Introduction to weather forecasting

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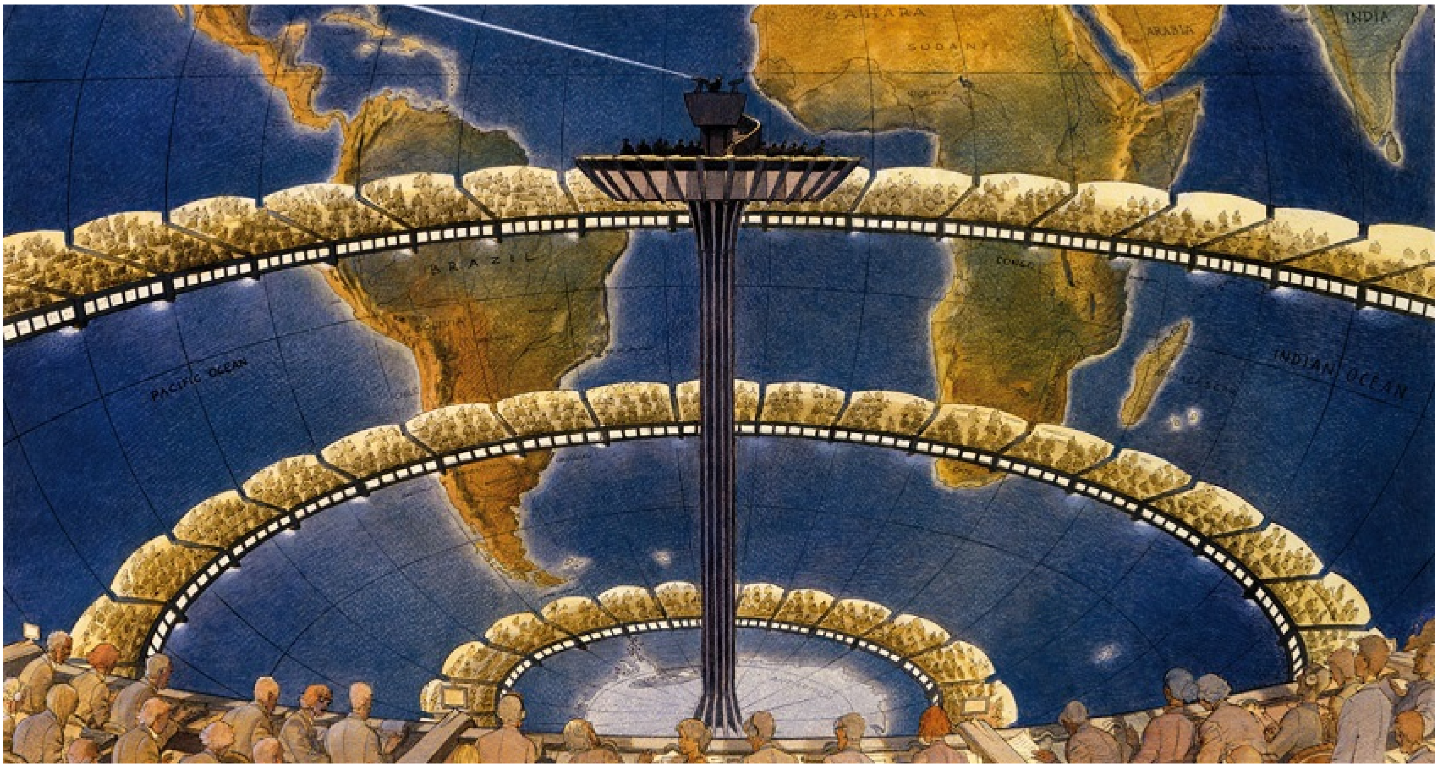

What time will we have next weekend? What are the risks of storms, thunderstorms and heat waves in the coming days? Meteorological services are now able to answer these questions in a useful way. But what mechanism is behind these forecasts? This article presents an overview of the functioning of Numerical Weather Forecasting centres that exist in various countries around the world, and introduces the essential concepts developed in the other articles of this sub-section.

1. Introduction

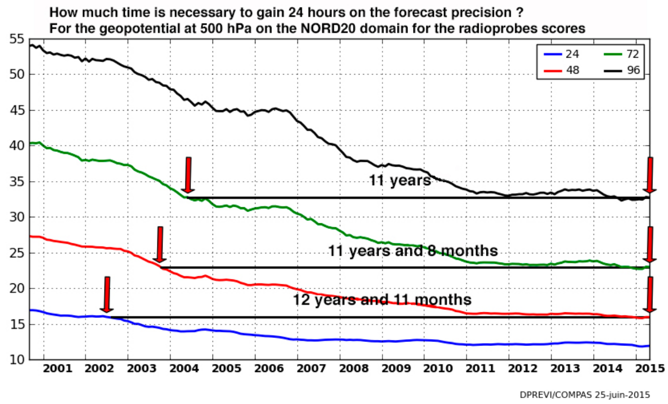

Figure 1. Evolution of the quality of the forecasts of the ARPEGE model over the last 15 years. The score shown is the mean square error of the geopotential forecasts at 500hPa (geopotential is the precise altitude of the 500 hPa pressure surface, which is approximately 5000 m), averaged over the entire Northern Hemisphere north of 20° latitude, for the lead-times 24, 48, 72, and 96 hours. There has been a steady improvement in quality, which has resulted in an improvement of about 24 hours in 11 to 12 years. [Source: © Météo-France]

The remarkable improvement in the quality of weather forecasts is one of the great successes of environmental science in the 20th century, which continues at a sustained pace at the beginning of the 21st century (see Figure 1 and Bauer et al, 2015). This is due to the progress of numerical prediction systems and the increasing **number** and variety of **observations of** the state of the atmosphere and related media (ocean, soils, vegetation, cryosphere), including observations from Earth observation satellites. The **rapid development of supercomputers** has been one of the keys to this success, which has also required significant scientific work.

Each country in the world has a National Meteorological Service (NMS), whose mission is to make regular observations of the atmosphere and to issue forecasts for government, industry and the public. But **only the most advanced countries have Numerical Weather Prediction (NWP) centres**, whose products are also distributed to other countries, in exchange for their observations, within the framework of the World Meteorological Organization [1].

Among the main NWP centres outside Europe are those in the United States, Canada, Japan, Korea, China, Russia, Australia, India, Morocco, South Africa and Brazil. In Europe, only France, the United Kingdom and Germany make numerical forecasts for the entire globe, while the other countries have NWP centres covering only regional areas. The European countries have also come together in a "super-centre" [2], which is responsible for providing them with medium-range numerical forecasts.

2. The different functions of NWP centres

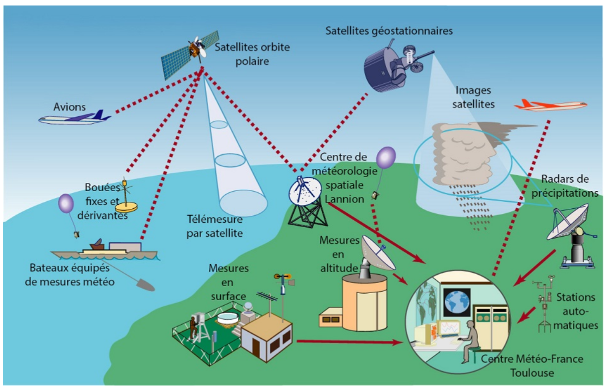

Figure 2. Observation systems used in operational meteorology [Source: WMO/Météo-France]

The organization of NWP centres varies from one country to another, but there are some shared major functions described below. The **first** important **function** is **the reception of observations.** Observations means any numerical data characterizing the state of the atmosphere or related media. These observations are very varied (see Figure 2), we will note in particular:

Surface level measurements made by Meteorological Services worldwide, either at land stations or on offshore buoys;

Altitude measurements made by ascending balloons (radiosondes) or meteorological radars [3];

Measurements made by meteorological satellites or, more generally, Earth observation satellites (there are currently more than fifteen such satellites);

Measurements taken on board commercial aircraft or vessels.

The composite observing system thus constituted represents the **bulk of the cost of meteorology, and this cost is shared by all countries in the world**. The fact that different countries freely exchange observations (even sometimes in times of war) is one of the most remarkable achievements of meteorology.

The **volume of these data is considerable** (tens of millions of observations every day, spread over the entire globe) and every effort is made to ensure that they reach the NWP centres as quickly as possible, usually less than three hours after the measurement is made. These centres must have powerful telecommunication and information processing systems to receive, process and archive observations as they become available.

The **second function** is **the critical examination of observations** to detect possible false (if a measurement system is faulty), redundant, or biased observations. This is usually done by comparing neighbouring observations, or by comparing each observation with a recent forecast of the same parameter (if the observation is very different from the forecast, it will tend to be considered suspicious unless it is confirmed by neighbouring and independent observations). Any anomalies found on certain observations are reported to the originating services, which can then take corrective action.

The **third function** consists in **producing,** from the varied and heterogeneous set of recent observations, **a "state" of the atmosphere** in the form of mathematical fields that can be used to start the forecast model. This task of producing the initial state of the forecast is called **Data Assimilation** (see Meteorological Data Assimilation). The natural aim is to produce the initial state as close as possible to reality at a given time, but this is very difficult because the observations are all affected by small uncertainties, are not synchronous and do not cover all points on the globe. It is therefore necessary to interpolate spatially and temporally and to search for the "most probable" initial state taking into account all the available information.

The **fourth function** is **the forecast itself,** which is carried out **by a numerical model of the atmosphere** (see Weather forecasting models). The model solves the equations of fluid dynamics and calculates the successive states to project itself in time at 24h, 48h, etc... The main NWP centres actually use several forecast model configurations: a global version for a general forecast with a lead-time of several days, then one or more "regional" versions covering areas of particular interest, such as their national territory or overseas regions, for a forecast with a shorter lead-time and on a more detailed computing grid. In Météo-France, the global configuration is called ARPEGE (Pailleux et al. 2015), and the regional configuration is called AROME (Bouttier, 2007).

There is a growing trend to replace the deterministic forecast (a single forecast made from the best possible initial state) with the probabilistic forecast (several simultaneous forecasts made from slightly different initial states to account for residual uncertainties in the initial state). This is called **the Ensemble Forecast** (see The Ensemble Forecasting). From these different forecasts, we can calculate the probability that certain feared or expected events will occur.

Finally, atmospheric parameter forecasts are used to **force "impact models"** that more accurately calculate sea state, river flows, snowpack conditions and avalanche risks, air quality, road conditions, etc..

Other forecasting systems are also used to better cover very short or very long deadlines: **Immediate forecasting** systems extrapolate observations up to a few hours, with very frequent refreshing and are more efficient than NWP models for these short deadlines. Once per month, **seasonal forecasting** systems calculate the probable climatic anomalies in the next 3 to 6 months, with results of highly variable quality depending on geographical areas and seasons (see The seasonal forecast). Seasonal prediction models are very similar in design to the climate models used for IPCC reports [4].

The raw results of all forecasting systems are stored in databases as they are produced, and these databases are constantly queried by algorithms that feed the various applications where users find the finalized information they want (e.g. websites or mobile applications). For the **most sensitive applications,** particularly those related to the security of people and property, the **databases are supervised by an expert forecaster**. The latter examines the consistency of forecasts from several models, the most recent observations, and may decide to trigger weather warnings. In France, this applies in particular to the Vigilance Map procedure (see The role of the forecaster).

The last important function of a NWP centre is **the a posteriori verification of forecasts.** This is done by comparing forecasts with the most reliable observations, accumulating results over time long enough to create scores. NWP centres calculate a very large number of scores on a daily basis and exchange this information with each other. This makes it possible to know the average quality of forecasts, to verify that a new version of a forecasting system represents an improvement over the previous version, or to compare the performance of two NWP centres. It also makes it possible to verify that developments in observing systems improve the quality of the forecast (e. g. when an end-of-life satellite is replaced by a more recent generation satellite). Figure 1 is an example of such forecast scores.

As the quality of forecasts has now reached a high level, it is necessary to test any changes in forecasting systems over long periods of time (several months) to ensure that the forecasts are never degraded. In **addition, the natural variability of atmospheric predictability**, which is independent of the quality of forecasting systems, **must also** be taken into account. It is well established that some parameters are easier to predict in summer than in winter, or vice versa, but it is also clear that the atmosphere can behave very differently, and more or less predictably, over several successive winters (or summers). **This slow variability is one of the most exciting aspects of atmospheric dynamics**, which is still very poorly understood.

3. The quality of the forecasts

The **quality of the numerical weather forecasts varies according to the parameter considered and the lead-time** (see table). At short notice the temperature is generally predicted with an error not exceeding a few degrees, and the wind with an error not exceeding a few metres per second, except in stormy areas. For rainfall, especially thunderstorms, this level of quality is not reached, as small errors on previous quantities result in larger errors on rainfall.

Precisely predicting the precise location of a storm and the amount of rainfall associated with it or the risk of hail remains extremely difficult, even a few hours in advance. The same is true for the amount of snow in winter, especially when the temperature is close to 0°C on the ground, and a small temperature error can lead to an error in the nature of precipitation (rain or snow). This is also the case for fog, which remains very difficult to predict, even a few hours in advance, because its formation depends on the humidity, which is very variable. For tornadoes, only a risk of occurrence should be indicated.

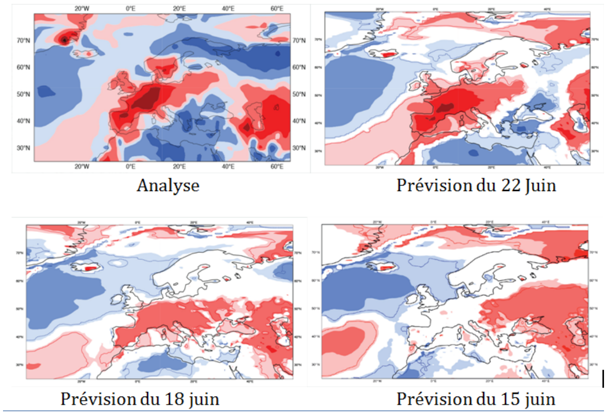

Figure 3. Forecast of the heat wave at the beginning of July 2015 using the ECMWF model. This major event was observed between 29 June and 7 July, with temperature records broken in several European countries. The figures show the average temperature anomaly over the week in question (+10°C for dark red), as observed (Analysis), and predicted on June 22, June 18, and June 15. It can be seen that the first forecast giving a relevant indication was issued 11 days before the start of the event (June 18). [Source: © ECMWF]

On the other hand, **the forecasting of severe winter storms such as Xynthia (night of 27-28 February 2010) has made great progress**, the risk can now be indicated 72 to 120 hours in advance, and on the basis of very accurate forecasts made 24 to 48 hours in advance, public authorities can take the necessary measures to protect people and property (closure of certain traffic routes, cancellation of outdoor events, etc.). The same applies to the beginning and end of cold waves or heat waves, which are now planned several days in advance, with very correct reliability (Figure 3).

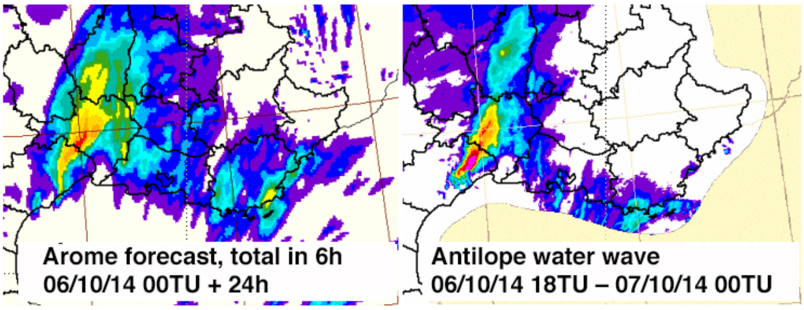

Figure 4. State of the art of intense rainfall forecasting in the Mediterranean arc (so-called "Cévennes" episodes): on October 6, 2014, 260mm were recorded in 6 hours in Prades-le-Lèz in Hérault. On the left, forecast of rain accumulation between 18hTU and 24hTU by the AROME model of Météo-France (from the initial state of 00hTU) compared on the right to the cumulations observed by weather radars and rain gauges for the same time slot. The forecast was sufficiently relevant for "orange - flood and rain" vigilance to be declared (appropriately) for the departments of Hérault and Gard, however the model underestimated the maximum rain intensity, and gave a position slightly shifted to the northeast of the maximum rainfall. [Source: © Météo-France]

Floods are quite predictable in slow-dynamic river basins, where floods develop in several hours, but almost unpredictable in small basins with rapid dynamics, which can react in a few tens of minutes to heavy storm rain (for example the disaster of 3 October 2015 in Cannes). **Improving the forecasting of flash flood risks in the Mediterranean regions is therefore one of the most important objectives of Météo-France** (see Goulet, 2015 and Figure 4). This will probably require the development of ensemble forecasts to characterize the probability that precipitation will exceed certain critical thresholds in the following hours.

The **quality of the forecasts with monthly to seasonal lead-times is still very modest**. In tropical regions, some phenomena such as El Niño [5] are predictable several months in advance. On the other hand, in Europe, it is still impossible to predict the temperature more than a few weeks in advance.

4. The computing power

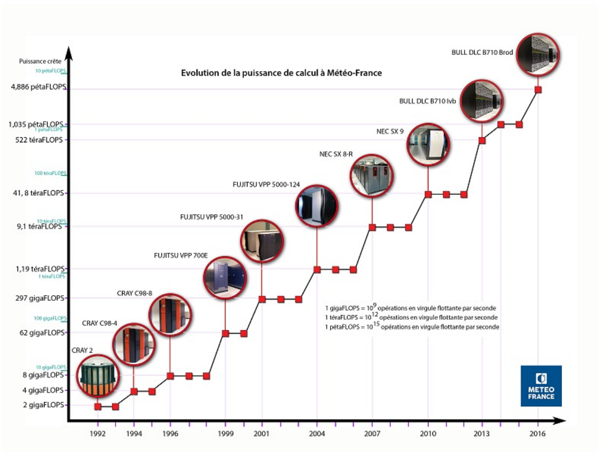

Figure 5. Evolution of the computing power of a NWP centre (FLOP stands for Floating Operations per Second, the most common unit for measuring the power of a computer). [Source: © Météo-France]

The computing power available in NWP centres must be considerable to produce quality forecasts in a timely manner (Figure 5). A constant question is **to ensure optimal use of this computing power**. The time at which a new forecast must be distributed to users is imposed by social habits, so it is necessary to organize the production process to respect this time (for example 6h/16h every day for the vigilance of Météo-France). There are two contradictory requirements: use the most recent observations, which tend to delay the start of production as much as possible, and use more precise, and therefore slower, models, which on the contrary require that this time be brought forward. We have to find the best possible compromise.

The degrees of freedom are numerous: the number of observations actually used, the complexity of the observation validation/assimilation algorithms, the resolution of the prediction models (i.e. the fineness of the computing grid), the complexity of the equations that can represent the processes in more or less detail, and the size of the prediction ensembles (generally the ensembles have several tens of members, but for some applications it could be advantageous to increase to several hundred). Finally, the distribution of computing power between atmospheric prediction and impact models requires careful consideration to ensure an optimal final result.

In the end, the start time of production varies according to the centres and products, from about ten minutes to several hours before the broadcast time.

5. R&D in anticipation

The improvement of NWP systems is based on the R&D departments of the NMS, which cooperate extensively with each other, but **also with Universities and Research Organizations**. There are still major knowledge challenges in the field of atmospheric processes and predictability, with obvious societal benefits that justify the public authorities devoting significant resources to this subject (in France, in university and CNRS laboratories in particular). The development of observation systems also leads to **active technological research**, with significant industrial benefits, particularly in the space sector, but also for ground-based radars and lidars [6].

Among the major R&D trends currently observed (2016), we can note in particular:

- The profound rewriting of codes to make the most of the new massively parallel computer architectures (problem of "scalability" [7]).
- The development of "coupled" prediction systems, in which one or more of the following modules are added to the atmospheric dynamics and physics model: underlying continental surface, ocean and wave dynamics, atmospheric composition (chemical species and especially aerosols). For this reason, **NWP models increasingly resemble climate models**, and most countries are seeking to share developments for NWP and climate.
- The development of ensemble predictions, which are now applied not only to the atmosphere, but also to other models (ocean and sea state, air quality, hydrology, snow cover, etc.)
- The accuracy and number of satellite observations are changing rapidly: the first direct wind measurements from Earth orbit are expected in 2017 (ESA's ADM-AEOLUS Doppler lidar) and the first hyperspectral measurements in infrared from a geostationary satellite (3rd generation Meteosat IRS Instrument) are expected in 2020. Weather radar measurements are also becoming more efficient and varied.
- Indirect information on the state of the atmosphere from an increasingly diverse range of sources is gradually becoming available (so-called Big Data Paradigm [8]). For example, the trajectory of commercial aircraft is analyzed to estimate wind speed, wireless telecommunications disruptions provide information on rainfall, GPS networks provide information on air humidity, cars and mobile phones are now equipped with temperature and pressure sensors as standard. Capturing this new data and using it to improve forecasts will be one of the major challenges of the near future.
- In the United States and Europe, NMS are gradually moving towards the free distribution of raw NWP data over the Internet (see PSI Directive [9] in Europe).
- The private sector is also beginning to take an interest in the production of NWP, which is seen as an activity that can generate profits. Panasonic and IBM (The WeatherCompany [10]) recently communicated on this topic.

Table: Weather forecast deadlines

Immediate delay	the coming hour
Very short delay	one hour to one day
Short delay	one to three days
Mean delay	four to ten days
Extended delay	ten days to one month
Long delay	one to six months

References and notes

Cover image: As early as 1922, an English scientist, Lewis Fry Richardson, thought that it would one day be possible to calculate atmospheric flow fast enough to make forecasts. He imagined a **calculation factory** where hundreds of mathematicians would calculate the flow by hand, under the direction of a "conductor"! [© F. Schuiten, Météo-France]

[1] WMO is a United Nations family organization

[2] The European Centre for Medium-Range Weather Forecasting, located in Reading, UK (Woods, 2005).

[3] Meteorological radars make it possible to locate precipitation areas within a radius of about 80km by scanning the space in three dimensions at intervals of about two minutes.

[4] Intergovernmental Panel of Experts on Climate Change, set up by the UN.

[5] El Niño is the warming of the waters of the eastern tropical Pacific that occurs every 3 to 5 years around Christmas, with considerable impacts on regional activity.

[6] Meteorological lidars are instruments that emit a laser beam and measure the light backscattered by the atmosphere, based on the radar model; they make it possible to determine approximately the air speed and aerosol content in a volume of several kilometres around the instrument.

[7] The scalability of a code is its ability to efficiently exploit computers composed of a very large number of processors, computing in parallel. The most efficient weather codes distribute the calculations over tens of thousands of processors without loss of efficiency.

[8] *Big Data* is the set of methods and tools that extract useful information from the massive data flows that circulate on the Internet.

[9] Public Sector Information, a directive that requires public services to make their data freely accessible to citizens, unless there are justified exceptions.

[10] The WeatherCompany, based in the USA, is the world's largest private meteorological company. Since the beginning of 2016, it has been part of the IBM group.

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