Physics-Dynamics aspects of the AROME model and its coupling with ocean model NEMO and wave model WW3

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LACy/Tropical Cyclones

AROME = ALADIN-NH DYNcore + Cloud Resolving Physics from research model MésoNH (anelastic, FV, explicit)

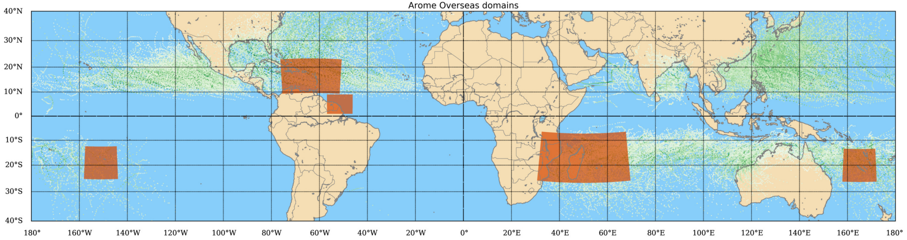
- Physics-Dynamics Coupling in AROME
- Ocean-Wave-Atmosphere Coupling (NEMO-WW3-AROME)

What about the weather in La Réunion ?

- Météo-France in La Réunion has been formally designated as Regional Specialized Meteorological Centre (RSMC) - Tropical Cyclones for the South-West Indian Ocean by the World Meteorological Organization (WMO) in 1993
- ⇒ Research in NWP applied to tropical cyclones
- ⇒ "Laboratoire de l'Atmosphère et des Cyclones" (LACy) is a joined lab between La Réunion University, Centre National de Recherche Scientifique (CNRS) and Météo-France.

AROME OverSeas (G. Faure, O. Nuissier, GMAP)

5 domains over French tropical overseas territories



- in operation from 2016,
- dynamical adaptation from HRES IFS, LBC every hour, +42h (+78h if needed), 4 times a day,
- 2.5 km hor. resolution, 90 levels, 60s time step
- **Ocean Mixed Layer Parametrisation, IC from Mercator-Ocean.**

PDC in AROME

PDC in AROME

From ALADIN to AROME (2003-2008)

from parametrised convection to explicit Convection in a LAM NWP Model

- High enough horizontal resolution (3 km to 500 m)
- Cloud Resolving Model Physics package : one moment microphysics scheme, TKE scheme + surface package, shallow convection scheme, radiation scheme ⇒MésoNH
- LAM, NH, fast, stable with long time steps, and robust DynCore ⇒ Aladin-NH
- Lego specialists to assemble the bricks (J.-F. Geleyn, Y.Seity, S.Malardel)

PDC : a very sensitive subject

- where to call the physics in a time step : divorce between ECMWF and MF...
- Fluxes or tendencies from Physics : civil war in MF and in the ALADIN Consortium
- C_{p_h} inside or outside the time derivative in enthalpy equation : we are still discussing the question....

PDC : theoretical analysis, recognized topic as such

Bibliography

Termonia P. and Hamdi R., 2007. Stability and accuracy of the physics – dynamics coupling in spectral models. Q. J. R. Meteorol. Soc. 133 :1589–1604.

Staniforth A., Wood N., Côté J., 2002a. Analysis of the numericsof physics–dynamics coupling. Q. J. R. Meteorol. Soc. 128 :2779–2799.

Wedi N. P., 1999. 'The numerical coupling of the physical parametrizations to the 'dynamical' equations in a forecast model'.Tech. Memo. 274, ECMWF.

PDC14, 16, 18, 21...

A series of regular workshops about PDC

DCMIP12, 16

Intercomparison exercices including academic test cases with physics

PDC : prognostic cloud condensates and precipitation

- In 2003 (still the case in the IFS in 2009), there was no prognostic "condensates" in IFS-ARPEGE-ALADIN.
- In Arpege and some Aladin configurations, q_v was still a spectral variable.
- CRM physics : new prognostic "water" variables : cloud droplets, cloud ice crystals, rain, snow and graupel (+ TKE)$\Rightarrow$ grid point variables.
- Lucky us : new data structure for state variables was coming from ECMWF (GFL and its attributes)

PDC : multiphase formulation of DynCore ⇒ prognostic condensates

moist air parcels = dry air + water vapour

$$p = p_d + p_v = \rho_h R_d T_v = \rho_h R_h T$$

with

$$\rho_h = \rho_d + \rho_v, \;\; R_h = (1 - q_v) R_d + q_v R_v$$

multiphasic air parcels = dry air + water vapour + condensates

$$p = p_d + p_v = \rho_m R_d T_v = \rho_m R_m T$$

with

$$\rho_m = \rho_d + \rho_v + \sum_j \rho_j, \;\; R_m = (1 - q_v - \sum_j q_j) R_d + q_v R_v$$

PDC : multiphase formulation of DynCore

Water loading

$$\rho_m \vec{\gamma_m} = -\vec{\nabla} p + \rho_m \vec{g} + \text{Coriolis} + \text{Physics}$$

Thermal Inertia

$$C_{p_m} \frac{DT}{Dt} = \frac{R_m T}{p} \frac{Dp}{Dt} + \dot{Q} \quad \text{with}$$

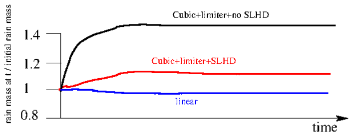
$$c_{p_m} = q_d c_{p_d} + q_v c_{p_v} + (q_c + q_r) c_l + (q_i + q_s + q_g) c_i$$

- impact of water loading significant from about 5km resolution
- in particular if the convection is explicit (condensates in parametrized convective clouds are not prognostic, except some detrained condensates at the top).
- R and c_p not always consistent between parametrisations and dynamics.

PDC : SL advection, diffusion, conservation of condensates

Getting the right amount of condensates is not only a question of cloud scheme or microphysics parametrization

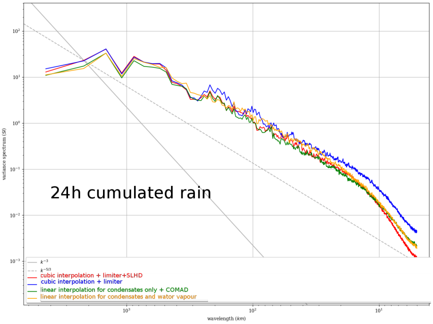
- SL advection : high order interpolation versus conservation $\rightarrow$ SL is not conservative, in particular if a min/max limiter is needed,
- IFS : linear SL interpolation, no extra diffusion,
- until now in AROME : cubic SL interpolations + limiter + Semi-Lagrangian Horizontal Diffusion (SLHD) to smooth the heavy rain (but unfortunatly also light convection) and compensate the gain of rain mass from SL scheme (Seity, 2020)

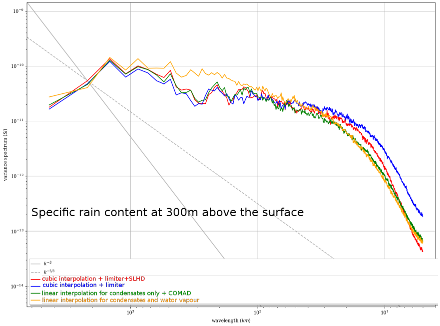


Evolution of the mass of rain in a simple test (Y. Seity)

PDC : SL advection, diffusion, conservation of condensates

for a better conservation and a better representation of light convection in AROME, from next cycle : linear interpolation + COntinuous Mapping about Departure points correction (COMAD), no need of SLHD





PDC : continuity and subgrid transport of water

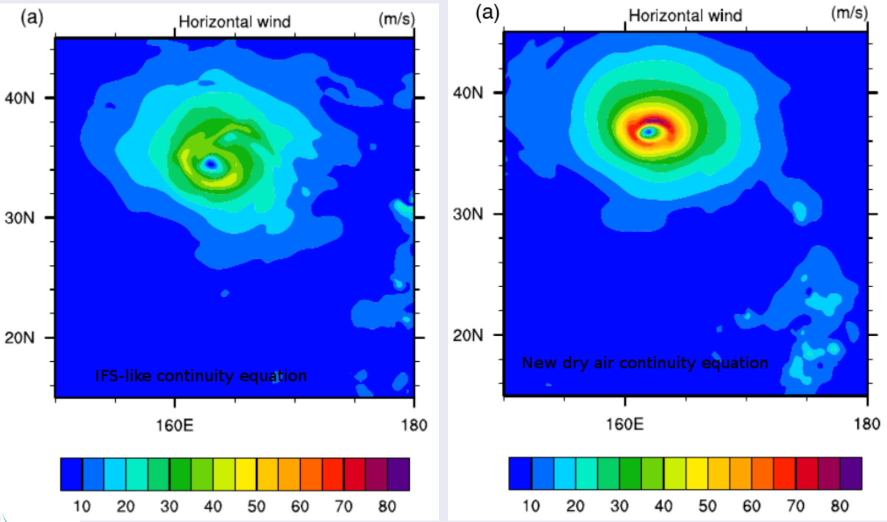
The continuity equation of IFS-ARPEGE-AROME formally conserves total mass instead of dry mass $\Rightarrow$ subgrid transport of water species and precipitation are conpensated by artificial transport of dry air in opposite direction which affect the composition of air parcels.

1. keep a continuity equation for the total mass but add source/sink of mass from physics (Malardel et al, 2019, ECMWF Tech. Memo.),
2. move to a continuity equation for dry air + dry hydrostatic pressure levels (Lautitzen et al, 2018, Peng et al, 2019, 2020)

In theory, both solutions are equivalent, but very different numerics.

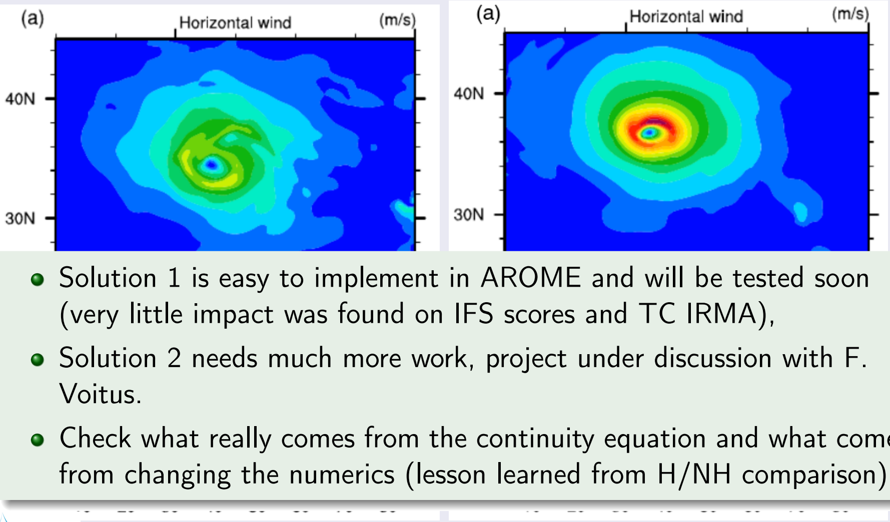
PDC : subgrid transport of water mass in parametrisation

Peng et al, 2020 : very large impact for DCMIP16 academic Tc



PDC : subgrid transport of water mass in parametrisation

Peng et al, 2020 : very large impact for DCMIP16 academic TC



- Solution 1 is easy to implement in AROME and will be tested soon (very little impact was found on IFS scores and TC IRMA),
- Solution 2 needs much more work, project under discussion with F. Voitus.
- Check what really comes from the continuity equation and what comes from changing the numerics (lesson learned from H/NH comparison).

PDC : Enthalpy versus Internal Energy equation

or : physics at constant pressure/c_p versus contant volume/c_v, NH physics

Thermodynamics equation

in IFS-ARPEGE-ALADIN (Hydro)

$$\frac{DT}{Dt} = \frac{1}{c_p}\frac{R_m T}{p}\frac{Dp}{Dt} + \frac{1}{c_p}\dot{Q} \qquad \frac{Dp}{Dt} = \omega \text{ is diagnosed.}$$

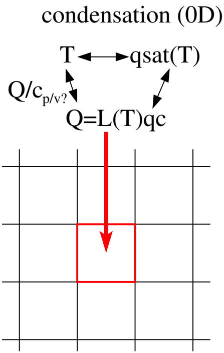
in AROME (and NH version of IFS-ARPEGE)

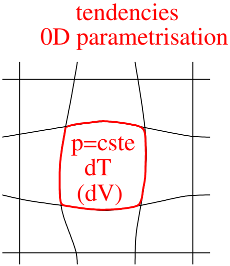
$$\frac{DT}{Dt} = -\frac{1}{c_v} R_m T\vec{\nabla}.\vec{u} + \frac{1}{c_p}\dot{Q} \qquad \frac{Dp}{Dt} = -\frac{c_p}{c_v} p\vec{\nabla}.\vec{u}$$

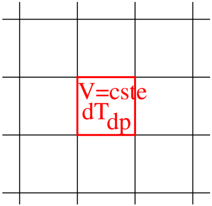
instead of

$$\frac{DT}{Dt} = -\frac{1}{c_v} R_m T\vec{\nabla}.\vec{u} + \frac{1}{c_v}\dot{Q} \qquad \frac{Dp}{Dt} = -\frac{c_p}{c_v} p\vec{\nabla}.\vec{u} + \frac{p}{c_v T}\dot{Q}$$

PDC : Enthalpy versus Internal Energy equation







- p=cste : only option in H model (p,V are strongly constrained by the H approximation)
- p=cste in NH model : implicit work of the internal pressure ; force already done ; guess to be adjusted by dyncore (advection, continuity, 3D solver) ;
- V=cste : work of internal pressure force explicitly computed in NH-Dyncore ;
- V=cste : makes sense if very small time step ;
- PDC and physics must be consistent.

PDC : Physics before or after Dynamics, parallel or sequential coupling

see Termonia and Hamdi, 2007 for a complete analysis

A-A-A : First order physics, parallel coupling

$$X_A^+ = X_D^o + \varphi_D^o + \mathcal{N}_M^{1/2} + \frac{1}{2}\,\mathcal{L}_D^o + \frac{1}{2}\,\mathcal{L}_A^+$$

IFS : Second order physics (SLAVEPP), sequential coupling

$$\begin{aligned} X_A^+ &= X_D^o + \mathcal{N}_M^{1/2} + \frac{1}{2}\,\mathcal{L}_D^o + \frac{1}{2}\,\mathcal{L}_A^o \\ &\quad \frac{1}{2}\,(\varphi_D^{\tilde{o}} + \frac{1}{2}\,\varphi_A^{\tilde{+}})_{rad,conv,cld} + (\varphi_A^{\tilde{+}})_{vdiff,cond} \\ &\quad -\frac{1}{2}\,\mathcal{L}_A^o + \frac{1}{2}\,\mathcal{L}_A^+ \end{aligned}$$

PDC : Physics before or after Dynamics, parallel or sequential coupling

Termonia and Hamdi, 2007 using the simple framework of Staniforth, Wood and Coté, 2002 :

- Important to have consistency between time and "parcel" position for physics contribution ($t^o \leftrightarrow D$, $t^+ \leftrightarrow A$)
- AAA : easier to maintain when several physics package for different applications, compute physics with a "clean" state,
- IFS-SLAVEPP : higher order, stronger PDC.
- SLAVEPP unstable for vert. diffusion scheme, but still IFS solution more accurate if VDIFF last in sequence of call (sequential call in physics too).
- Something to try in AROME; never too late, a lot of technical work...

A cubic grid for AROME ?

cubic : $\Delta x = 2.5$ km $\leftrightarrow \lambda_{min} = 10$ km – TEI=0.85

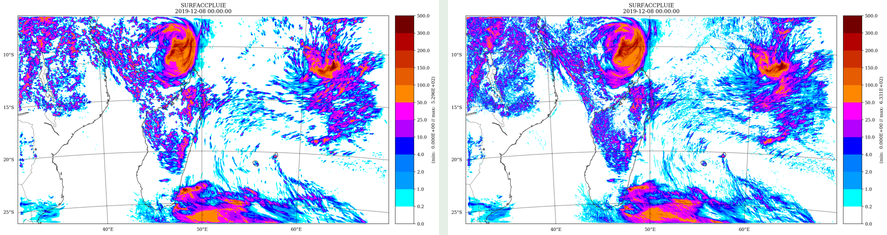
linear : $\Delta x = 2.5$ km $\leftrightarrow \lambda_{min} = 5$ km – TEI=1

$\Rightarrow$ cubic : $\Delta x = 1.25$ km $\leftrightarrow \lambda_{min} = 5$ km – TEI=3.5

$\Rightarrow$ linear : $\Delta x = 1.25$ km $\leftrightarrow \lambda_{min} = 2.5$ km TEI=4.3

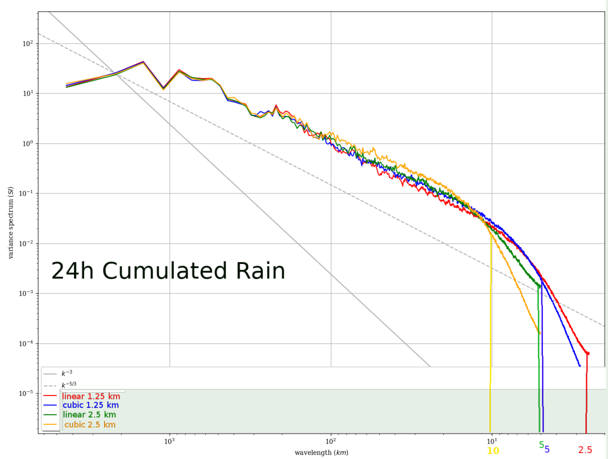
(test with same time step for all = 1 min)

24h cumul. precip.

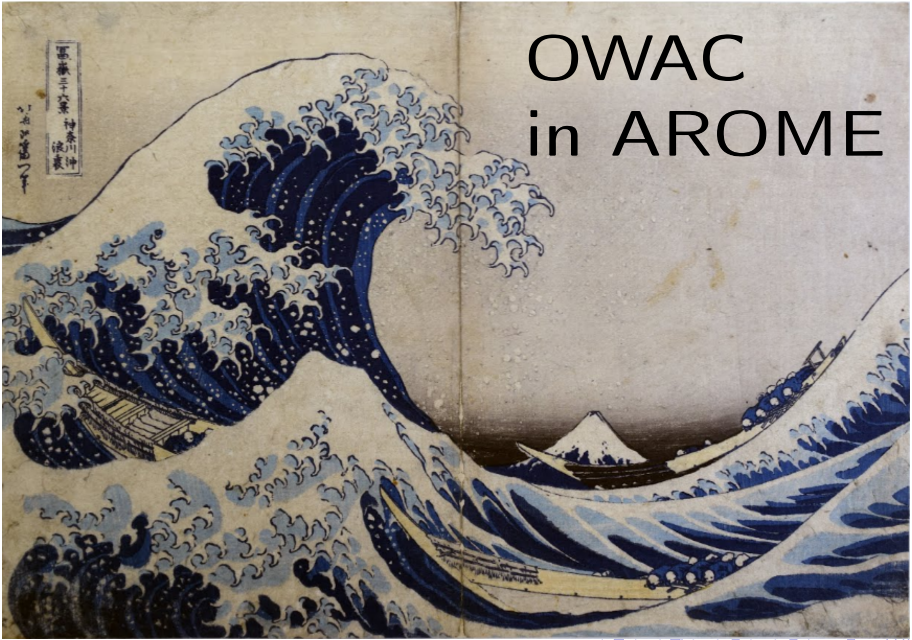


PDC : What grid for the physics ? What time step ?

24h cumul. precip. spectra

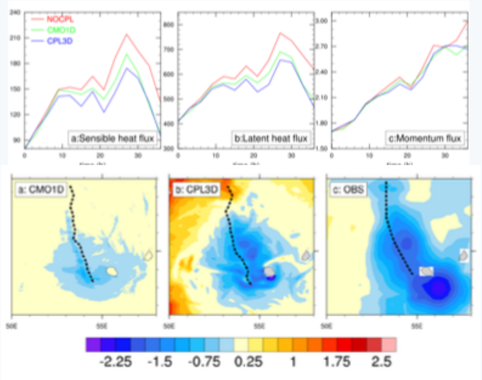


OWAC in AROME



OWA coupling using OASIS and SURFEX at LACy

Example: MésoNH-NEMO (Bielli et al, 2020)



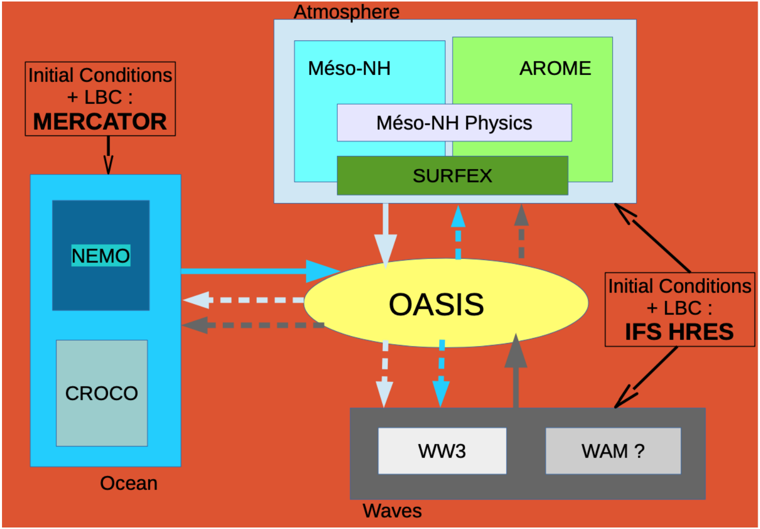
3 different simulations of Cyclone Bejisa (2014) : no coupling, 1D couling, 3D coupling

Surface fluxes

SST change between 01/01/2014 06UTC and 02/02/2014 12UTC

See also Pianezze et al, 2018 (MesoNH-CROCO)

OWA coupling using OASIS and SURFEX at LACy



OWA coupling using OASIS and SURFEX at LACy

AROME-WW3-NEMO

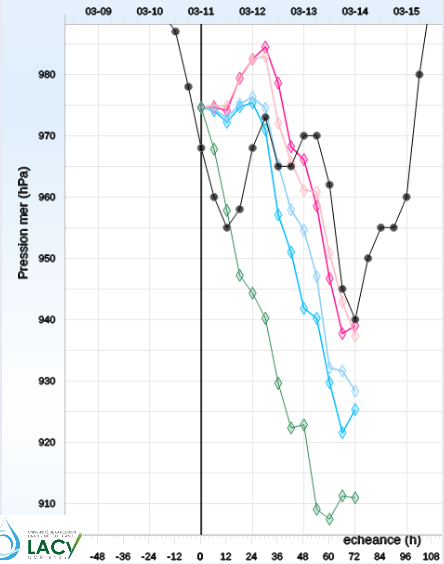
- AROME-OI : 2.5km
- NEMO : $1/12^o$
- Coupling with WW3, work in progress

IC and LBC for NEMO

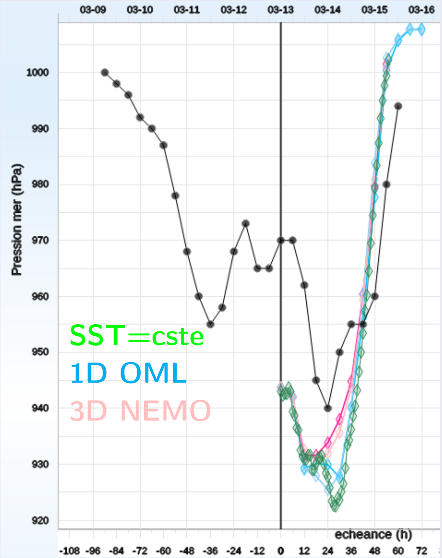
- $1/12^o$ Mercator-Ocean Analysis (Copernicus), available only on Wed.
- Updated oceanic state forced by HRES IFS available from Mercator-Ocean at 00-06-12-18 UTC every day (used as IC for OML),
- AROME-NEMO "warm-up" to cycle the Ocean from Wed. to any initial date of TC forecast.
- Not clear yet what IC and LBC will be for WW3 : directly from IFS ? Need a warm-up to build up a wave spectrum consistent with the AROME wind ?

Very first results of AROME-NEMO-OI for TCs - L. Corale

TC IDAI - 11032019 00UTC - 13032019 00UTC

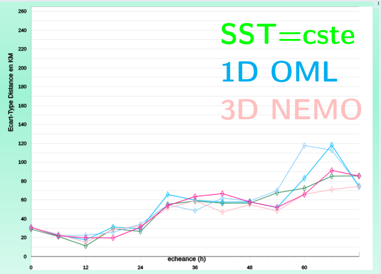


PDC and OWAC in AROME

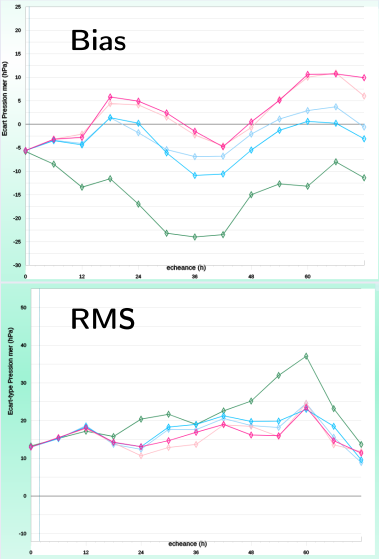


Very first results of AROME-NEMO-OI for TCs - L. Corale

Trajectory error (RMS)



Pmin error (Bias, RMS)



What's coming next for AROME-NEMO-WW3

- PhD of L. Corale : wave coupling (WW3) to improve surface flux at the interface in case of extrem winds (WASP).
- AROME-NEMO configuration avaible soon for the Hirlam-Aladin consortium (CY48t1), also used at Mercator-Ocean (J. Pianezze)
- Dynamical adaptation using HRES-IFS NEMO ocean state as IC and LBC (but only $1/4^o$, cycle the small scale ? availability of IFS-NEMO ocean fields ?)
- Ensemble-AROME-Overseas soon, including initial perturbation of the OML $\rightarrow$ coupled EP-AROME-overseas ?

Conclusion

AROME : coupling a Physics package used for very high resolution (LES) applications to a NWP "long time step" Dyncore,

IFS-FVM : coupling a DynCore package used for very high resolution (LES) application to a NWP "large scale" physics,

10-30 years from now ?

$\Longrightarrow$ IFS/AROME-FVM (+ NEMO, WAM) : FVM Dyncore+ MesoNH physics (3D turb., 2 moments microphysics, aerosols...) ?

- IFS-FVM : 1km hor. resolution global
- AROMEs-FVM : 100m hor. resolution