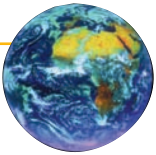
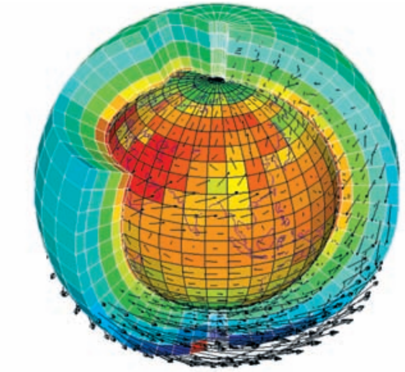
Predicting the weather



Claude Basdevant

Forecasting the weather or the climate is not an easy matter. It requires modelling of numerous natural phenomena and interaction between several sciences, ranging from mathematics to biology, via computer science, physics and chemistry.

Where does the weather bulletin that a smiling lady presents every night on the television come from ? No longer from frogs or thermometers, but rather from supercomputers which process huge amounts of data, obtained mainly by satellites, together with the laws of mechanics and physics, and also much, often recent, mathematics.



Artist's impression of the boxes used for calculations in a weather or climate prediction model. (Illustration L. Fairhead LMD/CNRS).

For computers to make forecasts, it is first necessary to develop what is called a numerical weather prediction model. Schematically, a prediction model for the range of up to eight or ten days describes the state of the atmosphere by the values taken by meteorological parameters (wind speed, temperature, moisture, pressure, clouds, etc) at the centres of « boxes » which partition the volume of the atmosphere. These boxes have sides about fifty kilometres long and height between a few tens and a few hundreds of metres. This imaginary partitioning of the atmosphere into boxes is necessary because it is impossible to specify the parameters at every point in the atmosphere (there are infinitely many of them!). In theory, the smaller (and therefore the more numerous) the boxes are, the more accurate the description of the state of the atmosphere is, and the more accurate the forecasts will be. But the sides of the boxes cannot in practice be made smaller than about fifty kilometres. Below that, the power of even the most powerful computers would be insufficient. The forecast must be ready in time, well within 24 hours!

Starting from the assumed state of the

atmosphere at the beginning of the prediction period, the numerical model computes the ensuing future evolution on the basis of the laws of physics and dynamics. The computation is performed stepwise, with timesteps of a few minutes. That is the principle that lies behind numerical weather prediction, a principle that had been known since the beginning of the 20th century, but had to wait until the advent of the first electronic computers in the 1940's and 1950's before it could be practically implemented.

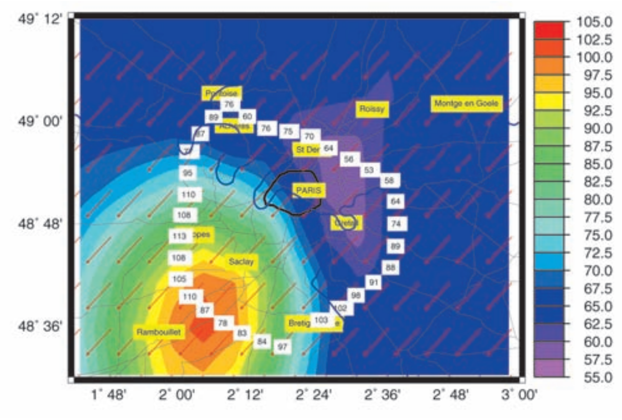
Meteorological measurements cannot be used directly

The first problem that arises in the ideal forecasting scheme that has been just described is the definition of the``initial state of the atmosphere”. Actual observations are not well-suited for that purpose. Surface weather stations are irregularly distributed over the globe and provide very few measurements in altitude. As for satellites, most of them sweep the Earth continuously, so their measurements are not obtained at the same time at all points. Moreover, satellites measure quantities that are integrals over the depth of the atmosphere (in general they measure the radiative energy flux over a given wavelength range) and not the meteorological parameters (wind, temperature, moisture, etc.) that enter the equations of the model.

One therefore has to deal with a heterogeneous mass of data, irregularly distributed over the surface of the Earth, spread out over 24 hours, from which to ``initialise” a forecast, i.e., to construct the starting point of the prediction. However, thanks to the theory of dynamical optimisation, a field to which the Russian mathematician Lev Pontryagin (1908-1988) and the French mathematical school have contributed much, methods known as ``variational assimilation” could be developed in the 1980’s, which made possible an optimal reconstruction of the initial state of the atmosphere. The basic idea underlying these methods, which have been used operationally by Météo-France since 2000, is to force the trajectory of the numerical model to pass ``close” to the data observed during the previous 24 hours. But variational assimilation is not the only modern mathematical technique that has contributed to deeply influence processing of observations: the use of neuromimetic networks or of wavelets, invented less than twenty years ago, has led to spectacular gains in efficiency, accuracy and speed in processing data provided by satellites.

Numerical analysis enters the picture...

Once the required initial state of the atmosphere is known, it is necessary to develop the computer programs which will calculate, on the basis of the physical laws, the weather to come. The physical laws are built on a continuous description of space and time. But our numerical model handles only a finite, albeit large, number of boxes; similarly, there is a time interval of several minutes between two successive computed states - one says that the problem has been ``discretised”. Transforming continuous physical laws into a discretised formulation, while preserving as much accuracy as possible, that is the object of numerical analysis, a branch of mathematics which has witnessed a real explosion since the advent of electronic computing. The aim of numerical analysis is to solve equations to the very end,



Ozone plume over the Paris area at an altitude of 300 m on August 7, 1998, at 4 PM. Colour coded, concentrations as simulated by the CHIMERE numerical model of LMD/IPSL; the measurements taken by an airplane are shown in the small boxes(Illustration MERLIN of Météo-France).

i.e., to the determination of numerical values, while saving as much time and effort as possible. Numerical analysis is necessary for the simulation not to be a mere simulacrum, and for evaluating the uncertainty of the forecasts. For example, significant progress has been made recently regarding methods for simulating the transport of chemical species or particles by atmospheric turbulence. This has led to significant improvement in the study and prediction of air pollution.

Can weather be predicted far in advance? The theory of dynamical systems says `no'

We have talked of short-term weather forecast, up to eight or ten days. But why does one not make long-term forecasts? The American meteorologist Edward N. Lorenz, in a famous article in 1963, showed that it is probably hopeless to try. The atmosphere is a chaotic system, i.e., any error in the initial atmospheric state, however small, is quickly amplified over time, so quickly that a forecast beyond ten days is completely unreliable. Nevertheless, that does not mean that one cannot predict climate - i.e., make a statistical instead of a deterministic forecast, in order to determine the average precipitation or temperature over a period of time, rather than the precise weather in Brittany on a particular day in July. The stakes are high: our climate is threatened by gas emissions due to human activities and it is necessary to predict the long-term effect of the resulting perturbations. It is the theory of dynamical systems which provides the tools for climate modelling.

This theory, of which the mathematician Henri Poincaré was a great precursor at the beginning of the 20th century, has undergone significant progress in the last twenty years. It makes it possible, for example, to identify what mathematicians call attractors, and meteorologists weather regimes. It also makes it possible to determine which weather regimes are most predictable and which are most unstable. In the case of instability, an appropriate tool would be probabilistic climate modelling, which explicitly takes into account the randomness of the forecast. Probabilistic climate models, which are still little developed, must be based on the new tools of the theory of stochastic partial differential equations and of statistics.

From weather prediction to climate prediction

Climate prediction models closely resemble weather prediction models, with two fundamental differences. They use larger ``boxes” (with sides of 200 to 300 km); as the time over which the simulation is to be performed varies from a few months to hundreds, or even thousands, of years, the numerical cost a higher resolution would be prohibitive. But the most significant difference comes from the fact that, as climate variations occur over long periods of time, it is no longer possible to neglect the interactions between the atmosphere, oceans, ice, and even the biosphere. That is why a climate model must combine a model of the atmosphere, a model of the oceans, a sea-ice model, and a model of the biosphere. Beyond the computational complexity of such a system, delicate mathematical problems arise in the combination of these different models, and in the specification of the conditions at the various interfaces between atmosphere and ocean, ocean and ice, etc. Also, for the calculations performed on ``large boxes” to remain meaningful, it is necessary to evaluate the statistical effect, at the scale of those boxes, of phenomena which occur on a much smaller scale (for example, what is the statistical effect, on the energy budget of a 300 km-wide box, of small cumulus clouds, with a size of a few km in diameter, that develop within the box?). In all these questions, there is scope for numerous future mathematical developments.

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A few references:

- Numerous references on *“Numerical Weather Prediction”* can be found on the net.
- La Météorologie, issue n° 30, special issue on numerical weather prediction (2000).
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