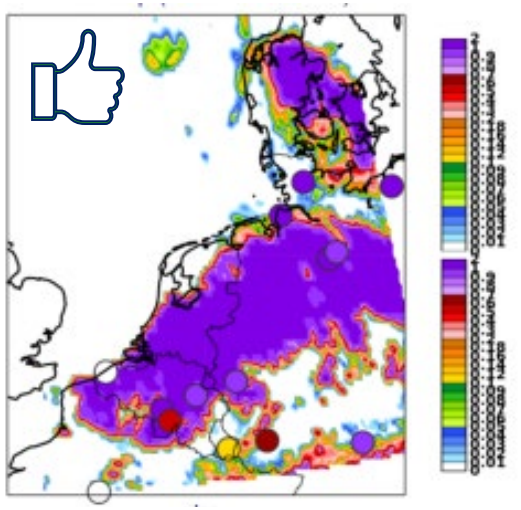
Cloud cover

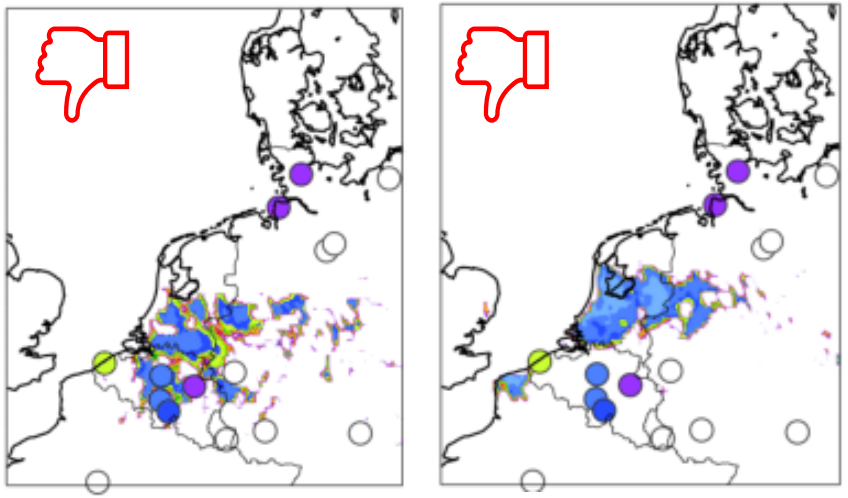
Visibility

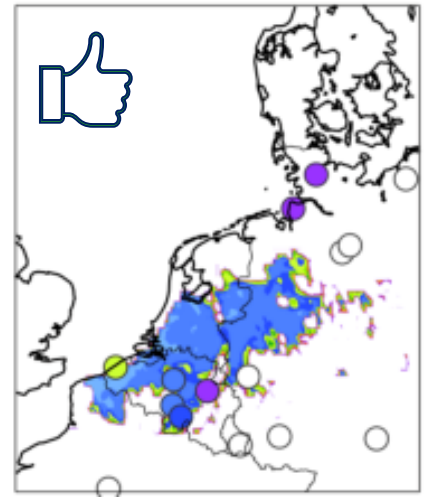
Current
first-order closure turbulent scheme

New
prognostic TKE turbulent scheme

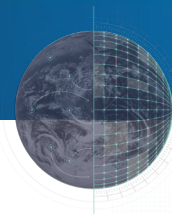








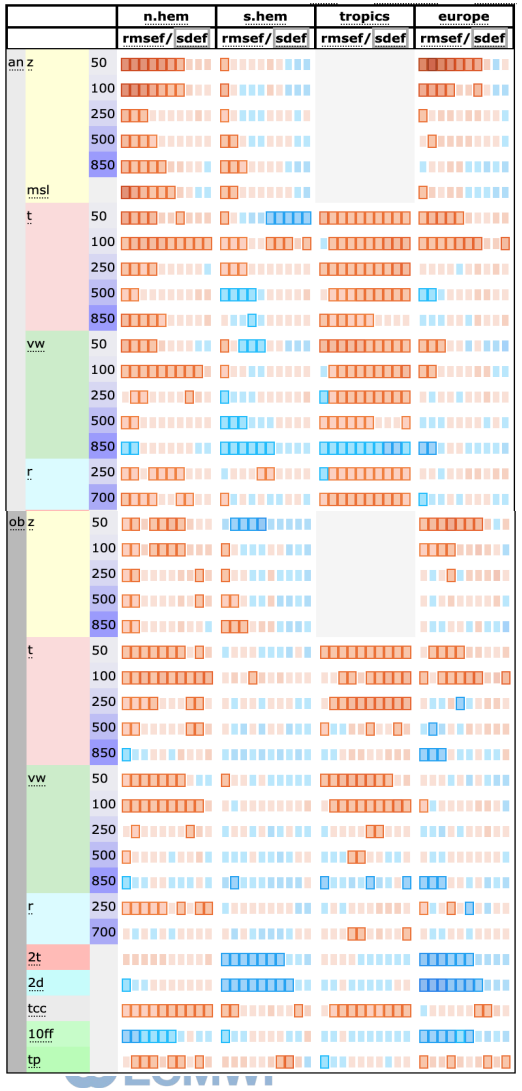
Ivan Bašták Ďurán



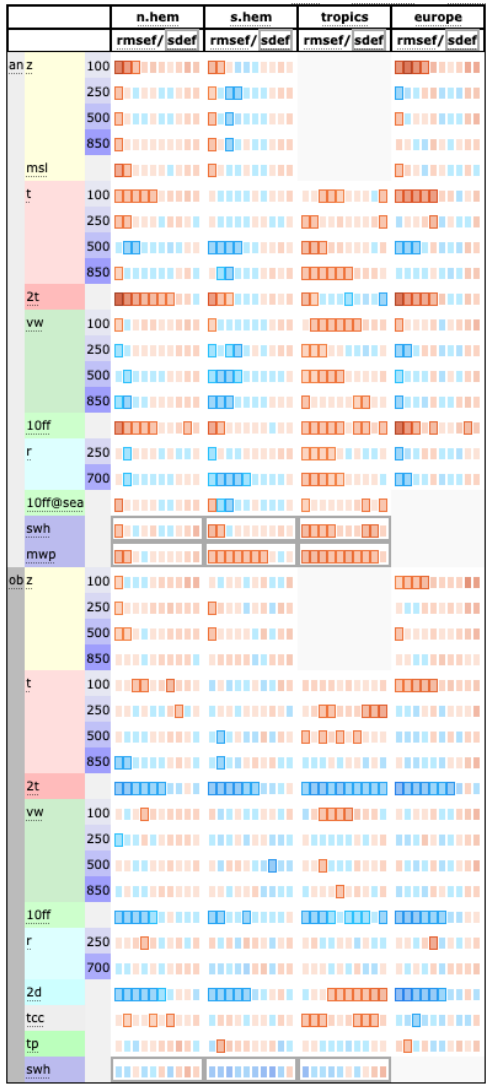
WHAT ARE THE CHALLENGES AHEAD?

HIGH-RESOLUTION DATA ASSIMILATION

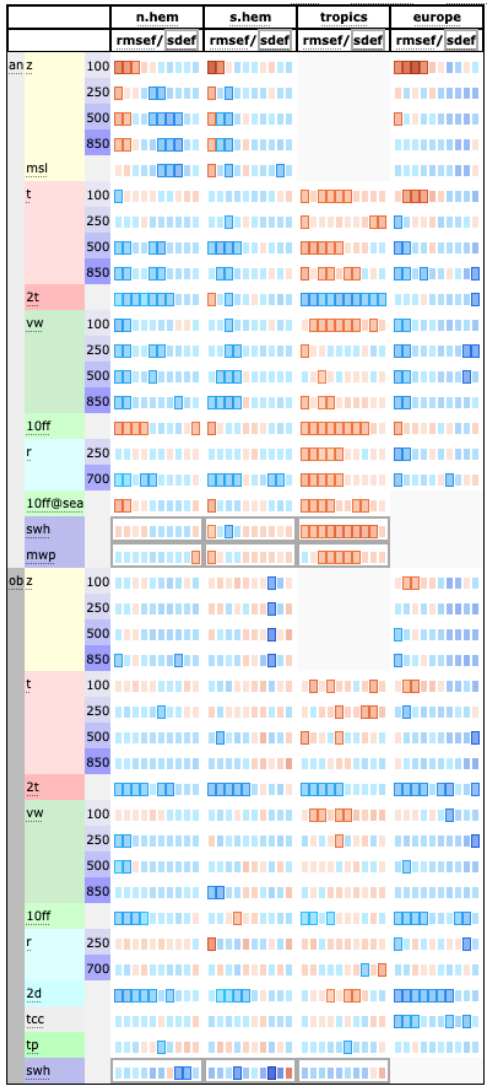
FC 4km vs 9km (old)



FC 4km vs 9km (new)



AN+FC 4km vs 9km



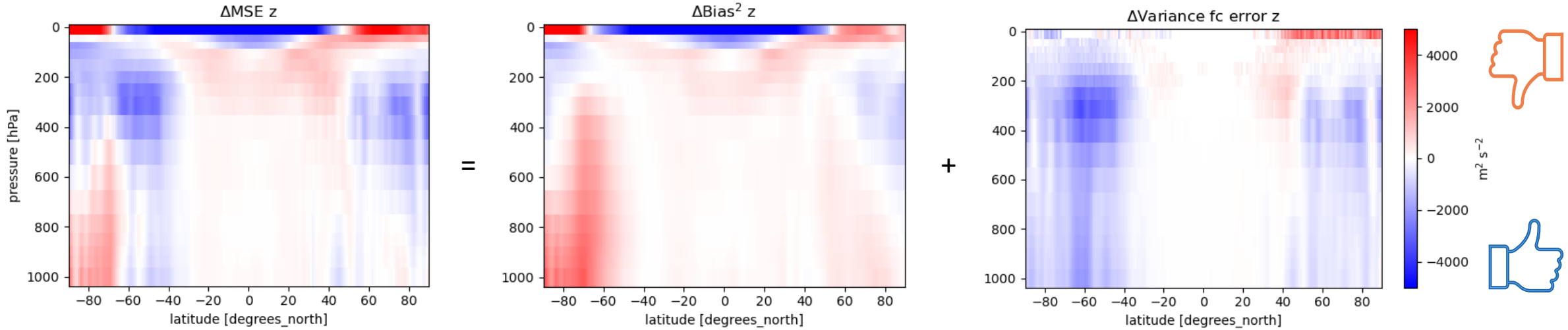
Setup of the high-resolution DestinE analyses:

- TCo2559 (4.4 km) **trajectory** using latest 49r1 DestinE forecast (new orog, time-step)
- Increased resolution of **minimisation** (TL319/TL399/TCo399/TCo511)
- Observation **time-slots** reduced from 1800s to 400s
- High-resolution geostationary satellite data (reduced **thinning**)

Z. Zaplotnik, J. Schröttle, E. Orlandi and J. Bandeiras

DOES SIMULATING THE KM-SCALE HAVE AN UPSCALE EFFECT?

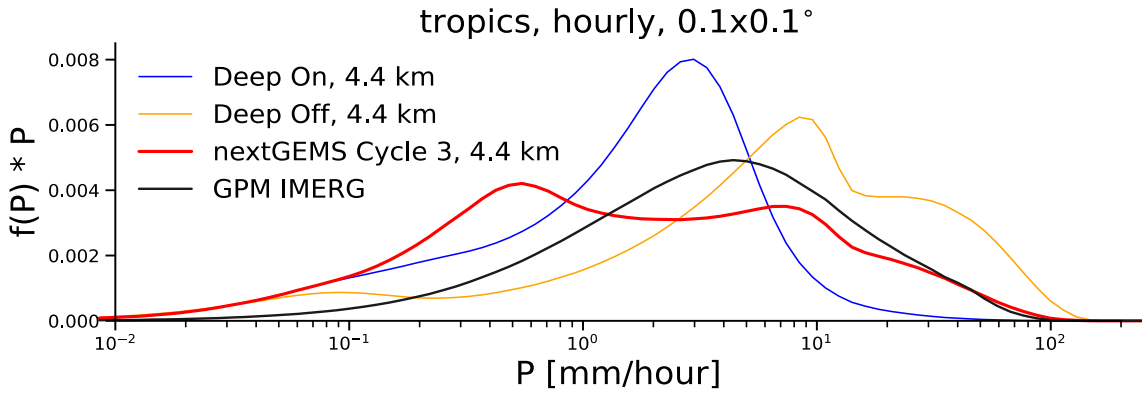
- One year of DestinE forecasts compared to OPER at T+72h (366 dates)
- MSE = BIAS^2 + VFE , VFE = variance of forecast error informs on predictive skill



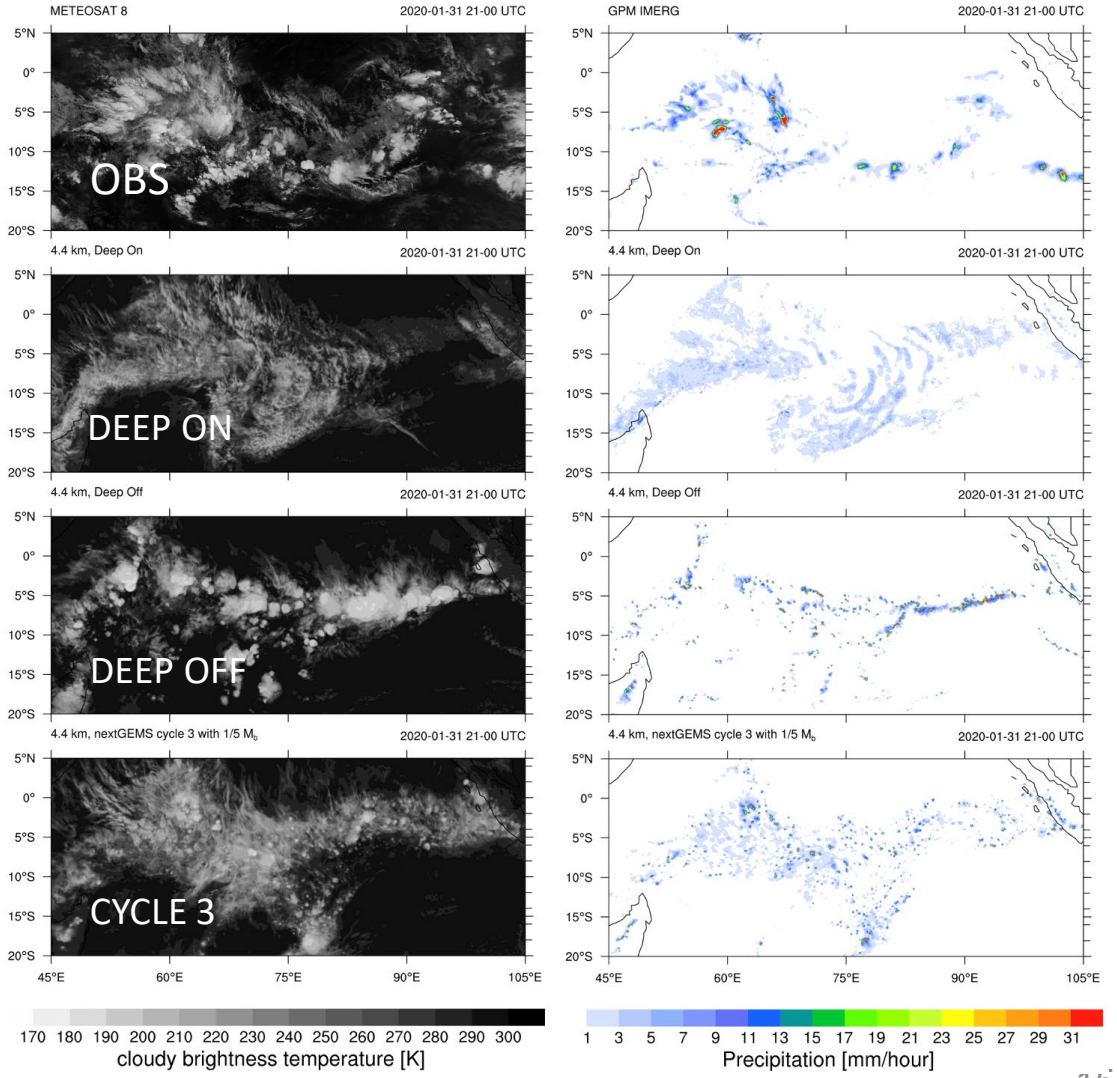
YES, first demonstration that simulating km-scale processes has a positive impact on the predictive skill in midlatitudes. However, it remains partly masked by bias.

Llorenç Lledò, Benoît Vannière

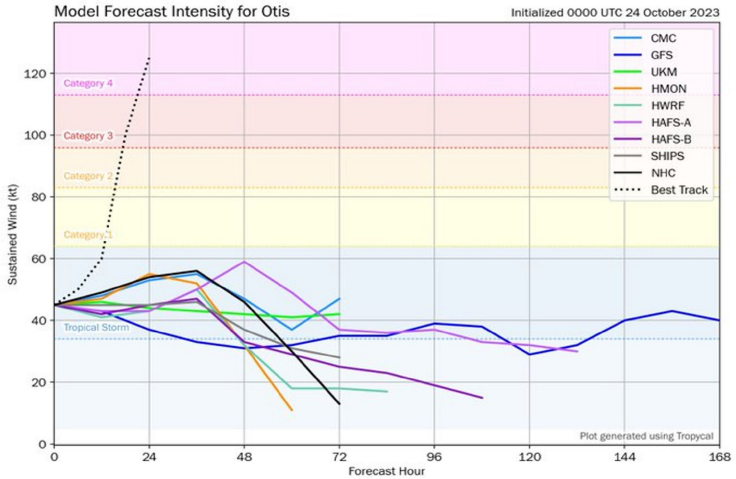
CAN WE TURN OFF THE PARAMETERIZATION OF DEEP CONVECTION?



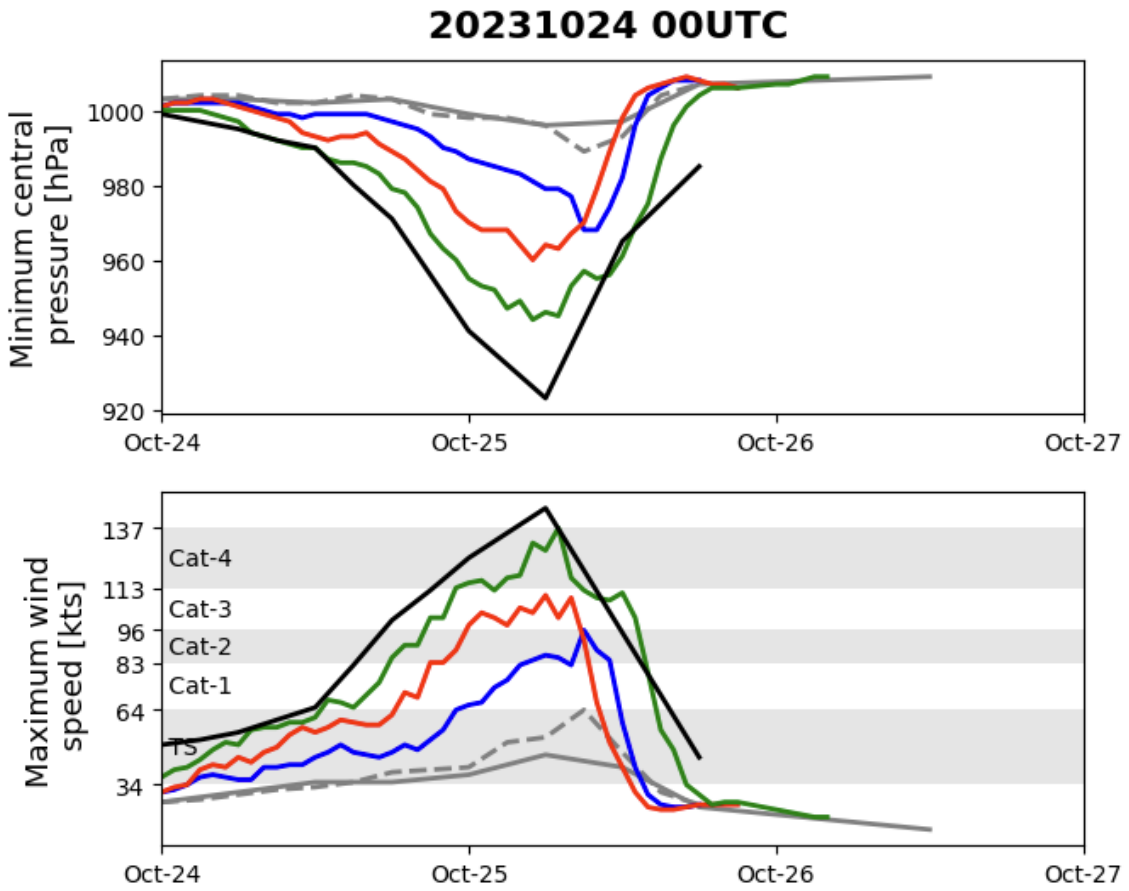
… **NO**, but a careful modification of the scheme is required which optimizes both NWP scores and physical realism



CASE OF TC OTIS



Combining successively extra observations, reduced parameterized convection and higher resolution 4D-Var dramatically increases the forecast skill of Otis.

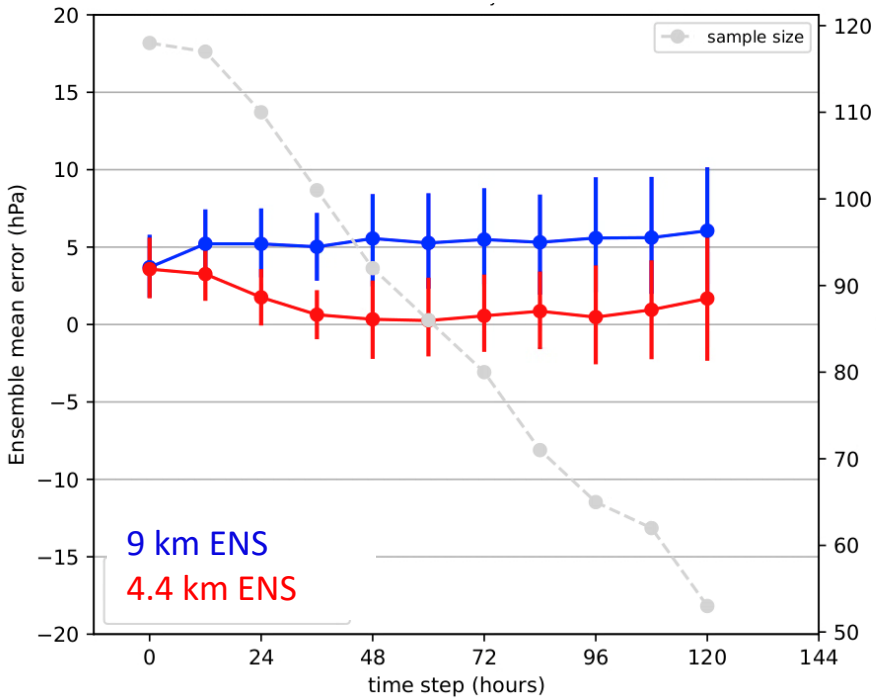


Ziga Zaplotnik, Michael Maier Gerber, Benoit Vanniere

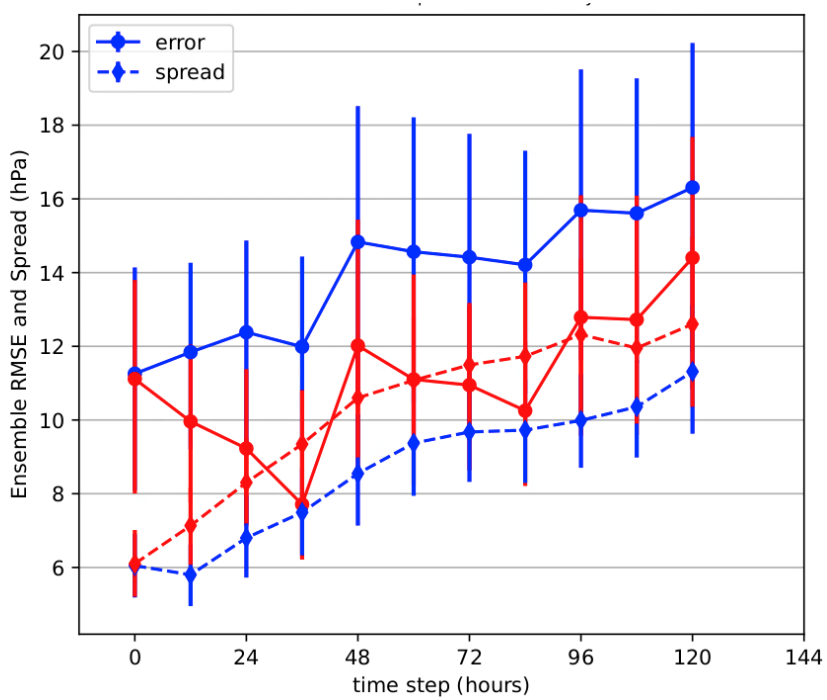
QUANTIFYING UNCERTAINTY

- ENS =10-member ensembles with SPP
- 30 initial dates
- Tropical cyclones minimum SLP

BIAS

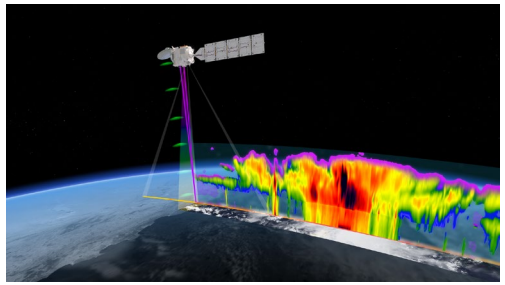


ERROR/SPREAD



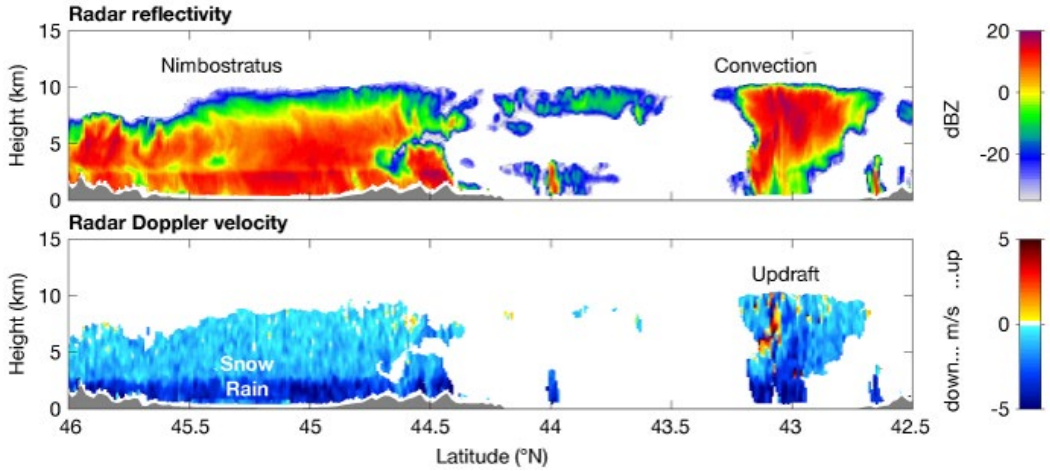
Aristofanis Tsiringakis

NEW INSIGHTS FROM EARTHCARE WILL BENEFIT KM-SCALE



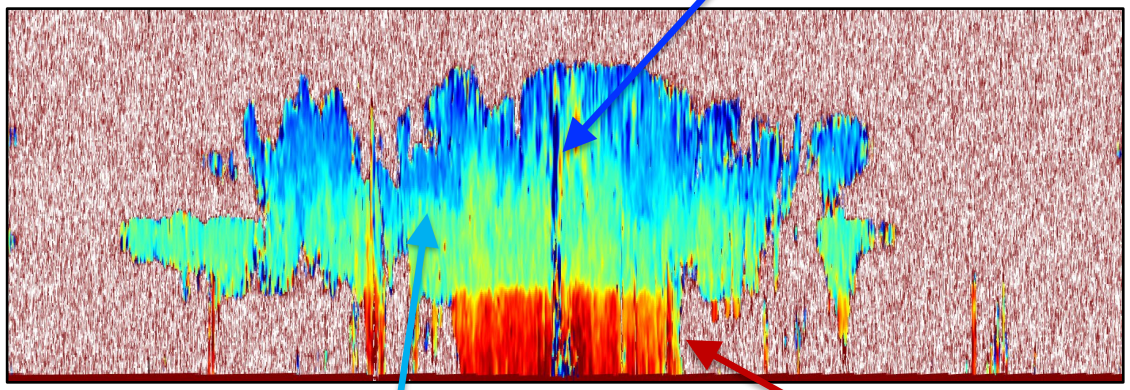
New EarthCare observations: Radar reflectivity and doppler velocity

- **Radar doppler velocity measures** rain and snow fall speed, aiding in drop size and rime fraction estimation
- Detailed insights on strength/width of convective updrafts



Air *rising* in storm core

GEM (NH model at 250 m resolution)

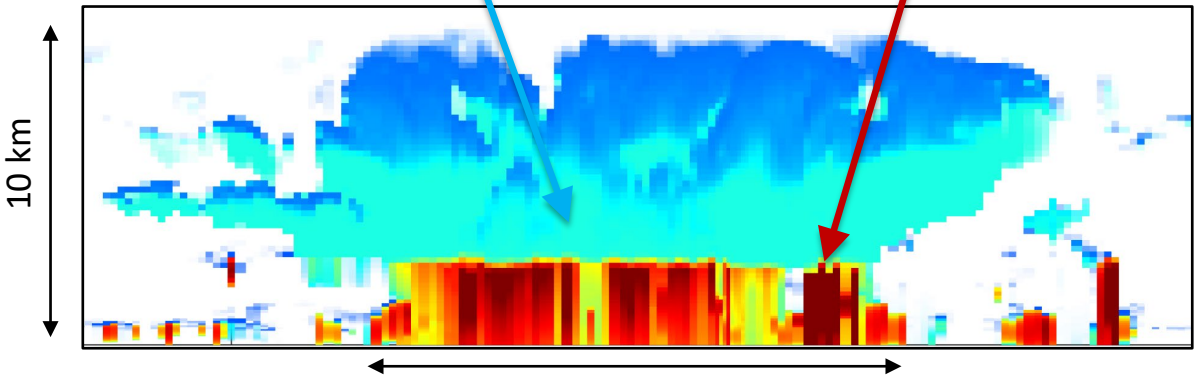


Snow

Better constraints on fall speeds

Rain

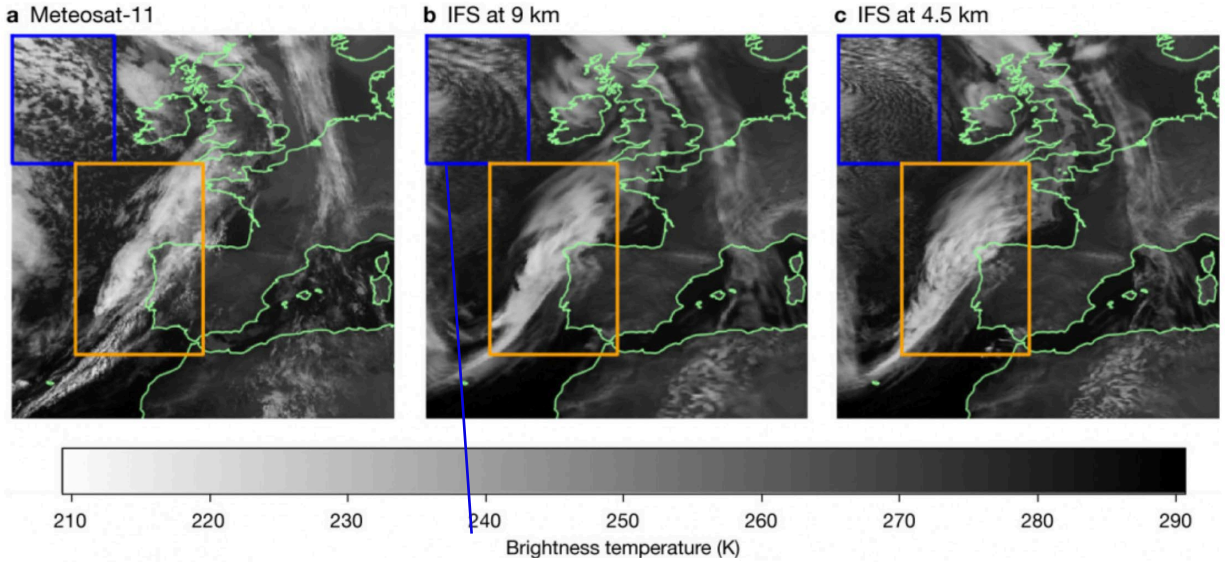
IFS (9 km resolution)

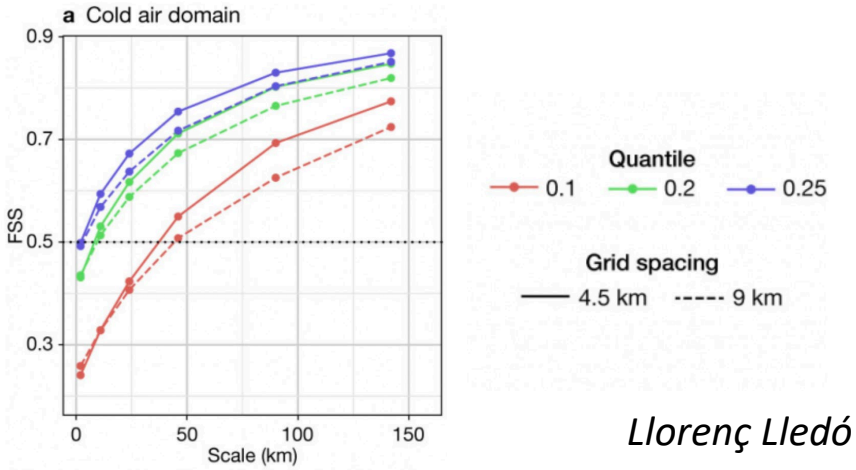


ECMWF *Mark Fielding, Robin Hogan*

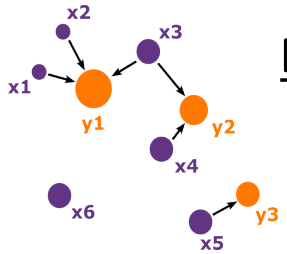
USING SPATIAL VERIFICATION METRICS FOR KM-SCALE PROCESSES

Fraction skill score

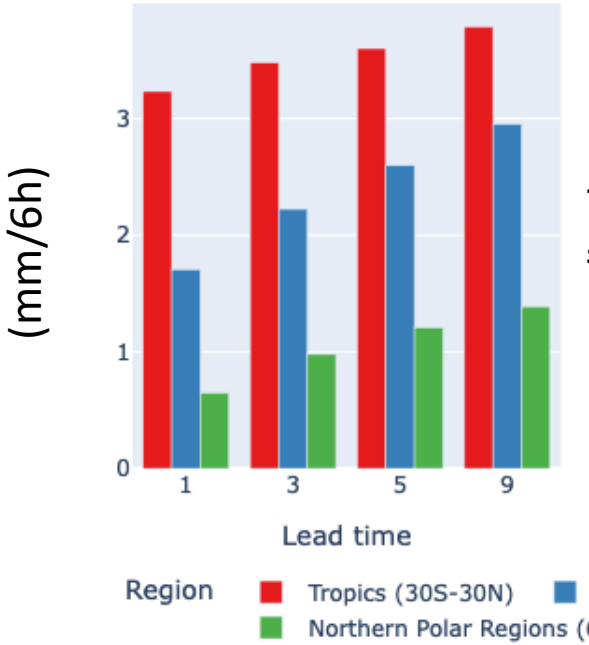




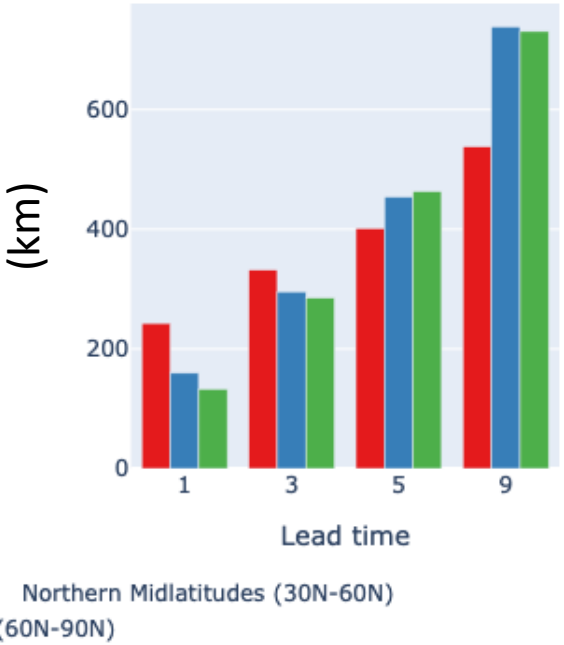
Error location metric



Root Mean Squared Error



Mean Location Error



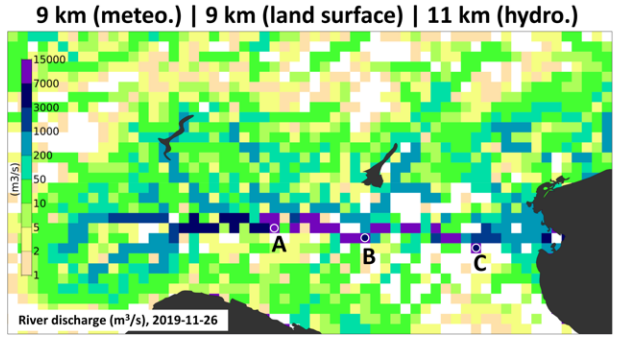
DATA

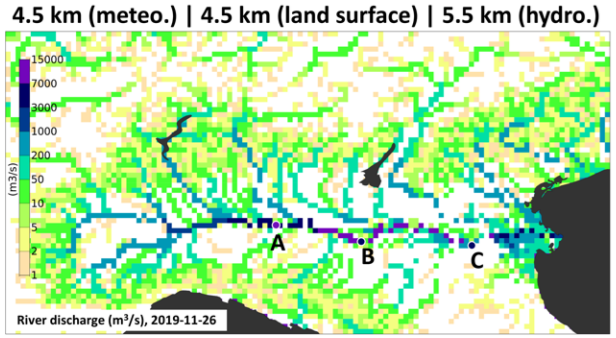
7 years of 9km operational forecasts, verified with analysis-proxy

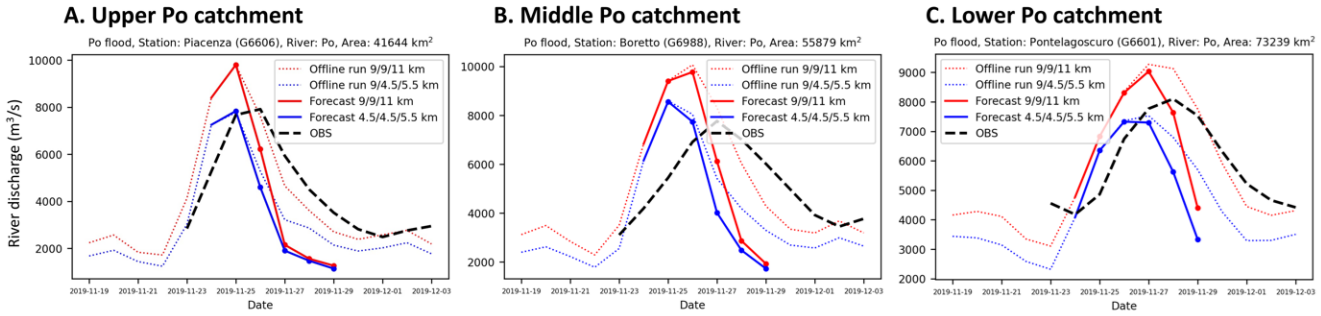
Llorenç Lledó

INTEGRATION OF IMPACT SECTOR MODELS IN THE KM-SCALE MODEL

CAMA-Flood



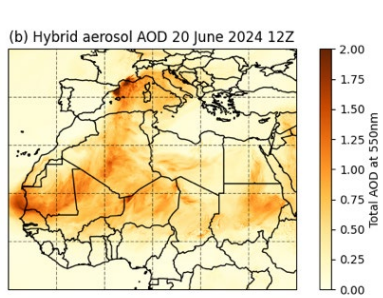


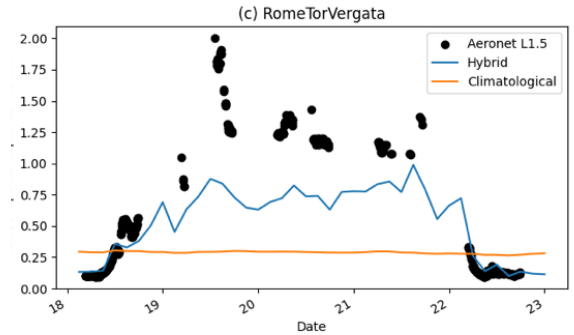


Improved representation of peak intensity of floods at km-scale

Flexible prognostic aerosols scheme

Prognostic dust aerosols, CAMS climatology otherwise, 2024 June 10 12Z





New feature to include custom combination of prognostic and climatological aerosols species in the radiation scheme

Jasper Denissen, Peter Hill, Ramiro Checa-Garcia

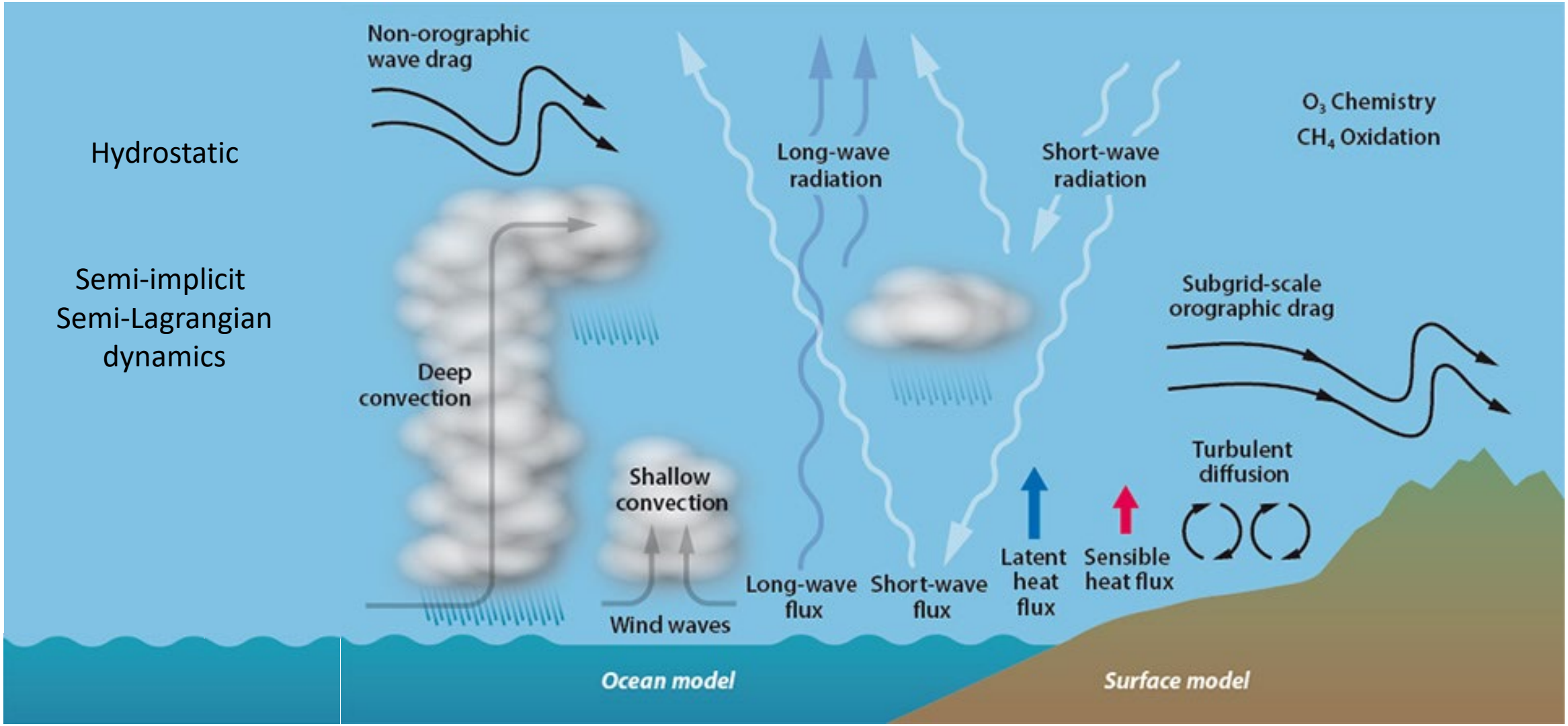
KM-SCALE MODELLING AT ECMWF

- Clear improvement of the km-scale to simulate several types of extreme weather
- DestinE operationalizes km-scale IFS simulations for weather prediction and climate projections by leveraging EuroHPC supercomputers
- Delivers better information to application sectors and improves boundary conditions for ACCORD models
- Adapting moist physics for km-scale remains challenging but developments to the representation of convection, turbulence and microphysics, and new observations of cloud and precipitation from EarthCARE provides a good way forward
- Km-scale models present a major opportunity for training AI-based NWP, and improve their representation of meso-scale and extreme weather prediction

NEXT STEPS IN KM-SCALE MODELLING AT ECMWF

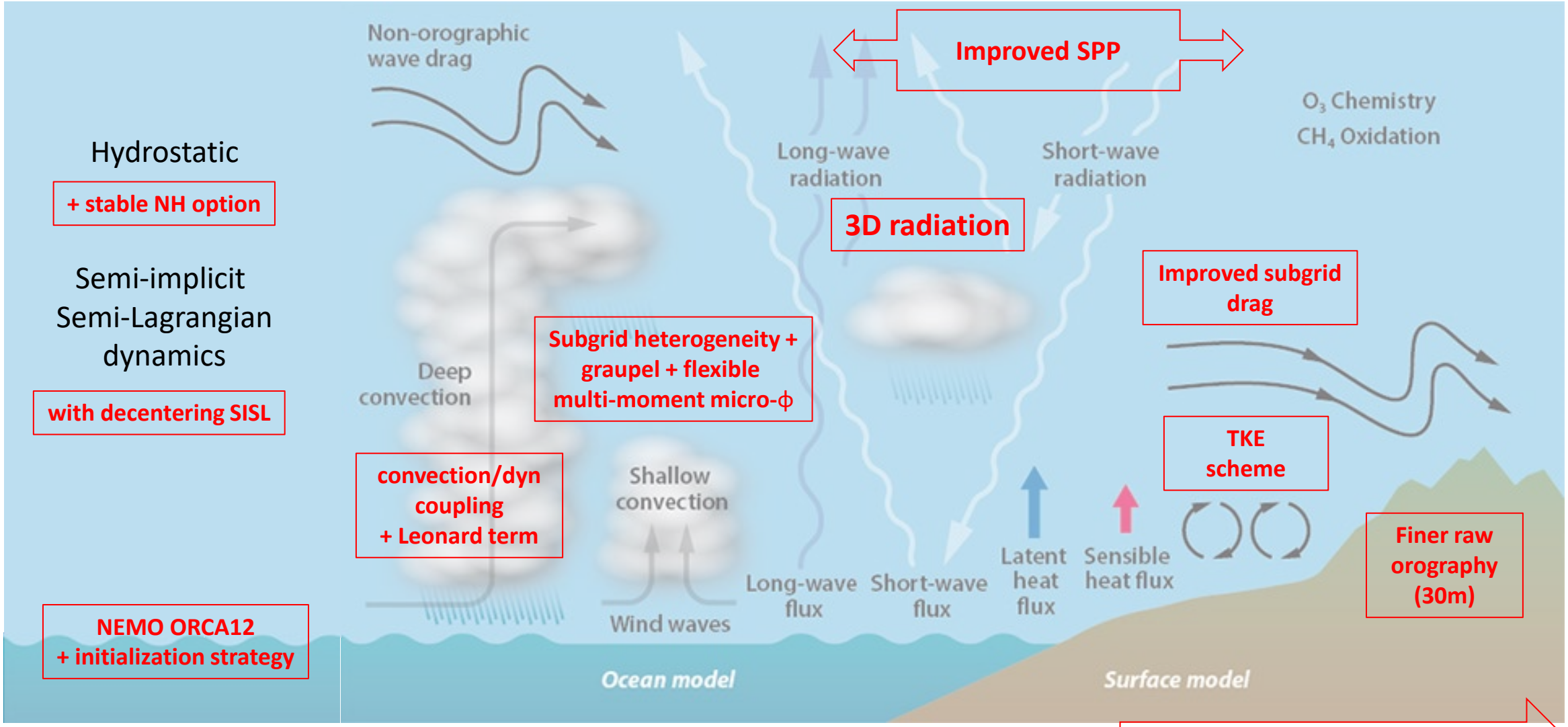
Hydrostatic

Semi-implicit
Semi-Lagrangian
dynamics



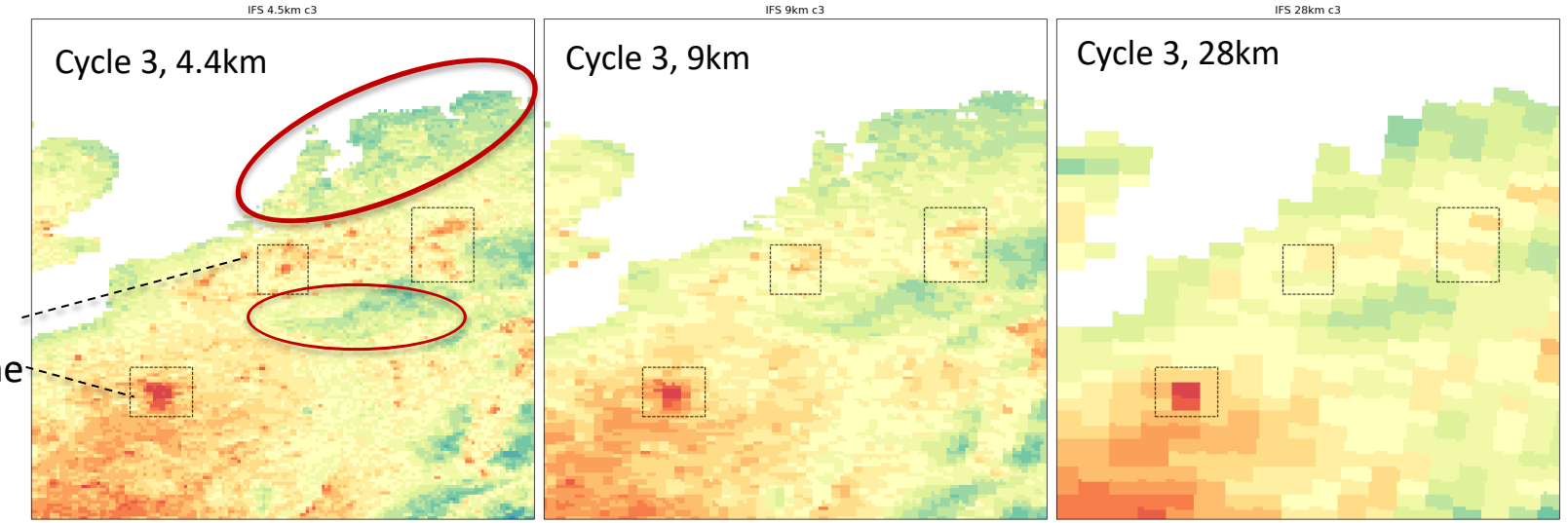
ECMWF

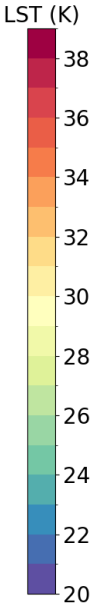
NEXT STEPS IN KM-SCALE MODELLING AT ECMWF



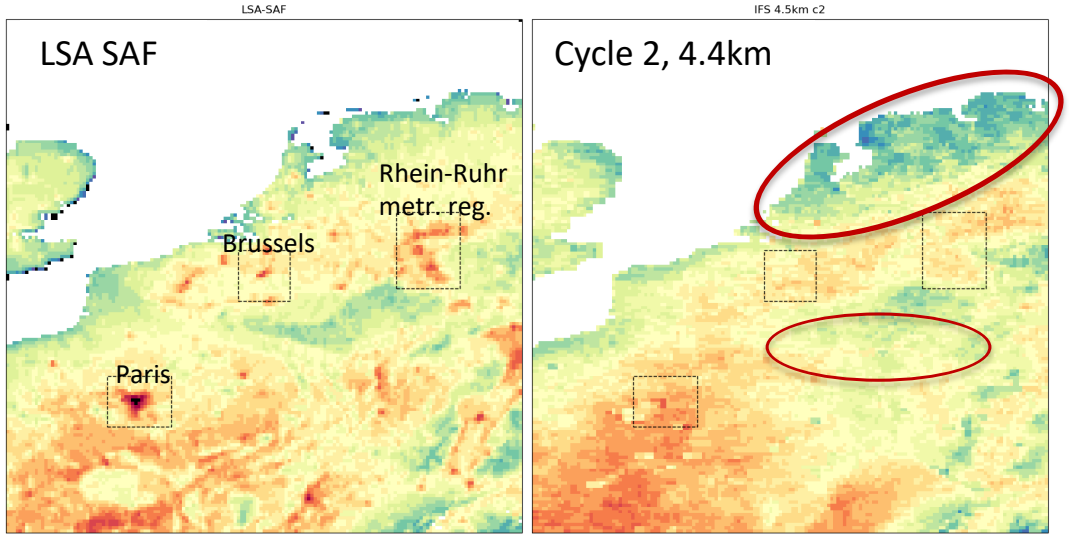
ECMWF

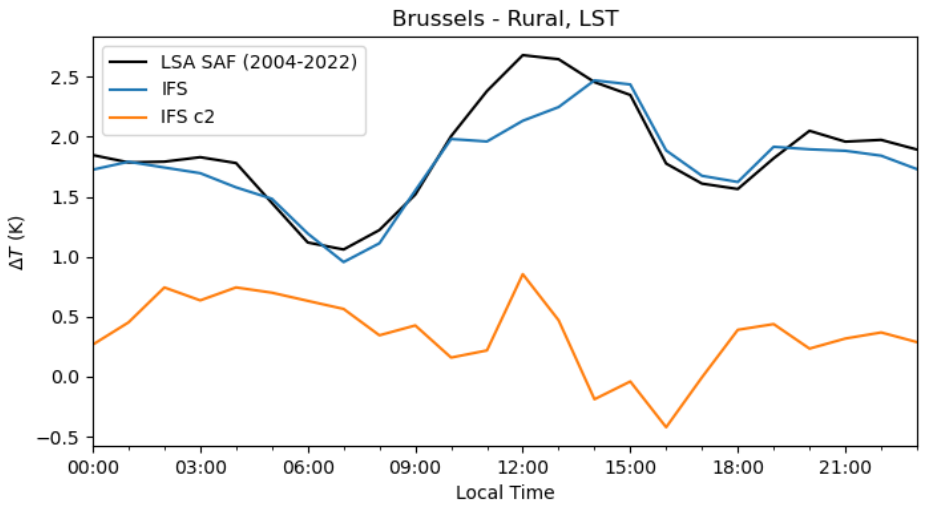
IMPACT OF CITIES AT THE LOCAL SCALE





New LU/LC + urban scheme shows urban imprints





next GEMS

X. Pedruzo-Bagazgoitia

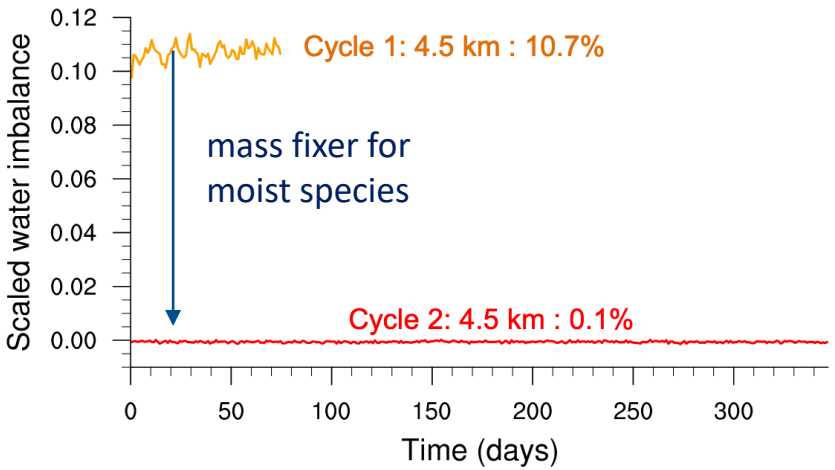
*JJA, clear sky,
5 year simulations at 14 UTC

TUNING A GLOBAL KM-SCALE CLIMATE MODEL

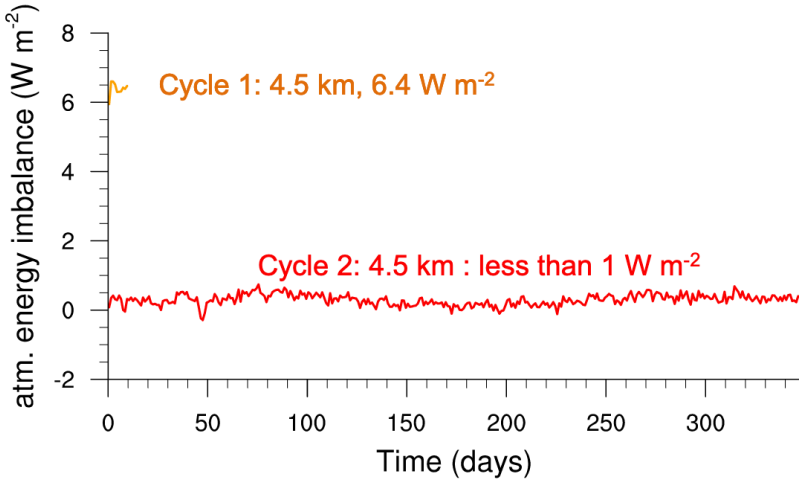
Biases identified during nextGEMS Hackathon in climate simulations…

… improve scores of ENS forecasts and extreme DTs

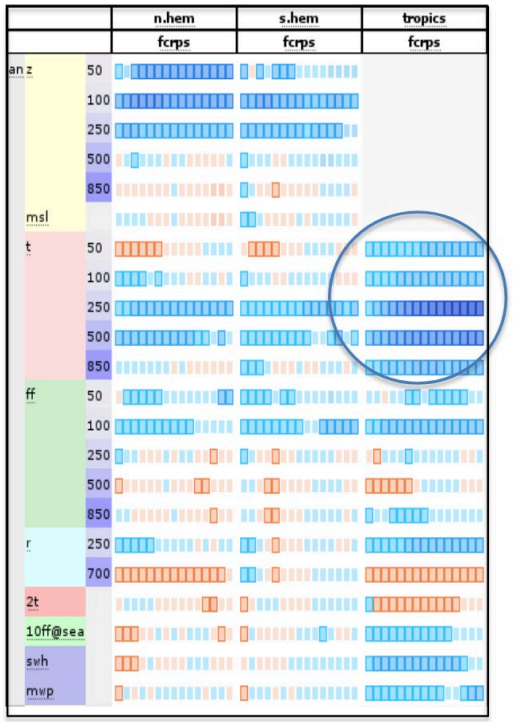
Water budget



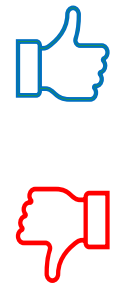
Energy budget



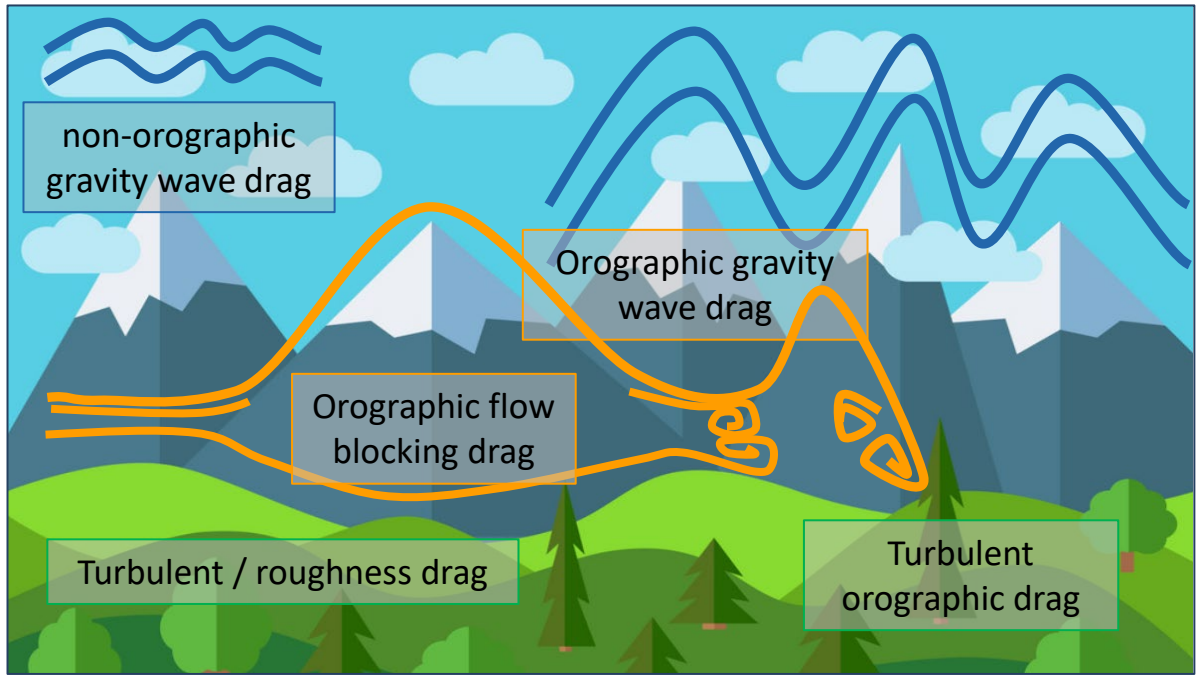
9km ENS

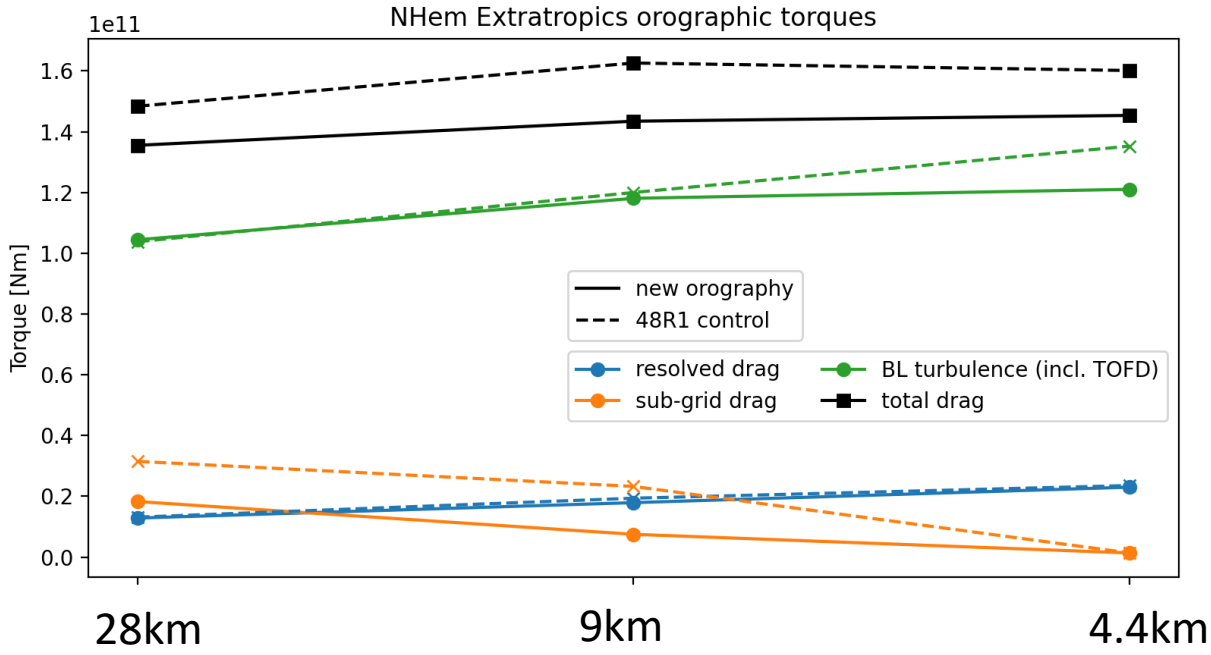


8-member d(fCRPS)



SUB-GRID OROGRAPHIC PROCESSES STILL IMPORTANT AT HIGH RESOLUTION



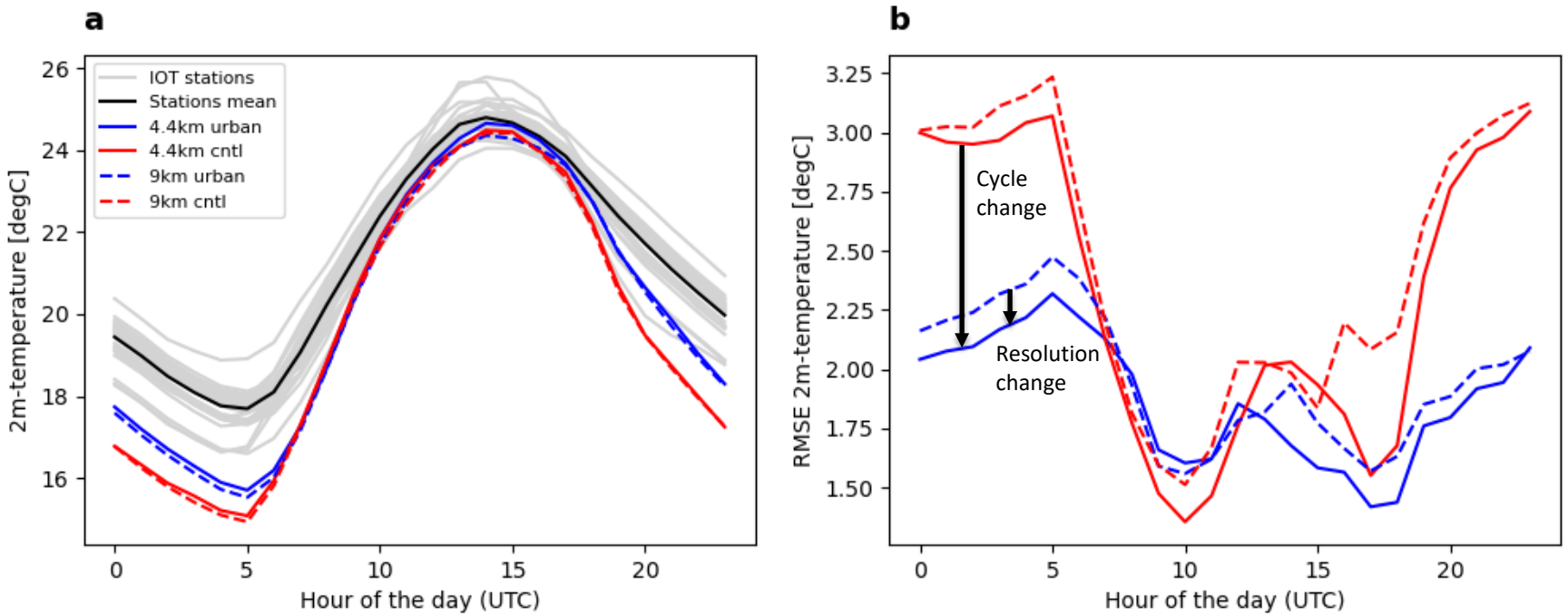


Annelize Van Niekerk, Birgit Sützl

- Updated field processing so that subgrid drag evolves smoothly and consistently with resolution.
- Exploiting high-resolution data to build ancillary fields (Copernicus DEM at resolution 30m)
- Bayesian optimization strategy for tuning subgrid drag

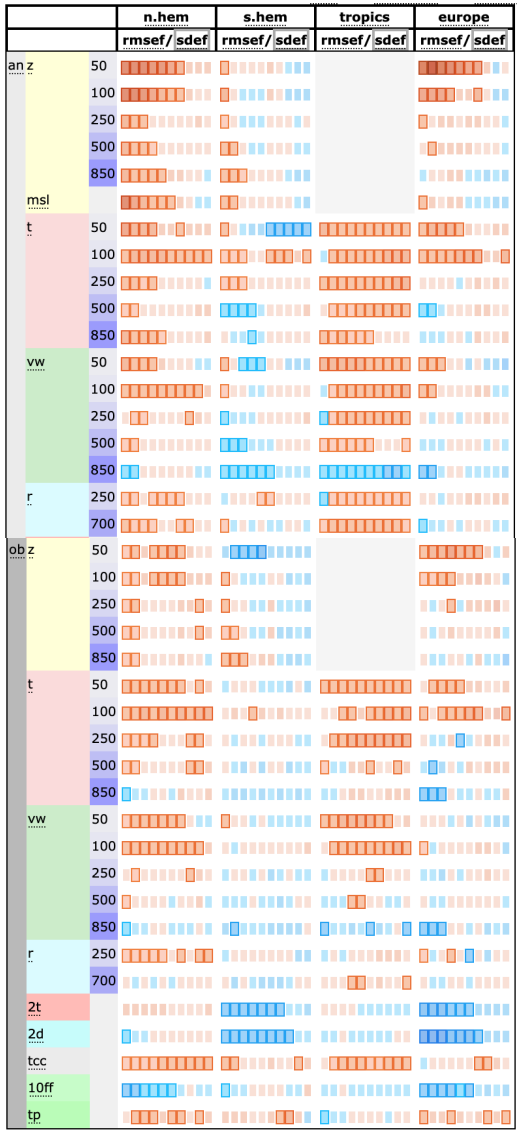
IMPACT OF CITIES AT THE LOCAL SCALE

Paris RDP project evaluating Paris t2m against 30 IOT stations

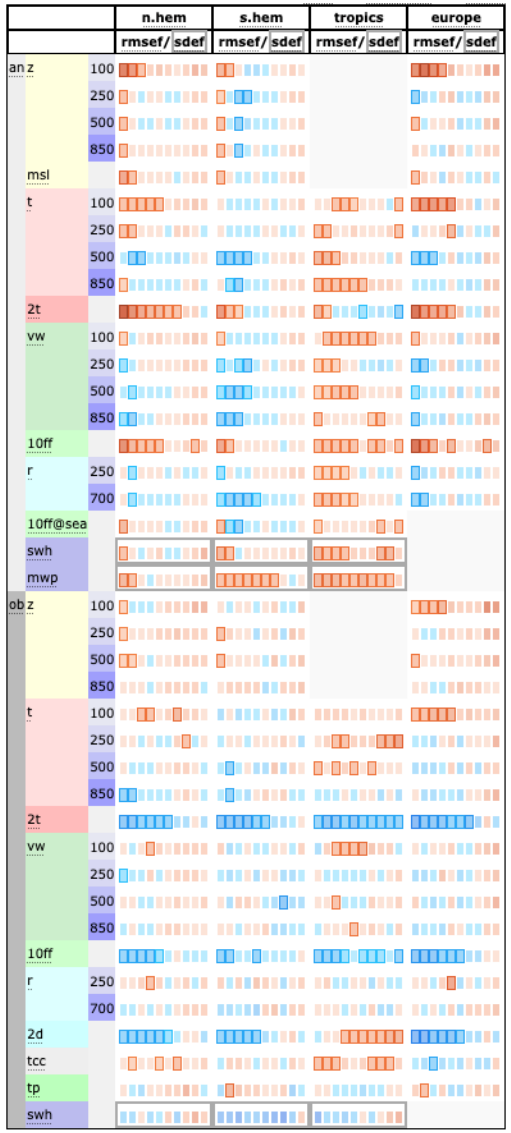


HIGH-RESOLUTION DATA ASSIMILATION

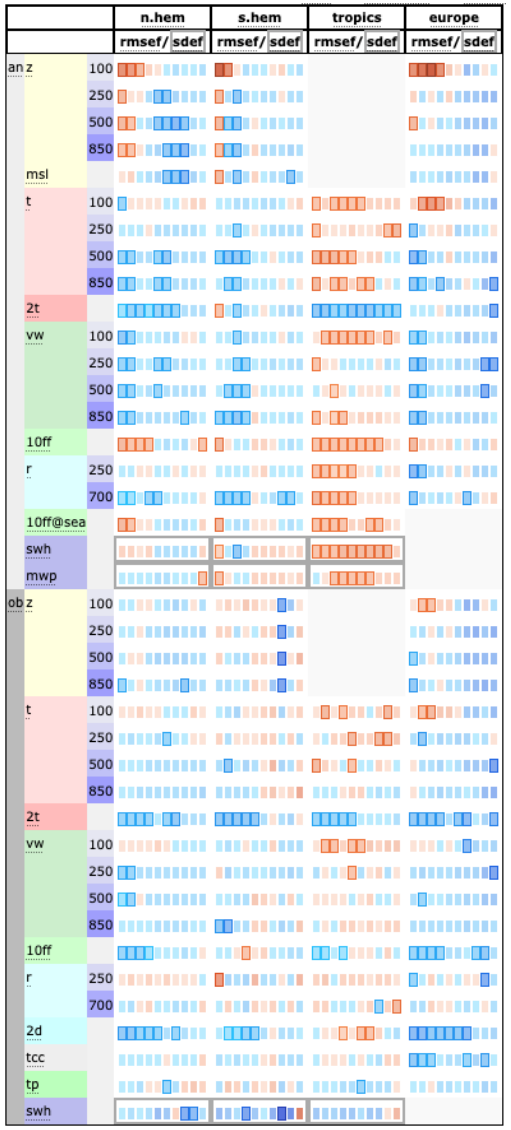
FC 4km vs 9km (old)



FC 4km vs 9km (new)



AN+FC 4km vs 9km

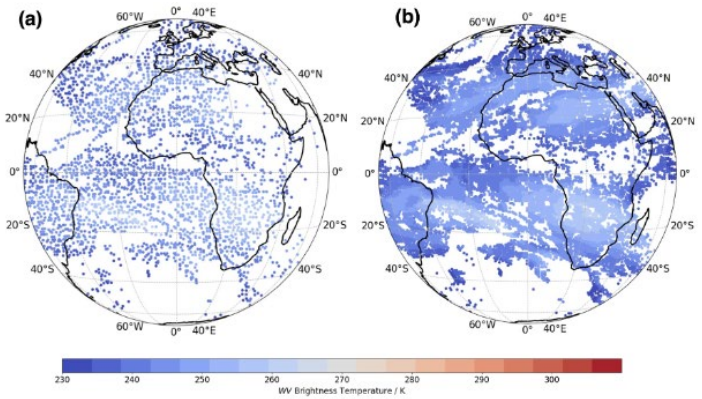


Setup of the high-resolution DestinE analyses:

- TCo2559 (4.4 km) trajectory using latest 49r1 DestinE forecast (new orog, time-step)
- Increased resolution of minimisation (TL319/TL399/TCo399/TCo511)
- Observation time-slots reduced from 1800s to 400s
- High-resolution geostationary satellite data :

125 km thinning

75 km thinning



Z. Zaplotnik, J. Schröttle, E. Orlandi and J. Bandeiras

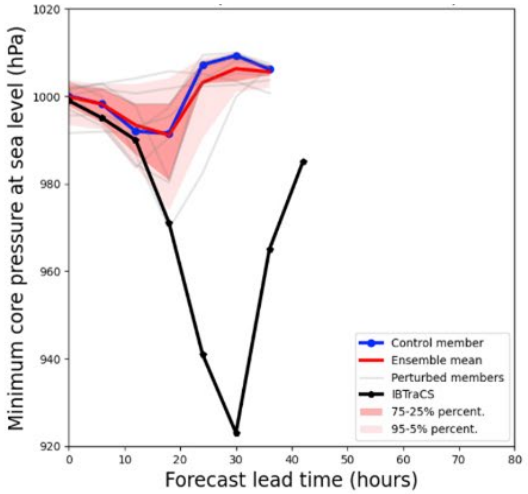
QUANTIFYING UNCERTAINTY

Evaluating 4.4 vs 9 km
10-member ensembles with SPP + additional physics changes

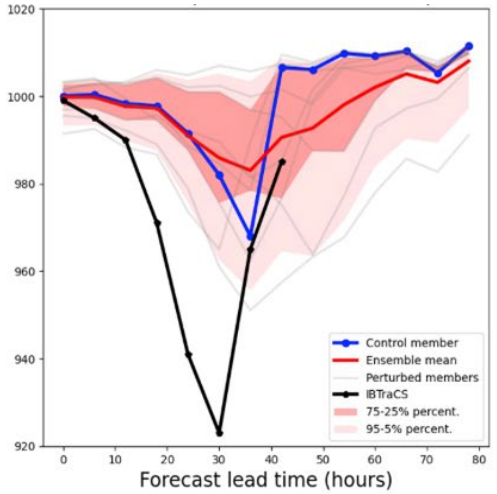
Tropical Cyclone Otis
(24-25 Oct 2023)

30 initial dates

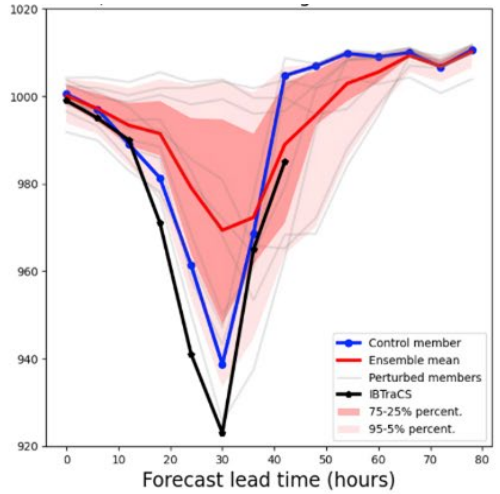
9 km fc



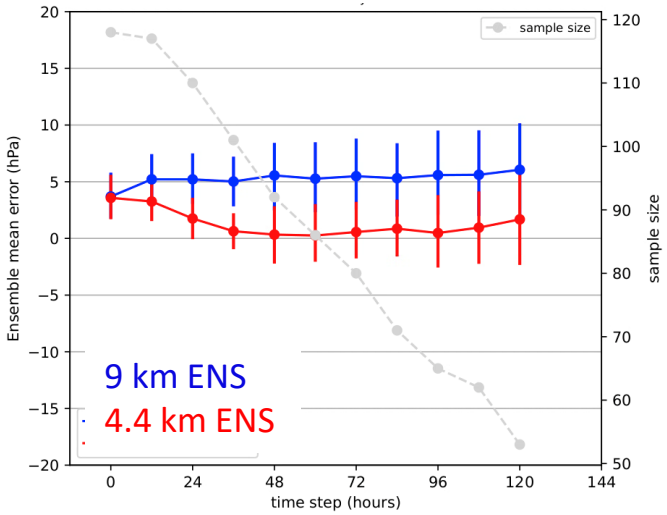
4 km fc



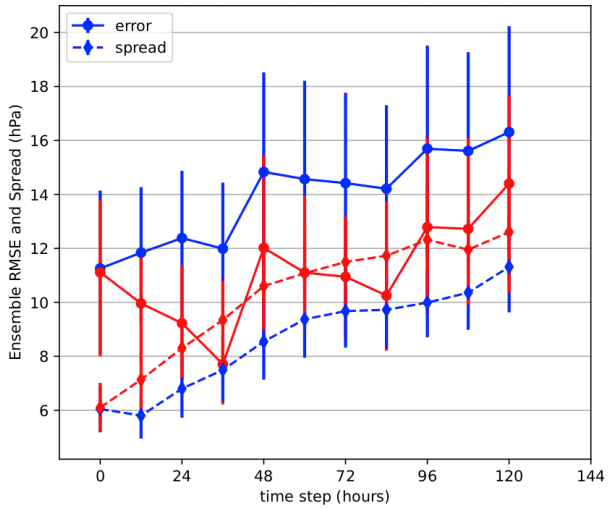
4 km fc
(h-res DA + RCBMF)



BIAS



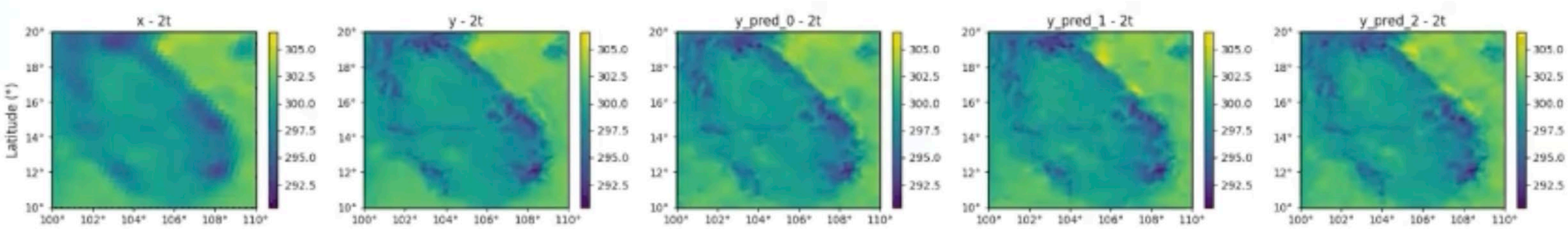
ERROR/SPREAD



Aristofanis Tsiringakis
ECMWF

Representing uncertainties at kilometre scale resolutions

- Funded by **Destination Earth**, work is on-going to test and further develop uncertainty representations at high resolution ($\Delta x \leq 4.4$ km)
- Lack of affordability to run large IFS ensemble at km-scale in the next five to ten years
- Alternative approach: Use ML to learn probabilistic downscaling and assess realism via comparison with IFS km-scale simulations



Input
36 km resol.
subseasonal
hindcast

Target
9 km resol.
medium-range
hindcast

ML Predictions 1, 2, 3
9 km resolution, diffusion approach
using input on the left + noise
zoom on SE Asia, date in 2022 (validation)