METEOROLOGY, CLIMATE AND ENERGY

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Abstract. After studying the needs within various energy sectors, this chapter aims to present solutions that meteorologists can provide, using specialized tools (Satellite observation, climatology, modelling) combined with their know-how and knowledge.

Keywords: Energy needs; meteorological solutions; climatology; forecast

1. How Meteorology Developed

Climatic and meteorological events have punctuated people's lives since time immemorial, affecting them every day, week, season and year. With the emergence of new technological possibilities in the twentieth century, much progress was made in the field of meteorology, opening up new perspectives for weather forecast users.

Weather forecasting appeared with systems based on differential equations, solved according to the physical rules governing atmospheric movement. In order to be able to solve these equations, based on the continuous movement of the atmosphere, and forecast meteorological situations before they even took place, calculation times had to be reduced:

- By removing the less significant parameters to simplify the equations
- By taking into account a horizontal resolution of several tens of kilometres
- By limiting the number of vertical levels
- By considering a greater incremental time for atmospheric changes

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Today, the tools have clearly evolved:

- Transmission systems have changed making it possible to define a satisfactory atmospheric state in a short amount of time.
- Observation data have been transformed with the arrival of satellites: these provide a substantial amount of information at a high frequency (every quarter of an hour) and covering the entire planet, including the oceans and uninhabited areas.
- Developments to IT tools continue to make headway. With the emergence of supercomputers and their new architectures, more calculations can now be run (today's order of magnitude is the teraFLOP: 1,000 billion operations/s). This has led to improved system resolution accuracy and extended forecasting ranges. With the enhancements made to computerised data storage capacity, it is now possible to work on observation and forecast data bases.

These developments have provided National Meteorological and Hydrological Services (NMHS) with a higher quality and greater number of tools to ensure the safety of property and people, which is part of their mission. The other part of their job involves providing top-quality information about forthcoming weather conditions for the benefit of every individual. The reliability of the information allows professional users to include it in their risk management and hence optimise their activity and, consequently, their profits.

This safeguarding role explains why the aviation and marine sectors were the first professional users of weather forecasts. However, energy sector professionals were probably the first to actually integrate meteorological information in the day-to-day management of their activity (and their profits).

2. The Meteorological Needs of Energy Specialists

The primary role of energy specialists is to supply each energy subscriber with the energy they need (electricity, gas, oil, etc.). To do this in an affordable manner, the specialist has to forecast the possible consumption of their customers as accurately as possible. This is so they can better manage available energy in terms of source, storage (if applicable), production and transmission.

Like meteorologists, energy specialists rely on systems of equations, to be solved in real time, in order to constantly plan ahead for future consumption. Of course, the different parameters used in consumption calculation systems include economic information (consumption on a week day differs from that on a public holiday), but also data about the weather conditions (e.g. a drop of 1°C across France means an additional national consumption of 2,100[1] MW).

Owing to the fluctuation of energy prices on the markets, the input data for these systems (user consumption profile, meteorological data, availability of production means, etc.) are strategic for energy specialists. This is why they constantly strive to improve their consumption and/or production calculations by including new parameters or new methods in order to obtain the best value from their model input data.

From a historic point of view, the first forecasts produced by these specialists were based on consumption. Today, the need to optimise procurement costs (for purchasing or production) has created new meteorological requirements. Similarly, given the national importance of energy supplies for all users, governments require energy transmission means to be managed in the best conditions.

Depending on the specific problem of the energy specialist, different meteorological parameters are used.

2.1. TO ESTIMATE CONSUMPTION

- Temperature is the parameter offering the highest correlation. Its biggest effect is in the winter when heating is used, but it is becoming increasingly important in summer with the appearance of air conditioning systems in houses and buildings.
- Modelling of the consumption linked to lighting is based on cloud cover.

Depending on the energy specialist's sector (electricity, gas, etc.), consumption is calculated according to the need for heating, air conditioning and lighting. This is why temperature and nebulosity are useful parameters for such specialists.

2.2. TO OPTIMISE PRODUCTION MEANS

Depending on the production techniques used, energy specialists have different needs in terms of meteorological data and may be required to forecast their production.

[1] Information collected by RTE, the French transmission system operator, in October 2008.

- Hydroelectricity: the history and data relating to rainfall are useful when decisions have to be taken about whether or not to use hydropower dams to produce electricity.
- Wind electricity: at the early stage of a project to set up a wind farm, energy specialists may call on NMHSs to determine the geographic areas offering the best wind potential to produce electricity.
- Photovoltaic electricity: as with wind energy, specialists may need to use weather forecasting services to target the most advantageous locations for installation.
- Temperature: the efficiency (and even use) of many production means (e.g. nuclear power plants and cogeneration plants) varies according to temperature.

2.3. TO OPTIMISE TRANSMISSION

When transmission facilities are located outdoor they are subject to weather conditions. These conditions have to be taken into account in order to ensure better management and prevent loss:

- Depending on the temperature, the transmission capacity of high voltage lines may be lowered.
- Extreme events (such as strong winds, icing, etc.) must be forecast as early as possible so that maintenance teams are ready to act. It should be noted that transmission specialists who are aware there is a risk of icing (based on temperature, humidity, etc.) can adopt transmission methods to reduce this risk.

2.4. TO PLAN INFRASTRUCTURES

Energy specialists generally need to plan ahead for the infrastructures needed in the coming decades, if not the next century. This is why their planning has to take into account future lifestyles, industrial resources and climate conditions. With the current change in climate, forecasting climatic conditions is of prime importance, at least in terms of the parameters with the highest energy correlation.

3. Meteorologists' Solutions to Energy Specialists' Problems

The French NMHS, Météo-France, has the meteorological skills to match the aforementioned needs of energy specialists. Its expertise covers the following areas:

- Climatology
- Studies associated with climatology
- Supply of real-time observations
- Short and medium-term weather forecasting
- Long-term weather forecasting

Each type of data provides energy specialists with information enabling them to better manage the risks relating to their activity.

3.1. CLIMATOLOGY

NMHSs are generally in charge of saving data about the weather, in other words the meteorological data measured in stations across the country. Depending on the agency's capacity, the information saved and archived may or may not be re-usable (electronic or hand-written data, data that may or may not be integrated into databases, etc.).

Today, such data can be backed up by the new observation means available. Additional information can be provided by satellites but it is also possible to recreate climatological data using atmospheric models.

3.1.1. *Conventional Climatological Data*

The various NMHSs across the world have set up coordinated observation networks and transmission systems so that the meteorological information measured in their stations is accessible to all. Used for research purposes and by other NMHSs, this information is of course available to other users within the framework of international, commercial and institutional agreements.

Each NMHS is thus responsible for its observation network. Each network is characterised by its density, the parameters measured, the periodicity of measurements, the rules for transmission on the WMO Information System (WIS) and archiving.

As a general rule, all hourly data measured are now archived thanks to the introduction of automatic systems. In the past, only 3-hourly, or even 6-hourly, data were kept.

The parameters available are:

- Temperature in a sheltered location
- Humidity
- Wind (force and direction)
- Rainfall
- Pressure

Other parameters may also be available but not necessarily in every station or country:

- Ground temperature
- Radiation (diffuse, direct and/or global)
- Cloud cover
- Current weather encoding

Generally speaking, all the existing data in data bases can be made available to customers in the form of a computer file. This availability may or may not depend on local commercial agreements.

3.1.2. *Climatology Satellite Pictures*

Since around 1980, atmospheric observations have been backed up by satellite observations. The latter provide meteorologists and users with spatial data at a higher production rate.

NMHSs like Météo-France validate and match up the data measured using surface meteorological stations. The pictures (and corresponding data) are archived by NMHSs and may be re-used in studies.

3.1.3. *Climatology Using Atmospheric Models*

All atmospheric models analyse the state of the atmosphere before calculating forecasts. Through this analysis, all observations, whether based on spot data (from meteorological stations, radio surveys, etc.) or spatial data (from satellites) are transformed into points on model grids.

The analyses are archived according to the native resolution of the model: for example, the ECMWF (European Centre for Medium range Weather Forecasts) provides information every 0.5° (with this resolution all points on the globe are less than 43 km from a grid point) at different altitude levels.

In some cases, it is necessary to work on long series of data. Analyses must therefore be homogenised as their results depend on the quality of the model. To provide homogeneous data, the ECMWF and its members have created an archive of re-analyses over a 40-year period. The data is referred to as ERA-40 and is available with a 1° resolution (all points on the globe are less than 90 km from a grid point) at different altitude levels.

3.1.4. *Combining Different Sources*

To ensure better results, it is often necessary to link up different observation systems in order to extend the limits of one system thanks to the qualities of another. The joint use of spot data (i.e. measurement points) and spatialised data (satellite or radar pictures) offers spatialised information with a resolution of 1 km. Ground measurements are used to complete satellite or radar images hence providing high resolution spatial views. Pyranometers and satellites can be used to generate radiation maps and data making it possible to measure potential sunshine. Likewise, rain gauges and radar images can be used to measure rainfall and hence define the size of hydropower facilities.

3.2. USING CLIMATOLOGICAL DATA FOR STUDIES

The study of climatology is often associated with excellent skills in mathematical and statistical techniques. This high level of knowledge is generally available in NMHSs.

3.2.1. *Temperature Studies*

The first possible use of temperature data is to calculate the correlation between the temperature and the electricity consumption of a given place. This kind of spot study can be extended to a study involving different meteorological stations in a country in order to calculate a weighted temperature correlated with a more global consumption. It is thus possible to forecast the consumption of an entire country. Such forecasts are highly useful for companies in charge of transmitting and distributing energy to customers.

This first type of information provides all energy specialists with a preliminary estimation of energy use. In this way, it can be used to define long-term energy purchasing and sales. This first type of study is relatively simple as it involves the direct use of data that is archived and validated by NMHSs. The study can be improved by homogenising the data in order to take into account modifications to series of measurements (e.g. changes in station location or station sensors) and to fill in any measurement gaps. The tool needed to homogenise the data uses Fourier Transforms.

Based on such homogenised data, new tools can be made available to energy specialists. In fact, data homogenisation helps to provide a better definition of the current climate change. Hence, correlating historical data with global warming is a means of improving statistical studies. It opens up the possibility of calculating temperature distributions and working on extremes: these studies can then be used, for example, to determine how long new extreme events will last. With the right kind of risk management, energy specialists can then set up the necessary means. Depending on their activity, these may involve energy storage systems (water in dams, gas, etc.), production or transmission facilities, and so on.

3.2.2. *Cloud Cover Studies*

The use of cloud cover data has pointed to a relationship between cloud cover and electricity consumption due to the lighting in buildings and the greenhouse effect, which acts on their heating. This kind of study is possible everywhere thanks to the observation networks near major cities (stations at airports obliged to measure cloud cover are usually close to cities where consumption can be high).

Today, these studies can be improved using satellite data and the automatic cloud determinations developed by NMHSs such as Météo-France. These improvements will make it possible to focus on the real cloud cover of the area consuming the electricity rather than on the airport, which, although it might be located close to an urban area, is not necessarily representative of the largest conurbations. They will also provide greater accuracy, by differentiating areas according to consumption, and make it possible to pool information covering larger regions. The different possibilities will provide energy specialists with several solutions based on cloud cover information.

3.2.3. *Wind Studies*

As with other studies, wind surveys can simply be based on the parameters measured by NMHSs sensors, for example to plot ground wind maps and wind roses at observations points. In other words, they can be used as a starting point in terms of wind potential. However, Météo-France has expertise that allows it to push beyond the limits of physical observations (e.g. number of measuring points and a single measuring height [generally 10 m] for the anemometer).

By using model-based climatology and scaling down data, Météo-France is able to plot potential wind energy maps. These have a highly accurate scale of roughly 1 km and meet the height required by energy specialists (between 80 and 120 m). Once the areas have been determined, tools such as wind roses or frequency tables can be supplied to estimate the wind energy potential of a given area. These tools provide information about the different activities in the sector (construction, project development, finance, etc.), the number of hours during which the wind turbines will be able operate, together with the different efficiency values, and hence the amount of electricity they should produce. Based on these studies and using an even more detailed mapping system, it is possible to determine the exact location of the turbines to guarantee optimal efficiency.

3.2.4. *Radiation Studies*

As previously stated, it is possible to use the climatological data provided directly by station sensors but, again, the same restrictions apply: depending on the country there may be a limited number of sensors.

Météo-France takes things a step further by merging this data with the climatology provided by satellite pictures. Thus, climate-related information can be spatialised and provide data every square kilometre. Météo-France has already done this for France. The atlas quality and resolution for other regions in the world will depend on local measuring means.

3.3. SHORT AND MEDIUM-TERM WEATHER FORECASTING

A weather forecasting model has different characteristics in order to meet customer needs:

- The physics behind the model: in some cases, certain parameters can be left out in order to speed up the calculation time. In other cases, they can be taken into consideration although this will have an effect on the forecasting term and extend calculation times. This is especially the case for Non Hydrostatic (NH) models, which are generally non operational and used for study purposes. AROME will be one of the first operational NH models for Météo-France.
- The assimilation method: a model can define its initial state based on an analysis at a given moment or over a given period. In the first case, the analysis is three-dimensional (3D) and static while in the second it is variational and dynamic (4DVAR).
- The type of forecast: if the model is only run once based on the initial state of the atmosphere, it will be considered as deterministic. If the initial state of the atmosphere is modified several times and the model generates forecasts for each new initial state, it can be considered as probabilistic.
- The model resolutions: the spectral models currently used are defined by their level of truncation (number of waves used in equation solving), their number of vertical levels and the horizontal resolution between grid points for which there are equations to be solved. The temporal resolution defines the time required to solve the differential equation. These calculation resolutions must not be confused with the model output information, which has a lower resolution for storage reasons.
- The model terms: depending on the model, the terms can vary between several hours and several days or weeks.

- The meteorological parameters: these are generally all required to solve the atmospheric thermodynamic equations. However, these data are initially only available on the model's grid points.

On top of the physical principles and the model-based calculation, the different results of a model and its output can also be useful to energy specialists. This is what we shall see in the next part.

3.3.1. *The Different Parameters*

Logically, energy specialists use the same parameters in their forecasts as the parameters with correlations in climatology. Meteorologists, therefore, aim to forecast the same basic parameters. Generally starting with data from models, this forecasting is then fine-tuned with statistical adaptations that take into account all the elements in the model able to improve the correlations between the model's forecasts and observation.

Temperature: depending on the energy specialist's field (gas or electricity), and the modelling means they use, the temperature data may be more or less integrated: they may take the form of forecast temperature on an hourly basis or forecast temperature on a daily basis (minimum, maximum and average temperatures).

Cloud cover: with the interest of cloud cover being mainly linked to lighting and the greenhouse effect in buildings, the most important forecasts are the daily ones. The lighting and greenhouse effect in buildings depend on this variable.

Precipitations: whether solid (snow) or not, precipitations are also monitored by hydropower producers. Precipitation forecasts can be used to better estimate the potential energy present in dams. But they can also be used to ensure the quality of the river water used to cool down power plants (especially nuclear power plants).

Meteorological phenomena: like any other industrialists with outdoor equipment subjected to bad weather, energy specialists like to be able to anticipate extreme phenomena such as:

- Storms: storm forecasting makes it possible to get teams ready ahead of time so that private electricity users' needs can be met as quickly as possible.
- Sticky snow: by forecasting this kind of snow, its build-up on cables can be prevented by modulating the current going through the lines.
- Thunderstorms and their possible consequences (strong winds, hailstones, heavy rain, etc.) can have repercussions on networks and their maintenance.

Today, such phenomena can be specifically monitored using immediate forecasting tools combining different sources of information. Météo-France, for example, combines radar data with rain gauges (detection and quantification of episodes of rain), satellite pictures with visibility sensors (detection of low clouds), and radar images with the impacts of lightning (detection and qualification of storm areas). It is also possible to link up observations with detailed forecasts drawn up by forecasters or high resolution models.

The wind: with the increasing number of wind parks, both across Europe and the world over, it is often necessary to estimate the production level of these farms in order to provide the best forecast of additional means to be implemented in order to meet peaks in consumption.

Radiation: The use of renewable energy sources like the sun has not yet become widespread. Radiation forecasting is therefore not used very much so far, but Météo-France is getting ready for it.

3.3.2. *Model Terms of Forecast*

With the ECMWF, forecast data are available every 3 h up to D +14. Météo-France also uses these data and different models with more detailed grids for shorter forecasting times. ARPEGE, with a 15 km grid covering Europe, goes up to 108 h, and ALADIN with a 10 km grid, goes up to 54 h with hourly forecasts up to H + 12. Météo-France's NH mesoscale atmosphere model AROME currently goes up to H+30 with a 2.5 km grid over a surface area that includes France.

On top of these possibilities, the ECMWF provides forecasts for the next 4 weeks once a week (on Fridays based on Thursday's analysis). The advantage of these forecasts is that they can point to substantial temperature anomalies in W+3, or even W+4. The cold period at the start of January 2009 was identified in this way by the ECMWF and reported by Météo-France 3 weeks ahead of time owing to the substantial and European-wide cold anomaly.

Using the output from these models, statistical calculations can be adapted to provide hourly data to match given points. These calculations can also take into account the latest observations.

3.3.3. *The Quality of Forecasts*

Meteorologists regularly measure the quality of a model's results against the 500 hPa geopotential forecasts (the measurement is based on the difference between the forecast height and that actually analysed).

For energy specialists, this quality measurement is not explicit enough. It is preferable to measure the quality of forecasts by comparing it to the parameters used (temperature, wind, cloud cover, etc.). Methods to measure this quality must therefore be defined. Météo-France generally proposes two criteria:

- The Root-Mean-Square Deviation (RMSD): this measures the quality of an observation-based forecast.
- The climatological score: this provides the additional information of a digital forecast compared with the usual climatological statistics.

3.3.4. *The Relationship Between Terms and Parameters*

Using climatological scores, it is possible to define the real value of forecasting terms. Even if a forecast has a high RMSD, it can help an energy specialist to better manage a risk if it provides additional information to the climatological data.

Thus, up to D+32, the temperature forecast by the EFC model and statistically adapted by Météo-France enhances the climatological data. However, cloud cover forecasts do not provide very much insight after 7 days. It should be noted that the main air mass movements can be perceived in the long term but that it is still very difficult to translate these into a meteorological situation at a given time.

3.3.5. *Types of Forecast*

Atmospheric changes have always been calculated using deterministic models: the equations are run based on the initial state of the atmosphere, considered to be correct.

However, with the progress made in information technology, these models can now run their calculations several times. The ECMWF has worked on the possibility of changing the initial conditions to check the stability of the chosen solutions in the equation solving. The initial conditions are modified 50 times. Next, 51 equiprobable scenarios are forecast. These create an envelope covering all the possibilities of change in the weather over the next few days.

This allows energy specialists to manage extreme temperature risks according to the desired level. They can also use the 51 scenarios quantitatively by applying their models' equations to each one.

3.4. LONG-TERM WEATHER FORECASTING

3.4.1. *Seasonal Forecasts*

Seasonal forecasting consists in predicting the quarterly average of the meteorological parameters (temperature, precipitations, etc.) for the next 4–6 months, on a scale of an area such as France.

A seasonal forecast expresses the most likely scenario from among three pre-defined scenarios: close, below or above average. For the temperature, this translates as “hot”, “normal” or “cold”. In terms of rainfall, the reference is to “wet”, “normal” or “dry”. The idea, for example, is to try and figure out whether next summer will be on average hot and dry or cold and wet in Western Europe.

How are seasonal forecasts made? Global models are used, as in conventional forecasting. But these also reproduce the behaviour of environments that interact strongly with the atmosphere, such as the ocean. The oceanic structure varies much slower than that of the atmosphere. On a seasonal scale the proportion of atmospheric predictability comes precisely from the fact that part of the ocean’s slow variation can be found in the atmosphere. Conditions can therefore be found in the atmosphere that are likely to encourage Atlantic disturbance to the far North, or radically modify areas subject to heavy rain in the tropics, or generate considerable heat and drought.

What are the limits of seasonal forecasts? The performance of seasonal forecasting varies greatly according to the place, the season and the meteorological parameter concerned. Performance is better for temperature than for rainfall. Temperature parameters perform better in winter than in summer. Forecasts are highly informative in the tropical belt, on the Pacific Rim. However, temperature forecasting in Western Europe, without being completely useless, is still very poor. This is due to the characteristics relating to the overall circulation of the atmosphere above the Atlantic Ocean at temperate latitudes. These forecasts should therefore be handled with care. Not too much should be read into them, at least under European latitudes.

Why do seasonal forecasting if it cannot be used? Seasonal forecasts are done on a global scale, i.e. they do not just cover Europe. They are extensively used in America, Western Africa and South-East Asia. Comparing seasonal forecasts with observations is probably not the best way to judge their reliability. Their real interest lies in the support they provide decision-makers involved in weather-related activities. By taking into account the probable future weather rather than the average climate, specialists can improve their management, anticipation and decision-making for time periods of several months. Thus, combined with other data, seasonal forecasts do offer a certain advantage for some economic sectors such as energy and the management of energy sources.

Météo-France has set up partnerships with companies working in the insurance and energy sectors in order to assess the economic interest of such information. The main aim of seasonal forecasting is to determine whether the coming season is likely to be hotter or colder than average or simply close to average. It cannot predict the exact temperature of a specific sequence of 1–2 weeks over the course of the 3-month season.

Does Météo-France make seasonal forecasts? For several years now Météo-France has been producing 4-monthly seasonal forecasts as part of an experiment using the Arpège- Climat model. The spatial resolution of this model is roughly 250 km and the parameters forecast are the average temperature and the overall rainfall for the "season". These forecasts are analysed by the Météo-France climatology department, 1 month before the close of the forecast quarter. The results are presented:

- In a "probabilistic" manner: the probability of conditions "below normal", "close to normal" or "above normal" is given.
- In a "deterministic" manner: the deviation from the normal average temperature and overall rainfall for the 3-month period is given for each point on the globe.

Since summer 2005, a second model, again based on Arpège-Climat but combined with an ocean model, has provided Météo-France with a new, normally better, source for its seasonal forecasts. This model will be part of the Euro-Sip experiment designed to produce seasonal forecast maps by blending the results of three models: 1 French, 1 English and 1 from the ECMWF. The ability to forecast meteorological parameters in the long term is indeed improved when there are more data sources. This is why Météo-France draws up a summary of seasonal forecasts based on the results available (generally 15 days before the end of the forecast quarter) from several centres – currently six – including the two models specific to Météo-France.

Who does seasonal forecasting in the world? Most large digital forecasting centres do this kind of forecasting. There is Météo-France, the ECMWF, NMHSs such as the Met Office in the UK, the Japanese, Korean, Chinese, Indian, Canadian, Australian and Moroccan offices, the American National Center for Environmental Prediction (NCEP), research organisations such as the Max-Planck Institute in Germany, the International Research Institute for Climate Prediction (IRI) in the United States and the CPTEC Brazilian research centre.

3.4.2. *Climate Studies*

Based on the scenarios outlined in the 2007 report of the IPCC (Intergovernmental Panel on Climate Change), Météo-France uses the ARPEGE-Climat atmospheric climate model developed by its research centre to simulate the climate for a given region in the world.

These simulations can then be adapted to the world of energy. For example, Météo-France has created town-by-town, chronological, 3-hourly temperature sequences for the coming century (the scenario considered in this case has a constant climate). This data can be used to create a statistical envelope reflecting the climate in the twentyfirst century and making it possible to plan ahead for changing energy needs and the corresponding infrastructures.

4. Conclusion

As can be seen, Météo-France and its weather specialists are constantly striving to improve their atmospheric observation and forecasting tools in order to better fulfill their state missions. The improvements linked to calculation capacities and observation transmissions are of course beneficial to the industrial and energy sectors. However, these sectors above all benefit from the studies carried out by the agency within the framework of commercial agreements. Finally, it has to be said that, given its importance, the energy sector has also spurred the progress made by National Meteorological and Hydrological Services.