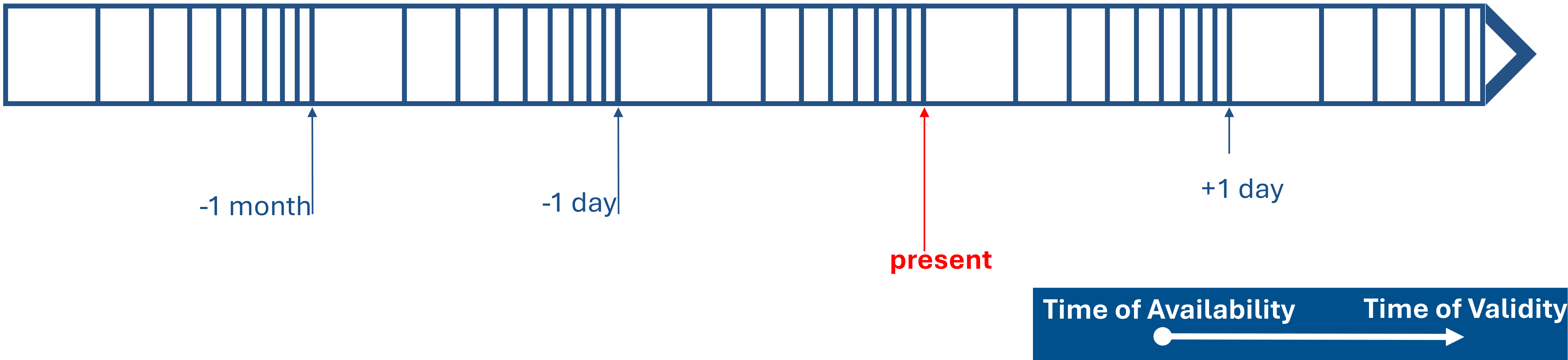
IPWG-11 Training Course :
Data assimilation within cloudy and precipitating areas

Philippe Chambon, with the contribution of many colleagues

Météo-France, Toulouse, France

Introduction

Rainfall products are needed for various applications : two requirements that will provide guidance on what product could be used are the Times of Validity/Availability of the needed rainfall estimates :



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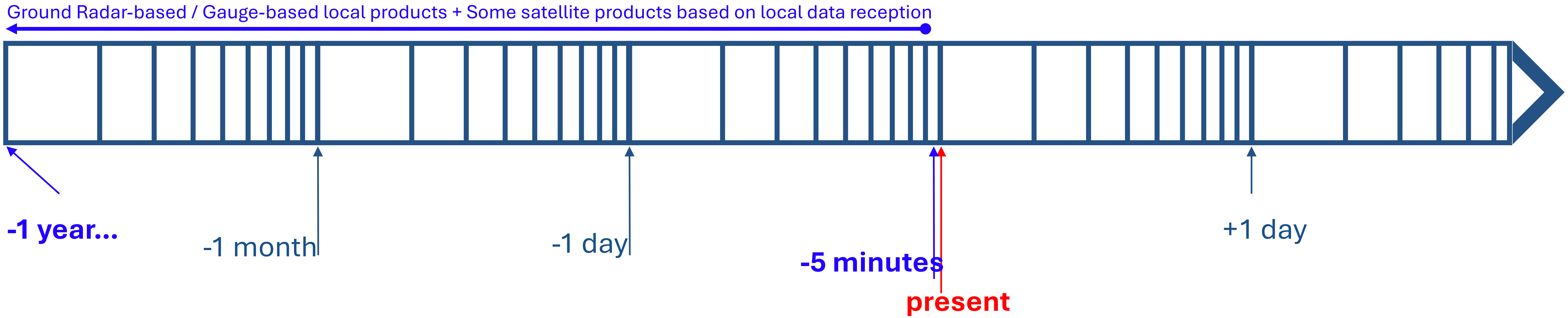

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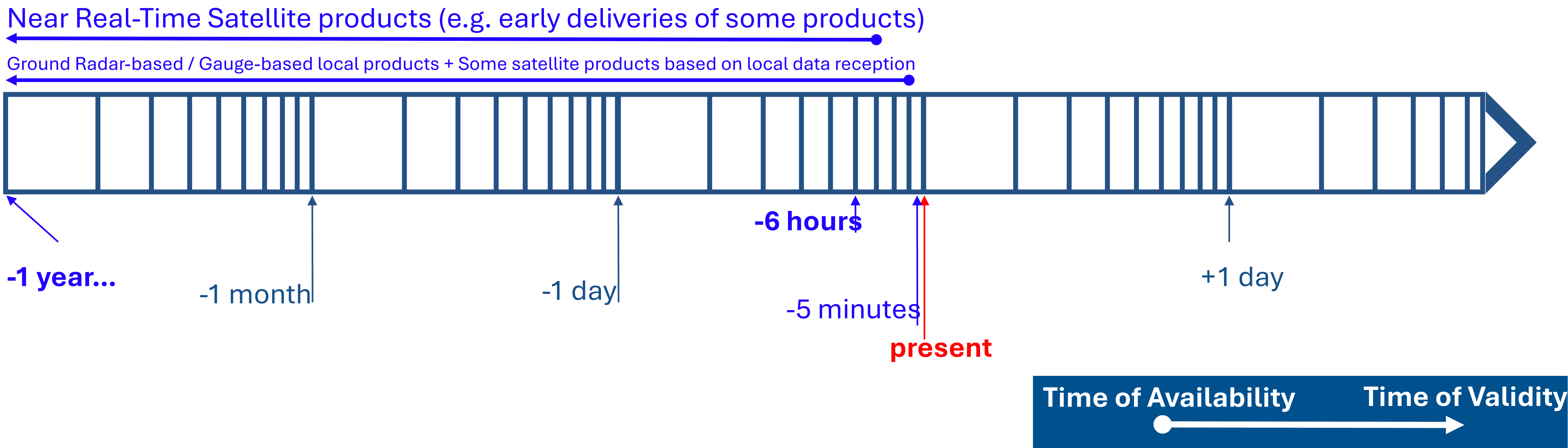

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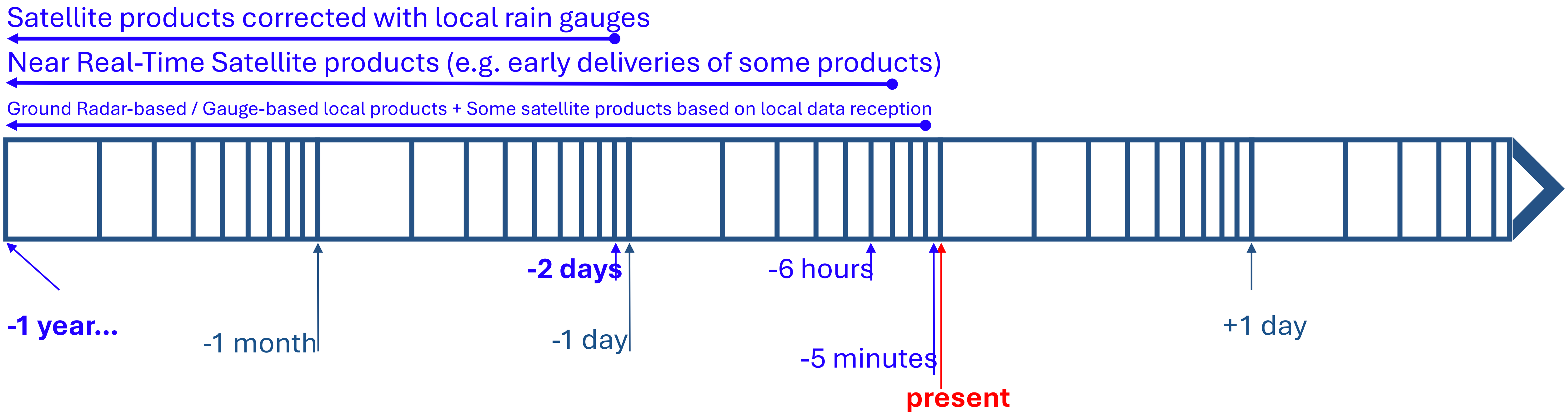

Time of Availability **Time of Validity**

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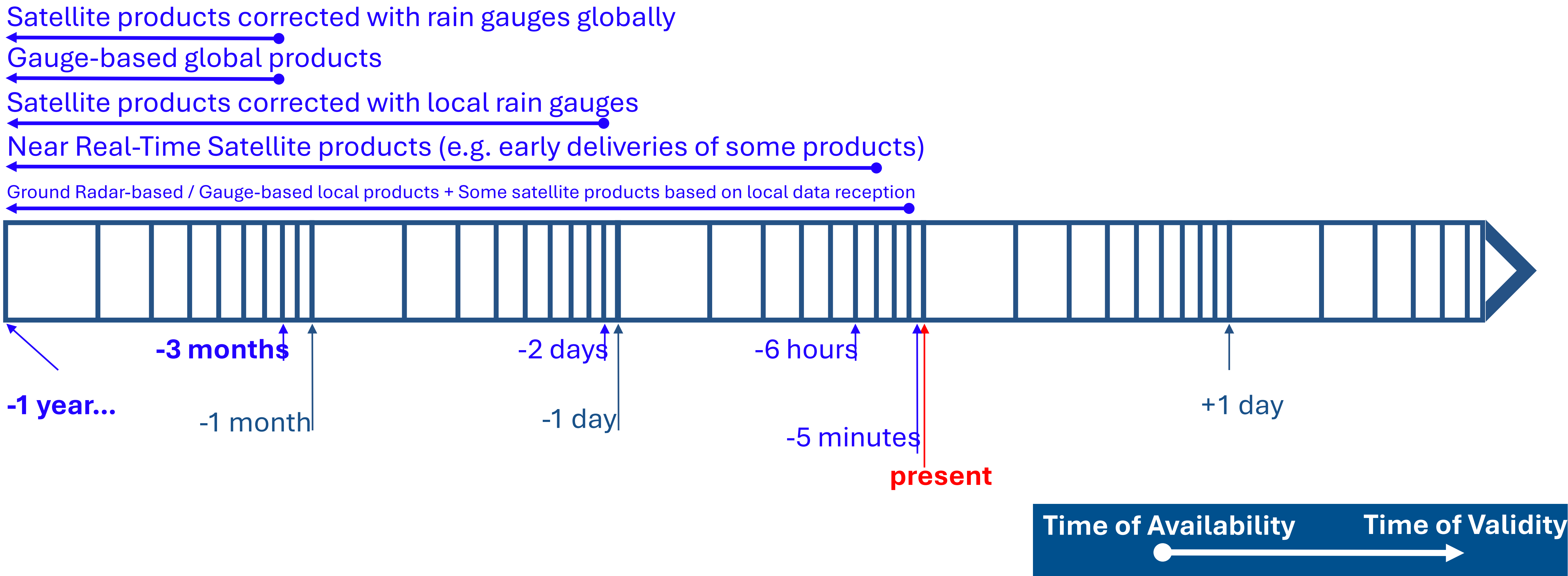

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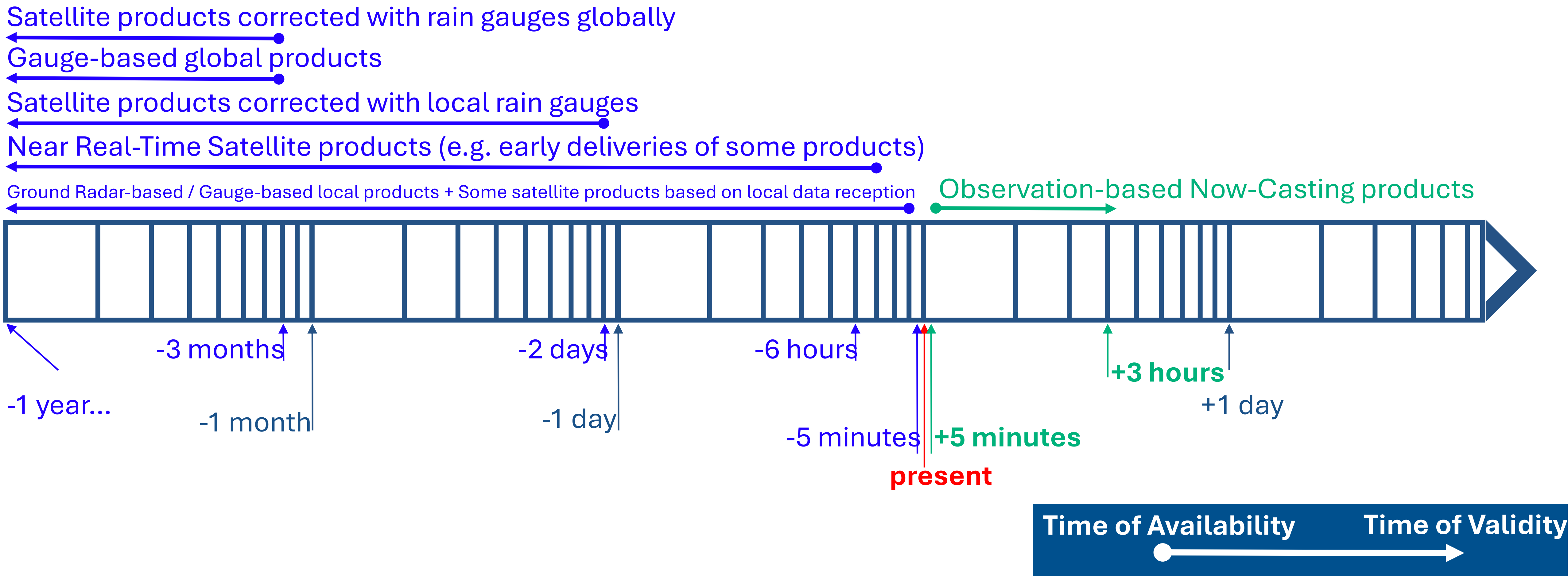

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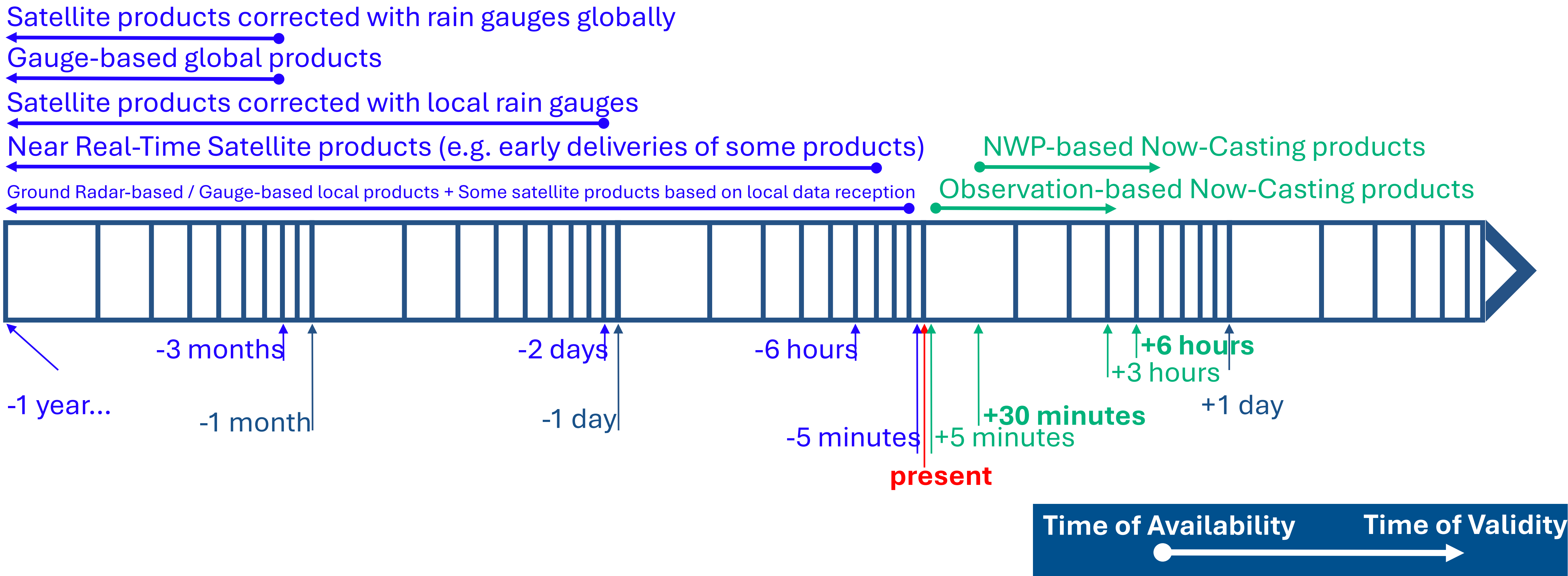

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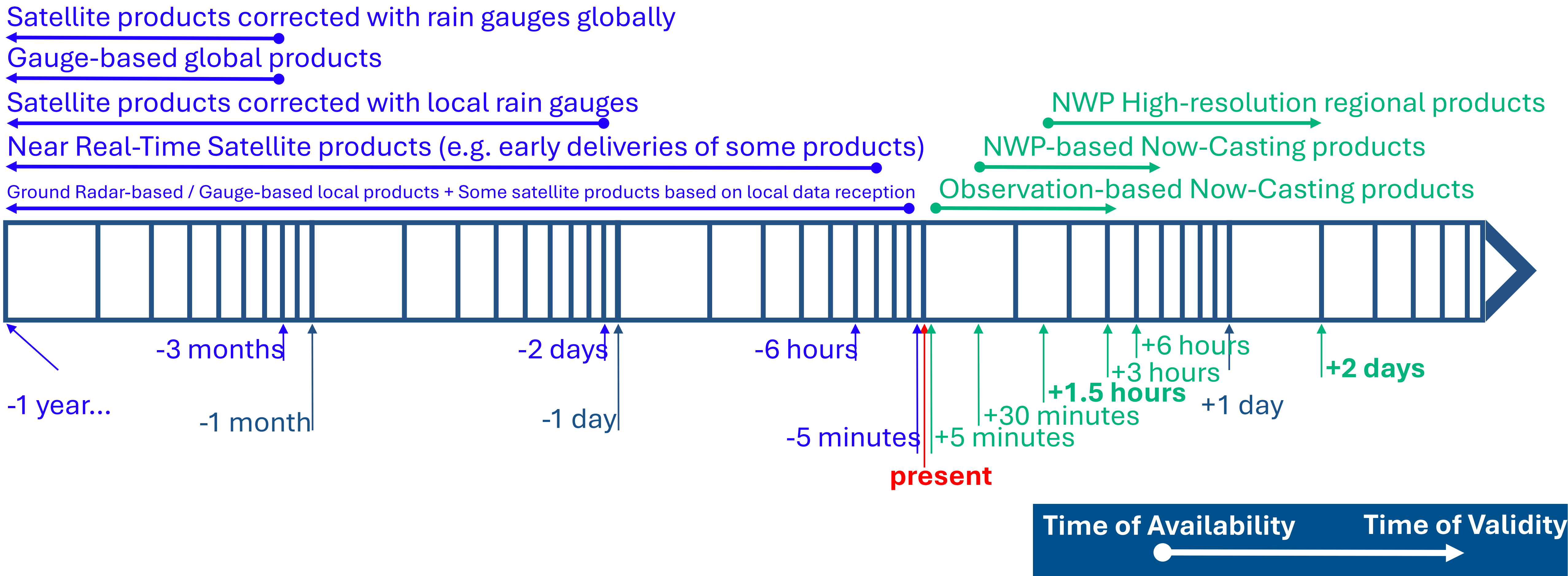

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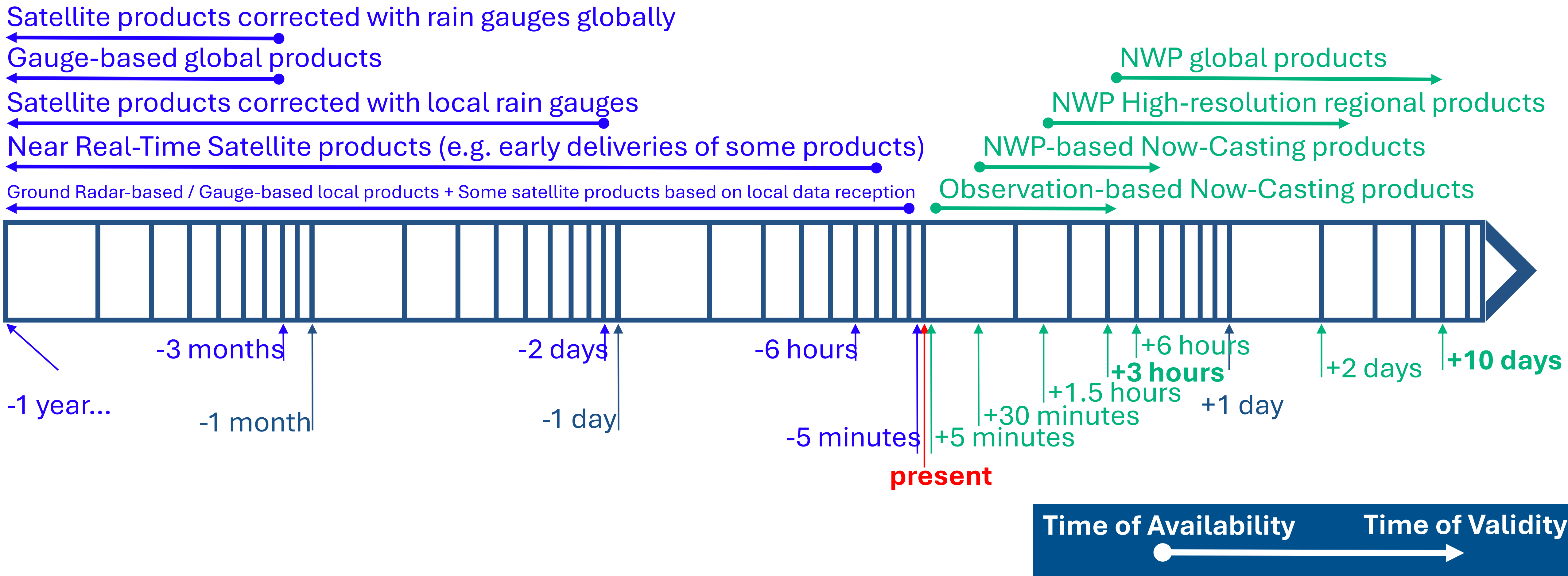

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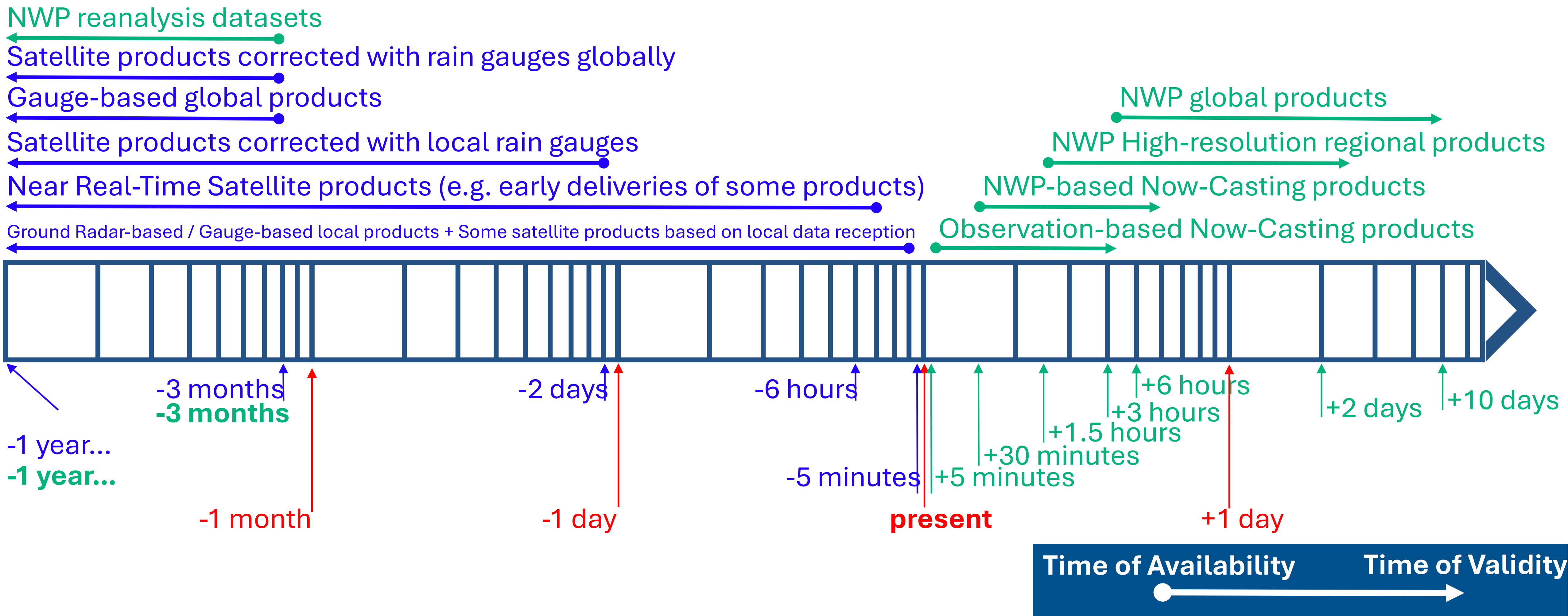

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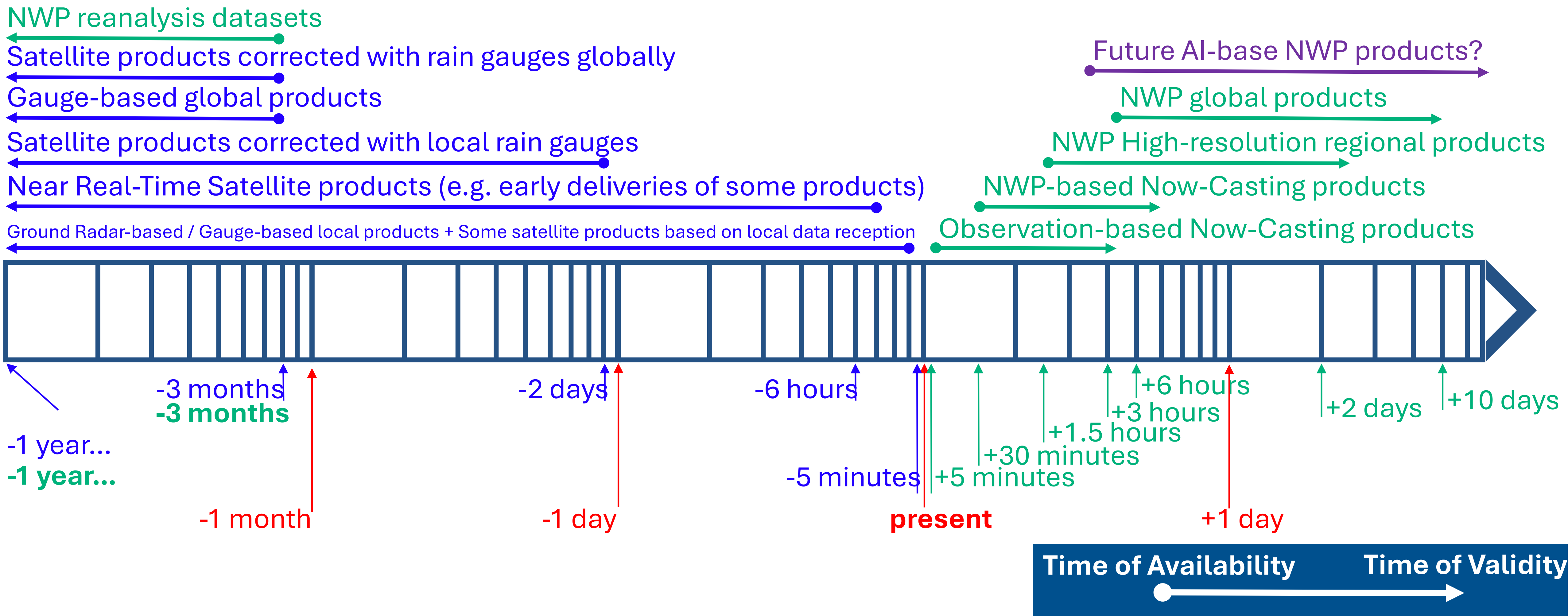

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Outline of the presentation

1. Current and Future NWP models: what are their strengths and weaknesses regarding rainfall forecasts ?
2. How rainfall forecasts can be validated ?
3. How rainfall forecasts can be improved ?

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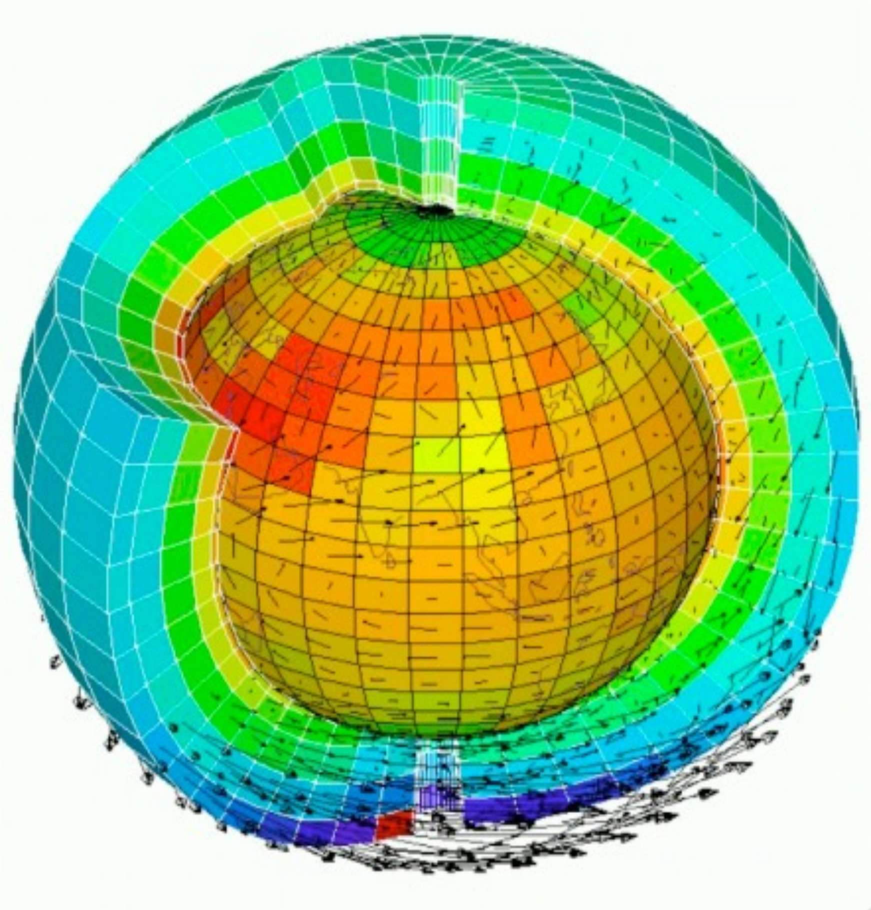
Current and Future NWP models: what are their strengths and weaknesses regarding rainfall forecasts ?

- **N**umerical **W**eather **P**rediction uses mathematical models of the atmosphere and oceans, in which time and the physical fields are discretized, to predict the weather **based on current weather conditions.**

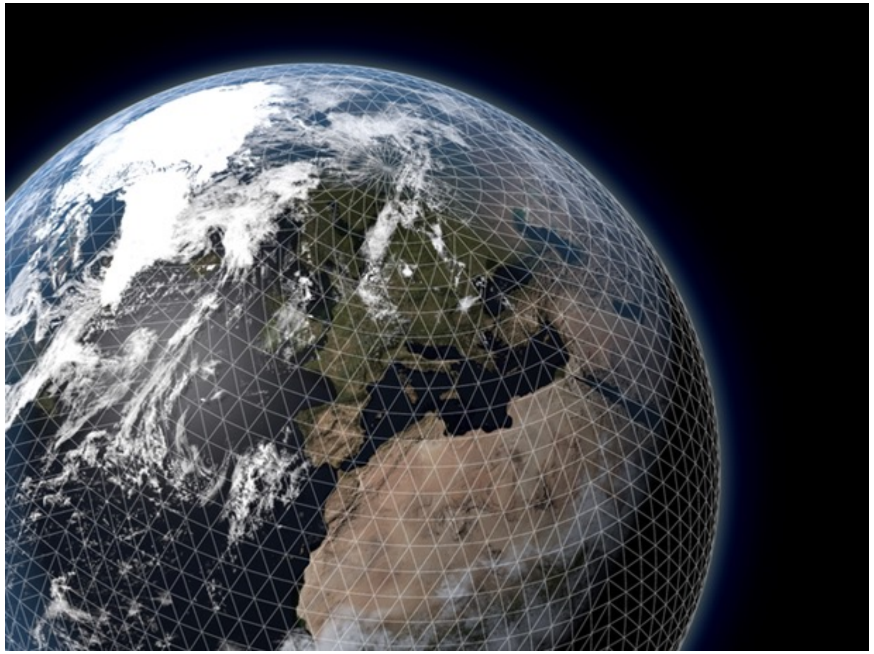
- It is impossible to solve exactly the partial differential equations that govern the atmosphere and **errors grow with the forecast range** during the model integration in time



(Source: http://pedagotech.inp-toulouse.fr)

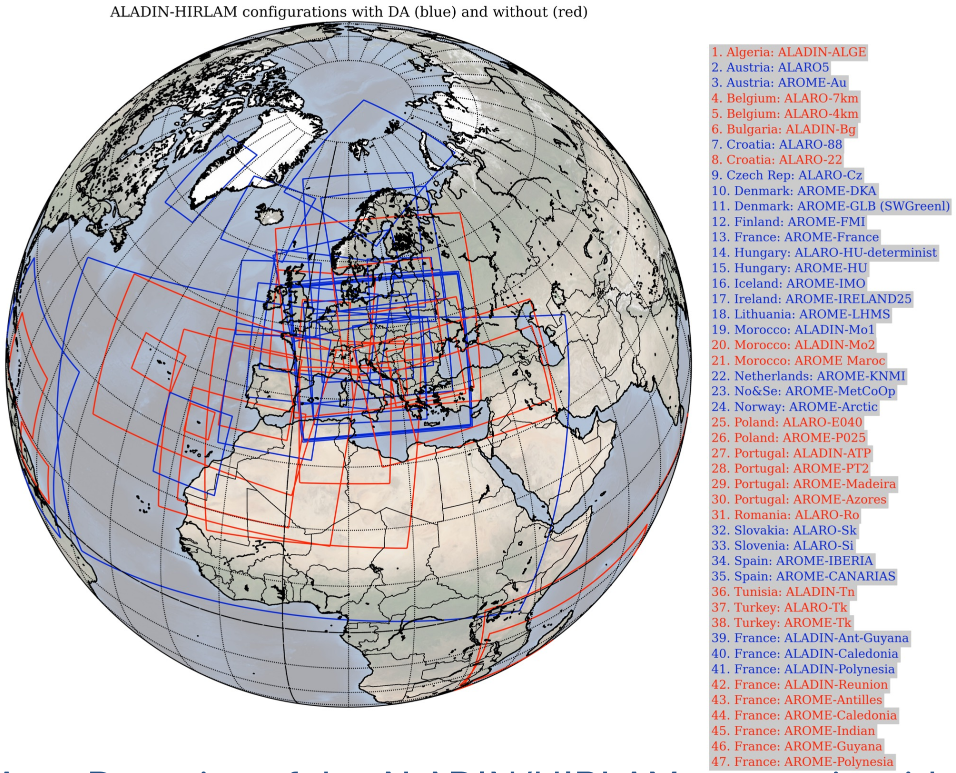
Current and Future NWP models: what are their strengths and weaknesses regarding rainfall forecasts ?

- The current generation of <u>operational</u> **global models** use parametrization for various processes like convection and provide forecasts at ***O***(10km) resolution



Artist view of the ECMWF 'cubic-octahedral grid' (Source: http://www.ecmwf.int)

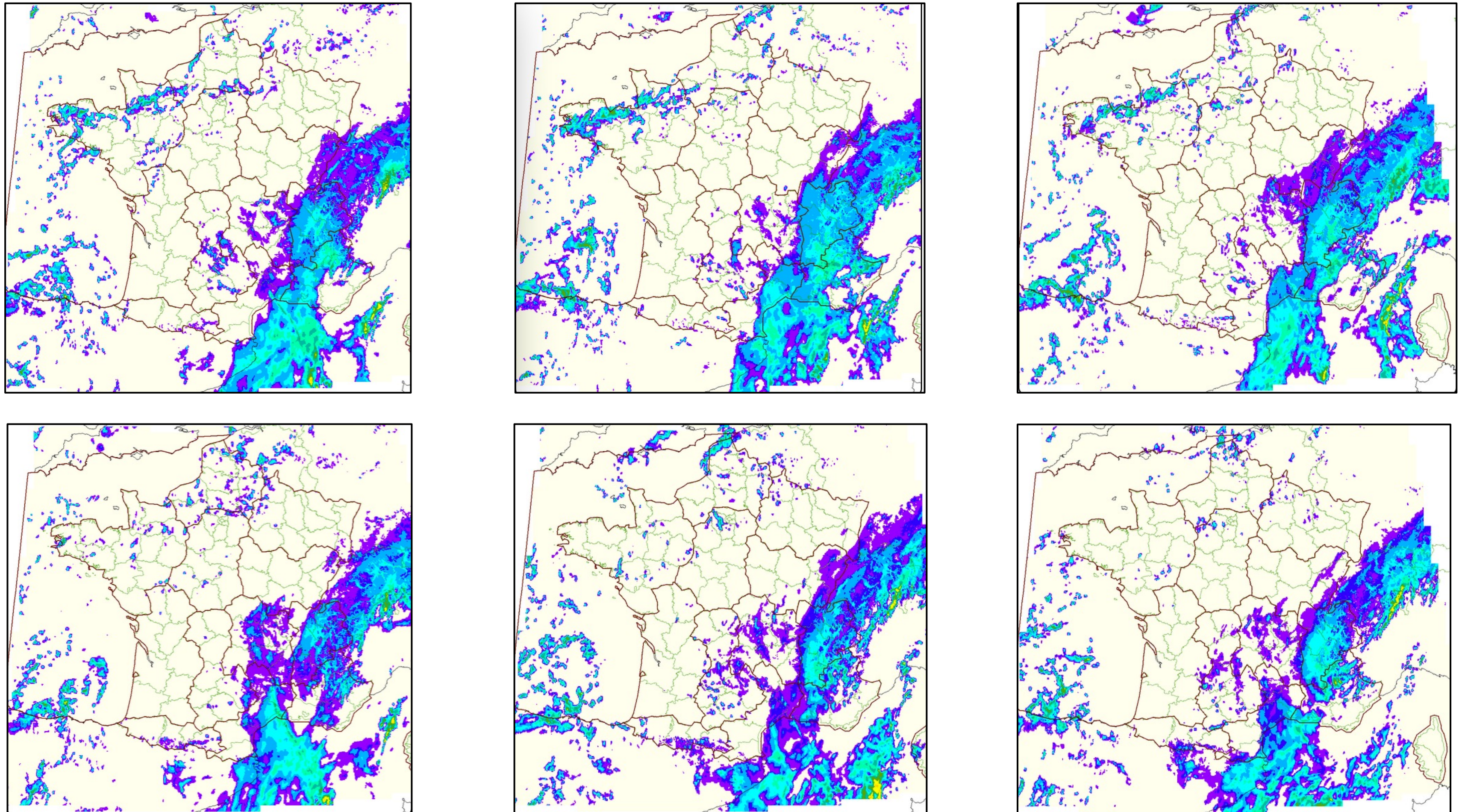
- The current generation of <u>operational</u> **regional models** are non-hydrostatic are resolve convection explicitly. They provide forecasts at ***O***(1km) resolution



Limited Area Domains of the ALADIN/HIRLAM consortia with **DA** and without **DA** (Source http://www.cnrm-game-meteo.fr/aladin/)

Current and Future NWP models: what are their strengths and weaknesses regarding rainfall forecasts ?

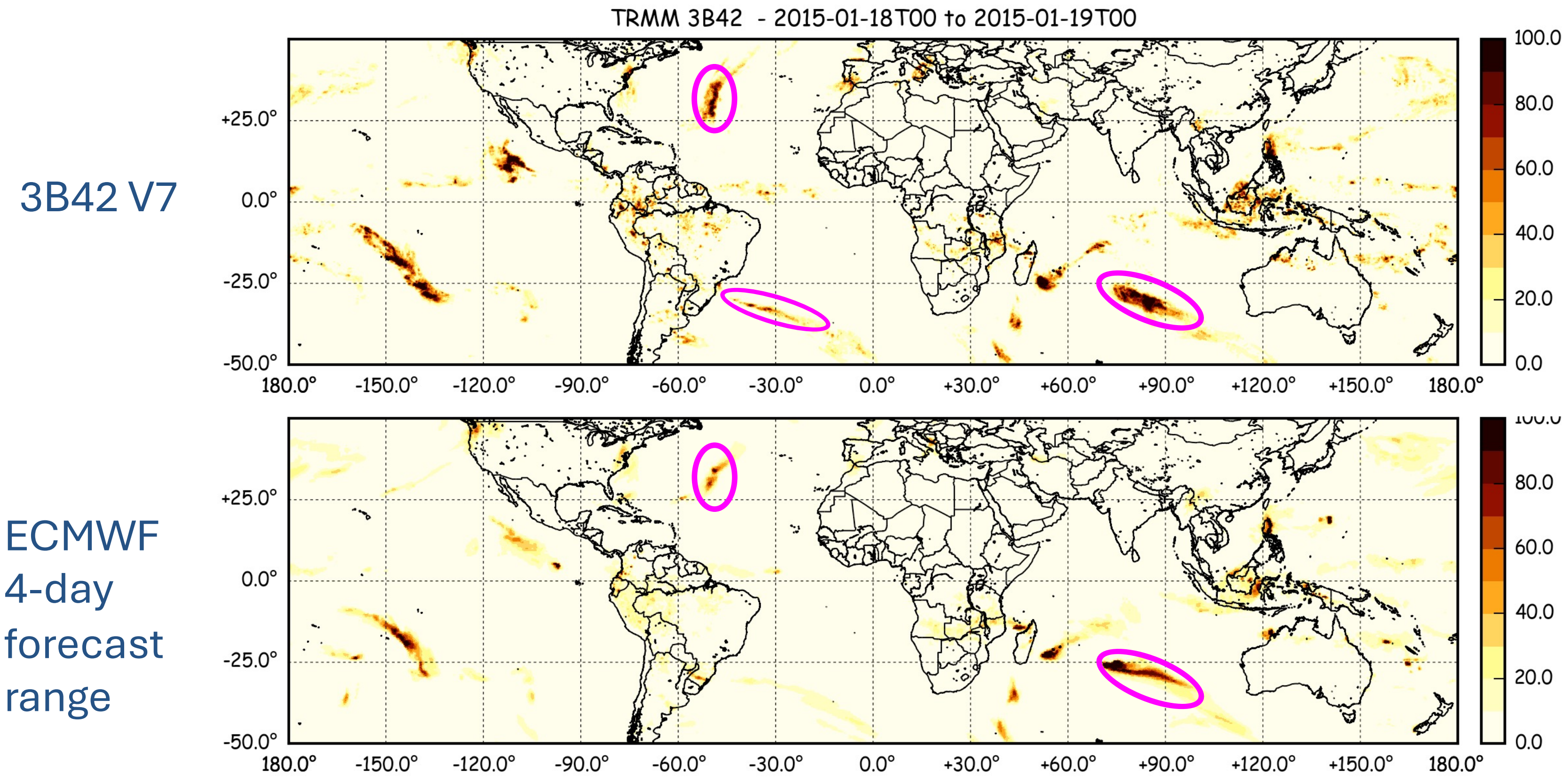
- Numerical Weather Prediction systems are now often based on ensembles, providing different scenario. The spread between these scenario can give an idea of the uncertainty level of the forecast



Example of several members from the AROME ensemble of regional forecasts of Météo-France for Oct 28, 2018

Current and Future NWP models: what are their strengths and weaknesses regarding rainfall forecasts ?

- One example of forecast error growth: 24h precipitation forecast for Jan 18th, 2015 from the ECMWF model



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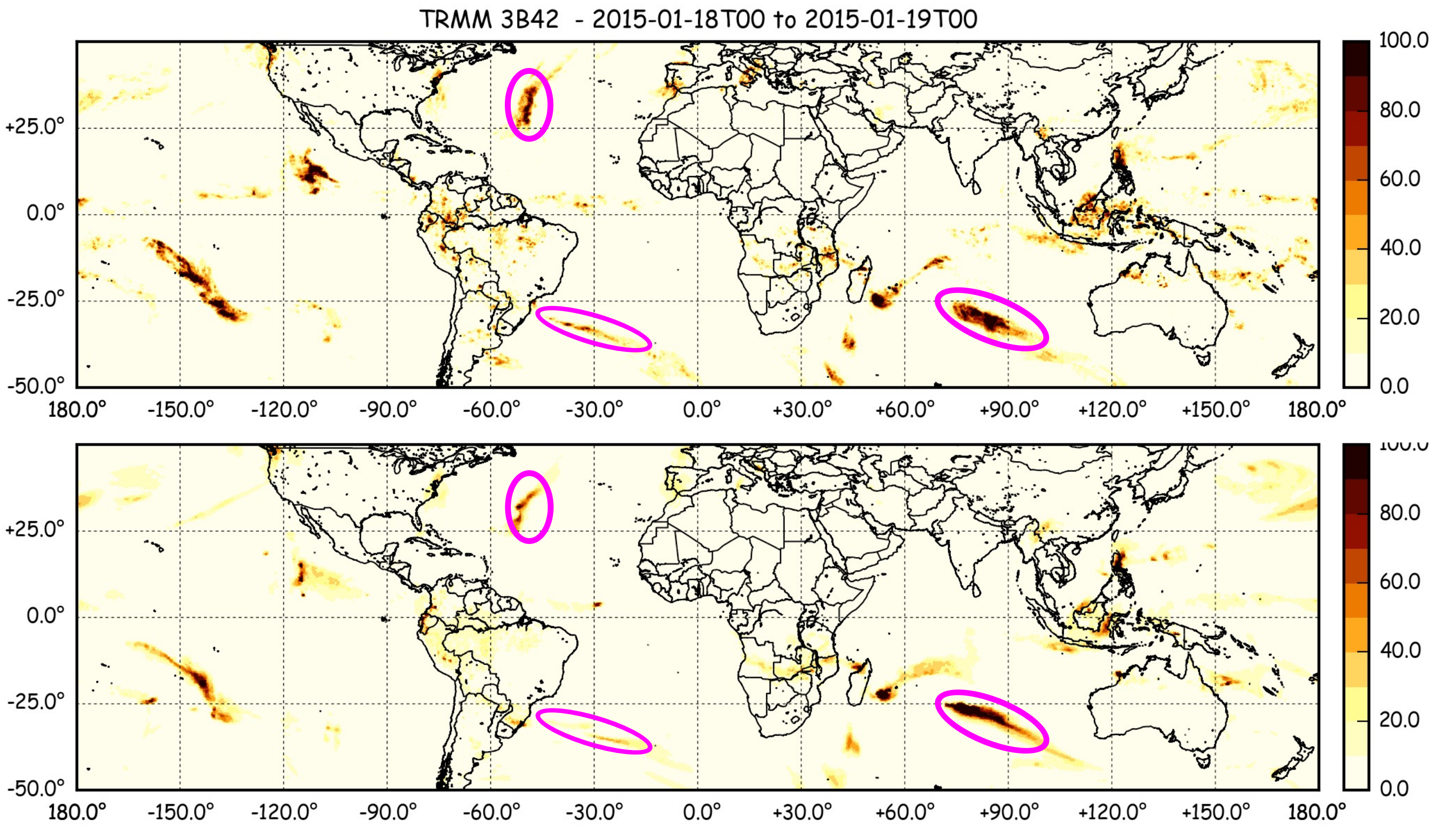
ECMWF 3-day forecast range



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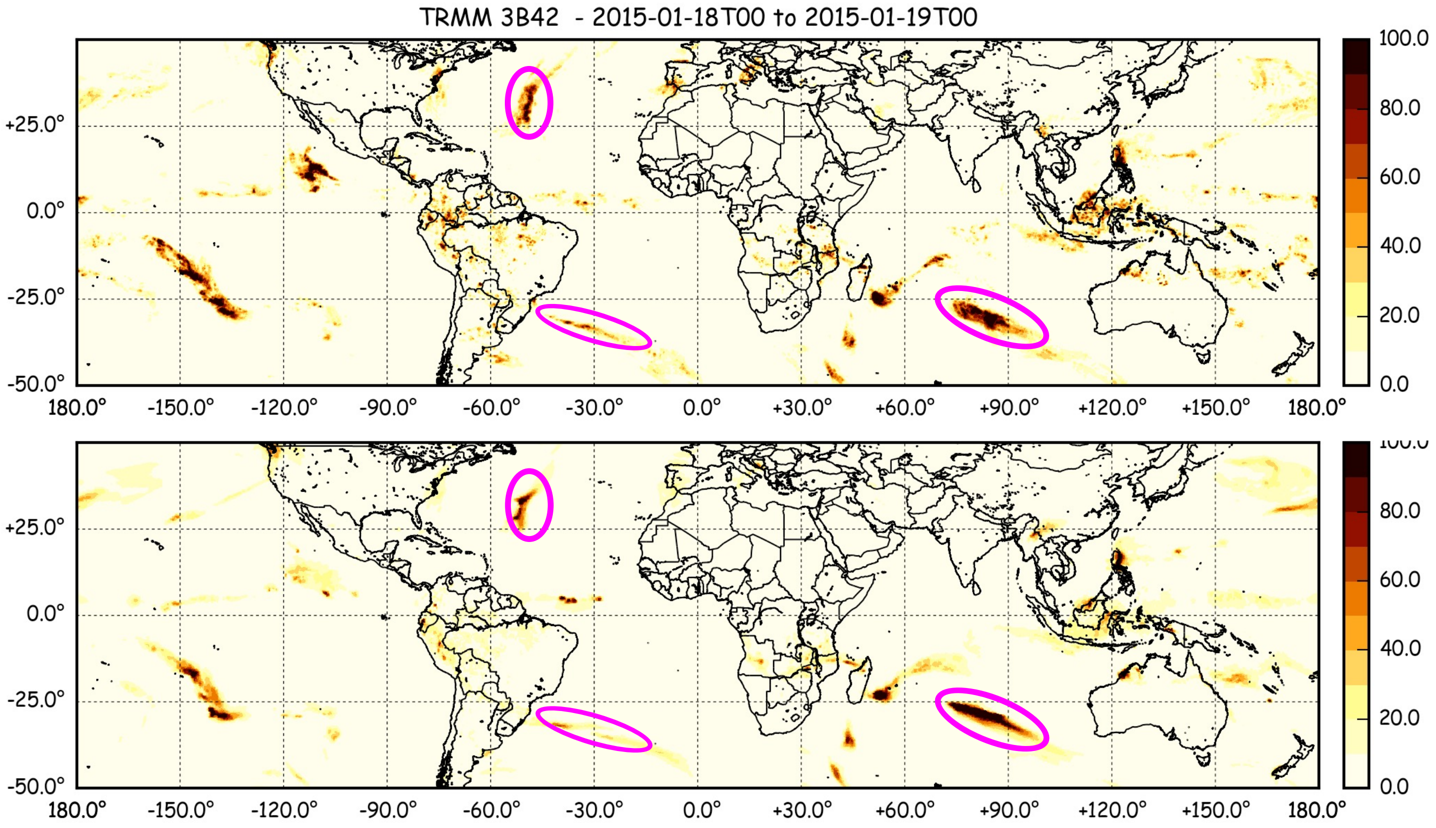
ECMWF 2-day forecast range



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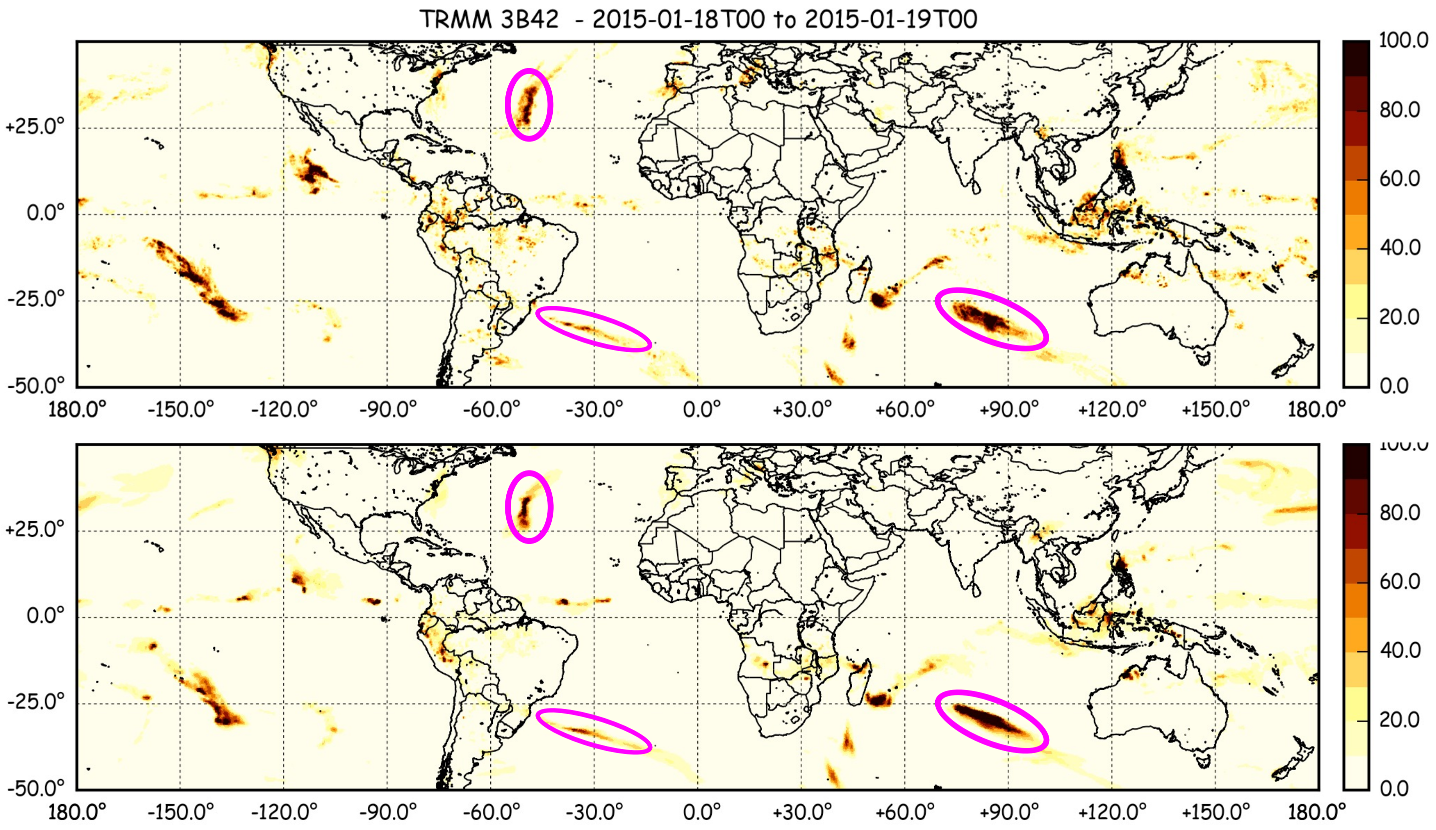


With shorter forecast range, precipitation forecasts skills improve ! Depending on the application and the accuracy needed, precipitation forecasts can be highly relevant products.

Current and Future NWP models: what are their strengths and weaknesses regarding rainfall forecasts ?

- From its beginnings, Numerical Weather Prediction has been confronted with having to solve an initial-value problem without the right initial data.
- Model state space:

  MASS (temperature, pressure...)

  Radiosondes, surface observations, satellite sounders, aircraft

  MOISTURE (humidity, clouds, precipitation...)

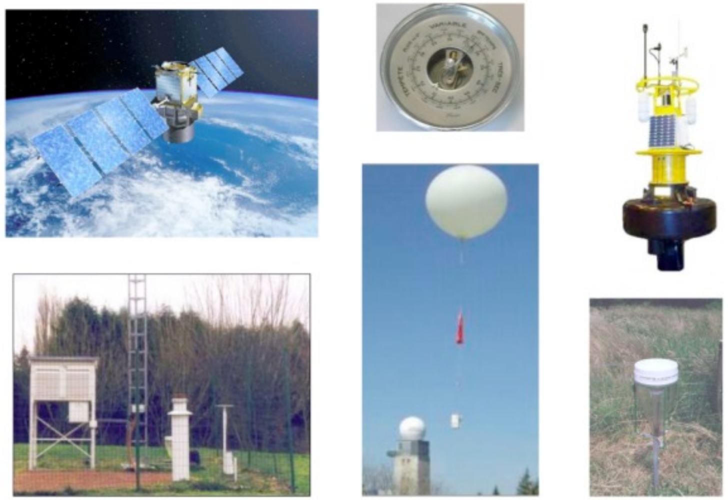
  Radiosondes, surface obs., satellite sounders and imagers, aircraft, radar, lidar

  DYNAMICS (wind, vorticity, convergence...)

  Radiosondes, surface obs., satellite imagers, satellite scatt./ radar/lidar, aircraft

  COMPOSITION (ozone, aerosol...)

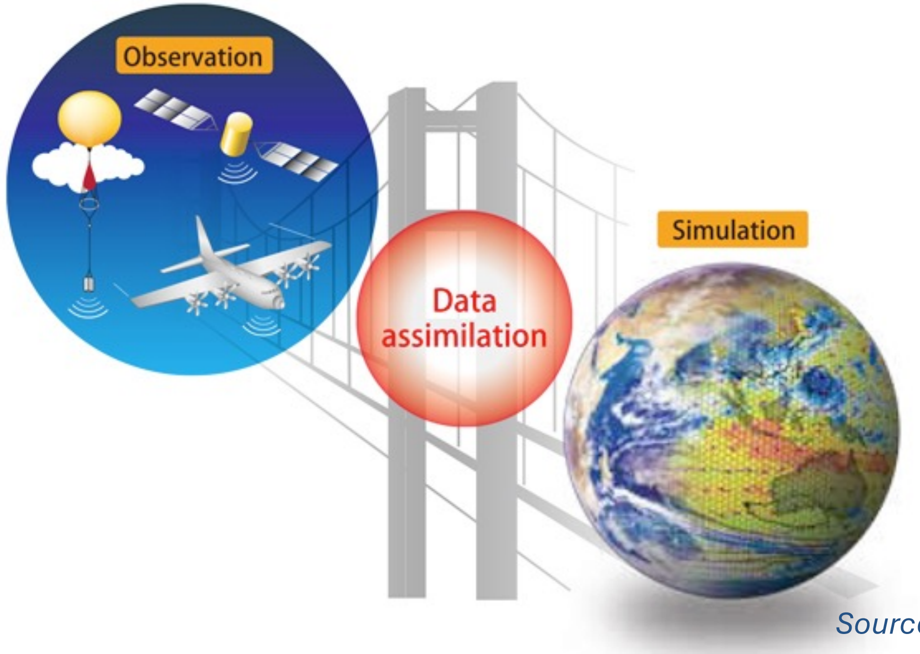
  Ozone sondes, surface observations, satellite sounders



Source: http://pedagotech.inp-toulouse.fr

Current and Future NWP models: what are their strengths and weaknesses regarding rainfall forecasts ?

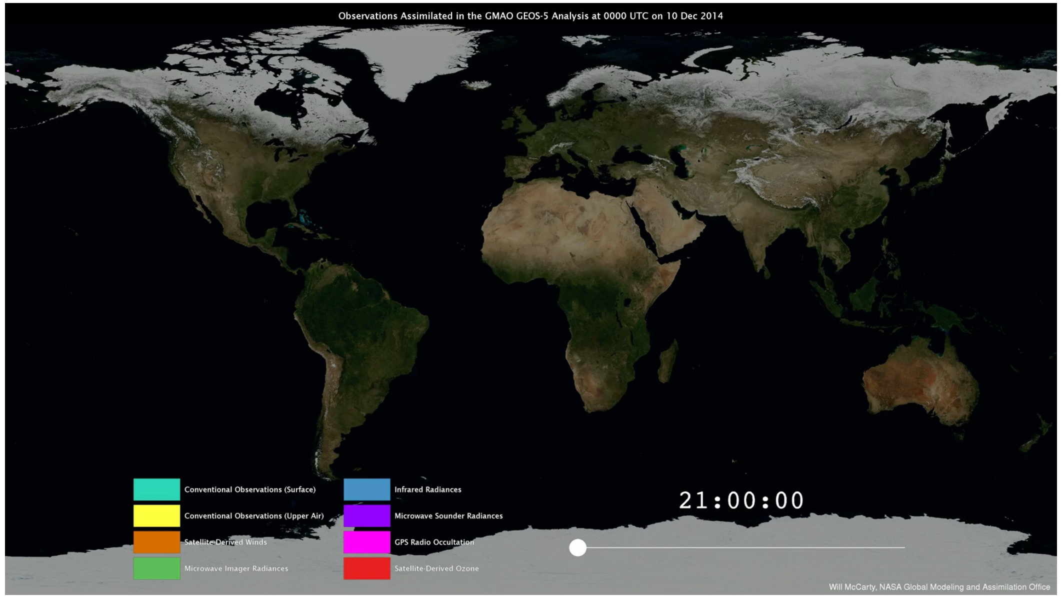
- The number of observations of the present observing system for analysis is orders of magnitude smaller than the number of values required to specify the model state. The initial state of the numerical model cannot therefore be determined from the available observations alone.
- An analysis of the present weather combines information from both the model and observations, thanks to data assimilation.



Source: http://daconf15.umd.edu/

Current and Future NWP models: what are their strengths and weaknesses regarding rainfall forecasts ?

- Performing an analysis is a complex mathematical problem which has many common points with the inverse problem (retrievals).
- One of the challenges it needs to face is to combine millions of observations of different kinds in an optimal way with a model prior information and compute the best estimate of the atmospheric state



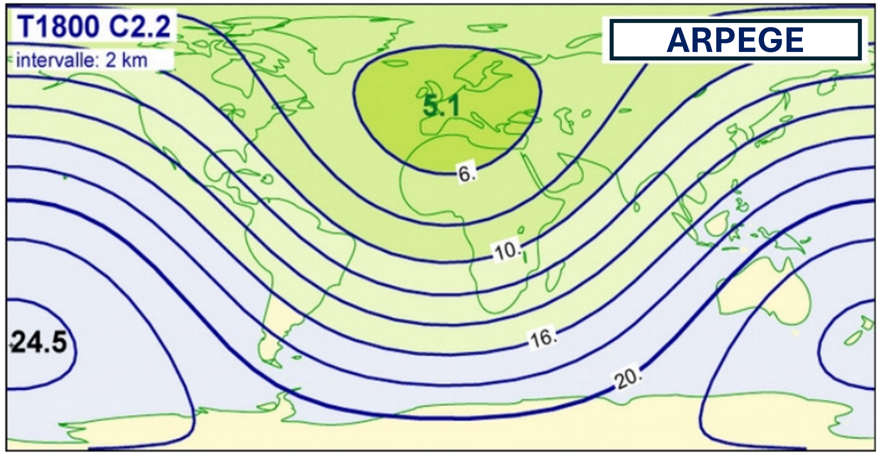
NASA's Global Modeling and Assimilation Office GEOS-5 global model

5 millions of observations during each 6-hour assimilation period

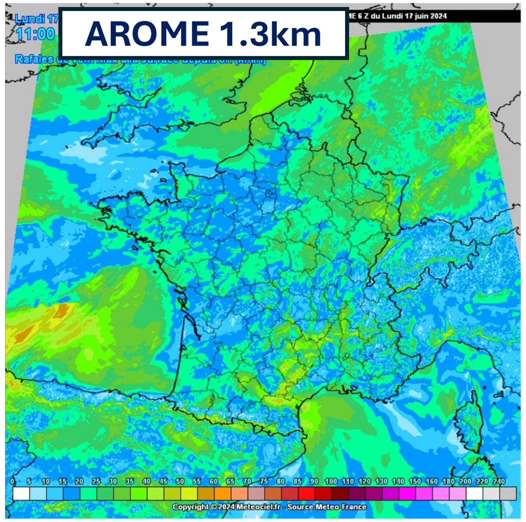
Source: https://svs.gsfc.nasa.gov/

Current and Future NWP models: what are their strengths and weaknesses regarding rainfall forecasts ?

- The current generation of NWP systems already suffer from a lack of constrain on its initial conditions with the current observing system.



~8.10^6 observations assimilated every 6 hours for ~200.10^6 variables to initialize



~100 000 observations assimilated every hours for ~800.10^6 variables to initialize


Radiosondes

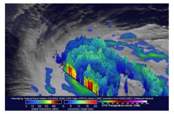

Surface stations

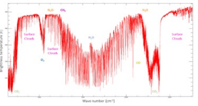

Aircraft data

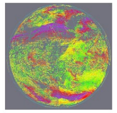

GNSS ground receivers


Wind lidar

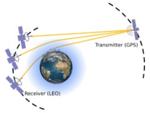

Ground radar


Microwave sounding from space


Infrared sounding from space


Winds derived from imagery


Scatterometer


GNSS Radio-occultation

Current and Future NWP models: what are their strengths and weaknesses regarding rainfall forecasts ?

- Model forecast skills vary from one region to another over the globe (e.g. over Europe, ECMWF rain forecasts often have more skills than any satellite retrievals, not the case in the Tropics)
- These precipitation products are **forecasts**, they thus fulfill different needs than satellite retrievals => different times of validity/availability
- There is still a lot of room for improving model rain forecasts, in particular with better initial conditions constraining clouds and precipitation

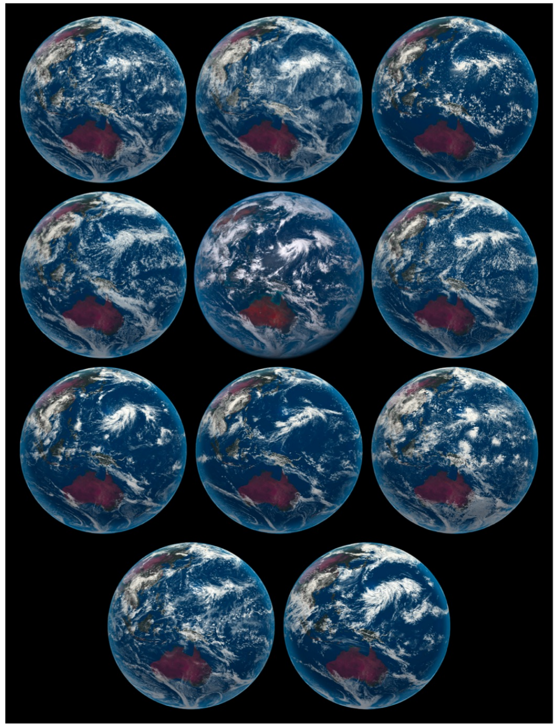
⇒ Satellite clouds and precipitation observations can be used to this endeavor, **See Section 3**

⇒ Model errors in clouds and precipitation need to be documented first with different kind of observations, **See Section 2**

Current and Future NWP models: what are their strengths and weaknesses regarding rainfall forecasts ?

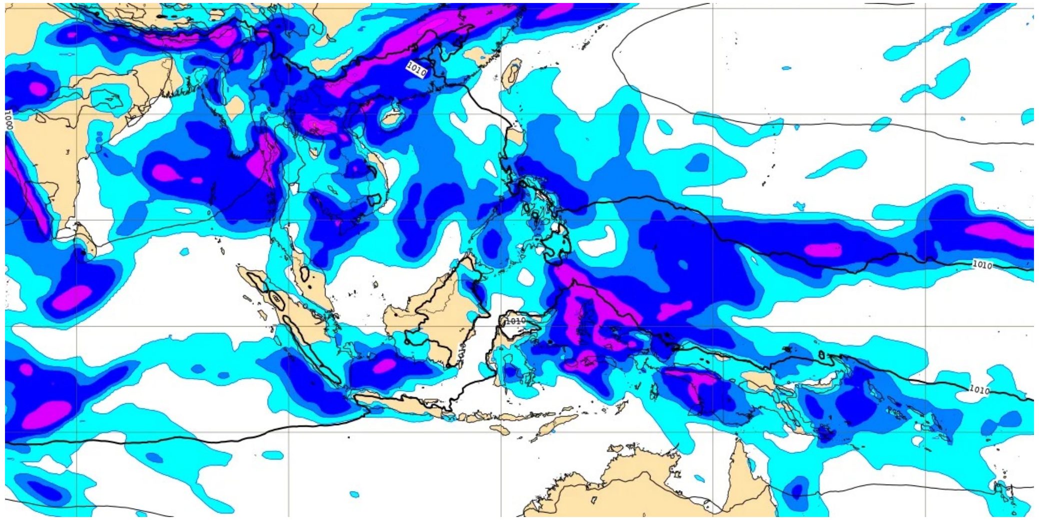
- Research on two major evolutions is ongoing with very different upcoming challenges for data assimilation :

Kilometric scale modeling of the Earth system



(Source : Stevens et al. 2019)

Numerical forecasts with AI-based models



(Source : ECMWF, AIFS ML model)

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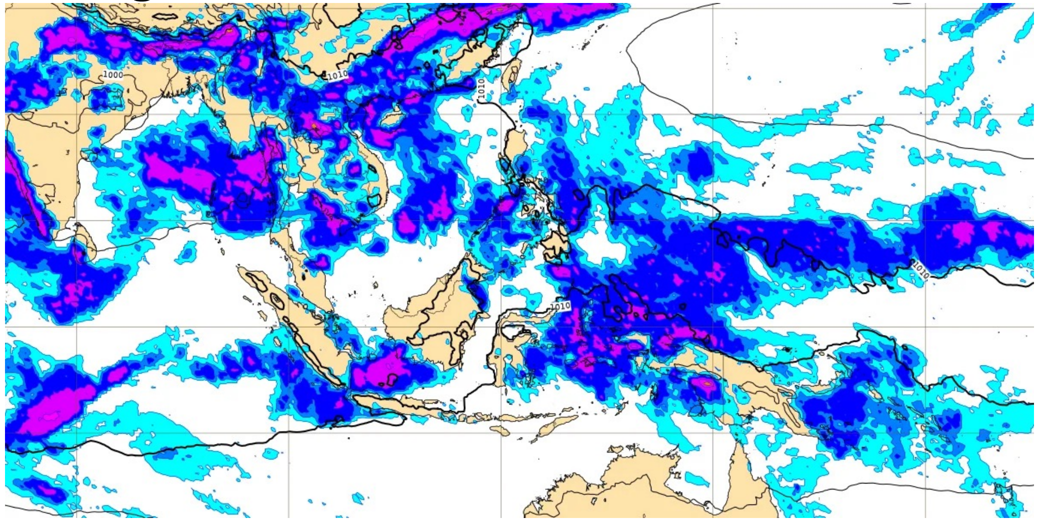
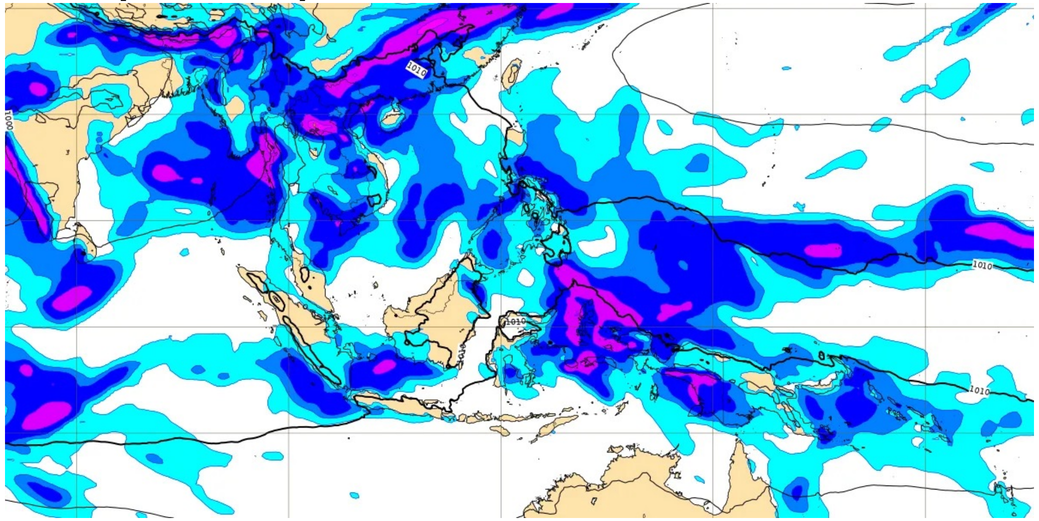
Tue 25 Jun 2024 00 UTC (T+12)

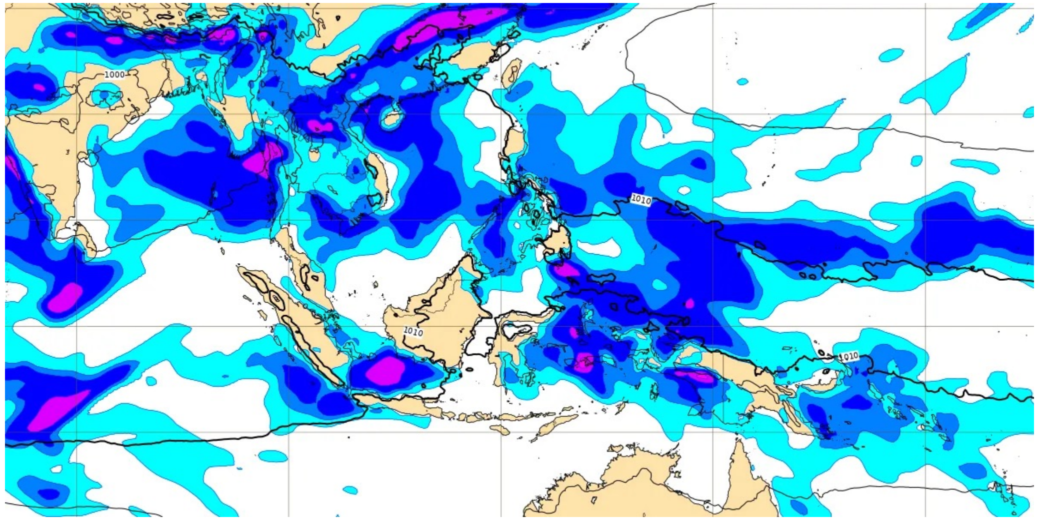
IFS High resolution forecast



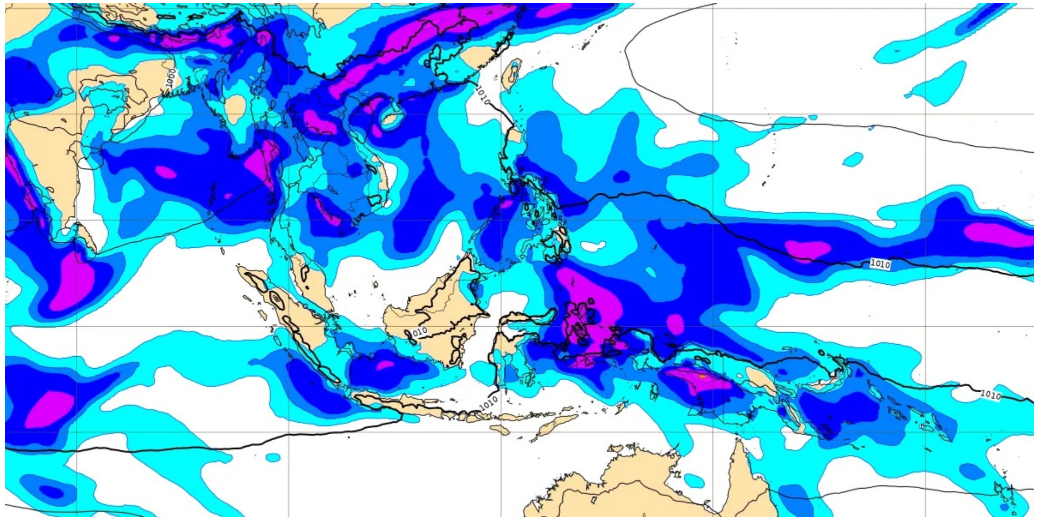
AIFS (ECMWF) ML model



FuXi ML model



GraphCast ML model



Runs of different AI-based models performed at ECMWF, initialized with the same analysis

ECMWF

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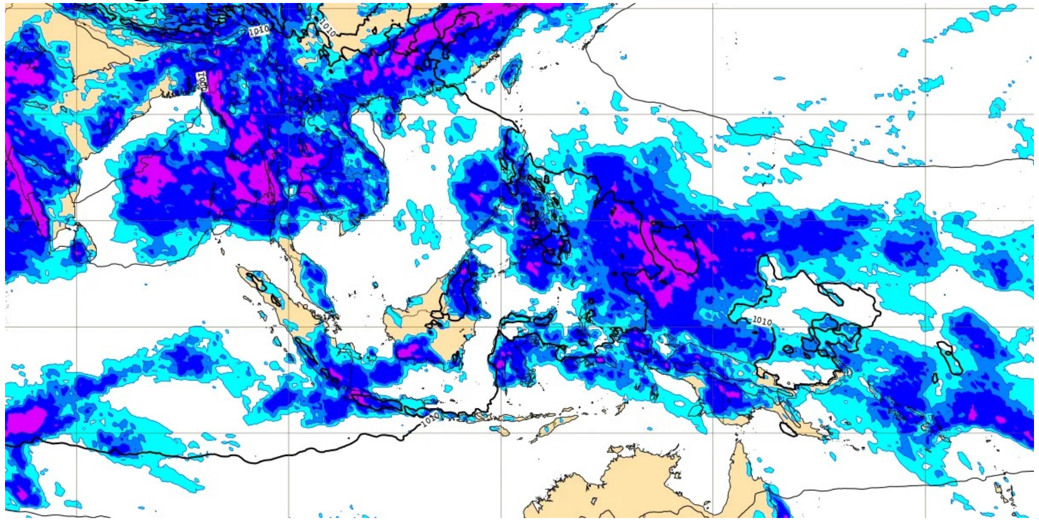
Tue 25 Jun 2024 00 UTC (T+24)

IFS High resolution forecast



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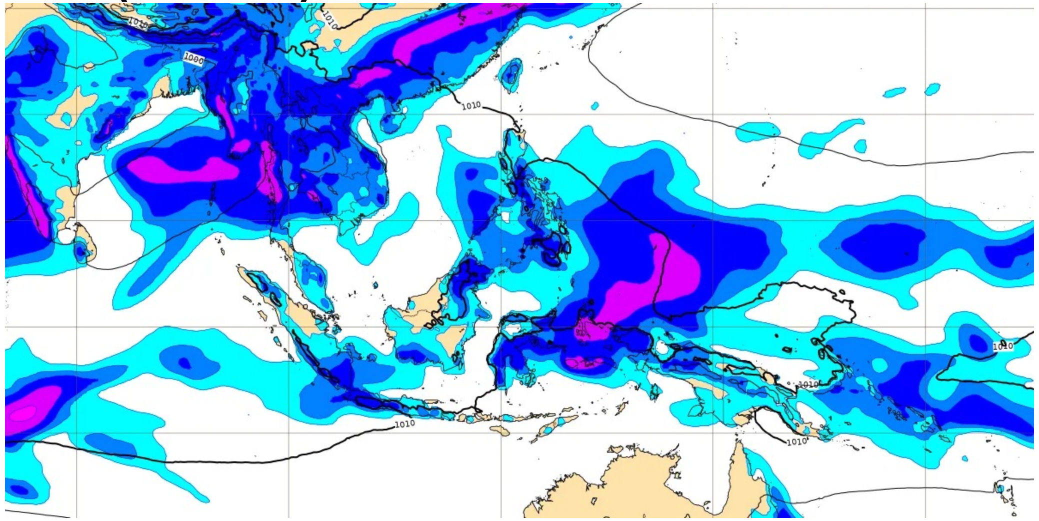

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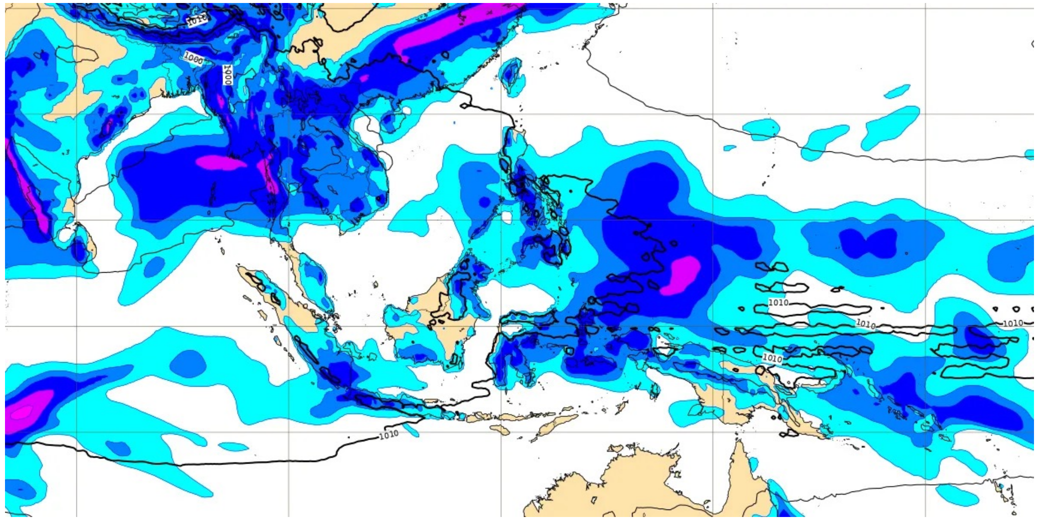

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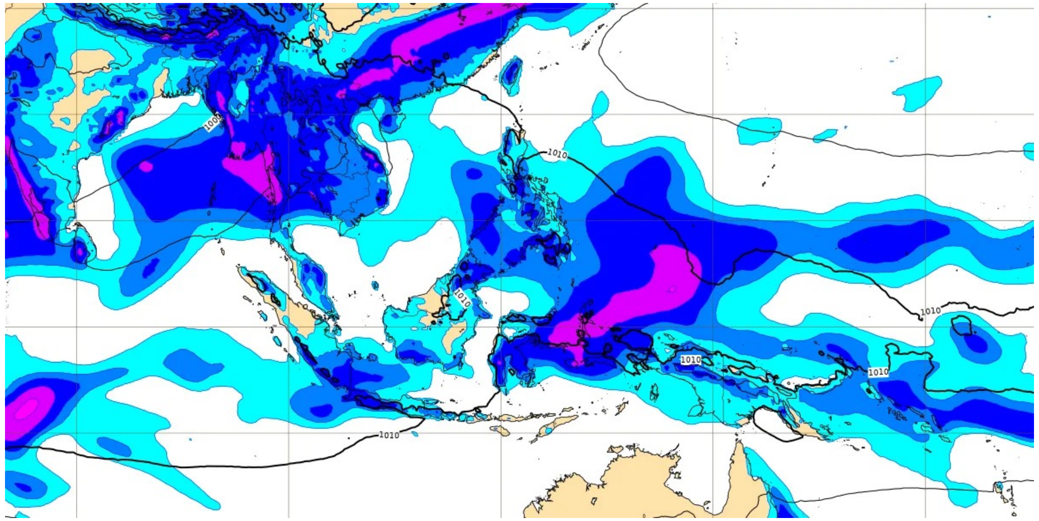

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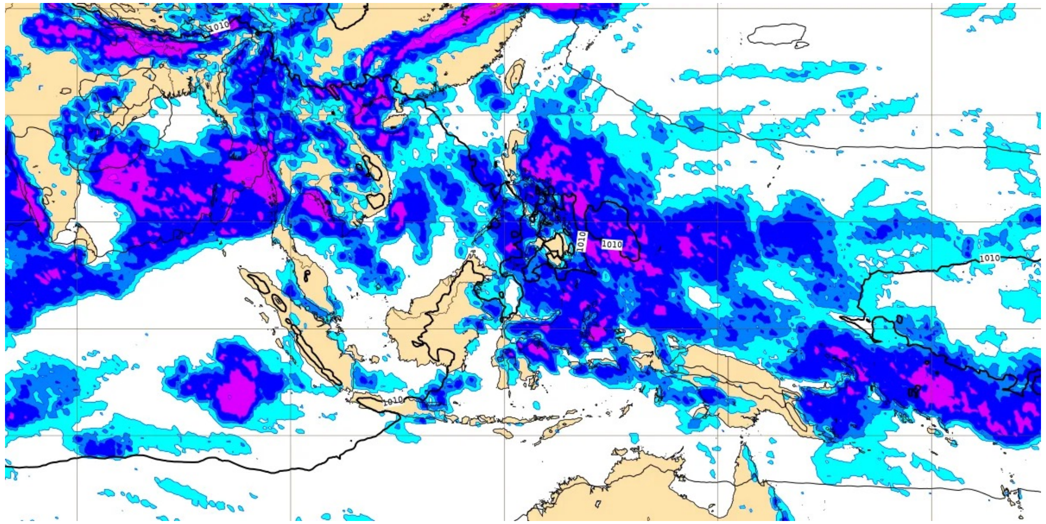
Tue 25 Jun 2024 00 UTC (T+36)

IFS High resolution forecast



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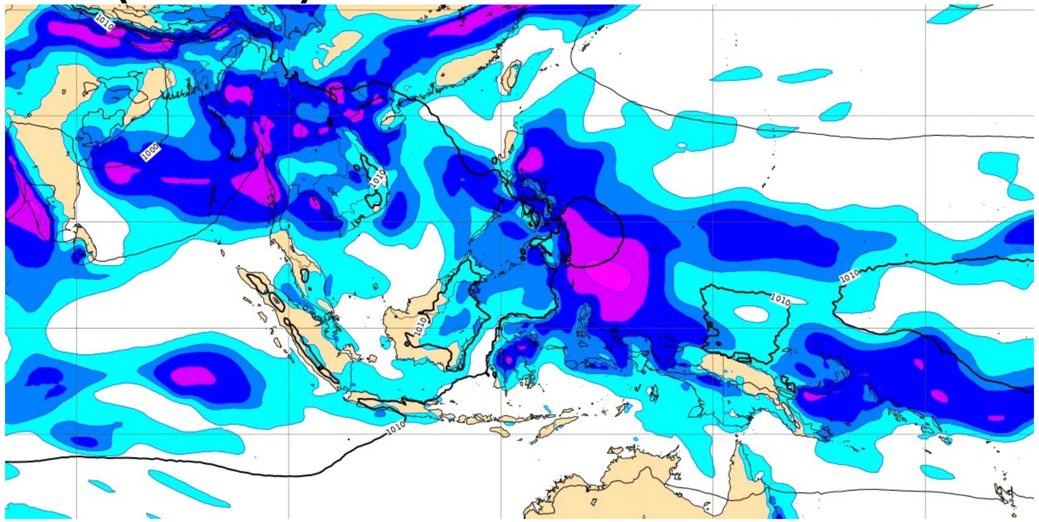

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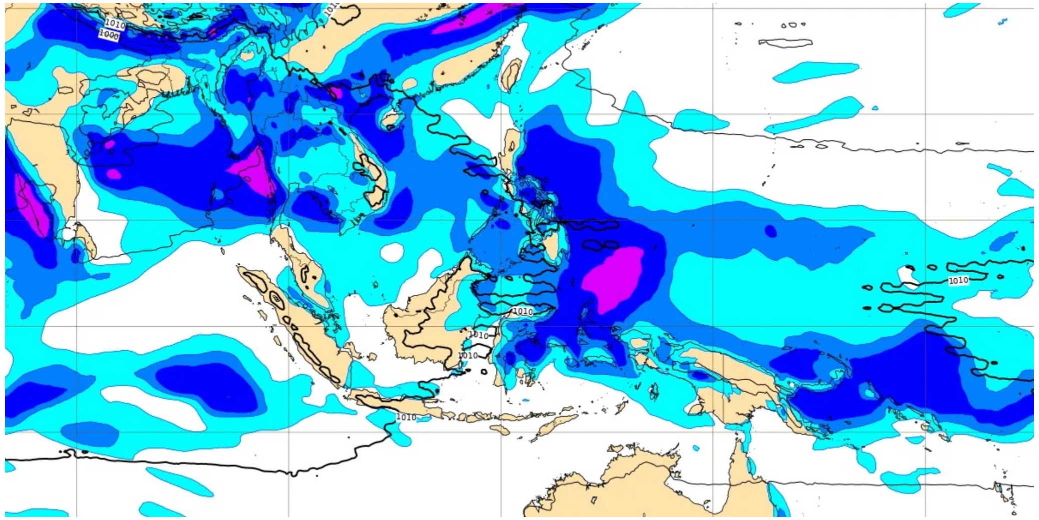
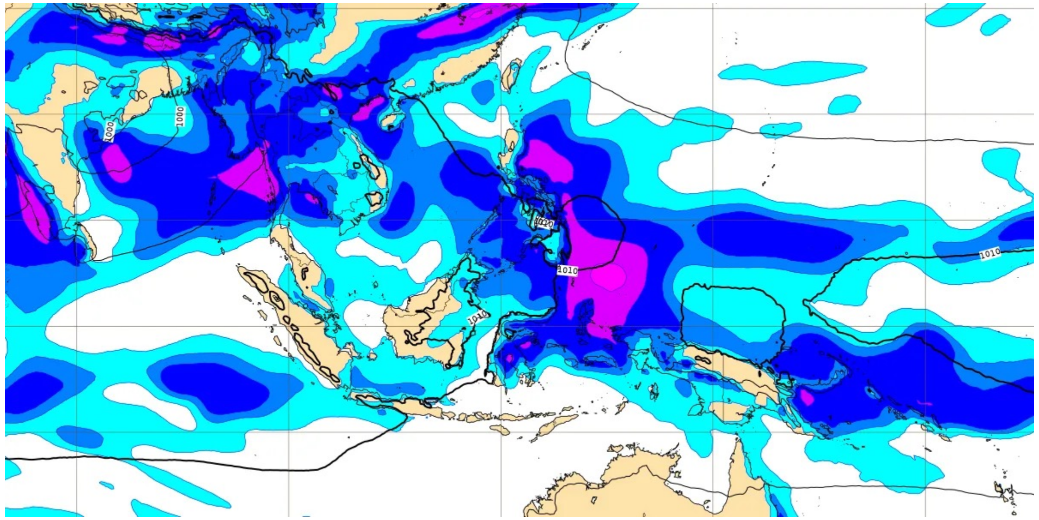


GraphCast ML model

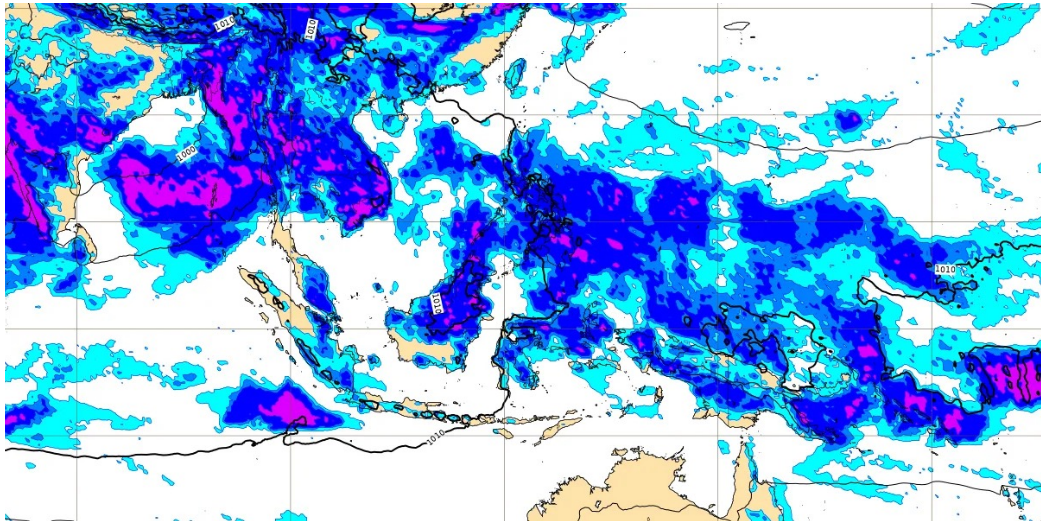


Runs of different AI-based models performed at ECMWF, initialized with the same analysis

ECMWF

Tue 25 Jun 2024 00 UTC (T+48)

IFS High resolution forecast



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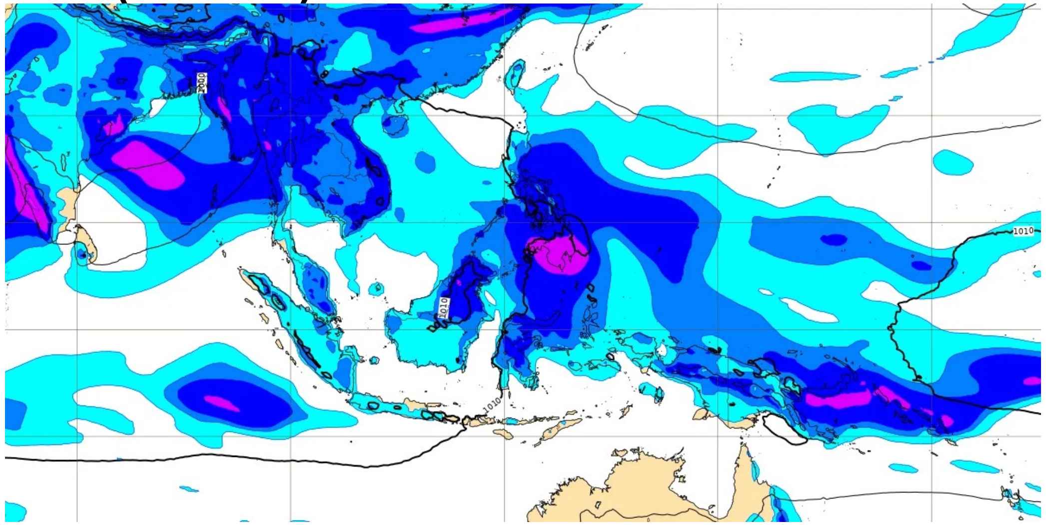

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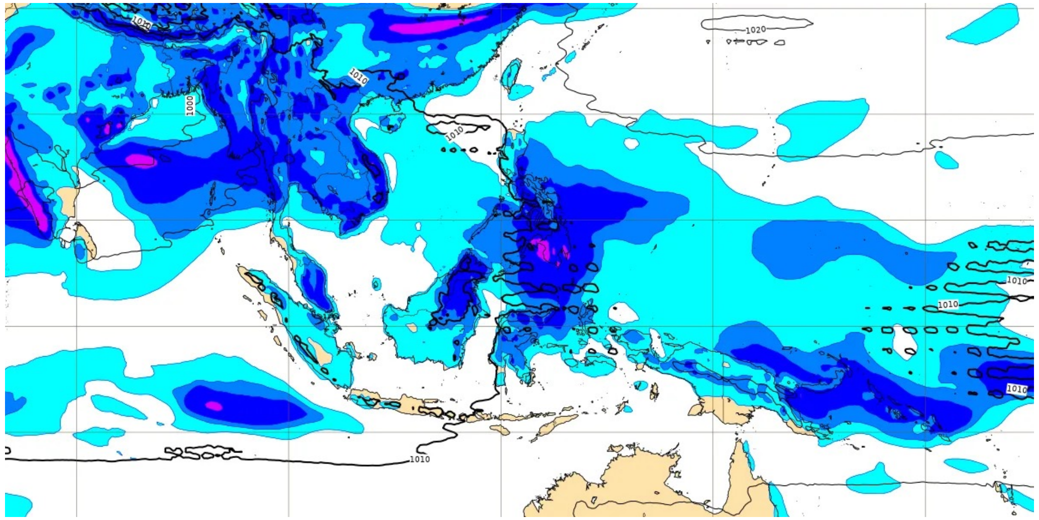

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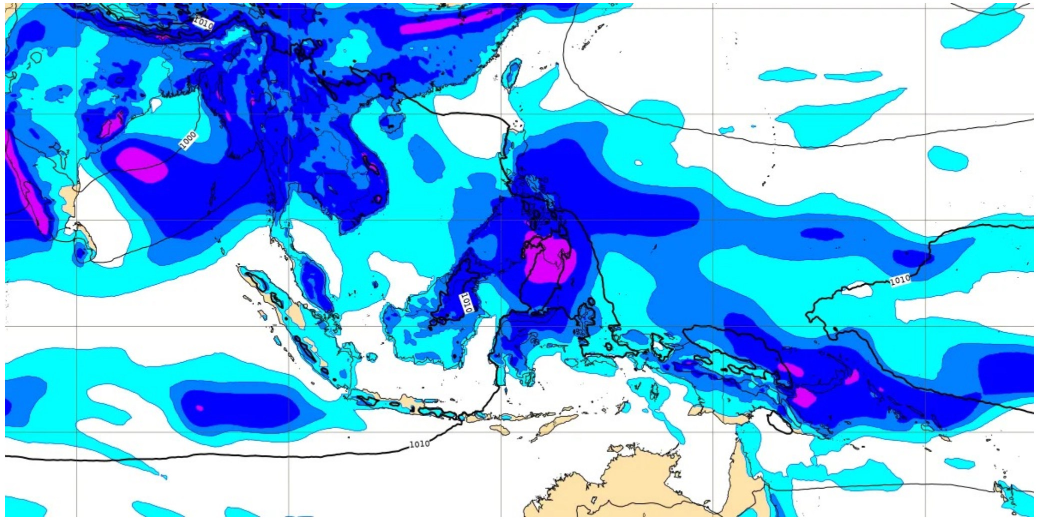


Runs of different AI-based models performed at ECMWF, initialized with the same analysis

Outline of the presentation

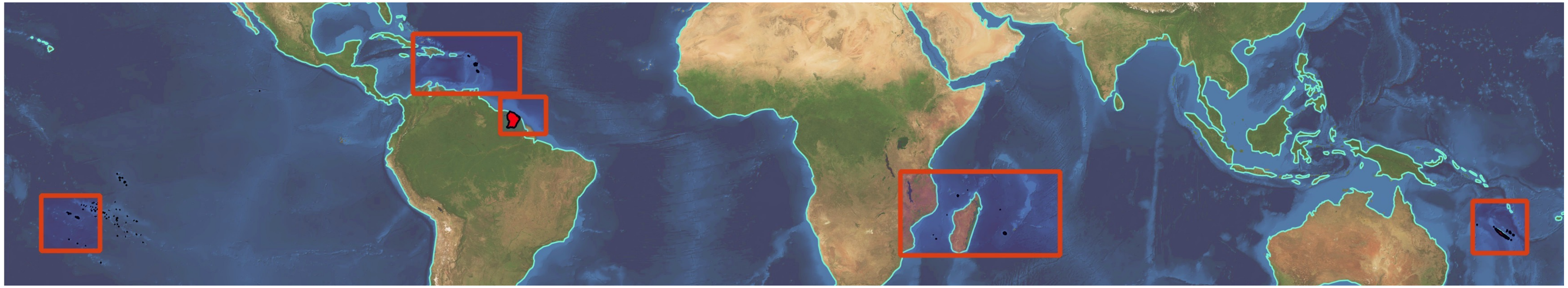
1. Current and Future NWP models: what are their strengths and weaknesses regarding rainfall forecasts ?
2. **How rainfall forecasts can be validated ?**
3. How rainfall forecasts can be improved ?

How rainfall forecasts can be validated ?

Rainfall forecasts need to be compared to observations for documenting their strengths and weaknesses:

- Over land and instrumented areas, rain gauges or radar data can be good references
- Over oceans or other less instrumented areas, satellite rainfall products can be good alternatives

Example of the AROME-OM domains operated at Météo-France:

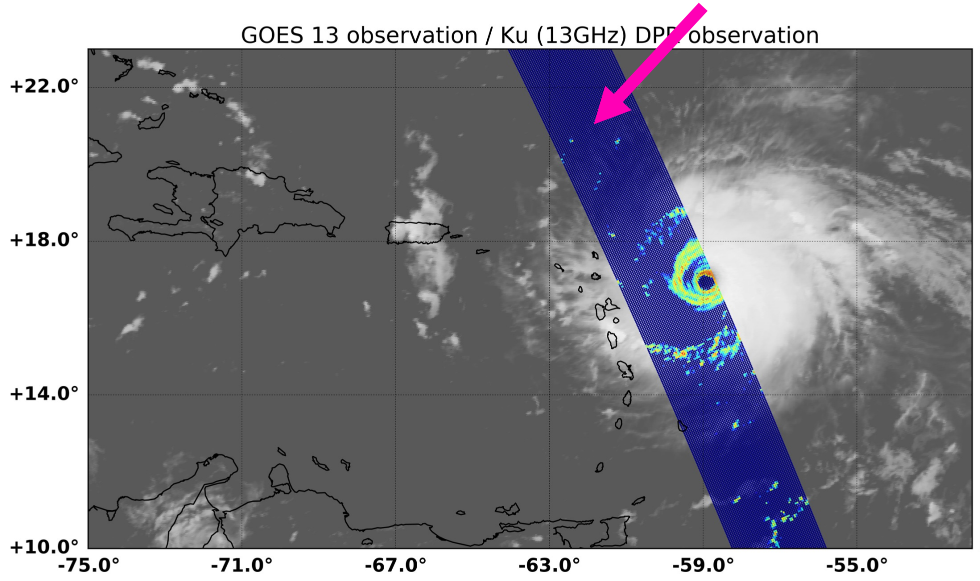


How rainfall forecasts can be validated ?

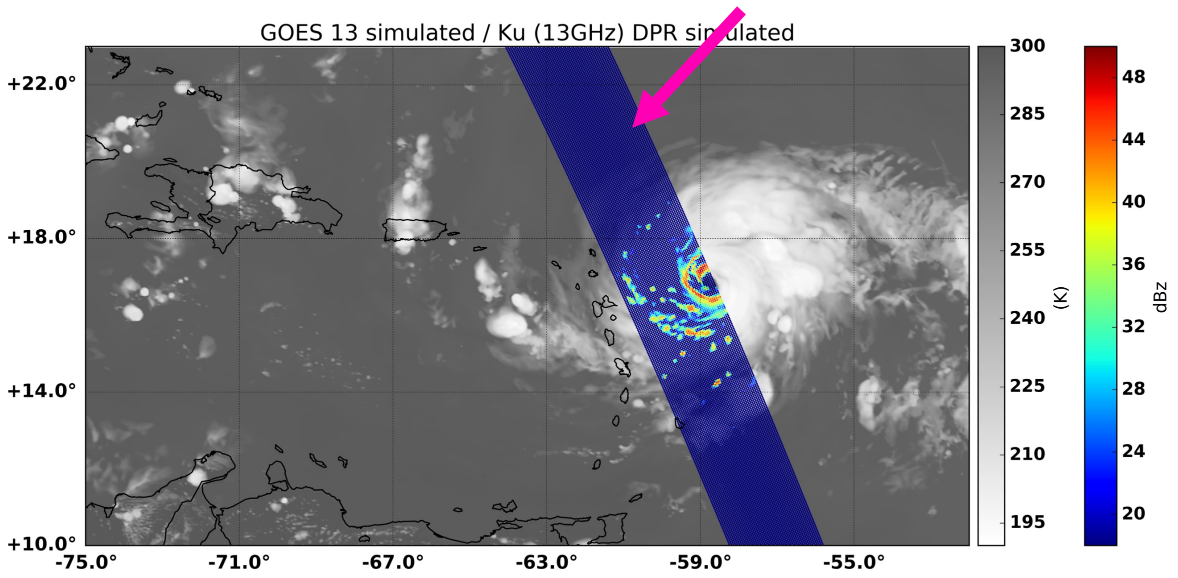
An important aspect is the spatial and temporal scale at which you want to validate your forecasts:

- **At fine scale** (e.g. kilometric, instantaneous), interesting references to use are space radar data: the comparison can be performed in both observation space (reflectivity) or model space (rain rate retrieval)

Observations from GPM/DPR/Ku at 4km



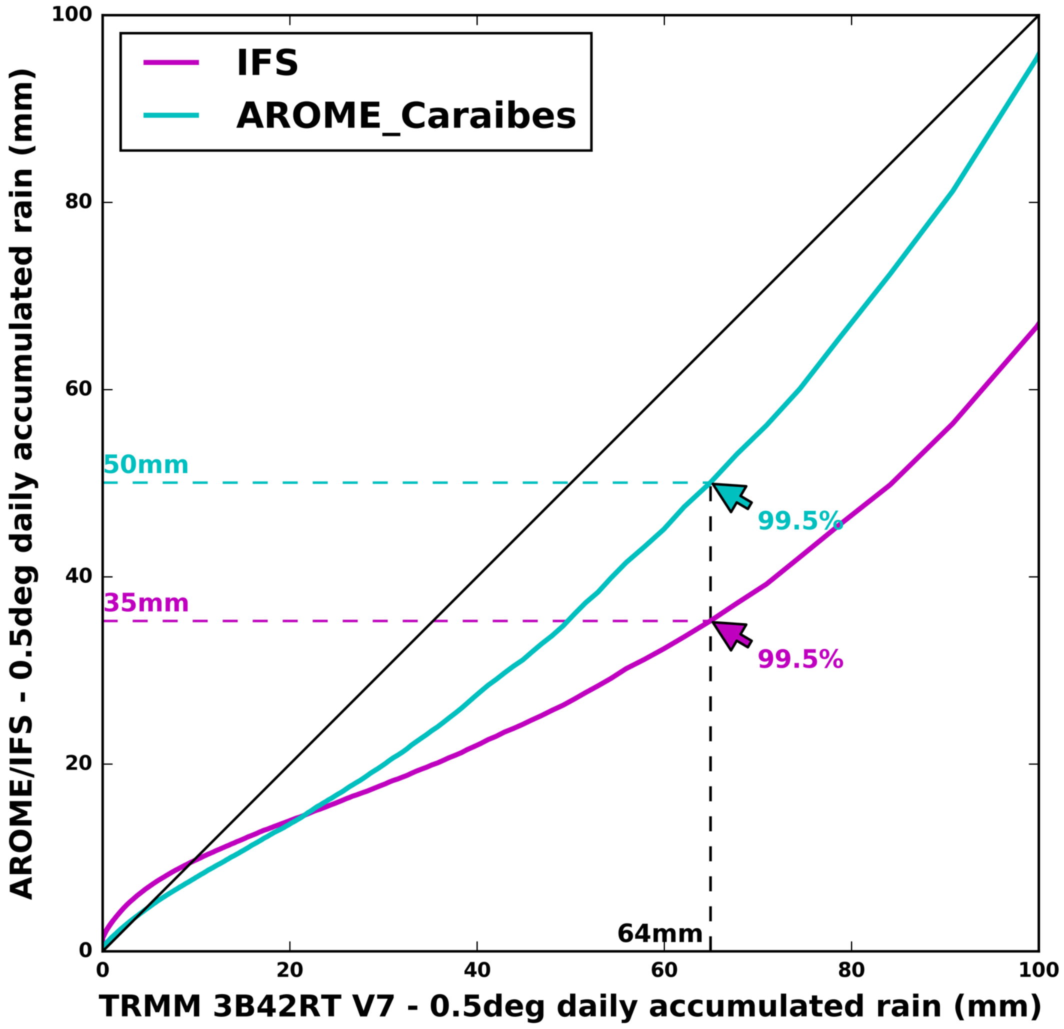
Simulation of GPM/DPR/Ku at 4km



How rainfall forecasts can be validated ?

- **At larger scale** (e.g. daily accumulation, 0.5° x 0.5°) combined IR+MW products are highly relevant references

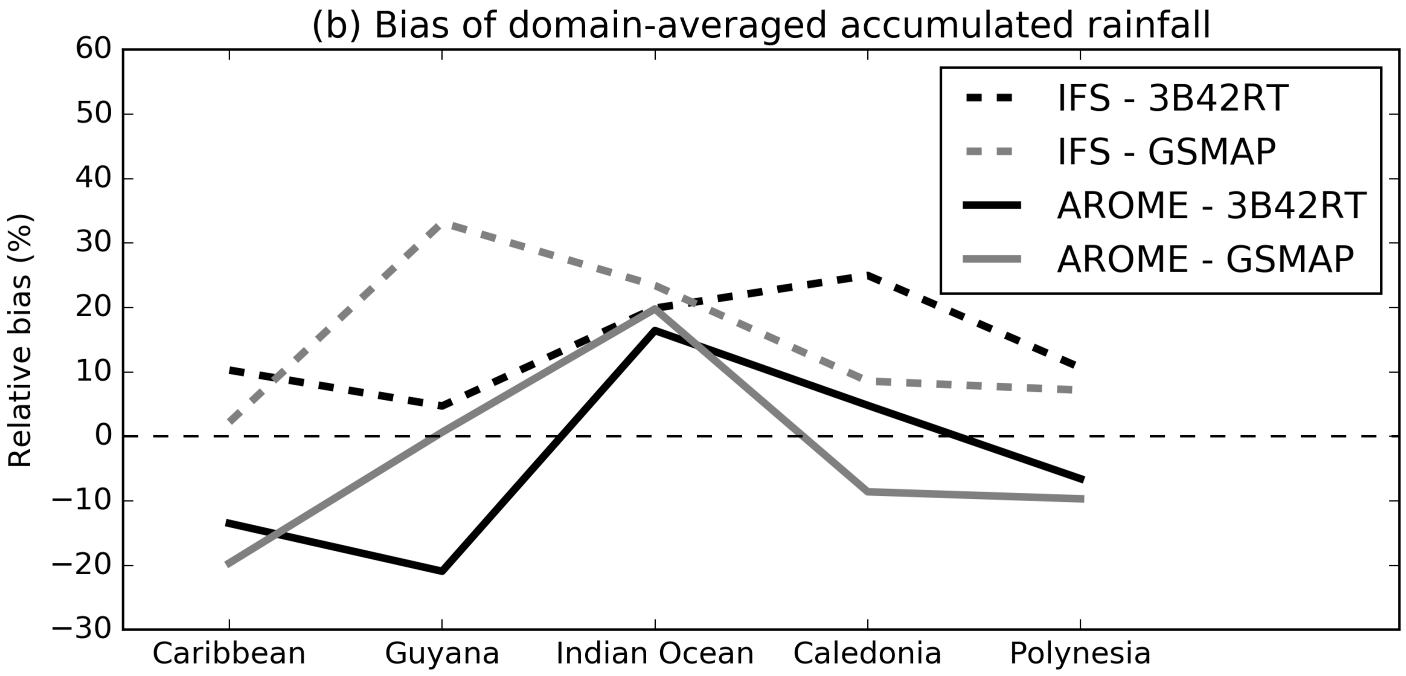
Example of comparisons between AROME over the Caribbean's, the ECMWF model and TRMM 3B42 rain estimations at 1-day/0.5°



How rainfall forecasts can be validated ?

- **At larger scale** (e.g. daily accumulation, 0.5° x 0.5°) combined IR+MW products are highly relevant references

For assessing biases, using several references are important, In particular when part of the model domain is over land (more uncertainty of the satellite rainfall products)

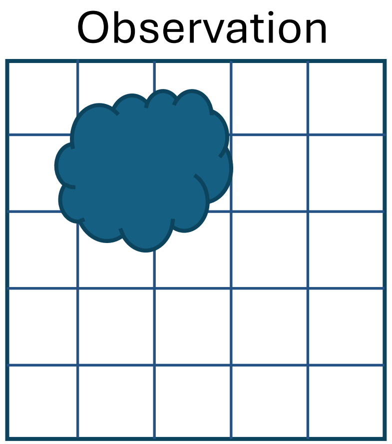


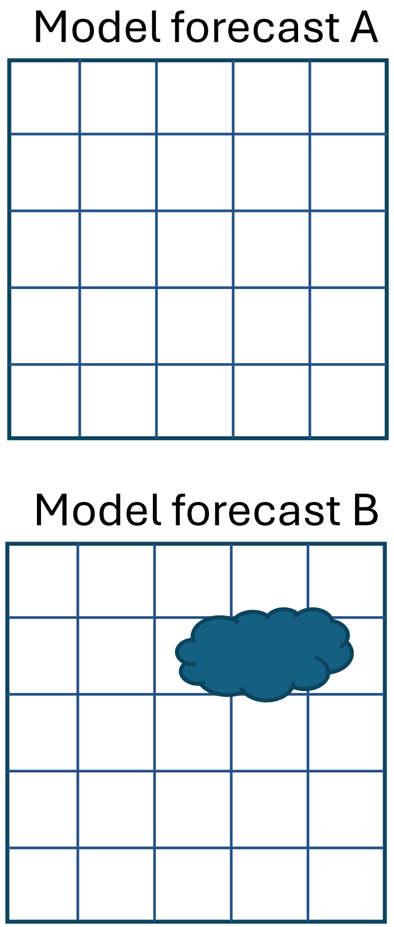
=> When a bias is identified, then the tricky part is to characterize the causes of it !

How rainfall forecasts can be validated ?

- **At larger scale** (e.g. daily accumulation, 0.5° x 0.5°) combined IR+MW products are highly relevant references

For assessing the representation of the model variability,
Fuzzy verification is often used (e.g. Ebert, 2008)
=> Take into neighborhood for the verification



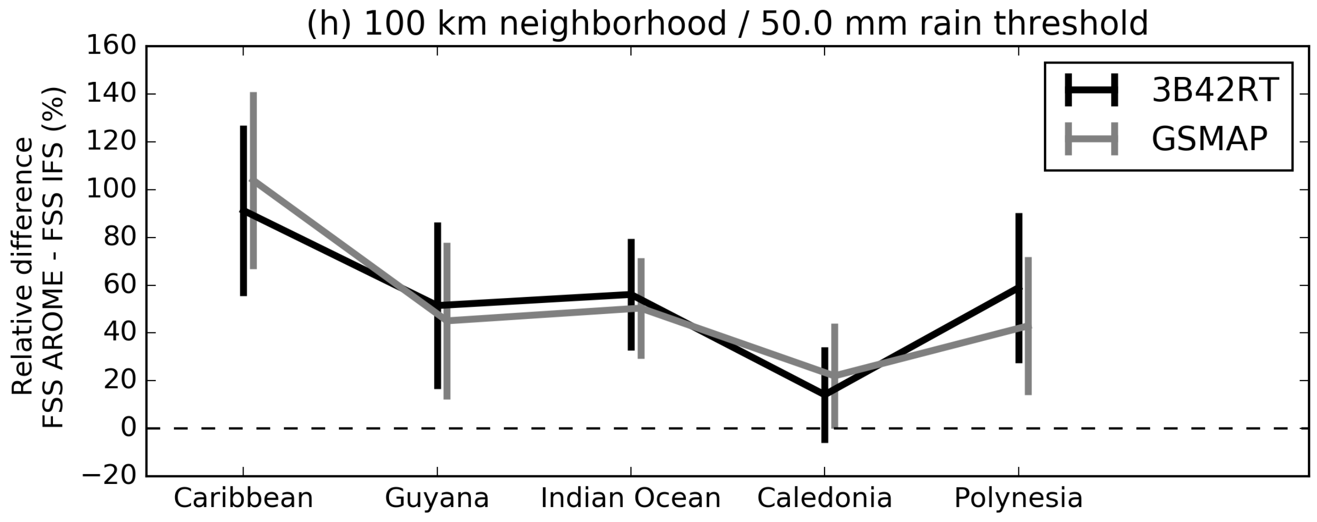


Is model-forecast B more useful than forecast A for your application?
For forecaster, the answer is often yes!

How rainfall forecasts can be validated ?

- **At larger scale** (e.g. daily accumulation, 0.5° x 0.5°) combined IR+MW products are highly relevant references

Example of Brier Skill Score differences between AROME in the Tropics, the ECMWF model and TRMM 3B42/GSMAP rain estimations at 1-day/0.5
Over a one year period



=> The representation of strong rainfall events is often better forecasted by regional non hydrostatic model with no parametrized convection

Outline of the presentation

1. Current and Future NWP models: what are their strengths and weaknesses regarding rainfall forecasts ?
2. How rainfall forecasts can be validated ?
3. **How rainfall forecasts can be improved ?**

How rainfall forecasts can be improved ?

Several pathways can be used to improve model precipitation forecasts:

- Model physics can be improved through different developments like parametrization improvements, microphysics scheme improvements etc

- Initial conditions can be improved through the assimilation of observations of clouds and precipitation => same data that are used in satellite precipitation product
  - Improvements can arise from new data assimilation algorithmic developments
  - Or new observational developments (e.g. usage of new observation types)

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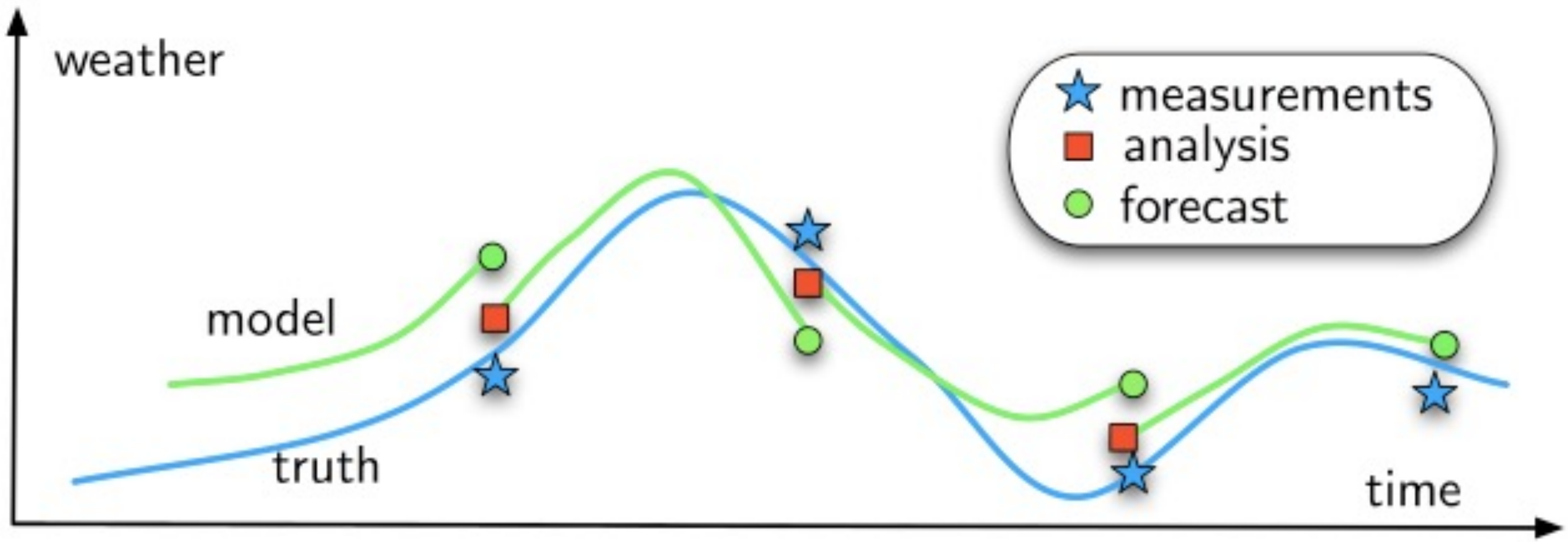
How rainfall forecasts can be improved ?

- The analysis minimizes a combination of distances :

$$J(\blacksquare) = \frac{1}{2}\| \blacksquare - \bullet \|_B^2 + \frac{1}{2}\| \bigstar - \mathcal{G}(\blacksquare)\|_R^2$$

- The model provides a forecast from which the observation operator extracts quantities which are compared to actual data observation. The analysis is a field that combines these observations with the model forecast. It is then used as an initial condition for the next forecast.



Source: http://pedagotech.inp-toulouse.fr

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How rainfall forecasts can be improved ?

$$\begin{aligned} \mathbf{x}_a &= \text{Arg}\min J \\ J(\mathbf{x}) &= (\mathbf{x}-\mathbf{x}_b)^T \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b) + (\mathbf{y}-H[\mathbf{x}])^T \mathbf{R}^{-1}(\mathbf{y}-H[\mathbf{x}]) \\ &= J_b(\mathbf{x}) + J_o(\mathbf{x}) \end{aligned}$$

In the classical data assimilation formalism:

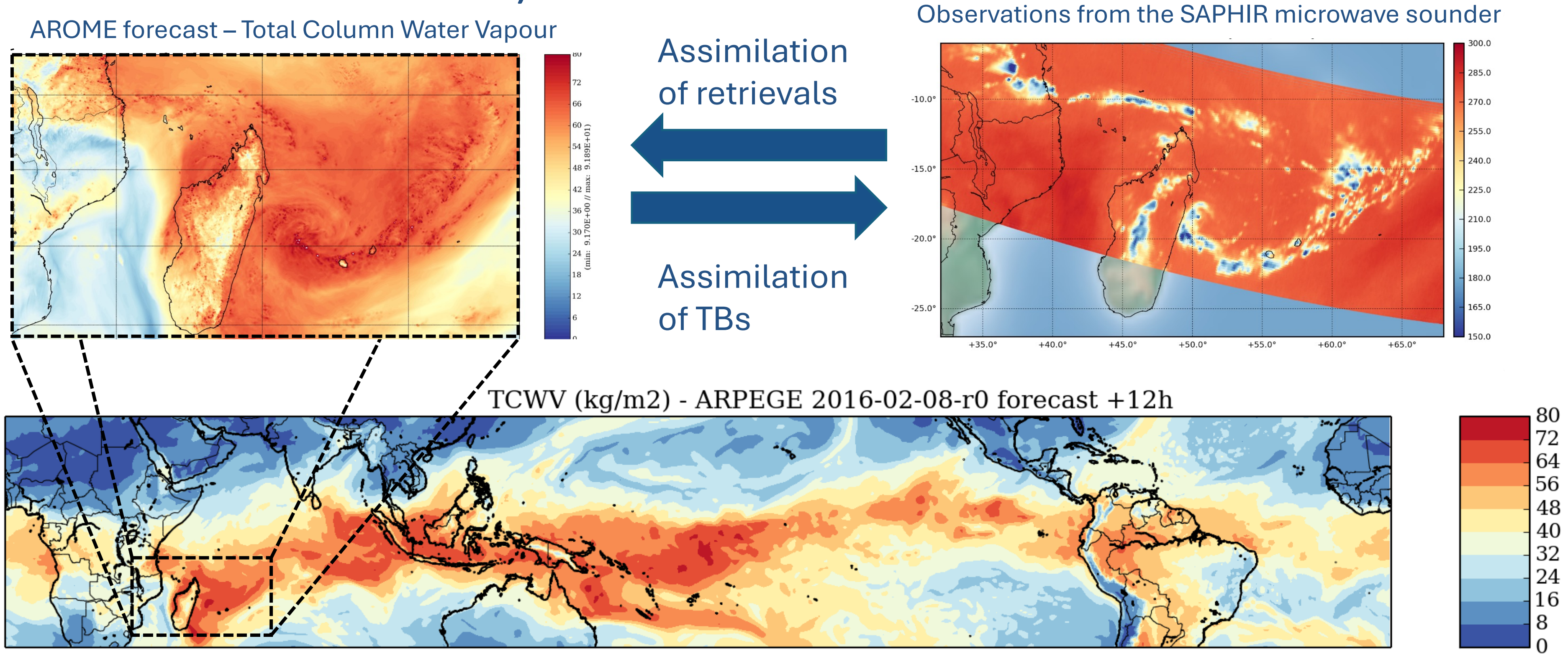
- x is the model state vector (temperature, humidity, hydrometeors,…)
- y is the observation vector (conventional, satellite, etc…)
- H refers to the observation operator

  => operator which transform the model state variables into observable quantities (e.g. for satellite, radiances or brightness temperatures)
- R refers to the covariance matrix of observation errors

  => R describes the errors of the difference (y-H[x]), including radiometric uncertainties and H errors

How rainfall forecasts can be improved ?

- Observations and model first guess need to be in the same space to be compared within a DAS framework => two possibilities
- The current trend in NWP centers is to assimilate TBs (mainly because observation errors tend to be easier to characterize)



How rainfall forecasts can be improved ?

$$
\begin{aligned}
\mathbf{x}_{\mathrm{a}} &= \mathrm{Arg\ min} J \\
J(\mathbf{x}) &= (\mathbf{x} - \mathbf{x}_{\mathrm{b}})^{\mathrm{T}} \mathbf{B}^{-1} (\mathbf{x} - \mathbf{x}_{\mathrm{b}}) + (\mathbf{y} - H[\mathbf{x}])^{\mathrm{T}} \mathbf{R}^{-1} (\mathbf{y} - H[\mathbf{x}]) \\
&= J_{\mathrm{b}}(\mathbf{x}) + J_{\mathrm{o}}(\mathbf{x})
\end{aligned}
$$

- B refers to the covariance matrix of background errors (a priori information from former forecast). B describes the uncertainties of the background (previous model forecast in a cycled assimilation process), as well as the error correlations between model variables.

- Accurate Background Error Covariances are required to update observed and unobserved model variables in a **balanced** way.

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How rainfall forecasts can be improved ?

- Depending on the “control variable” selected for clouds and precipitation, different background error statistics will be needed for the assimilation framework.

➢Specific Humidity? Relative humidity? (See Geer et al., 2017 for a summary of the control variables currently used in different NWP centers)

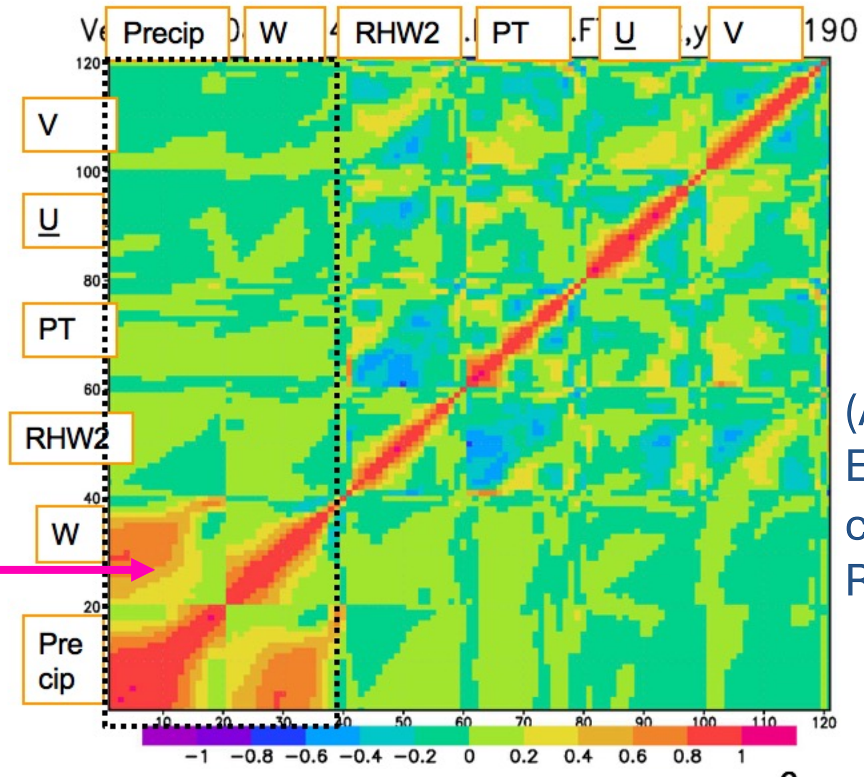
➢Hydrometeors?

(e.g. Michel et al., 2011; Zhang et al., 2013)

➢Vertical wind speed?

(e.g. Aonashi et al., 2017; Lee, et al., 2018)

Strong correlation between vertical wind speed and precipitation

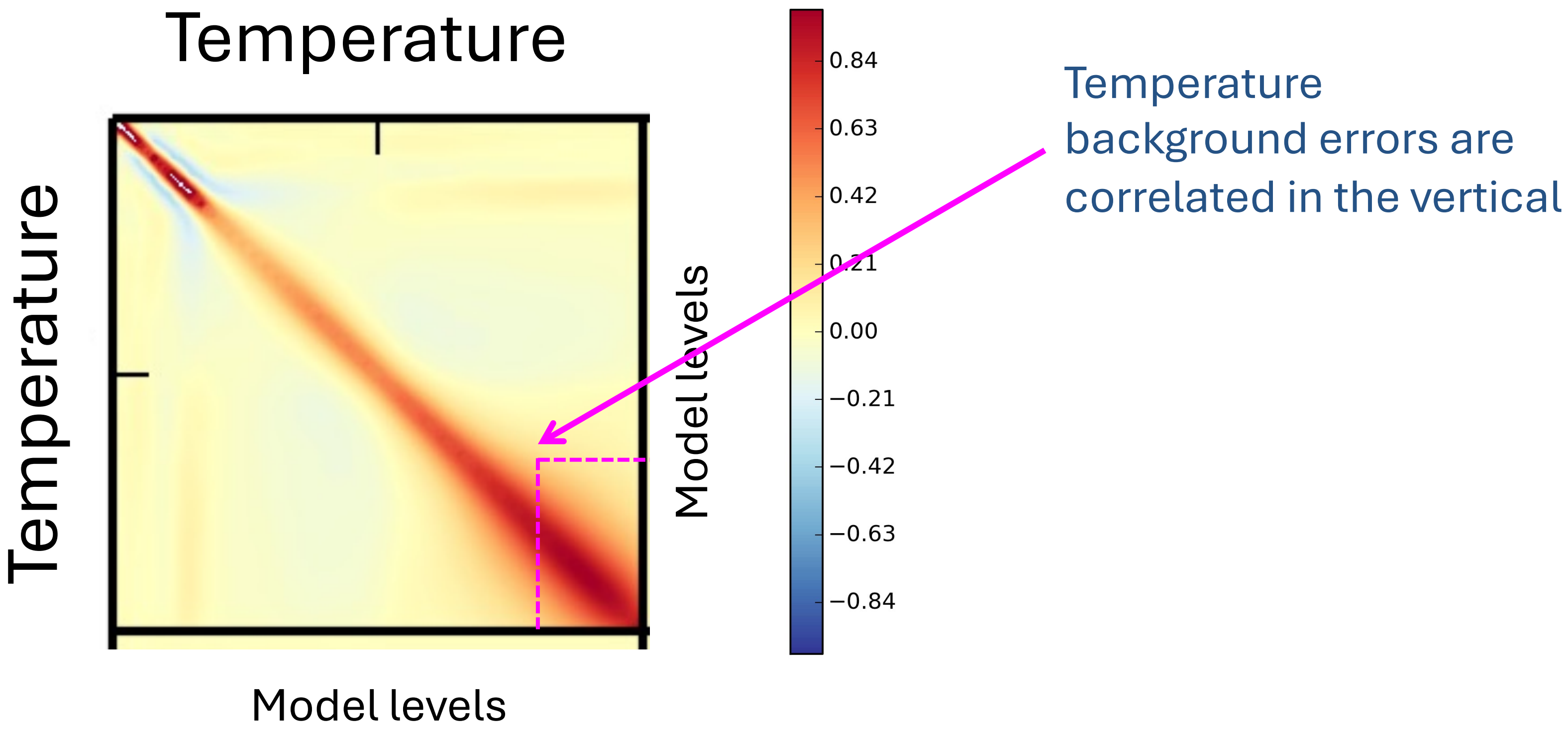


(Aonashi et al., 2017 ; EUMETSAT conference 2017, Rome, Italy)

How rainfall forecasts can be improved ?

- Example of multivariate background errors vertical covariances modeled in cloudy and rainy sky over the Indian Ocean of the AROME model

(Montmerle and Berre, 2011)



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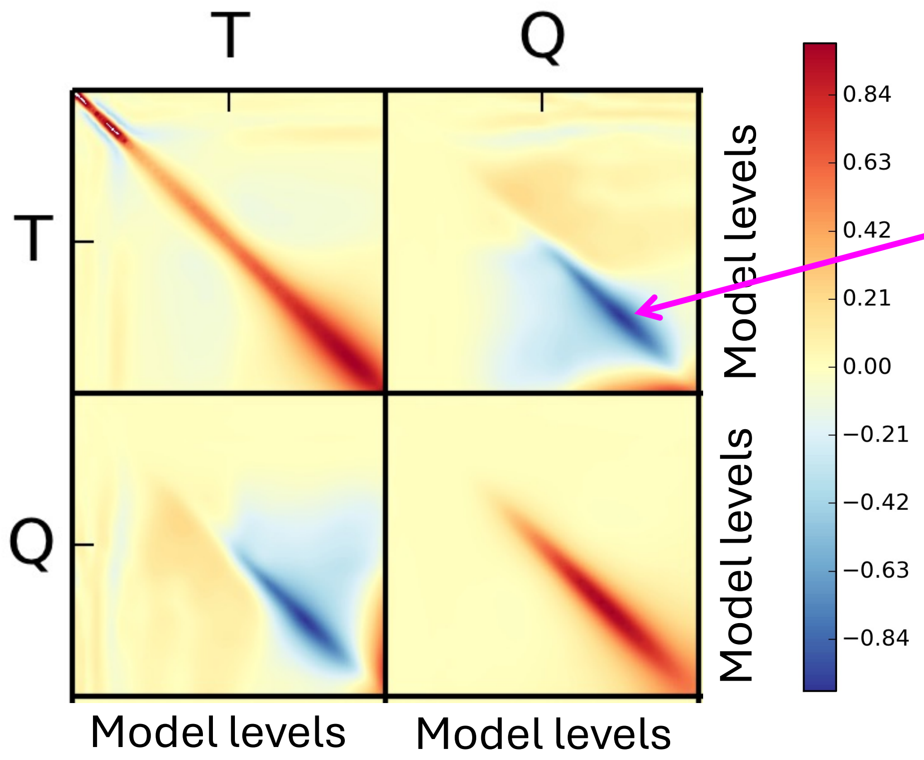
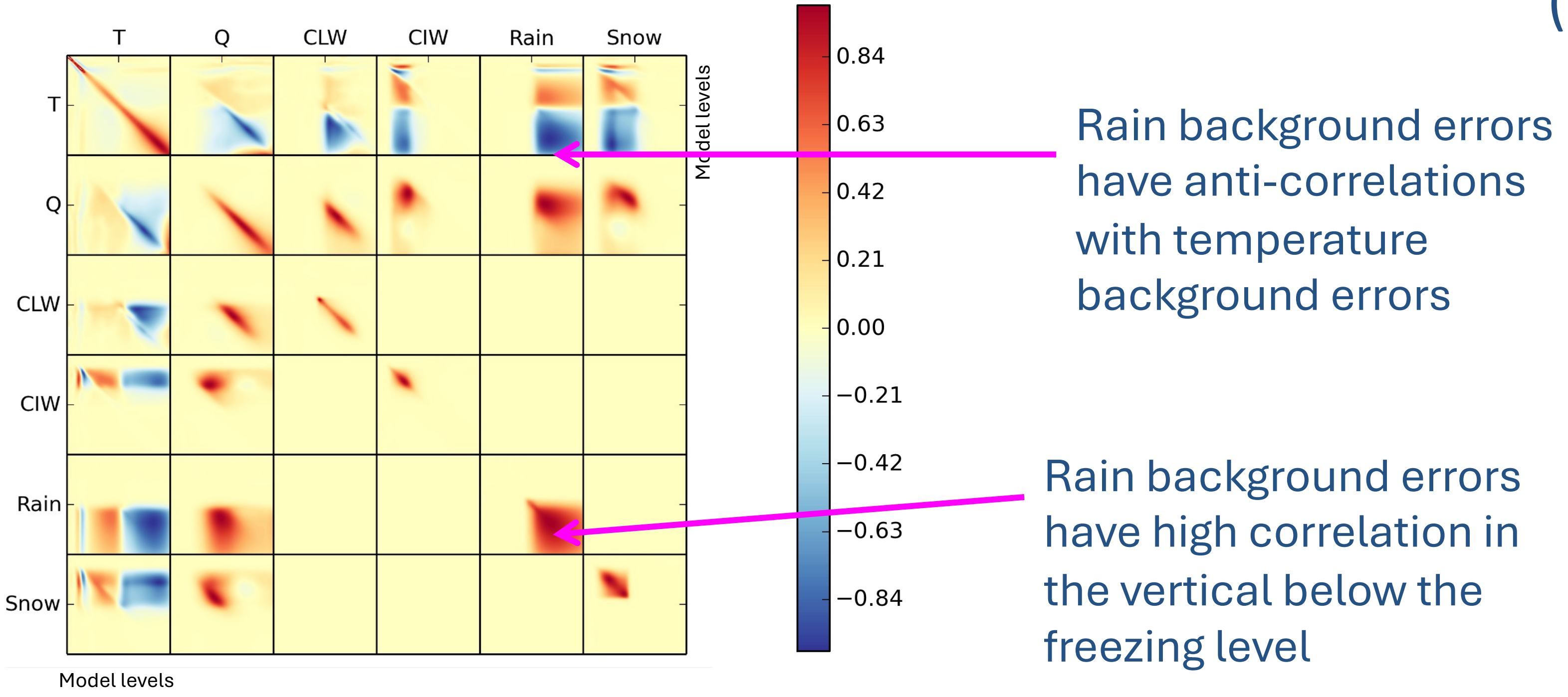


Humidity background errors are anti correlated in the vertical to temperature background errors

How rainfall forecasts can be improved ?

- Example of multivariate background errors vertical covariances modeled in cloudy and rainy sky over the Indian Ocean of the AROME model

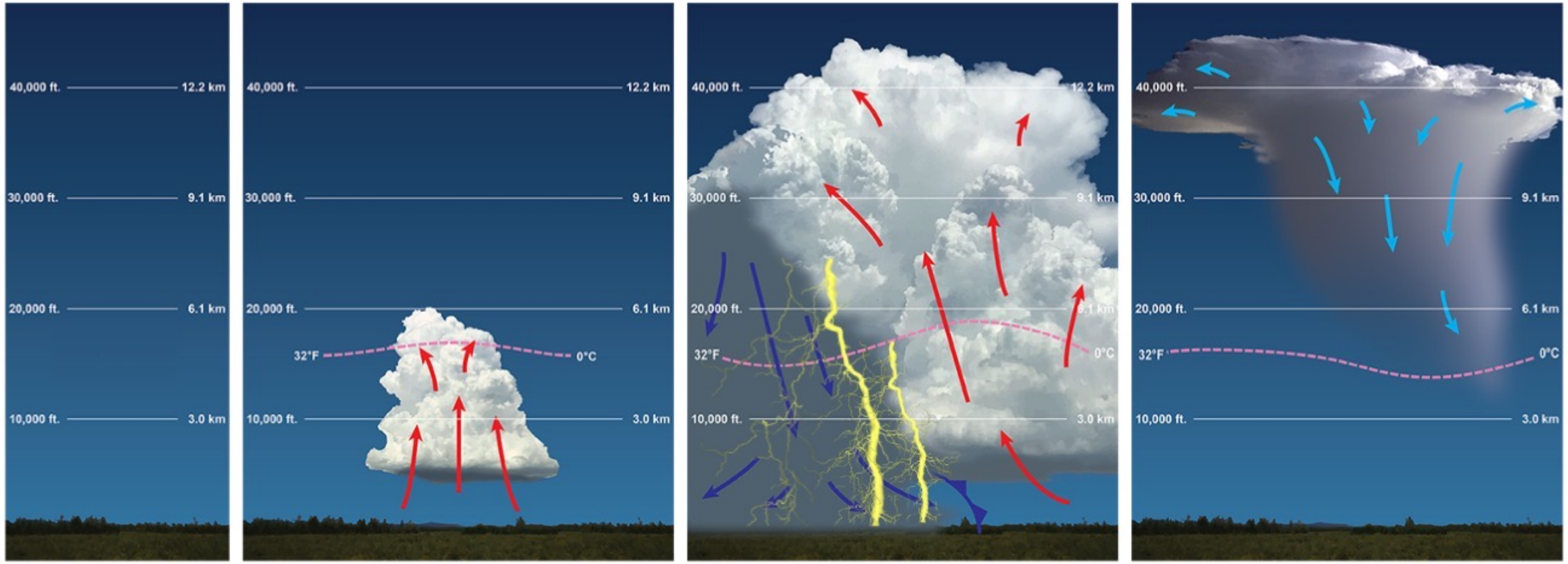
(Montmerle and Berre, 2011)



- These balances need to be preserved (in 3D) if one want the increments done during the analysis process to be sustained during a forecast

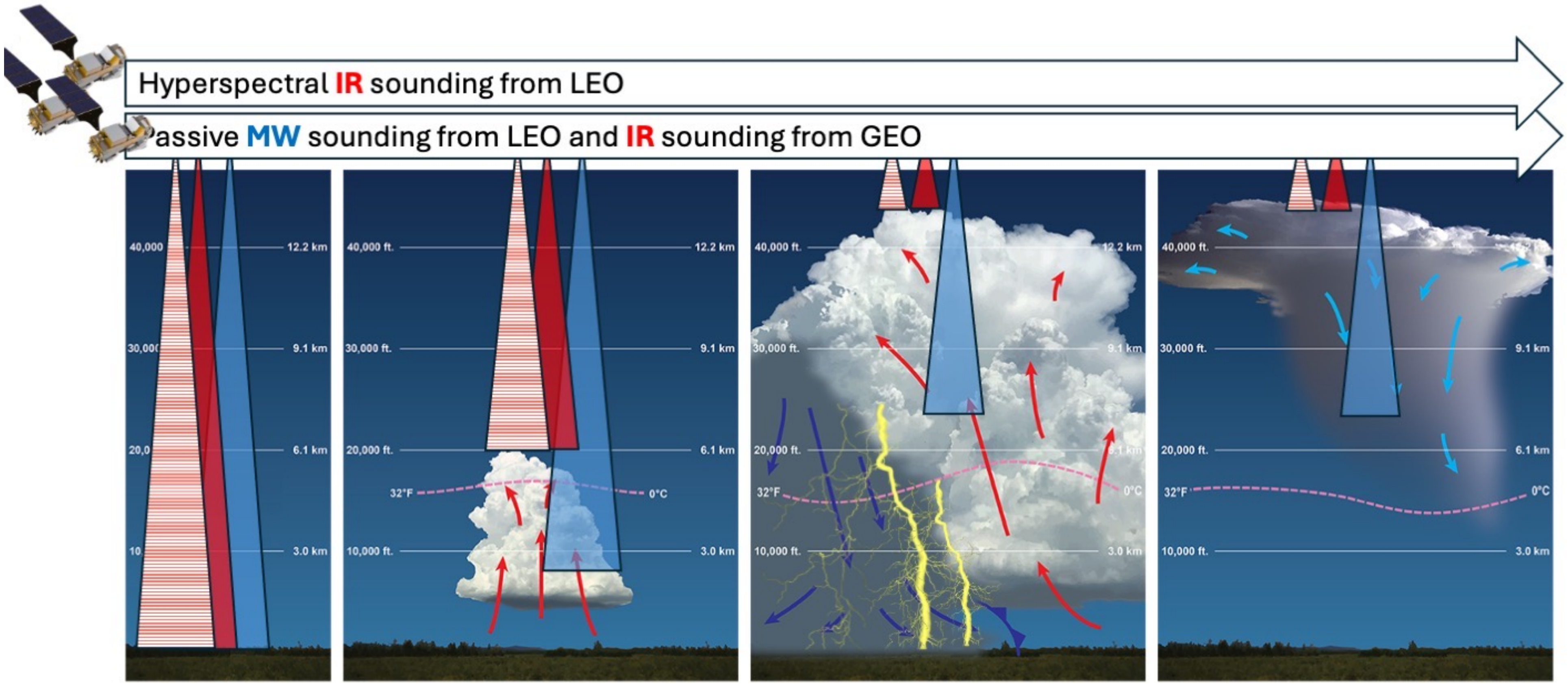
How rainfall forecasts can be improved ?

Development of favorable thermodynamical conditions | **Initiation phase** | **Mature phase** | **Dissipation phase**



(Figure adapted from https://www.weather.gov/spotterguide/life)

How rainfall forecasts can be improved ?



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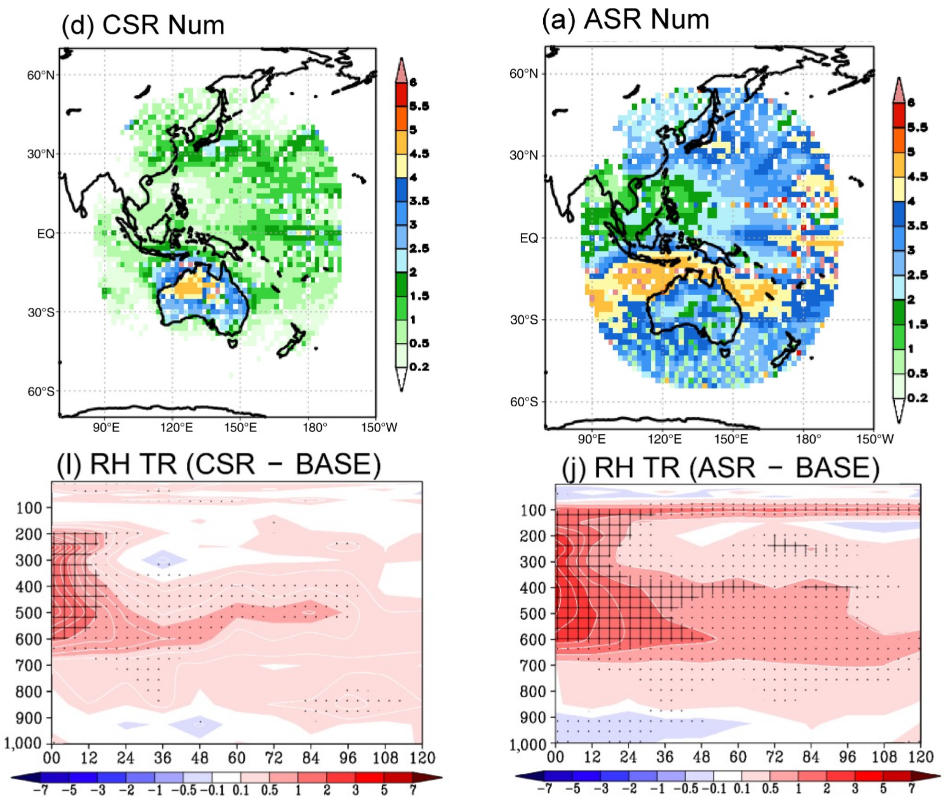
How rainfall forecasts can be improved ?

Transition from Clear Sky Radiances to Himawari AllSky Radiances

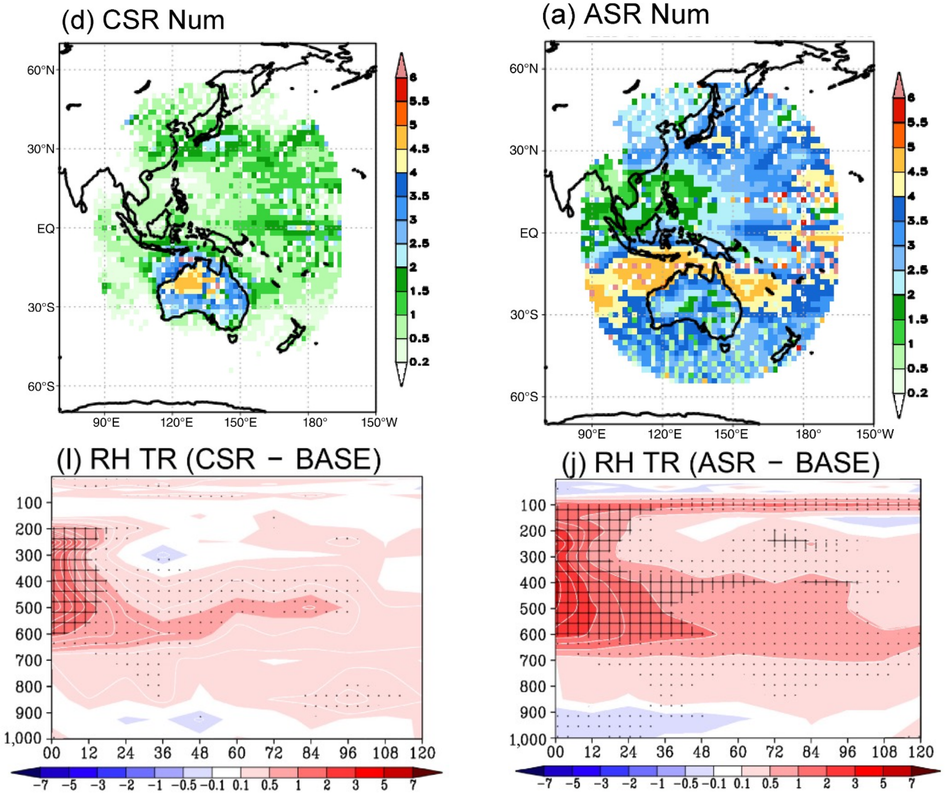


(Okamoto et al., 2023)

気象庁
Japan Meteorological Agency

How rainfall forecasts can be improved ?

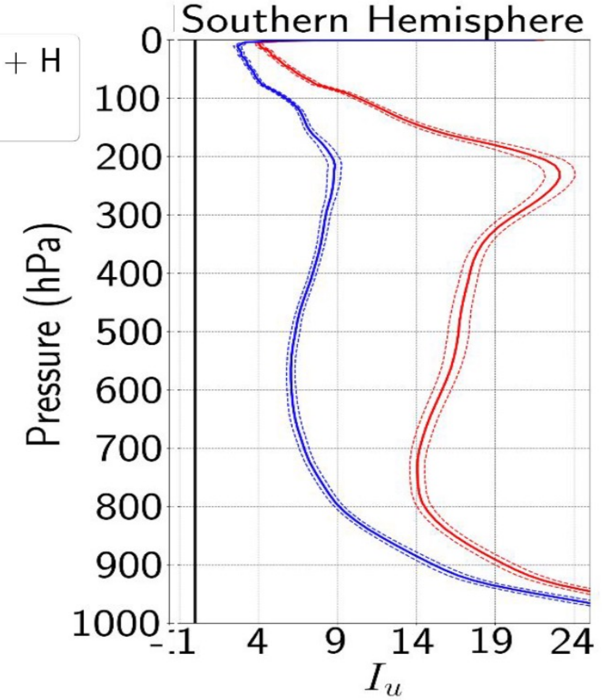
Transition from Clear Sky Radiances to Himawari AllSky Radiances



(Okamoto et al., 2023)

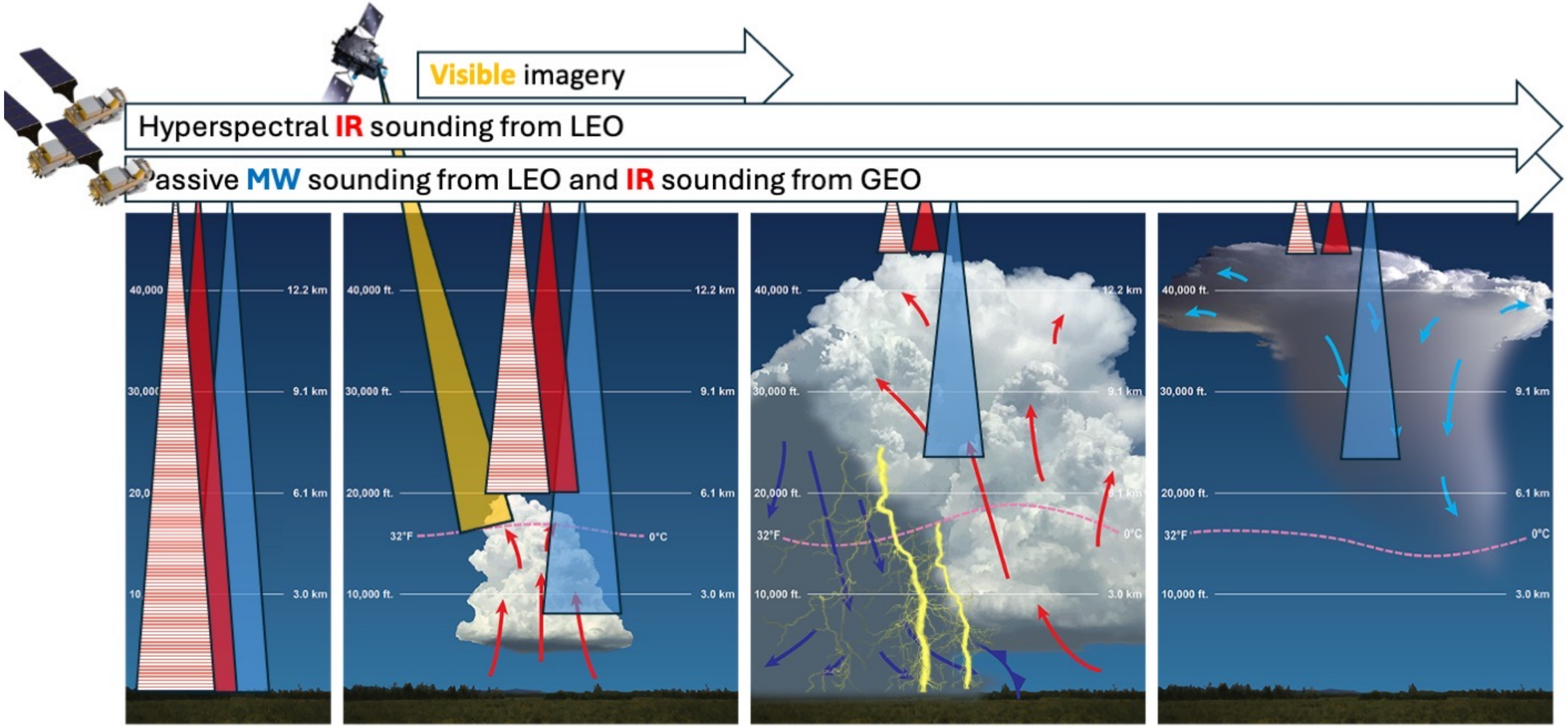
気象庁
Japan Meteorological Agency

Taking into account uncertainties of the forward model within DA => perturbing the observation oeprator

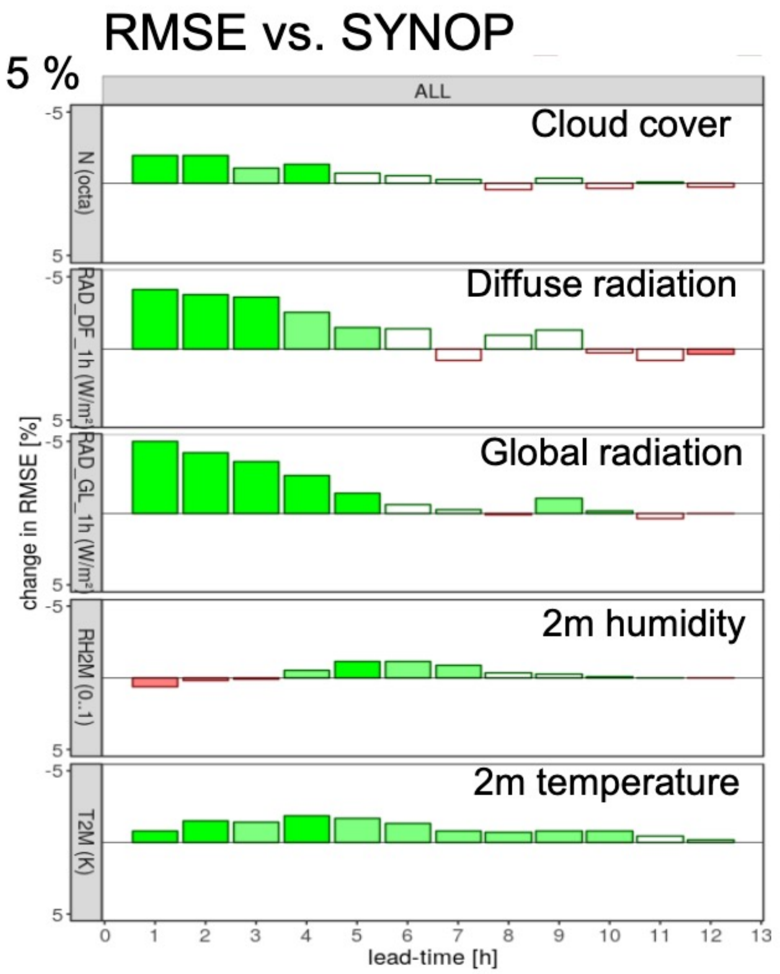


MF EDA spread increase perturbing Physics and H

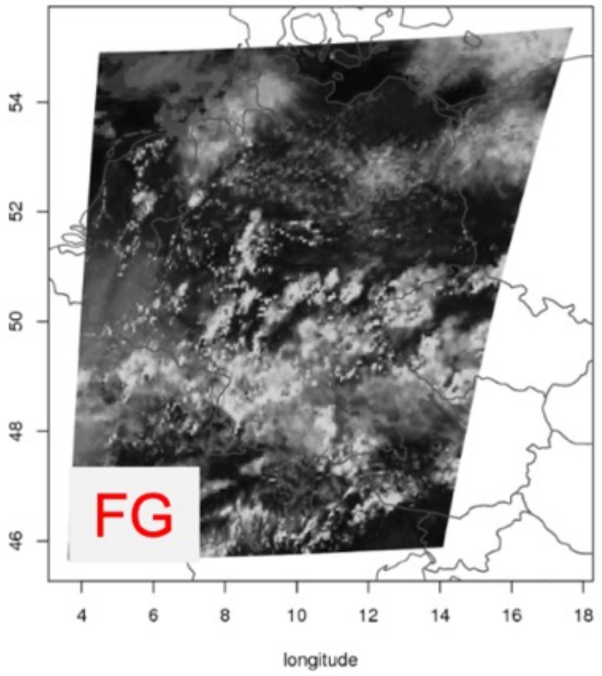
How rainfall forecasts can be improved ?



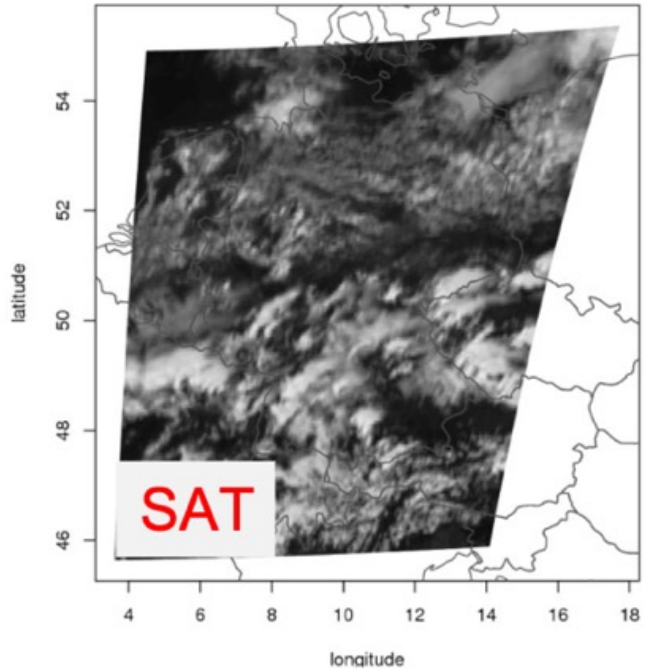
How rainfall forecasts can be improved ?



Impact of Visible observations in ICON

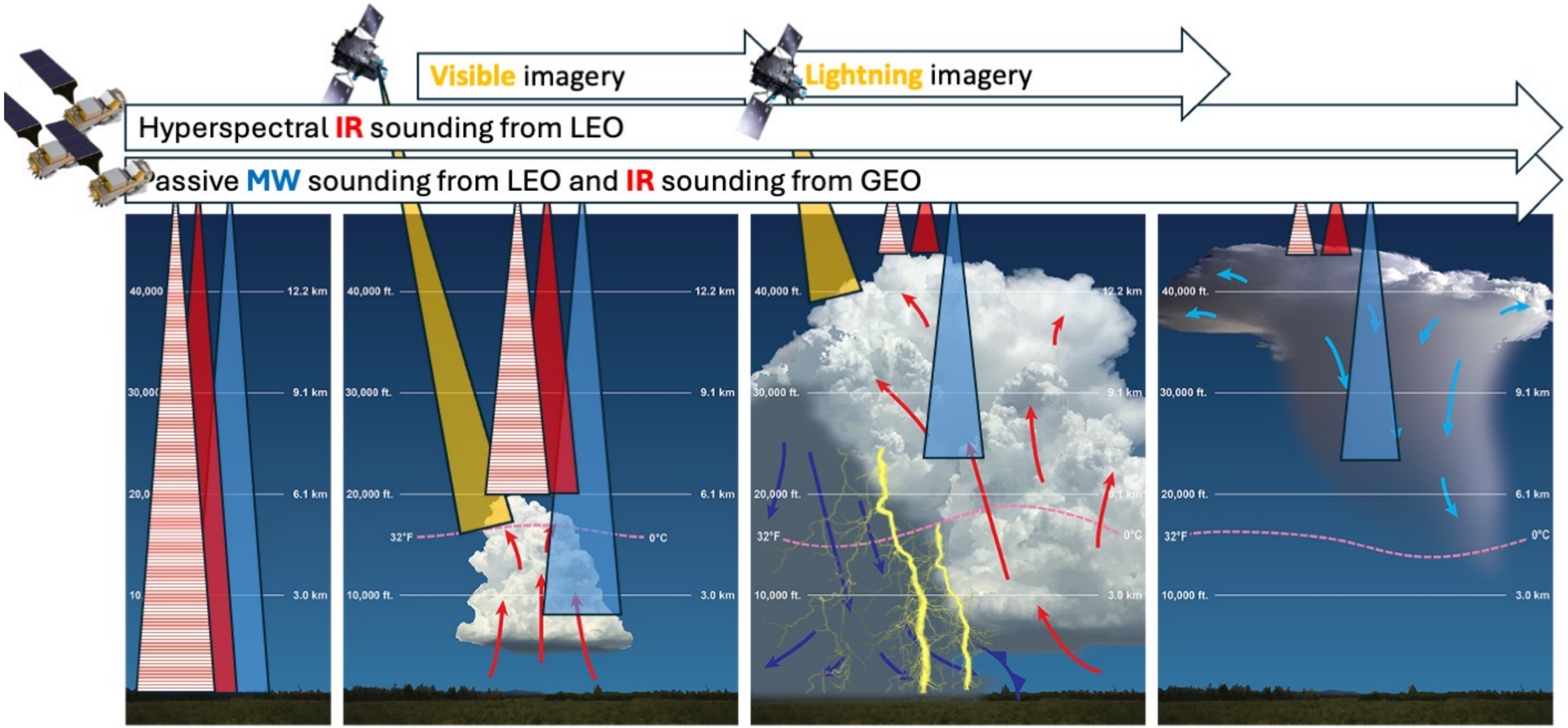


Observations SEVIRI



Simulations ICON

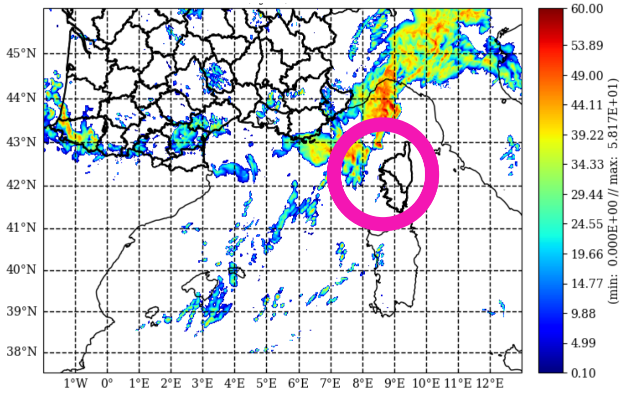
How rainfall forecasts can be improved ?

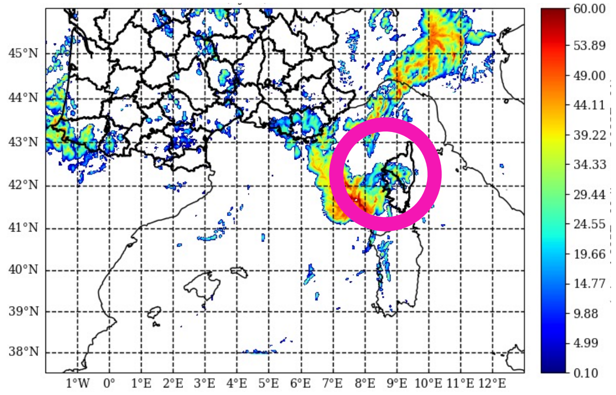


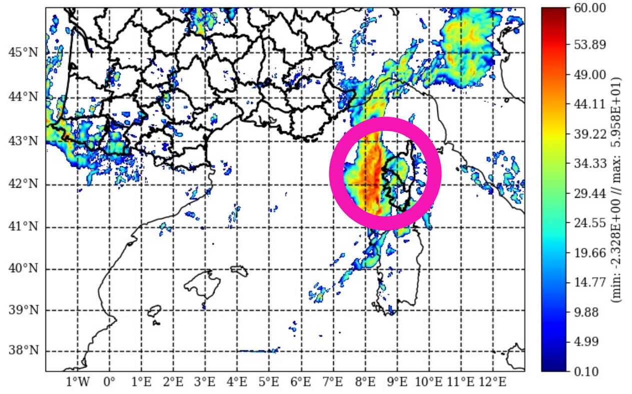
How rainfall forecasts can be improved ?

AROME OPER Cy46t1 (3D-Var)   *AROME double Cy48t1 (3DEnVar)*   *+ simulated MTG-LI*

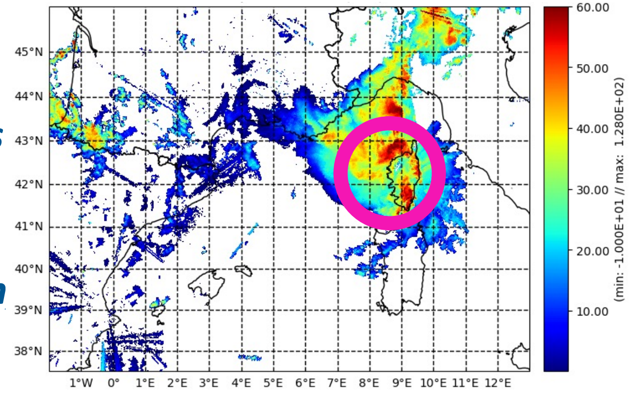
Forecasted reflectivities at range +4h Valid at 7h on Aug 18th, 2022



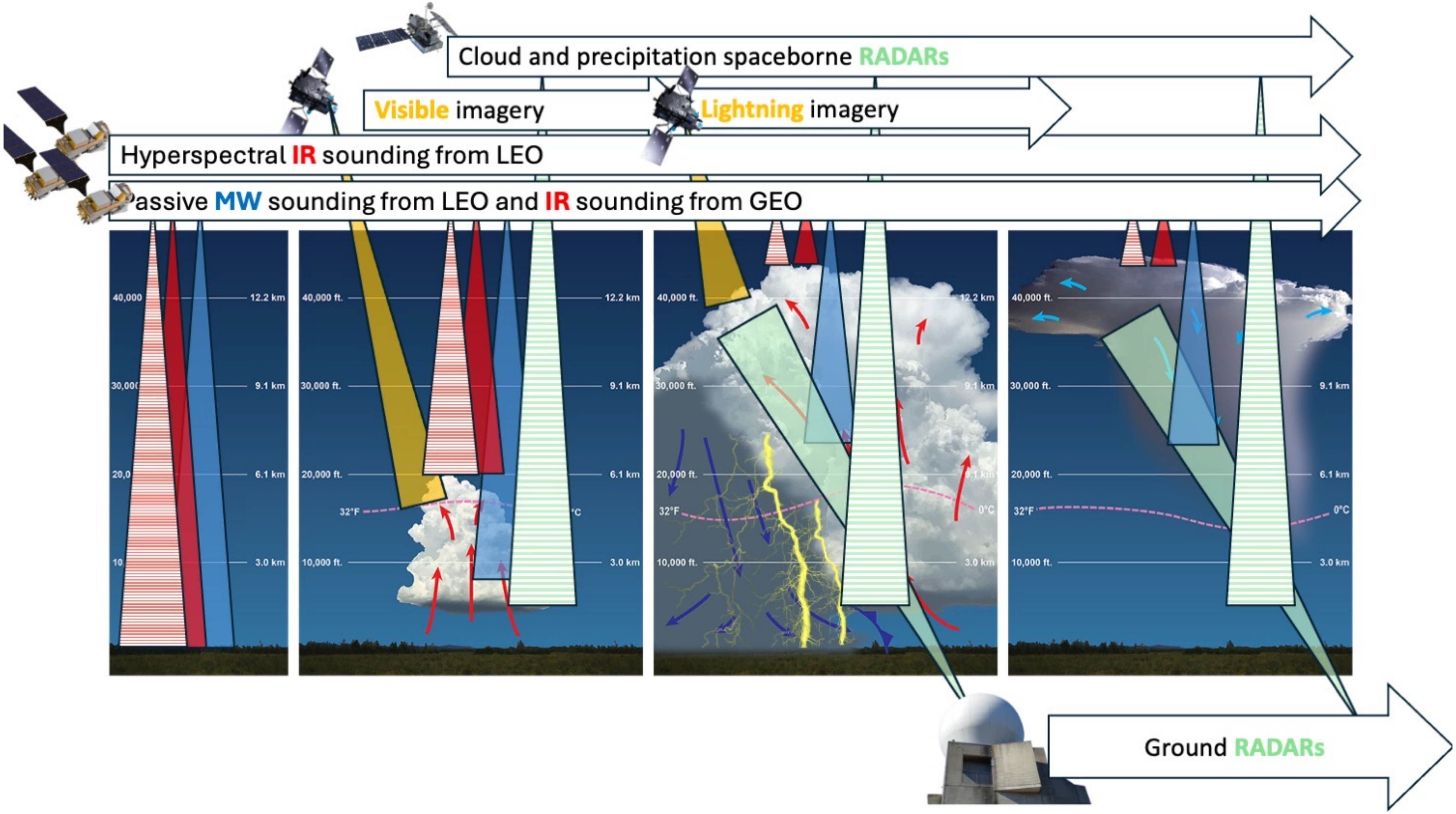




Observed reflectivities valid at 7h UTC On Aug 18th 2022

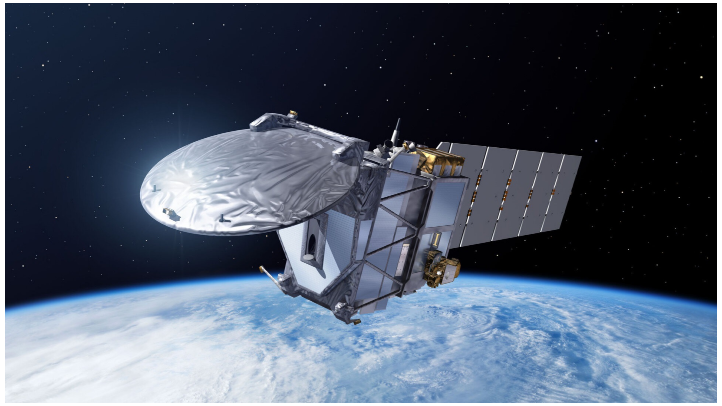


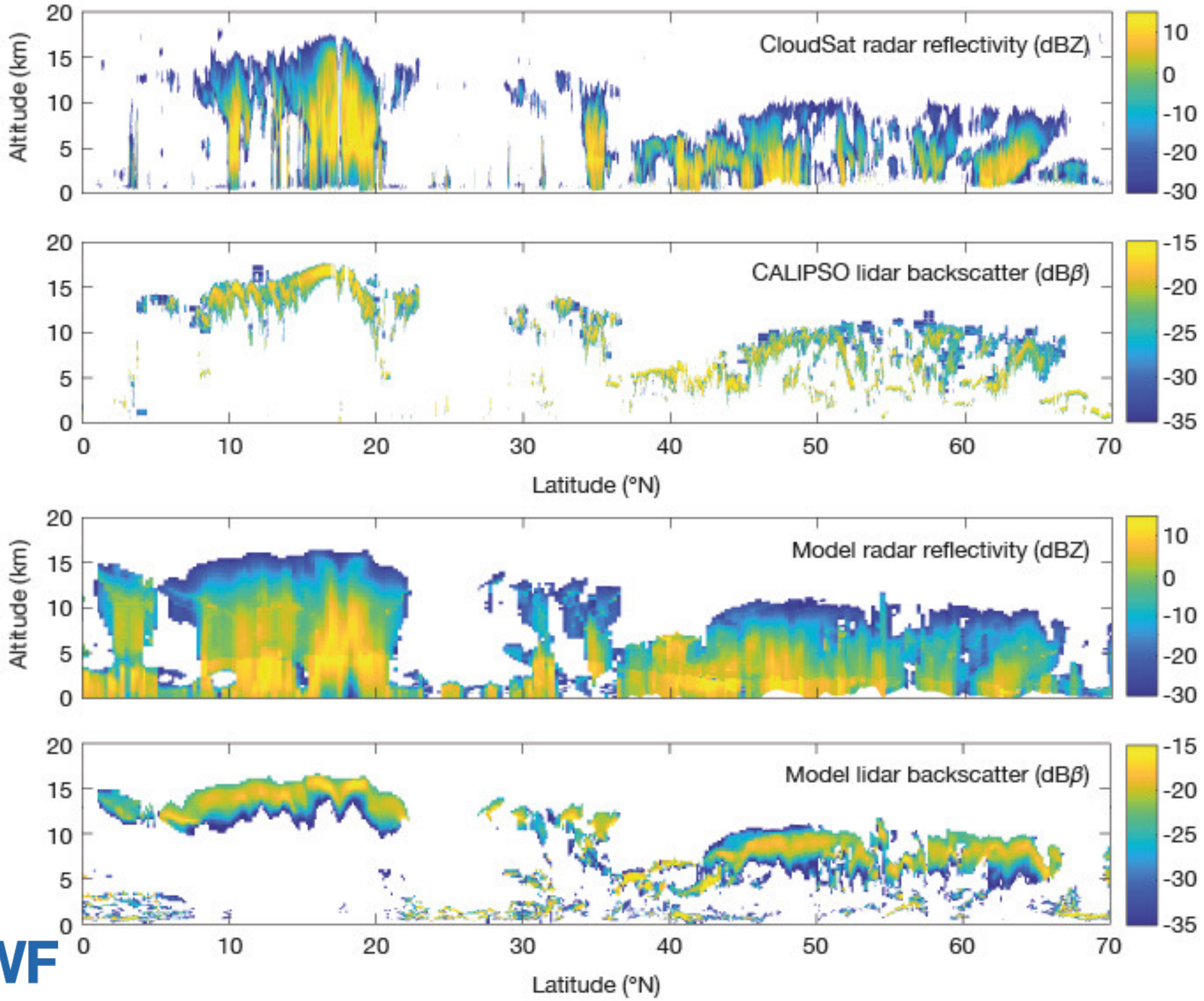
How rainfall forecasts can be improved ?



How rainfall forecasts can be improved ?

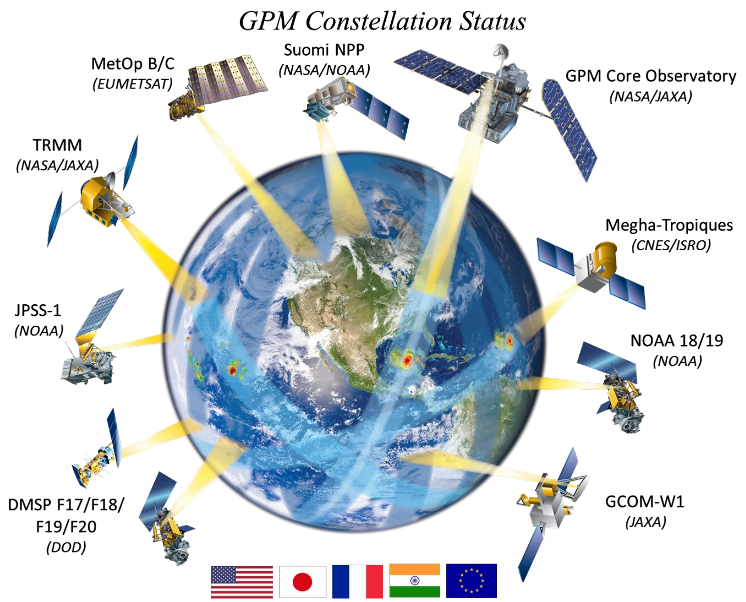
Preparing EarthCARE assimilation
with Cloudsat/Calipso data





Assimilating Satellite Observations of Clouds and Precipitation is a challenging field of research !!

- Non-linear observation operator
- Non-Gaussian error distributions
- Under-determined problem
- Complex, flow-dependent balance
- Significant model errors
- Variety of spatio-temporal scales



(Source http://pmm.nasa.gov)

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Thank you !