DESCRIPTION OF THE FORECASTING SYSTEM OPERATIONAL AT METEO-FRANCE IN JUNE 2023

Météo-France

1. Summary of highlights

New versions of NWP systems became operational on:

- 1st October 2019 (« CY43_op2.03 »): New satellite observations assimilated from IASI/Metop-C and CRIS/NOAA-20, new list of assimilated ground GPS stations.

- 15st January 2020 (« CY43_op3 »): Implementation of a snow analysis, assimilation of European radars (OPERA), new satellite observations assimilated (ScatSat1, AMSU-A & MHS/Metop-C, ATMS/NOAA-20, IASI/Metop-C) in AROME-France regional NWP system. New diagnostics for aeronautics (clear air turbulence and icing), assimilation of ASCAT/Metop-C, preparation of observation monitoring for AMV GOES17, NOAA-20, Metop-C, AEOLUS and GOES17 ABI radiances in ARPEGE global NWP system.

- 5th May 2020 (« CY43T2_op4 »): Assimilation of AMV GOES17 in ARPEGE, Variational bias correction on ground GNSS in production analysis, TAC2BUFR for RADOME-H data, use of AMDAR OMM in place of ACAR data, ADM-Aeolus monitoring, Bator modifications for Aeolus and TEMP data, Bugfix for GRIB2 headers.

- 9th June 2020 (« CY43T2_op4 »): Reassimilation of CRIS/S-NPP data, new template for Norwegian RS, assimilation of AFIRS and TAMDAR from FLHYT

- 30th June 2020 (« CY43T2_op6 »): Assimilation of new observations : ADM-Aeolus, GNSS-RO (KOMPSAT-5, PAZ, GNOS/FY-3D), DbNet IASI from METOP A/B, adaptation to new SEVIRI flux and other technical modifications
- 2nd February 2021 : Operational NWP suite on new HPC (BULL-AMD Rome)
- 29th June 2022 : New global physical package for ARPEGE: Tiedke-Bechtold convection scheme, radiation scheme, ocean-atmosphere fluxes, ice pack model. Snow cover analysis and revision of satellite obs selections under cloudy conditions. New radiances from GOES16 and FY3D and new scatterometers from HY2B and HY2C. New convection and aeronautical diagnostics. Change of semi-lagrangian interpolation for AROME. The same resolution is used for ARPEGE and PEARP (from 5 to 24 km) on the one hand, and for AROME-France and PEAROME (1.3 km) on the other. The 10 multi-physics of PEARP are replaced by a random choice of key parameters of the new ARPEGE physics and a supplementary convection scheme (PCMT). A more complete description is available in
- 1st February 2023 : 5 EPS-AROME over the same domains as AROME-OM with 1+15 members using a 2,5 km resolution and the hydrostatic approximation are coupled and spread around the IFA analysis with 15 selected perturbed members of PEARP.

2. Equipment in use at the Centre

- Information commutators on GTS are the TRANSMET computers (2 Dell PowerEdge6850, operating with Linux RHEL AS 4 and RDBMS Postgres).
- the management of the forecasting system (control of the data in input of NWP models, post processing, production of charts with the NWP output) is made on a Linux cluster running Oracle RDBMS, US-Navy originating NEONS meteorological data management system, and PV-WAVE graphical software. The file servers are doubled for backup.
- NWP operational models are running on a BULL SEQUANA XH2000 DLC (2307 nodes with 2 processors AMD Rome x86-64 bits of 64 cores). A similar configuration, dedicated to research is also used for backup.

- Dissemination of forecast and observation products (from GTS included), in particular to the French weather stations, is made through satellite communication (Eumetcast system).

3. Data and Products from GTS in use

Average number of messages by day for the global model **ARPEGE** :

AIRCRAFT	BATHY	BUOY	PILOT/ PROFILER	SHIP	SYNOP	TEMP/ TEMP-SHIP/ TEMP-DROP	GMI
1 640 000	**0**	**90 000**	**90 000**	**60 000**	**260 000**	**760 000**	**30 000**
LIDAR	ASCAT/ HSCAT	GEORAD	GEOWIND	SSMI/S	HIRS	ATMS	MWHS2
0	**260 000**	**1 110 000**	**590 000**	**234 000**	**0**	**1 600 000**	**150 000**
AMSU-A	AMSU-B+MHS	SAPHIR	AIRS	IASI	CRIS	GPS sol	GPS sat
1 400 000	**450 000**	**0**	**0**	**14 800 000**	**2 900 000**	**117 000**	**3 000 000**

Average number of messages by day for the limited area model over western Europe **AROME** :

AIRCRAFT	BATHY	BUOY	PILOT/ PROFILER	SHIP	SYNOP	TEMP/ TEMP-SHIP/ TEMP-DROP	GMI	RADAR Vr
120 000	**0**	**3 500**	**14 000**	**8 000**	**200 000**	**110 000**	**0**	**90 000**
LIDAR	ASCAT/ HSCAT	GEORAD	GEOWIND	SSMI/S	HIRS	ATMS	MWHS2	RADAR Hu
0	**2 300**	**56 000**	**1 100**	**1 100**	**0**	**4 600**	**0**	**460 000**
AMSU-A	AMSU-B+MHS	SAPHIR	AIRS	IASI	CRIS	GPS sol	GPS sat	
5 000	**1 500**	**0**	**0**	**42 000**	**0**	**25 000**	**5 000**	

4. Forecasting system

The operational forecast system at Météo-France is based on several configurations of one single code, ARPEGE/IFS. Although ARPEGE and IFS are both global models, limited area configurations have been developed within the same framework, that can be summarized by the code names AROME for a non-hydrostatic version with dedicated parameterizations.

The ARPEGE/IFS libraries have been developed jointly by Météo-France, ECMWF and several NMS gathered in the ACCORD consortium. ARPEGE is its usual name in Toulouse and IFS the one used in Reading:

IFS (Integrated Forecast System) is the ECMWF global model for medium range forecasts (4-15 days).

ARPEGE (Action de Recherche Petite Echelle Grande Echelle) is the Météo-France variable mesh global model run in Toulouse for short range predictions (1-4 days).

AROME (Application de la Recherche à l'Opérationnel à Mesoéchelle) combines a non-hydrostatic kernel and framework developed with the Aladin NWP consortium with physical parameterizations and surface representation developed by the French atmospheric research community within the Meso-NH project.

Météo-France belongs to the ACCORD consortium which integrates the national meteorological or hydro meteorological services of the following countries: Algeria, Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Hungary, Iceland, Ireland, Lithuania, Morocco, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Tunisia and Turkey. A large part of the cooperation is designed to share the improvements for the dynamical core and the physical packages used by AROME.

4.1 System run schedule and forecast ranges

The operational forecast system at Météo-France is based on ARPEGE, AROME using the following configurations :

ARPEGE, hydrostatic global system, provides lateral boundary conditions for the AROME forecast at the same analysis time as well as to several instances of AROME, performing only dynamical adaptation. One key feature of ARPEGE is its variable horizontal resolution. ARPEGE derives forecasts from a 4D-Var data assimilation with 6h windows for the assimilation cycle and shorter windows for the production cycle. An ensemble data assimilation of 50 members provides time and space varying first guess error statistics to the main 4D-Var assimilation.

ARPEGE is also used in ensemble mode, PEARP (Prévision d'Ensemble ARPEGE). This ensemble has 35 members, it is run 4 times a day : from the ARPEGE analyses up to 102h. PEARP also uses the geometric transform of ARPEGE, so that it is both a global ensemble prediction system specifically tuned for the short-range and a mesoscale one in the Europe-North Atlantic area.

AROME-France is run 8 times a day up to 48h. It has its own 3D-Var data assimilation cycle, with a 1-h period and time window.

AROME-NWC, which is the nowcasting version of AROME-France, allows to produce 6h forecast every hour at HH+30 min.

AROME-OM is run at 0 6 12 and 18 UTC up to 48h for 5 overseas different areas ; boundary and initial conditions are provided by ECMWF-IFS (atmosphere), ARPEGE (continental surfaces) and Mercator-Ocean PSY4 (ocean).

. Long cut-off ARPEGE analyses are performed after some shorter cut-off analyses. This is currently not done for AROME because the model is run later after nominal analyses times, so that most observations are available.

. at 00UTC, the ARPEGE analysis and forecast is run twice, in order to provide early products based on very short cutoff analyses. In order to run the 00UTC Arome forecast about 1h earlier than at other synoptic times, its boundary conditions are provided by this early Arpege run.

. the typical global product availability is :

initialised analyses (P0)	cut-off time+45'
forecasts	24h simulated every 10' wall-clock time

Furthermore, a number of limited area forecasts are performed using IFS-provided lateral boundary conditions. Namely, there are 5 AROME models which cover the 4 overseas areas: Caribbean and Guyana, La Réunion, New Caledonia and Polynesia. There is also the AROME-IFS model which performs a dynamical adaptation of IFS over Europe (same domain as AROME-FRANCE) four times a day.

All times are UTC in the table below.

UTC valid times	00.00		06.00	12.00	18.00
long cut-off	0800		1255	2005	0115
short cut-off	01.15	02.15	09.00	13.50	21.00
ARPEGE range (h)	54	102	102	114	102
end of ARPEGE	02.09	03.35	10.11	15.04	22.07
PEARP range		102	102	102	102
AROME range (h)	51		51	51	51
end of AROME	0235		1100	1550	2300
AROME-Indien	48		48	48	48
AROME-Antilles	48		48	48	48
AROME-Guyane	48		48	48	48
AROME-Caledonie	48		48	48	48
AROME-Polynesie	48		48	48	48
AROME-IFS	48		48	48	48
AROME-EPS					
AROME-EPS-Indien	48				48
AROME-EPS-Antilles		48		48	
AROME-EPS-Guyane		48		48	
AROME-EPS-Caledonie			48		48
AROME-EPS-Polynesie			48		48
AROME-NWC	Forecasts available at H + 30 mn every hour H				

UTC valid times	03.00	09.00	15.00	21.00
long cut-off				
short cut-off	04.04	11.36	17.18	23.36
ARPEGE range (h)				
end of ARPEGE				
PEARP range				
AROME range (h)	51	51	51	51
end of AROME	05.35	13.04	18.45	01.03
AROME-Indien				
AROME-Antilles				
AROME-Guyane				
AROME-Caledonie				
AROME-Polynesie				
AROME-IFS				
AROME-EPS	51	51	51	51
AROME-EPS-Indien				
AROME-EPS-Antilles				
AROME-EPS-				

Guyane AROME-EPS-Caledonie AROME-EPS-Polynesie					
AROME-NWC	Forecasts available at H + 30 mn every hour H				

4.2 Medium range forecasting system (4-10 days)

The operational ECMWF T1279 Ensemble Prediction System (EPS) is used from day 4 to day 9 for forecast bulletins. The forecasters also have a look at the medium range NCEP and CMC ensembles.
As mentioned in 4.3.4, statistical post-processing is produced with the ECMWF EPS until day 14.
Wave Ensemble Prediction System from ECMWF is used to anticipate risks of dangerous wave events.

4.3 Short-range forecasting system (0-72 hrs)

The short-range forecasting system run at Météo-France contains two main systems (data assimilations and forecast models): ARPEGE and AROME. ARPEGE is a hydrostatic global system. AROME is a non-hydrostatic LAM system with 1.3km horizontal resolution and a domain centered over mainland France. ALADIN is a hydrostatic LAM system which is no more operational in Météo-France.

ARPEGE, ALADIN and AROME use the same software, called ARPEGE/IFS, which is a common development between Météo-France, ECMWF and the ACCORD consortium of national (hydro-)meteorological services. ARPEGE/IFS is a versatile system originally based on a global spectral model and 4DVar data assimilation, it can be used for several applications: limited area modeling, 4DVar and 3DVar data assimilation, short-range prediction, medium-range prediction, climate research, ensemble prediction and ensemble data assimilation.

The ARPEGE system uses Schmidt's transformation to define a geographically variable resolution, with maximum resolution over mainland France (which is the stretching pole), a minimum resolution near New Zealand, and a smoothly varying resolution in between (Courtier and Geleyn 1988). T being the nominal truncation and C the "stretching factor", the local truncation of the model is T x C over the stretching pole, and T / C at the antipode; the local horizontal numerical resolution (in km) is 20000 / T x C at the stretching pole, and 20000 / T / C at the antipode

In June 2023, the horizontal ARPEGE configuration is T1798 C2.2 with a stretching pole over France (46.5N, 2.6E), leading to a horizontal resolution of the collocation grid of 5 km over France and 24 km in the SW Pacific. The collocation grid (3600x1800 points) is Gaussian linear with reduction at the poles, the mesh size is everywhere close to the resolution implied by the local spectral truncation. PEARP, the ensemble version of ARPEGE uses the same horizontal grid as ARPEGE. The AROME-France resolution is 1.3 km on a conformal tangent Lambert projection. This resolution is also used by the deterrministic oversea versions, AROME-IFS and AROME-Only the 5 EPS-AROME oversea versions use a 2,5 km horizontal resolution.

The vertical ARPEGE and AROME discretisations use a hybrid terrain-following, mass-based coordinate, following Simmons and Burridge (1981) with an increased resolution in the low atmosphere. ARPEGE use 105 levels, the lowest level is at 10 m above the ground and the highest corresponds to a pressure level at 0,1 hPa. AROME uses 90 levels leading to a higher

resolution in the troposphere and a lower resolution in the stratosphere than ARPEGE. PEARP, the ensemble version of ARPEGE has also 105 levels.
For further details about the model domains and vertical resolution, see http://www.cnrm.meteo.fr/gmap/

4.3.1 Data assimilation, objective analysis and initialization

4.3.1.1 In operation

The ARPEGE assimilation runs with a 6 hours cycle. The objective analysis is performed with a multi-incremental 4D variational (4DVar) scheme with first guess error statistics provided by 50-members ensemble: the departure obs-guess is computed at full resolution whereas the analyzed structures are produced at a lower resolution and with no stretching, by 2 minimization loops of increasing resolutions (T224C1 and T499C1). The guess is at the full resolution of T1798 C2.2. It is therefore assumed that the small scales (not corrected by the analysis) are forced by the (analyzed) large scales in the subsequent forecast. The 50-members ensemble uses only one minimization loop at the reduced truncation T224C1 in the 4DVAR assimilation (for a guess in T499C1). And its dispersion is maintained by randomly perturbing observations and inflating the corrections at each cycle. The AROME assimilation runs a 1 hour cycle with 3DVar at full model resolution.

assimilated data: ARPEGE uses SYNOP, SHIP, BUOY, BATHY, TEMP, TEMPSHIP, TEMPDROP and PILOT (part A, B, C and D), profilers, AIREP, AMDAR, ACARS, Atmospheric Motion Winds (GOES, Himawari, Meteosat), AMSU-A, B or MHS and HIRS (from NOAA, Aqua and Metop satellites), ATMS and CRIS (Suomi-NPP and from NOAA), Meteosat clear sky radiances, scatterometer winds (Seawinds from ASCAT from Metop, Scatsat), MODIS winds (Aqua and Terra satellites), SSMIS (from DMSP) and GMI, Megha-Tropiques, IASI (from Metop), AIRS (from Aqua), European GPS zenithal total delays, GPS radio occultation data from several sources) and wind profiles from ADM/Aeolus. AROME uses the same data as ARPEGE except that it also uses radar reflectivities and doppler winds, and additional SYNOP and ACARS information, as well as radiances at higher spatial resolution whenever possible.
assimilation cycle: ARPEGE uses a 6 hours cycle and AROME uses a 1-hour cycle.
analysis method: ARPEGE uses the so-called "mixed" 4Dvar and ensemble approach. AROME uses 3DVar.
analysed variables: Horizontal wind, temperature and specific humidity on model levels, plus surface pressure.
first guess: A 6-hour forecast of ARPEGE (or a 1-hour forecast of AROME, respectively) in normal operations
coverage: ARPEGE is global. AROME is regional.
horizontal resolution: The effective ARPEGE 4DVar increment resolution is T499c1. The assimilation ensemble increment resolution is T224C1. The ARPEGE background, and the AROME analyses, use the full resolution of the forecast model.
vertical resolution: as in the forecast models
initialization: in ARPEGE, weak digital filter constraint in the 4DVar variational cost function. In AROME, incremental analysis update.
surface: analysis of superficial and deep soil temperature and water content from observations of 2m temperature and humidity. Sea surface temperature is analyzed using SST reports and NCEP and OSTIA SST analyses. Sea-ice cover is based on OSI-SAF sea-ice products. Snow cover is analyzed in AROME not in ARPEGE where it is relaxed towards climatology.

4.3.2 Model

4.3.2.1 In operation

basis equations:
Primitive equations system in ARPEGE, fully compressible non-hydrostatic in AROME.

independent variables:
horizontal wind vector, temperature, specific humidity and surface pressure, cloud water and ice, precipitating water and ice, turbulent kinetic energy. Plus graupel, vertical velocity and hydrostatic pressure departure for AROME.

numerical technique:
Two-time-level semi-lagrangian spectral semi-implicit time-stepping and horizontal discretization scheme, vertical finite element discretization in ARPEGE , vertical finite differences in AROME.

integration domain:
global in ARPEGE, regional in AROME.

orography, gravity wave drag:
The orography of this model is computed on the forecast model collocation grid from the GMTED database for ARPEGE and AROME using a variational technique that controls the noise associated to Gibbs waves (see Bouteloup, 1995). The gravity wave drag in ARPEGE takes into account subgrid anisotropy, blocking and mid-tropospheric effects.

horizontal diffusion:
Implicit in spectral space and incorporating an orography dependent correction for temperature.

planetary boundary layer:
the PBL vertical diffusion is implemented as a CBR prognostic turbulent kinetic energy scheme that models the effect of subgrid eddies, plus a shallow convection scheme (KFB/EDKF) that simulates the mixing effect of subgrid non-precipitating convection.

resolution, time step:
ARPEGE and PEARP use T1798 C2.2 with a stretching pole over France (46.5N, 2.6E), leading to a horizontal resolution of the collocation grid of 5 km over France and 24 km in the SW Pacific. The AROME-France and PEAROME -France resolution is 1.3 km on a conformal tangent Lambert projection. The ARPEGE and AROME timesteps are 240s and 50s, respectively.

Earth surface:
ARPEGE and AROME use the SURFEX scheme which comprises four prognostic surface tiles (for soil/vegetation, sea/sea ice, lakes, towns), a snow scheme, a surface layer interpolator (Canopy), and the Ecoclimap physiographic database. SURFEX manages several dozens of prognostic variables. The exchanges of energy and water between the continuum ground-vegetation-snow and the atmosphere are represented with the ISBA-3L scheme, the snow scheme D95 and a ground frost scheme for the ground water. The 1D-version of the GELATO sea-ice model, is integrated into SURFEX.

radiation: A version of the RRTM scheme is used with 6 bands in the visible wavelengths, and 16 bands in the infrared.

subgrid convection:
The shallow convection scheme is documented in the PBL section. Deep convection is parameterized in ARPEGE only, as a Mass-flux scheme (Tiedke and Bechtold scheme operational in the ECMWF model IFS)

explicit microphysics:
ARPEGE uses a prognostic scheme derived from Lopez (2002), handling evolution and 3D advection of water vapor, cloud liquid water and ice,

precipitating rain and snow. The cloud cover is diagnosed according to Smith (1990).
AROME uses the ICE3 prognostic scheme to handle the same species plus graupel and the related processes. All models use statistical sedimentation numerical schemes for precipitation.
For more up-to-date details see http://www.cnrm.meteo.fr/gmap/

4.3.3 Operationally available NWP products

The above-described numerical models feed an analysis and forecast database, with the following characteristics:
- different horizontal domains for different horizontal resolution (from the global domain with a 0.25° mesh to the "France" domain with a 0.01° mesh)
- vertical levels are standard pressure levels, height levels, plus others (e.g. isentropic, PV levels)
- independence, from the originating model, of the format of the database products.

The meteorological fields stored in this database include:
- at upper levels: geopotential height, temperature, humidity, wind (including vertical velocity), cloud and precipitation variables, TKE
- at ground level: pressure, temperature, humidity, heat and radiation fluxes, snow and water content, etc
- at sea surface level: reduced pressure, QNH
- some data at particular levels: 500 hPa absolute vorticity, high medium and low cloudiness, iso 0° and iso -10°, tropopause, 3D cloud fields, potential vorticity, etc...

ARPEGE produces boundary conditions for the ACCORD applications run in Austria, Belgique, Bulgaria, Croatia, Czech Republic, Hungary, Morocco, Poland, Portugal, Romania, Slovakia, Slovenia, Tunisia

4.3.5 Ensemble Prediction System

4.3.5.1 In operation

An ensemble assimilation system runs operationally at Météo-France since July 2008. It features 50 4DVar data assimilation cycles using a uniform resolution version of ARPEGE i.e. T499C1, these assimilations are perturbed by applying random noise to the assimilated observations. The ensemble assimilation system provides initial perturbation information to the ensemble forecasts, and background error statistics to the ARPEGE and AROME data assimilation systems.

An ensemble prediction system, PEARP, runs operationally at Météo-France four times a day. The perturbations used in the ensemble are generated from the ARPEGE data assimilation ensemble at the horizontal resolution T499C1 with additional perturbations provided by singular vectors. Singular vectors are optimised over 18h or 24h at T95C1 horizontal resolution over various areas including both hemispheres, the tropics, and an emphasis on the Western European area. The tropical areas target active tropical cyclogenesis zones (they vary with seasons). The norm is a “total” energy in the extratropics and kinetic energy in the tropics. Forecast error is currently represented by randomly perturbating the key parameters of the operational ARPEGE physical package for each members at the beginning of each run. In order to increase the rain dispersion, a second convection scheme (PCMT) has been added to the Tiedke-Bechtold operational convection scheme. The ensemble features 35 members are similar to the deterministic ARPEGE system: T1798C2.2L105). Different products (Stamps, plumes, probabilistic charts and others) are provided to the forecasters within their worskstations.

A second ensemble prediction system, AROME-PE, runs operationally at Météo-France four times a day (at 3, 9, 15 and 21 UTC). This ensemble contains 16 perturbated members and a non-perturbated member equal to the AROME deterministic forecast which use 16 different initial conditions coming from a random choice among the 25 members of an ensemble of assimilations AE-AROME which has a horizontal resolution of 3,25 km. The lateral boundary conditions are coming from a hierarchical selection among the 35 PEARP members designed to represent the centre of classes of 2 or 3 members. Supplementary initial perturbations are added on surface parameters and stochastic physical physics perturbate the model at each time step of the forecast. Classical products (quantiles, probabilities, …) are available on the forecaster's workstation. A neighborhood treatment is also applied to the ensemble in order to increase local probabilities.

5 supplementary ensemble prediction systems, AROME-PE OM run operationally over oversea territories. These 5 sets of forecasts are built according to the same scheme: they start from the analysis of the IFS model unperturbed for the control member or perturbed for the 15 other members, by adding the deviation of the 15 PEARP members from their mean. These 15 members are selected from PEARP's 34 perturbed members according to the same classification as for PEAROME-France. The 15+1 forecasts all use the same AROME configuration: horizontal resolution of 2.5 km, hydrostatic approximation, coupling every 3 hours by the selected PEARP member, output on regular lat-lon grids of 0.025° resolution, coupling with a 1D oceanic mixing layer initialized from analyses of Mercator Ocean's PSY4 model, modeling of model error by stochastic perturbations of physical parameterization trends identical to those used in PEAROME-France.

AROME-NWC, the French nowcasting NWP model, has been in operation since March 2016 (see part 4.4.2). It has been designed for the forecasters issues and also as way of improving existing nowcasting products.

Some data fusion products between AROME-NWC and extrapolation leave progressively the research area for the operational area. The version for reflectivity, rainfall and hydrometeors are available on forecasters' workstation.

4.4.2 Models for Very Short-range Forecasting Systems

4.4.2.1 In operation

AROME-NWC nowcasting NWP model has been in operation since March 2016.

This system is built from a configuration of the existing mesoscale and limited area model AROME-FR. Both models share the same characteristics such as domain, physics and dynamics, 3DVar data assimilation system, spatial scale (1.3km), ARPEGE coupling model, etc.

Nowcasting's constraints lead to a compromise between the amount of new observation in the analysis process and computational time. Thus, the observation time window of AROME-NWC is narrower, and therefore contains fewer observations, than AROME-FR's one.

AROME-NWC is operated every hour. Its 3D-var assimilation system is made with a guess coming from the last available AROME-FR forecast valid at analysis time and observations belonging to a time interval extending from 10 minutes before to 10 minutes after analysis time.

AROME NWC is mainly designed for surface condition forecasting (rainfall, snow, fog, gusts, humidity and cloudiness). Its main characteristics are :

- High frequency of forecast (hourly refreshed)
- High spatial and temporal resolution: 1.3 km mesh and for a given forecast, forecast fields are produced every 15 minutes
- Maximum forecast range of 6 hours
- The forecast parameters are available within 30 minutes after the analysis time.

Synthetic diagnosis are computed from the AROME Nowcasting forecasts concerning convection, fog, winter conditions like snow or freezing rain.

An assessment of AROME-NWC's forecasts vs AROME-FR forecasts available at the same time confirms the positive impact of the one hour refresh cycle up to 2-3 hours range although its assimilates less observations (Auger et al. 2015). More recent scores of the current operational versions of these two models show similar conclusions.

For operational use of hourly refreshed forecasts, a dashboard has been created and tailored to meet forecaster's expectations. This dashboard aims to warn forecasters when some fields exceed fixed thresholds and to help them to visualise relevant maps. It also enables to visualise several available forecasts for a given hour.

4.4.2.2 Research performed in this field

The ability of such models to properly handle convective cells, both in a frequent assimilation cycle and during the very first hours of model integration, remains an important research challenge. The new needs of air traffic control management and optimization provide the initial incentive for this research, but there are others such as improving weather crisis management at local scale.

In addition to AROME-FR improvments that will benefit AROME-NWC, other avenues are being explored :

- AROME-NWC is not cycled and does not use its own predictions for future predictions (too short cut-off). Research performed in this field aims to work on AROME-NWC's assimilation system in order to make a better use of observations and former runs informations. Idea is to use a cycled assimilation with a daily anchor to AROME-FR to avoid any drift between models. Results are encouraging

- The other field of improvement concern the assimilation of observations like MSG in rapid scan mode or GPS data.

4.5 Specialized numerical predictions

4.5.1 Assimilation of specific data, analysis and initialization (where applicable)

4.5.1.1 In operation
[information on the major data processing steps, where applicable]

4.5.1.2 Research performed in this field
[Summary of research and development efforts in the area]

4.5.2 Specific Models (as appropriate related to 4.5)

4.5.2.1 In operation

Marine forecasts

<u>Wave hindcast and forecasting system</u>

For determining the sea states on high seas, seven models based on the WAM code, run operationally at Météo-France :

A global wave model (MFWAM-GLOB-ARPEGE) computing the waves over all the oceans up to 114 hours forecast, from the wind outputs of large scale fields derived from the global atmospheric models ARPEGE

Type:	wave model
Integration domain:	Global
Grid:	regular grid; resolution: 0.2°
Frequency resolution:	30 frequency components, logarithmically spaced from 0.035 Hz to 0.555 Hz
Direction resolution:	24 equally-spaced direction components
Integration scheme:	time step = 600s
Boundary forcing:	winds at 10m level from ARPEGE, updated every 3 hours Surface classification: sea ice deduced from ARPEGE SST
Assimilation:	4 assimilations/day using significant wave heights from Jason 3, Saral, Cryosat2, Sentinel-3A and 3B, CFOSAT altimeters and the SAR data from CFOSAT, Sentinel-1A and Sentinel-1B (waves spectra)

Another global wave model (MFWAM-GLOB-ECMWF) computing the waves over all the oceans up to 240 hours forecast, from the wind outputs of large scale fields derived from the global atmospheric models IFS (ECMWF)

Type:	wave model
Integration domain:	Global
Grid:	regular grid; resolution: 0.1°
Frequency resolution:	30 frequency components, logarithmically spaced from 0.035 Hz to 0.555 Hz
Direction resolution:	24 equally-spaced direction components
Integration scheme:	time step = 240s
Boundary forcing:	winds at 10m level from IFS (ECMWF), updated every 3 hours Surface classification: sea ice mask from ECMWF, surface currents from CMEMS-MFC global ocean system.
Assimilation:	4 assimilations/day using significant wave heights from Jason 3, Saral, Cryosat2, Sentinel-3A and 3B, CFOSAT altimeters and the SAR data from CFOSAT, Sentinel-1A and Sentinel-1B (waves spectra)

A regional model (MFWAM-REG-ARPEGE) forecasting the waves up to 114 hours with 3 hours step, over a vast area centered on Europe (North Atlantic, Mediterranean Sea, Baltic, North Sea and Black Sea...), from the wind outputs of small scale fields (1/10°) derived from ARPEGE and nested in the MFWAM-GLOB-ARPEGE wave model.

Type:	nested wave model
Domain:	European Seas : 80N-10S-100W-100E
Grid:	regular grid; resolution: 0°1
Frequency resolution:	30 frequency components, logarithmically spaced from 0.035 Hz to 0.555 Hz
Direction resolution:	24 equally-spaced direction components
Timestep:	300s
Boundary forcing:	winds at 10m level from ARPEGE, updated every 3 hours .
Assimilation:	4 assimilations/day using significant wave heights from Jason 3, Saral, Cryosat2, Sentinel-3A and 3B, CFOSAT altimeters and the SAR data from CFOSAT, Sentinel-1A and Sentinel-1B (waves spectra)

A Indian Ocean model (MFWAM-INDIAN OCEAN-AROME), forecasting the waves up to 42 hours with 3 hours step, over part of the Indian Ocean (centered on La Réunion Island), nested in the MFWAM-GLOB-ECMWF model, from the wind outputs of Arome-Indian Ocean (1/40°) and of IFS from ECMWF (1/8°)

Type:	Nested wave model
Domain:	0S-32S-31.5E-88.5E
Grid:	regular grid; resolution: 0°1
Frequency resolution:	30 frequency components, logarithmically spaced from 0.035 Hz to 0.555 Hz
Direction resolution:	24 equally-spaced direction components
Timestep:	300s
Boundary forcing:	winds at 10m level from Arome-Indian Ocean, updated every 3 hours.
Assimilation:	4 assimilations/day using significant wave heights from Jason 3, Saral, Cryosat2, Sentinel-3A and 3B, CFOSAT altimeters and the SAR data from CFOSAT, Sentinel-1A and Sentinel-1B (waves spectra)

A Polynesian model (MFWAM-POLYNESIAN-AROME), forecasting the waves up to 42 hours with 3 hours step, over Polynesia, nested in the MFWAM-GLOB-ECMWF model, from the wind outputs of Arome-Polynesia and of IFS from ECMWF (1/8°).

Type:	Nested wave model
Domain:	1S-31S-196E-232E
Grid:	regular grid; resolution: 0°1
Frequency resolution:	30 frequency components, logarithmically spaced from 0.035 Hz to 0.555 Hz
Direction resolution:	24 equally-spaced direction components
Timestep:	300s
Boundary forcing:	winds at 10m level from Arome-Polynesia, updated every 3 hours.
Assimilation:	4 assimilations/day using significant wave heights from Jason 3, Saral, Cryosat2, Sentinel-3A and 3B, CFOSAT altimeters and the SAR data from CFOSAT, Sentinel-1A and Sentinel-1B (waves spectra)

A New Caledonia model (MFWAM-New-Caledonia-AROME), forecasting the waves up to 42 hours with 3 hours step, over New Caledonia sea, nested in the MFWAM-GLOB-ECMWF model, from the wind outputs of Arome-New-Caledonia and of IFS from ECMWF (1/8°).

Type:	Nested wave model
Domain:	10S-30S-156E-174E
Grid:	regular grid; resolution: 0°1
Frequency resolution:	30 frequency components, logarithmically spaced from 0.035 Hz to 0.555 Hz
Direction resolution:	24 equally-spaced direction components
Timestep:	300s
Boundary forcing:	winds at 10m level from Arome-New-Caledonia, updated every 3 hours.

A local model (MFWAM-France-AROME), forecasting the waves up to 30 hours with 1 hour step, over France, nested in the MFWAM-REG-ARPEGE model, from the wind outputs of AROME-France.

Type:	Nested wave model
Domain:	38N-53N-8W-12E
Grid:	regular grid; resolution: 0°025
Frequency resolution:	30 frequency components, logarithmically spaced from 0.035 Hz to 0.555 Hz
Direction resolution:	24 equally-spaced direction components
Timestep:	60s
Boundary forcing:	winds at 10m level from AROME-France, updated every hour.

These 7 models are available at 00UTC, 06UTC, 12UTC and 18UTC runs.

MFWAM-GLOB-ARPEGE and MFWAM-REG-ARPEGE are run with a long-cut-off and short cut-off at 00 UTC.

Since March 2015 (but 2017 for overseas territories), six other models have been implemented to detail the sea state near the coasts of France with different atmospheric forcings. These models are based on the WW3 code with an unstructured grid and a minimum mesh size of 200 meters on the coast :

A coastal model 1 (WW3-FranceATL-ARPEGE), forecasting the waves up to 72 hours with 1 hour step (for the 36 first hours, 3h step after), over West and North France, nested in the MFWAM-REG-ARPEGE model, from the wind outputs of ARPEGE (1/10°).

Type:	Nested wave model
Domain:	french Atlantic, Channel and North Sea coasts
Grid:	irregular grid; resolution: up to 200 m on the french coast
Frequency resolution:	30 frequency components, logarithmically spaced from 0.035 Hz to 0.555 Hz
Direction resolution:	24 equally-spaced direction components
Timestep:	10s
Boundary forcing:	winds at 10m level from ARPEGE, updated every 3 hours.

A coastal model 2 (WW3-FranceATL-ECMWF), forecasting the waves up to 72 hours with 1 hour step (for the 36 first hours, 3h step after), over West and North France, nested in the MFWAM-REG-ECMWF model, from the wind outputs of IFS/ECMWF (1/8°).

Type:	Nested wave model
Domain:	french Atlantic, Channel and North Sea coasts
Grid:	irregular grid; resolution: up to 200 m on the french coast
Frequency resolution:	30 frequency components, logarithmically spaced from 0.035 Hz to 0.555 Hz
Direction resolution:	24 equally-spaced direction components
Timestep:	10s
Boundary forcing:	winds at 10m level from IFS/ECMWF, updated every 3 hours, surface currents and sea level from HYCOM-2D (storm surge model).

A coastal model 3 (WW3-FranceMED-ARPEGE), forecasting the waves up to 72 hours with 1 hour step (for the 36 first hours, 3h step after), over South France, nested in the MFWAM-REG-ARPEGE model, from the wind outputs of ARPEGE (1/10°).

Type:	Nested wave model
Domain:	french Mediterranean Sea coasts
Grid:	irregular grid; resolution: up to 200 m on the french coast
Frequency resolution:	30 frequency components, logarithmically spaced from 0.035 Hz to 0.555 Hz
Direction resolution:	24 equally-spaced direction components
Timestep:	10s
Boundary forcing:	winds at 10m level from ARPEGE, updated every 3 hours, surface currents and sea level from HYCOM-2D (storm surge model).

A coastal model 4 (WW3-FranceMED-AROME), forecasting the waves up to 42 hours with 1 hour step (for the 36 first hours, 3h step after), over South France, nested in the MFWAM-France-AROME model, from the wind outputs of AROME (1/40°).

Type:	Nested wave model
Domain:	french Mediterranean Sea coasts
Grid:	irregular grid; resolution: up to 200 m on the french coast
Frequency resolution:	30 frequency components, logarithmically spaced from 0.035 Hz to 0.555 Hz
Direction resolution:	24 equally-spaced direction components

Timestep:	10s
Boundary forcing:	winds at 10m level from AROME, updated every 3 hours.

A coastal caribbean and guyanese model (WW3-AG-AROME), forecasting the waves up to 42 hours with 3 hours step, over West Indies and french Guyana, nested in the MFWAM-CARIBBEAN-AROME model, from the wind outputs of AROME-Antilles/Guyane (1/40°) and of IFS from ECMWF (1/8°).

Type:	Nested wave model
Domain:	french coasts of West Indies and Guyana
Grid:	irregular grid; resolution: up to 200 m on the french coast
Frequency resolution:	30 frequency components, logarithmically spaced from 0.035 Hz to 0.555 Hz
Direction resolution:	24 equally-spaced direction components
Timestep:	10s
Boundary forcing:	winds at 10m level from AROME, updated every 3 hours, surface currents and sea level from HYCOM-2D (storm surge model).for Guyana.

A coastal model for Mayotte and Réunion islands in Indian Ocean (WW3-OI-AROME), forecasting the waves up to 42 hours with 3 hours step, nested in the MFWAM-**INDIAN OCEAN**-AROME model, from the wind outputs of AROME-Indian-Ocean (1/40°) and of IFS from ECMWF (1/8°).

Type:	Nested wave model
Domain:	coasts of Mayotte and Réunion islands
Grid:	irregular grid; resolution: up to 200 m on the coast
Frequency resolution:	30 frequency components, logarithmically spaced from 0.035 Hz to 0.555 Hz
Direction resolution:	24 equally-spaced direction components
Timestep:	10s
Boundary forcing:	winds at 10m level from AROME, updated every 3 hours.

Operational simulations of the oceanic circulation in tropical Atlantic

The oceanic primitive equation model OPA7, developed by CNRS/LODYC, has been run operationally every month, using all the surface fluxes produced by the operational ARPEGE model. Its main characteristics are 17 horizontal levels in z coordinate with a realistic bathymetry, and a 1/3 degree horizontal resolution. Systematics comparisons have been performed with bathythermic observations sent through the GTS, and against sea surface temperatures from ERS data (ATSR).

Storm surge model

A depth-averaged, numerical storm-surge model (Hycom2D since January 2014, proprietary model before) has been configured to compute storm-surges forecasts along coastlines of metropolitan France (2 domains : Atlantic to North Sea and Mediterranean Sea), of SW Indian Ocean and of West Indies and French Guyana. The grid mesh size is around 1 kilometer at the coast (curvilinear grid) except for Channel (500 m), SW Indian Ocean (3 km), Mayotte (200 m), Réunion (800 m) and French Guyana (2 km).

Metropolitan domain: Atmospheric fields are taken from atmospheric numerical models: IFS (ECMWF), ARPEGE, AROME and AROME-IFS (Météo-France). The system (based on a proprietary model until 2014) has been operated since October 1999 for the Channel and Bay of Biscay, March 2002 for the Mediterranean Sea and November 2002 for the North Sea. The model is now run 15 times per day (for the 2 configurations describing the metropolitan domain): 4 times with Arpege forcings (10 m winds and surface pressure), 5 times with Arome forcings, 2 times with Arome-IFS forcings and 4 times with IFS forcings.
Up to 120 hours forecast are produced on a 1/24° grid mesh for the two domains : Mediterranean Sea and NE Atlantic Ocean (Bay of Biscay, Channel and North Sea). Storm surge and total sea

level forecasts for about 120 locations along the French coast are also provided up to 120 h (every 10 minutes).

Overseas domain: for the Hycom2D model, the atmospheric forcing is AROME, completed by IFS to cover the whole 2 domains of Hycom2D (SW Indian Ocean and West Indies to French Guyana). These 2 models run 4 times per day to produce up to 48h forecasts. The storm surge and the total sea level are available at around 60 targeted locations for each of the 2 configurations.

Another system, based on a proprietary storm surge model, can be used for overseas domains and in case of tropical cyclones :
atmospheric fields are inferred from an analytical-empirical cyclone model which requires only cyclone position, intensity and size. The model has been operated since 1994 in the French Antilles, 1995 in New Caledonia, 1997 in the French Polynesia and 1998 in La Reunion. The model can be used in two different ways. In real-time mode as a tropical cyclone is approaching an island or in climatological mode: a cyclone climatology is used to prepare a data base of pre-computed surges. Due to the still low accuracy of tropical cyclone trajectory forecasts, the second mode seems to be, at present time, the best way to use the model.
The grid mesh is fixed for each domain and varies from 150 m to 1850 m.

Drift model (oil spills, containers, Search & Rescue)

Météo-France is in charge of spill drift predictions within the spill response plan POLMAR-MER in case of a threat for the French coastline. At an international level, Météo-France can intervene within the Marine Pollution Emergency Response Support System (MPERSS) for the high seas. Météo-France is Area Meteorological Coordinator for METAREA II and III west, and supporting service for METAREA I, III east, VII B and VIII C.
Météo-France developed a drift model named MOTHY (Modèle Océanique de Transport d'HYdrocarbures). MOTHY is an integrated system that includes hydrodynamic coastal ocean modelling (2D+1D) and atmospheric forcing from ARPEGE, AROME, AROME-IFS or IFS models. The low-frequency oceanic currents (below the Ekman layer) are also used by MOTHY, provided by the CMEMS data base (https://marine.copernicus.eu/) : the global model with a resolution of 1/12°, the IBI model at 1/36° and the MFS model at 1/24°. The hydrodynamic coastal ocean is linked to an oil spill model, where oil slick is considered as a distribution of independent droplets. These droplets move with shear current, turbulent diffusion and buoyancy. The system has been operated since 1994 and can be used for oil spills or drifting objects. New developments, exercises and training are jointly conducted with CEDRE (Centre de documentation de recherche et d'expérimentations sur les pollutions accidentelles des eaux). MOTHY correctly predicted the drift of the oil during Erika (December 1999), Prestige (2002-2003) and Grande Americe (2019) in the Bay of Biscay. For the Search And Rescue, an object drift model has been developed with 2 versions : a leeway one (for 73 object types) and a container one (every rectangular object) and a leeway one (for 73 object types). The last version has been operational since 1999.
The domain is global with a better accuracy on specific areas, including French seas.
Forecasts are produced up to 5 days on fixed grid from 150 m to 9 km.

4.6 Extended range forecasts (ERF) *(10 days to 30 days)*

4.7 Long range forecasts (LRF) *(30 days up to two years)*

5. Verification of prognostic products

5.1 Annual verification summary :

Scores against analyses

	24 hours			72 hours			
	NH	SH	TR		NH	SH	TR
Z500 RMSE	6.4	7.5			20.4	24.4	
W250 RMSEV	3.5	3.6	3.7		7.9	8.4	6.2
W850 RMSEV	2.1	2.3	2.2		4.2	4.8	3.3

NH : Northern Hemisphere SH : Southern Hemisphere TR : Tropics

Scores against observations

24 hours

	NA	EU	AS	AU/NZ	TR	NH	SH
Z500 RMSE	9.1	9.2	11.9	6,9		11.3	9.8
W250 RMSEV	5.4	4.9	5.0	5.2	4,9	4,9	5.3
W850 RMSEV	3.8	3.6	3.6	3.8	3.4	3.7	4.3

72 hours

	NA	EU	AS	AU/NZ	TR	NH	SH
Z500 RMSE	21.3	20.2	20.5	16.2		21.9	20.0
W250 RMSEV	9.5	8,6	8.2	8.1	6,5	8.4	8.5
W850 RMSEV	5.2	5.0	5.0	5.3	4.3	5.1	5.6

NA : North America EU : Europe AS : Asia AU/NZ : Australia / New Zealand
NH : Northern Hemisphere SH : Southern Hemisphere TR : Tropics

6. Plans for the future *(next 4 years)*

7. Consortium

8. References

P. Bénard, R. Laprise, J. Vivoda and P. Smolíková. 2004: Stability of Leapfrog Constant-Coefficients Semi-Implicit Schemes for the Fully Elastic System of Euler Equations: Flat-Terrain Case. *Mon. Wea. Rev.,* 132, 1306–1318.

Bougeault P., 1985 : "Parameterization of cumulus convection for Gate. A diagnostic and semi-prognostic study". *Mon. Wea. Rev.*, 113, 2108-2121.

Bougeault and Lacarrère 1989: Parametrization of orography-induced turbulence in a Mesobeta-scale model, Mon. Wea.Rev, 117, 1872-1890

Bouteloup Y., 1995: "Improvement of the spectral representation of the earth topography with a variational method", *Mon. Wea. Rev.,* 123, 1560-1573

Courtier, P. and J.F. Geleyn, 1988 :"A global numerical weather prediction model with variable resolution: application to the shallow-water equations"". *Quart. J. Roy. Meteor. Soc.*, 1114, 1321-1346.

Cuxart et al. 2000: A turbulence scheme allowing for mesoscale and large eddy simulations, Quart. J. Roy. Met. Soc. 126, 1-30. DOI: 10.1002/qj.49712656202

Giard, D., and E. Bazile, 1999 : Implementation of a new assimilation scheme for soil and surface variables in a global NWP model, submitted to *Mon. Wea. Rev.*.

Louis J.F., 1979: "A parametric model of vertical eddy fluxes in the atmosphere", *Bound. Lay. Met.,* 17, 187-202

Lopez 2002: Implementation and validation of new prognostic large-scale cloud and precipitation scheme for climate and data-assimilation purposes. Quart. J. R. Met. Soc. 128, 229-257.

Louis J.F., M. Tiedtke and J.F. Geleyn, 1981 :"A short history of the PBL parameterization at ECMWF". *ECMWF Workshop on PBL parameterization,* ECMWF, Reading, UK, 59-80.

Masson, V., Le Moigne, P., Martin, E., Faroux, S., Alias, A., Alkama, R., Belamari, S., Barbu, A., Boone, A., Bouyssel, F., Brousseau, P., Brun, E., Calvet, J.-C., Carrer, D., Decharme, B., Delire, C., Donier, S., Essaouini, K., Gibelin, A.-L., Giordani, H., Habets, F., Jidane, M., Kerdraon, G., Kourzeneva, E., Lafaysse, M., Lafont, S., Lebeaupin Brossier, C., Lemonsu, A., Mahfouf, J.-F., Marguinaud, P., Mokhtari, M., Morin, S., Pigeon, G., Salgado, R., Seity, Y., Taillefer, F., Tanguy, G., Tulet, P., Vincendon, B., Vionnet, V., and Voldoire, A. (2013). The SURFEXv7.2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes, Geosci. Model Dev., 6, 929-960, doi:10.5194/gmd-6-929-2013.

Morcrette, J.-J., 1991 : Radiation and clouds radiative properties in the European center for medium-range weather forecasts forecasting system. J. Geophys. Res., 96, 9121-9132.

Morcrette, J.-J., and Y. Fouquart, 1985: On systematic errors in parametrized calculations of longwave radiation transfer. Quart. J. Roy. Meteor. Soc., 111, 691-708.

Nicolau, J., 2002. Short-range ensemble forecasting. WMO/CSB Technical Conference meeting, Cairns (Australia), December 2002 (Proceedings).

Noilhan, J., and S. Planton, 1989 : A simple parameterization of land-surface processes for meteorological models, *Mon. Wea. Rev.,* 117, 536-549

Piriou et al. 2007: An approach for convective parameterization with memory, in separating microphysics and transport in grid-scale equations. DOI: 10.1175/2007JAS2144.1. Journal of Atm. Science, 64, 4127-4139.

Seity Y., P, Brousseau, S. Malardel, G. Hello, P. Benard, F. Bouttier, C. Lac and V. Masson, (2011) : The AROME-France convective-scale operational model, Monthly Weather Review, 976-991 (139

Simmons A.J. and D.M. Burridge, 1981 : "An energy and angular momentum conserving vertical finite difference scheme on a hybrid vertical coordinate". *Mon. Wea. Rev.*, 109, 758-766.

Yessad K. and P. Bénard, 1996 :"Introduction of a local mapping factor in the spectral part of the Météo_france global variable mesh numerical model". *Quart. J. Roy. Meteor. Soc.*, 122, 1701-1719.