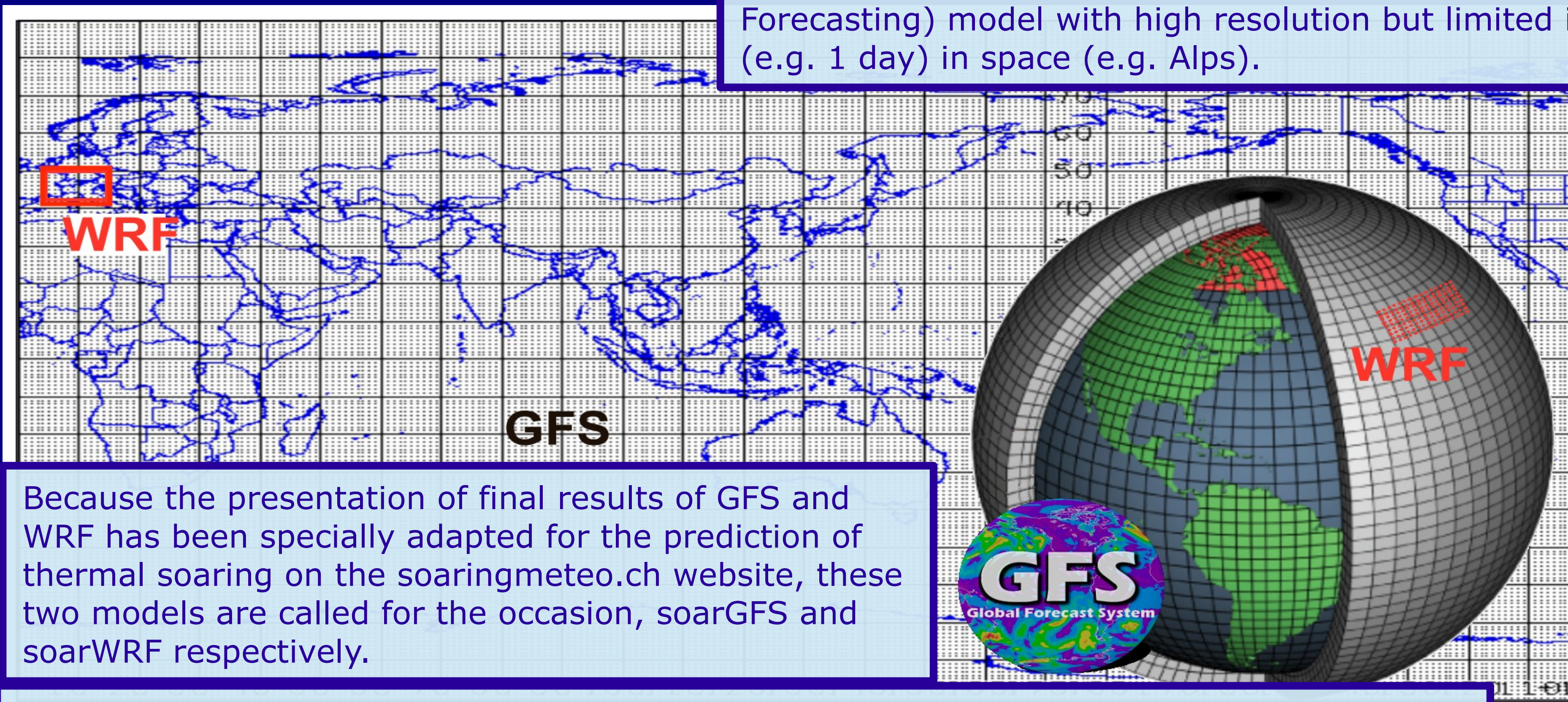
The purpose of this document is to explain how do work the numerical weather models and how to interpret them. We mainly speak about GFS model (Global Forecast System) with low resolution but long-term forecast (7 days) and valuable for the whole world and about WRF (Weather Research & Forecasting) model with high resolution but limited in time (e.g. 1 day) in space (e.g. Alps).



Because the presentation of final results of GFS and WRF has been specially adapted for the prediction of thermal soaring on the soaringmeteo.ch website, these two models are called for the occasion, soarGFS and soarWRF respectively.

Numerical weather models

Jean Oberson – soaringmeteo.ch - Version 1

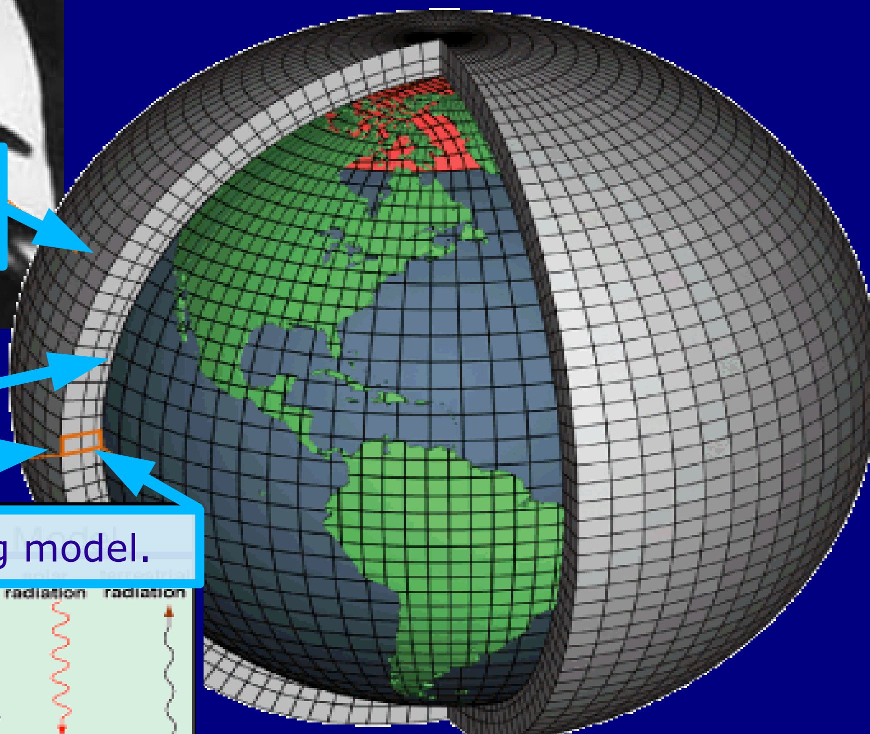
Bjerknes, 1862-1951, Norwegian geophysicist, mathematician and physicist.

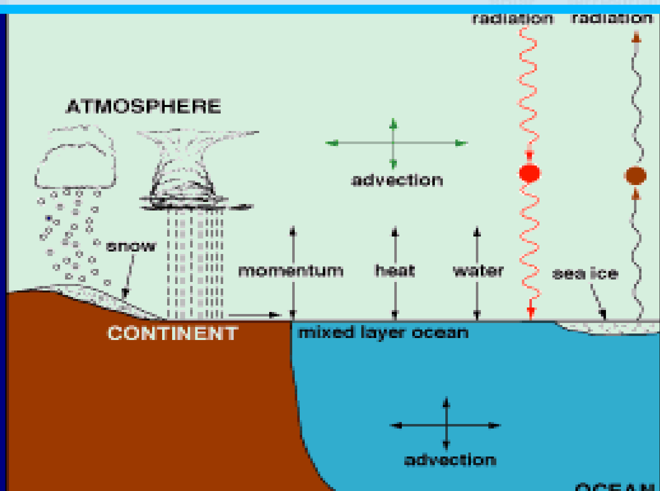
In the early 20th century, Bjerknes and Richardson have already set out the principles of the mathematical simulation of the weather from a known and measured start condition. This simulation is based on the laws of fluid physics.

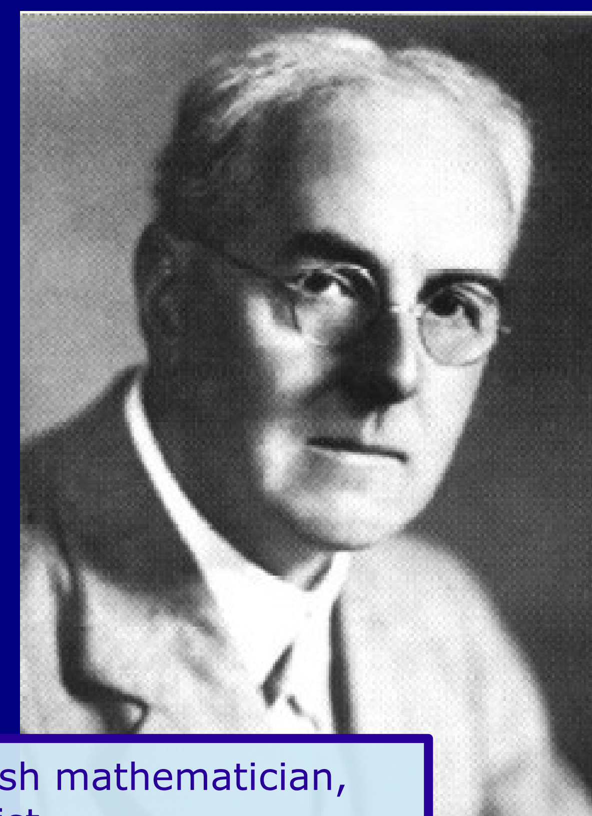
Horizontal component of the grid.

Vertical component of the grid.

Physical processes leading model.

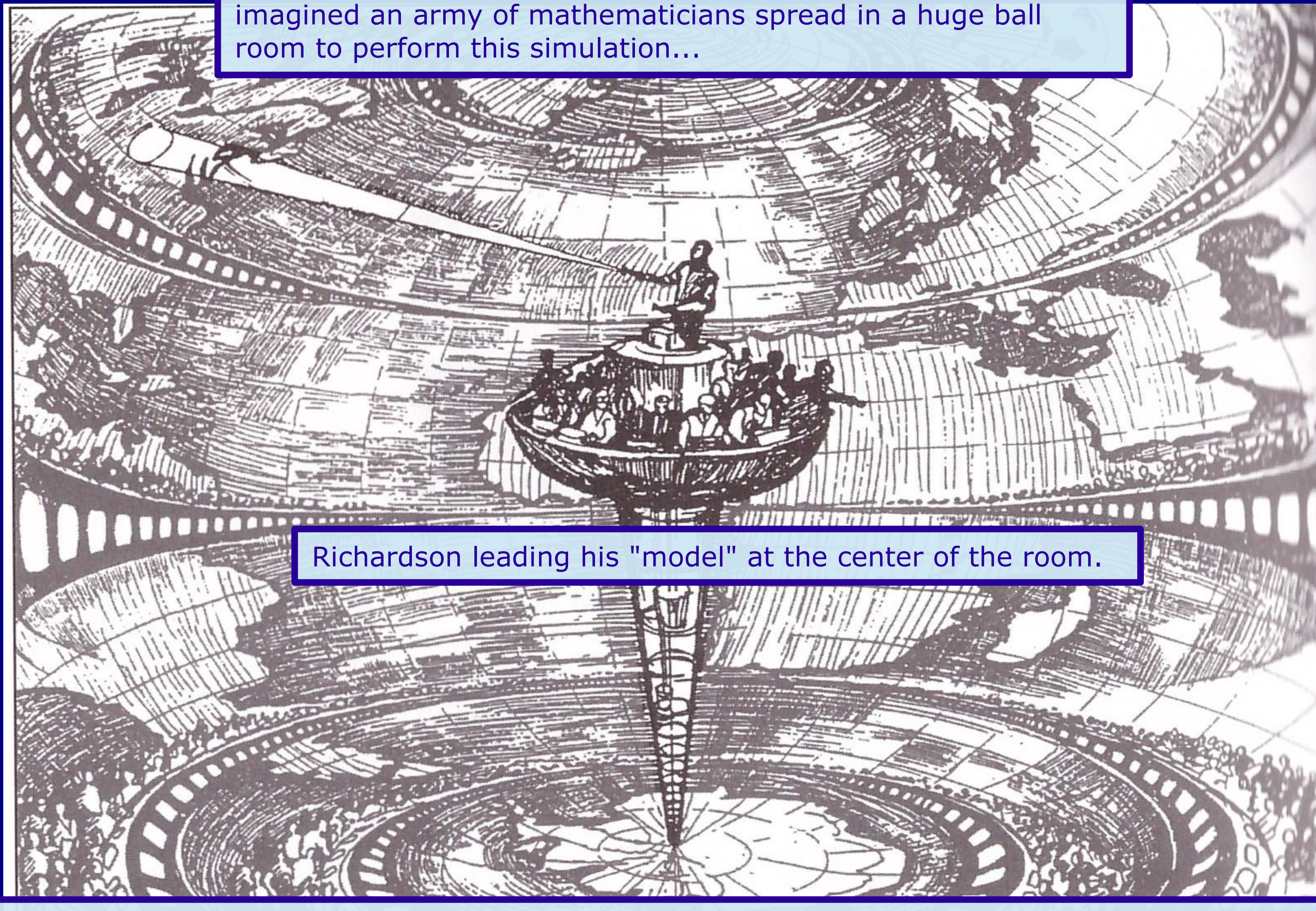






Richardson, 1881-1953, British mathematician, meteorologist and psychologist.

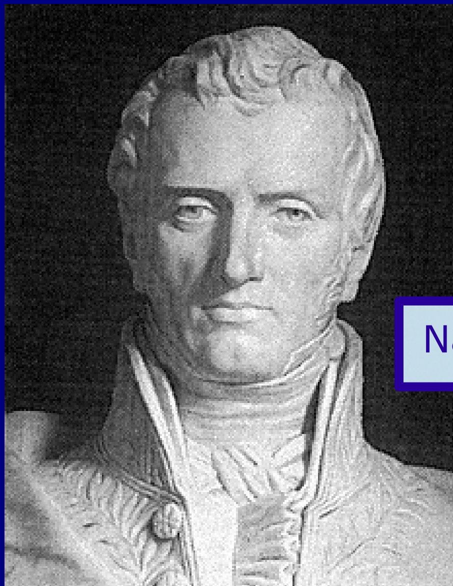
Small amusing anecdote, Richardson, before computers, had imagined an army of mathematicians spread in a huge ball room to perform this simulation...



Richardson leading his "model" at the center of the room.

It was not until 1950, with the first computers that these principles have been applied first experimentally. The first operational NWP were introduced in the early 1960s. Models have continued to grow since then, thanks to the dramatic increase in computational power of computers and the enormous progress in computational methods and in theoretical meteorology.

Primitive atmospheric equations are a variant of the Navier-Stokes equations that describe the motion of fluids, taking into account the principle of conservation of mass, energy and momentum. These are the equations that are used in the basic calculations of models.

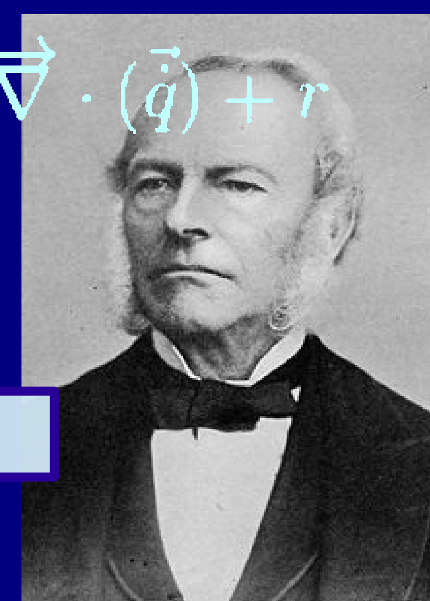


Navier, 1785-1836, French engineer and mathematician.

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

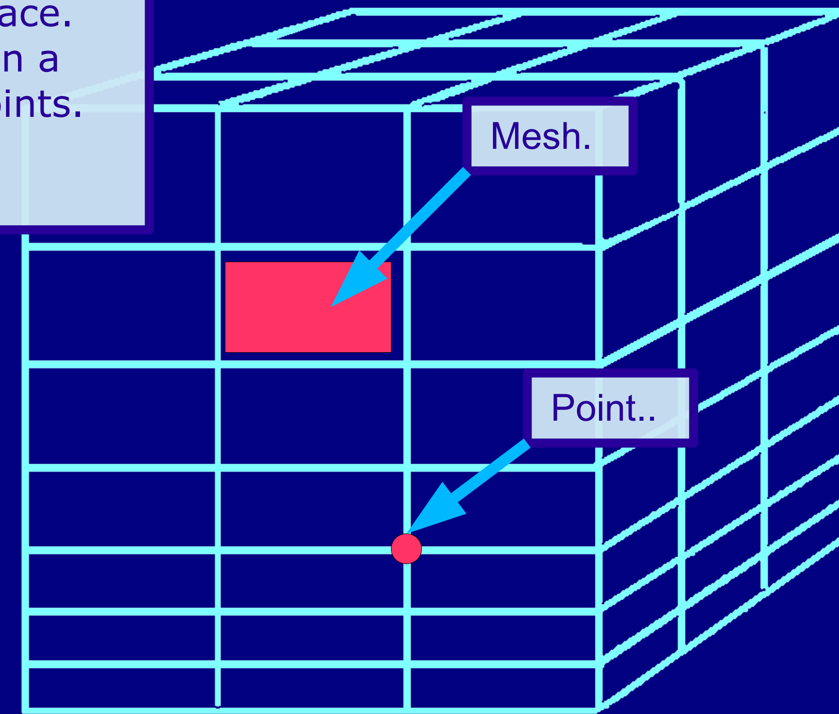
$$\frac{\partial (\rho \vec{v})}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v} \otimes \vec{v}) = -\vec{\nabla} p + \vec{\nabla} \cdot \bar{\bar{\tau}} + \rho \vec{f}$$

$$\frac{\partial (\rho e)}{\partial t} + \vec{\nabla} \cdot [\, (\rho e + p)\, \vec{v}\,] = \vec{\nabla} \cdot (\bar{\bar{\tau}} \cdot \vec{v}) + \rho \vec{f} \cdot \vec{v} - \vec{\nabla} \cdot (\vec{\dot{q}}) + r$$



Stokes, 1819-1903, British mathematician and physicist.

To limit the calculations, the continuity of the real phenomena scale (in practice the molecular scale) must be broken in time and space. The simulation thus becomes discontinuous in time and space on a three-dimensional computational grid with mesh between its points. The results of this simulation therefore have a "pixelated" appearance, similar to a coarse digital image.

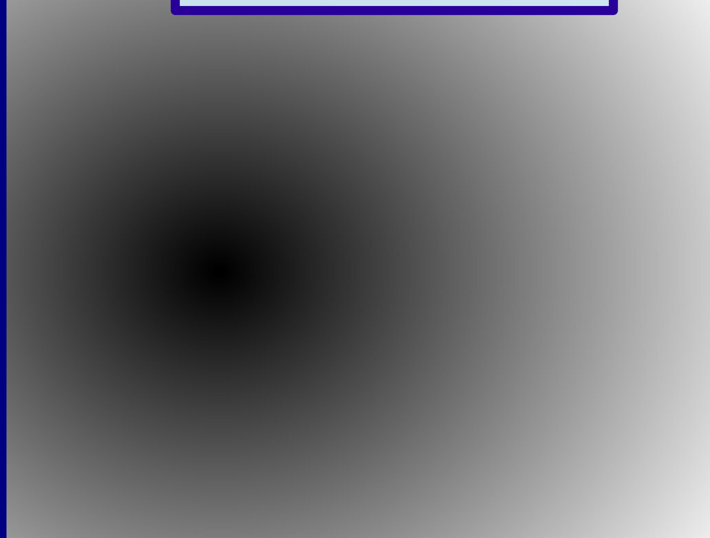


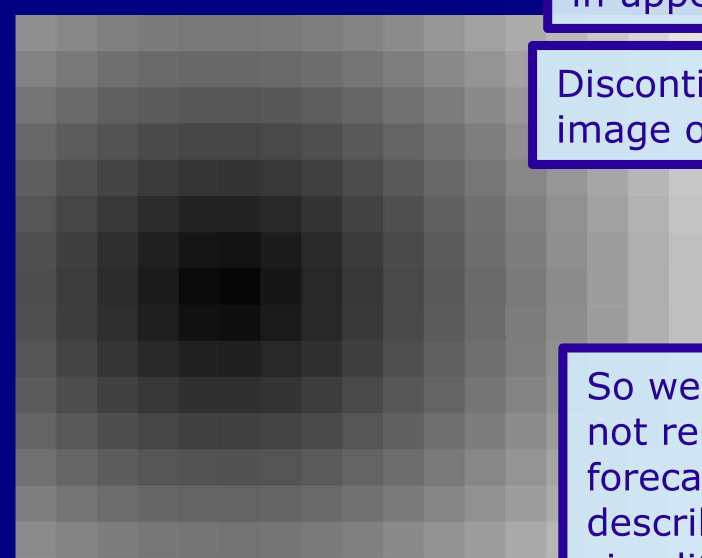
As well, time is not a continuous variable, the calculations jumping from one step to the next.

The parameters can be located either at the points or at the centers of the meshes of the grid.

In general, the meshes (vertical component) are thinner in low than in upper atmosphere.

Continuous reality.





Discontinuous and pixelated image of reality (model).

So we can say that the models do not represent or do not provide forecast of real weather, but describe a rough, average and simplified image of weather.

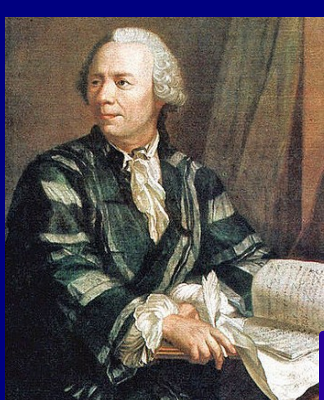
There are two types of models classified according to the method of calculation. Lagrangian models, rarely used, and Eulerian models. The Lagrangian description consist in examining the properties of the fluid following a particle in its motion. The Eulerian description consist in a fixed local investigation of the properties of a fluid in motion.

Lagrange, 1736-1813, Italian and French, mathematician, engineer and astronomer.

Eulerian description.

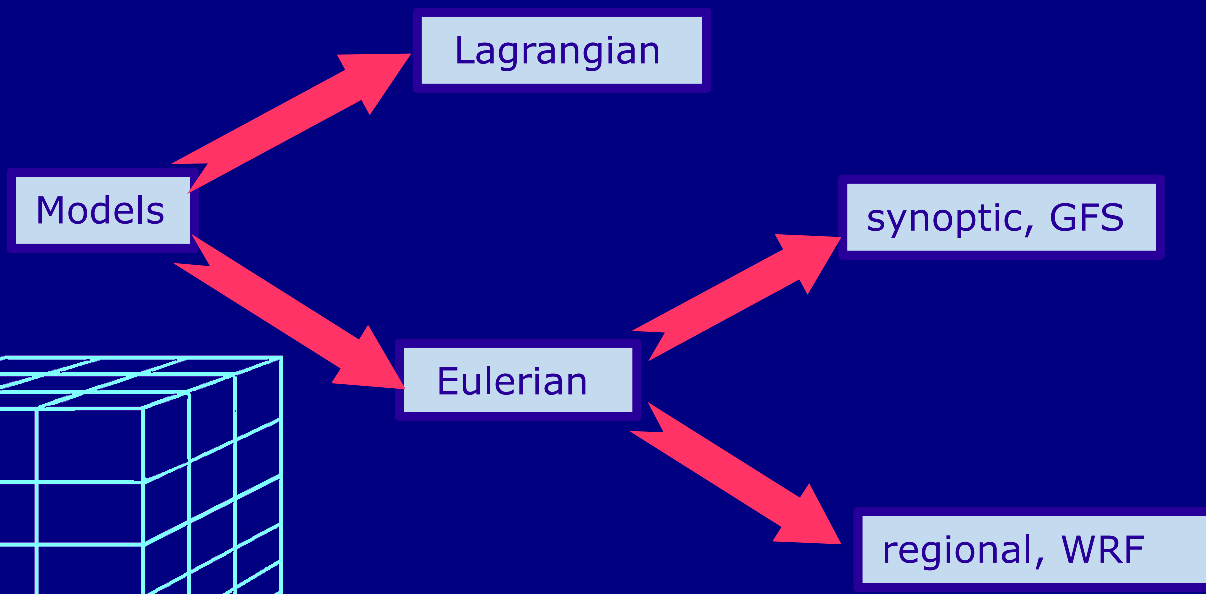
Here's an analogy with measuring speed of cars on a road: An Eulerian description consists to pick fixed points on the road, and to measure the speed of each car that passes through these points. A Lagrangian description consists in being in a car and measuring the speed at several moments.

Lagrangian description.

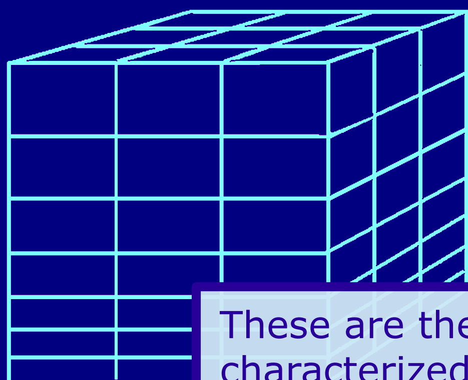


Alptherm, developed by Dr. Bruno Neininger in the 90s, is a simple Lagrangian model describing convection (thermal) air. This model requires the results (that is to say, must be paired with) Eulerian models to operate. But in this paper it is described that the Eulerian models.

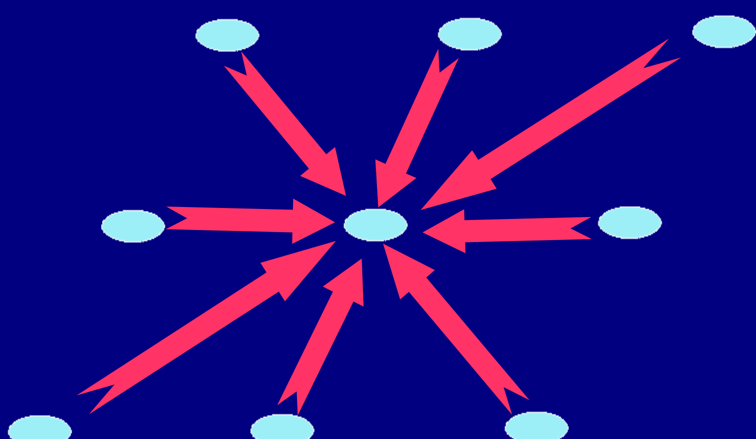
Euler, 1707-1783, Swiss mathematician and physicist.



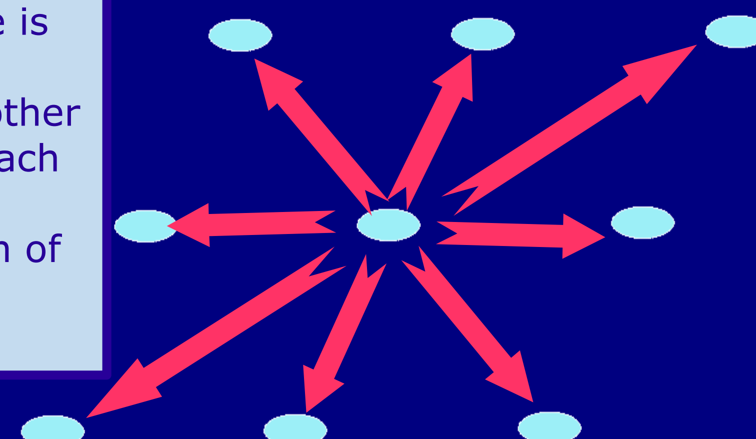
For Eulerian models, there are two types of models classified according to the resolution of their grid. Global models synoptic scale (macro-scale with wide mesh of about 40 Km) and those regional scale (mesoscale) better spatial and temporal resolution (with meshes of a few km), but limited to a region.



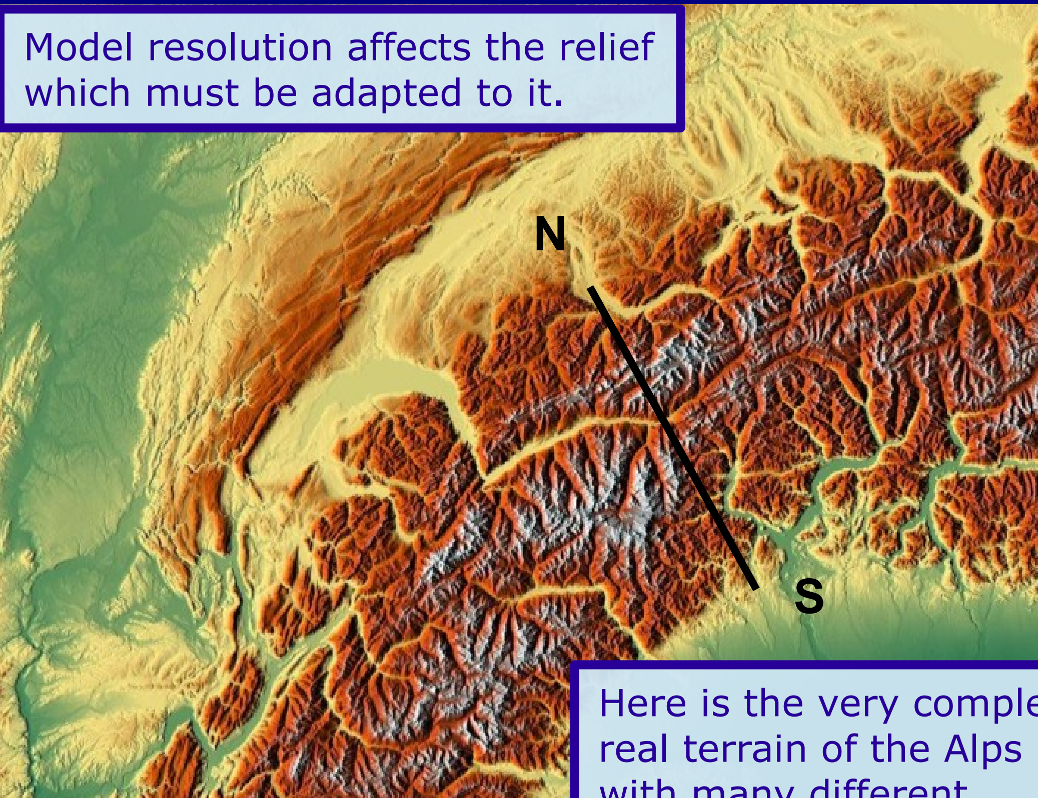
These are the Euler models which are characterized by a three-dimensional calculation grid whose points and the center of the cells may represent the location of the calculated meteorological parameter.



An important principle is that each grid point is influenced by all the other points of it and that each point influences the others in the evolution of meteorological parameters.

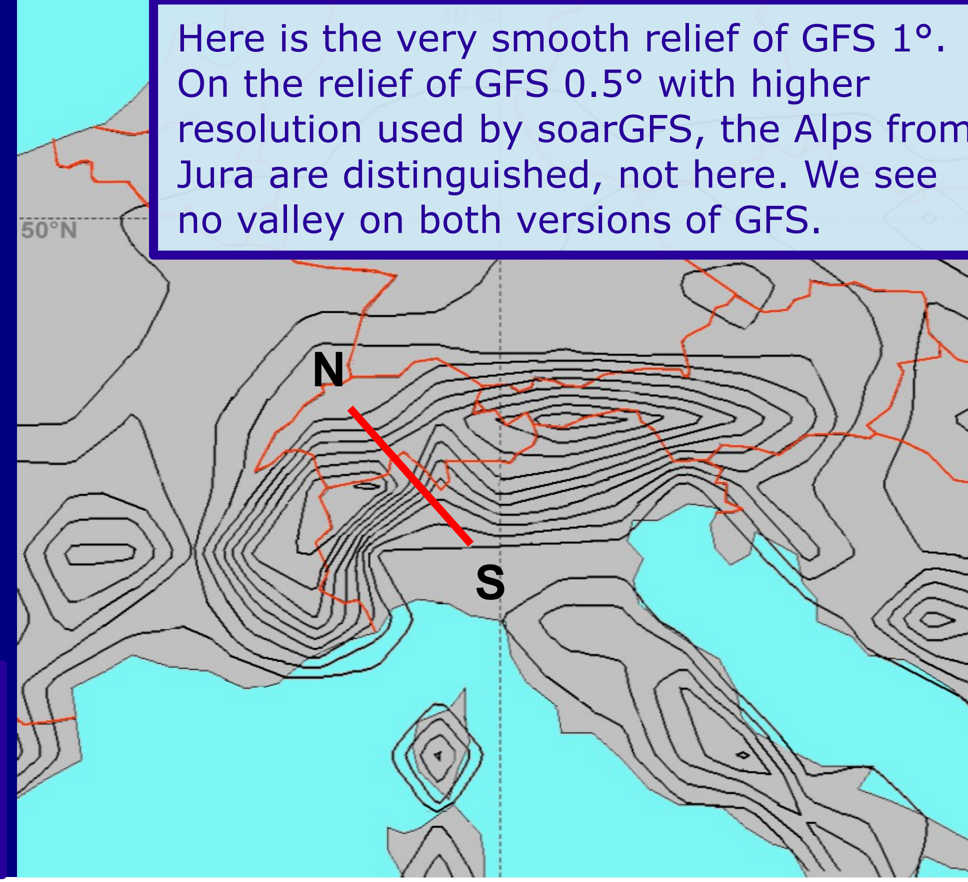


Model resolution affects the relief which must be adapted to it.

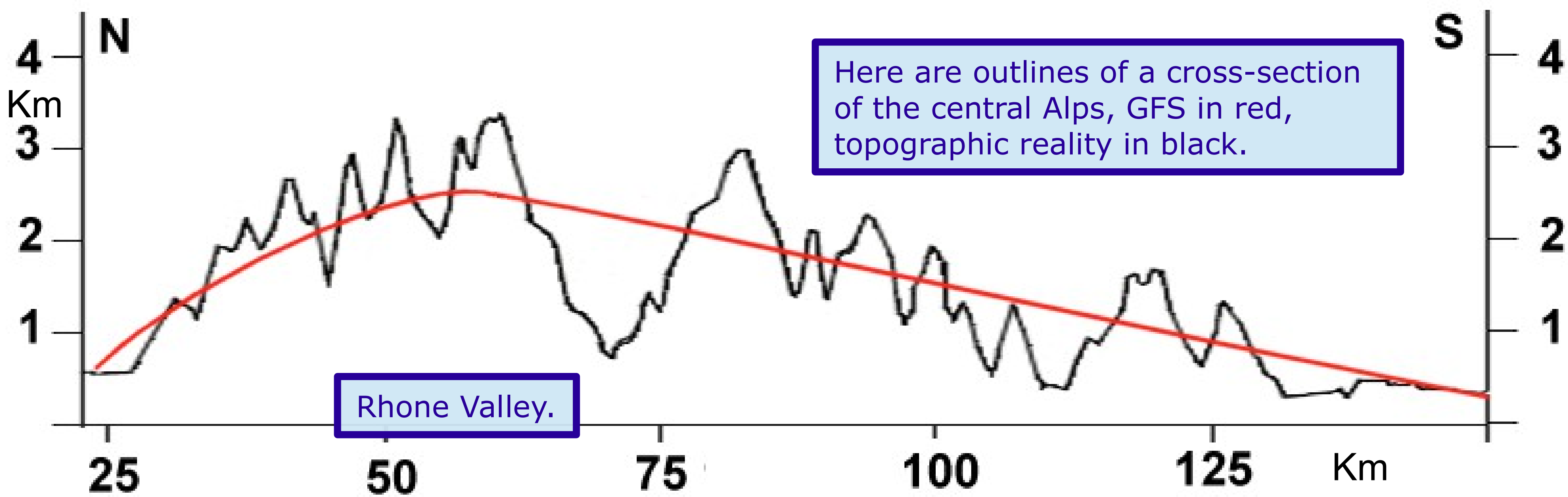


Here is the very complex real terrain of the Alps with many different peaks and valleys.

Here is the very smooth relief of GFS 1°. On the relief of GFS 0.5° with higher resolution used by soarGFS, the Alps from Jura are distinguished, not here. We see no valley on both versions of GFS.

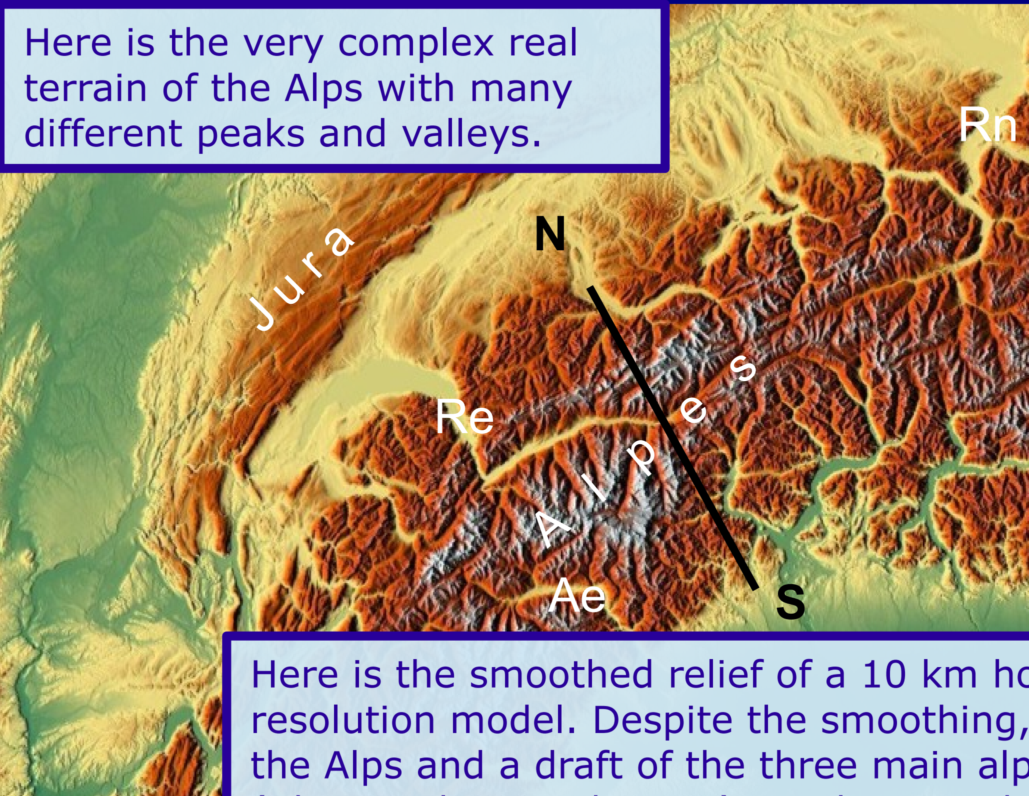


Here are outlines of a cross-section of the central Alps, GFS in red, topographic reality in black.

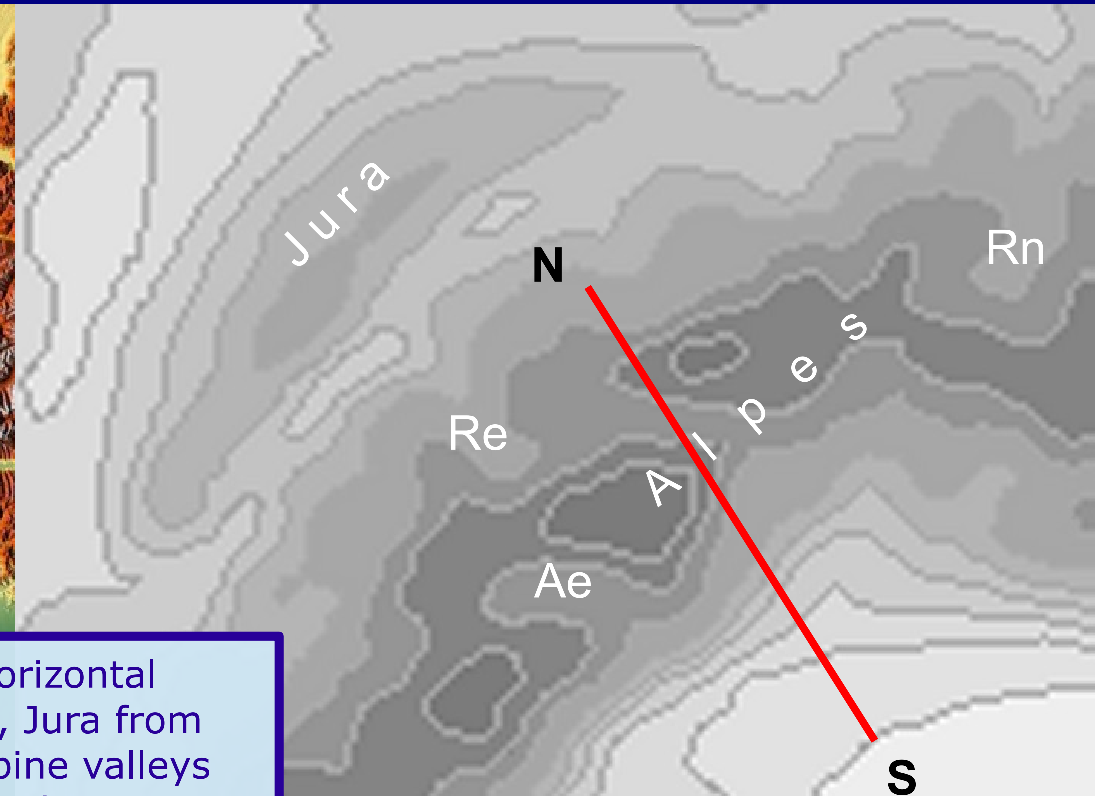


Rhone Valley.

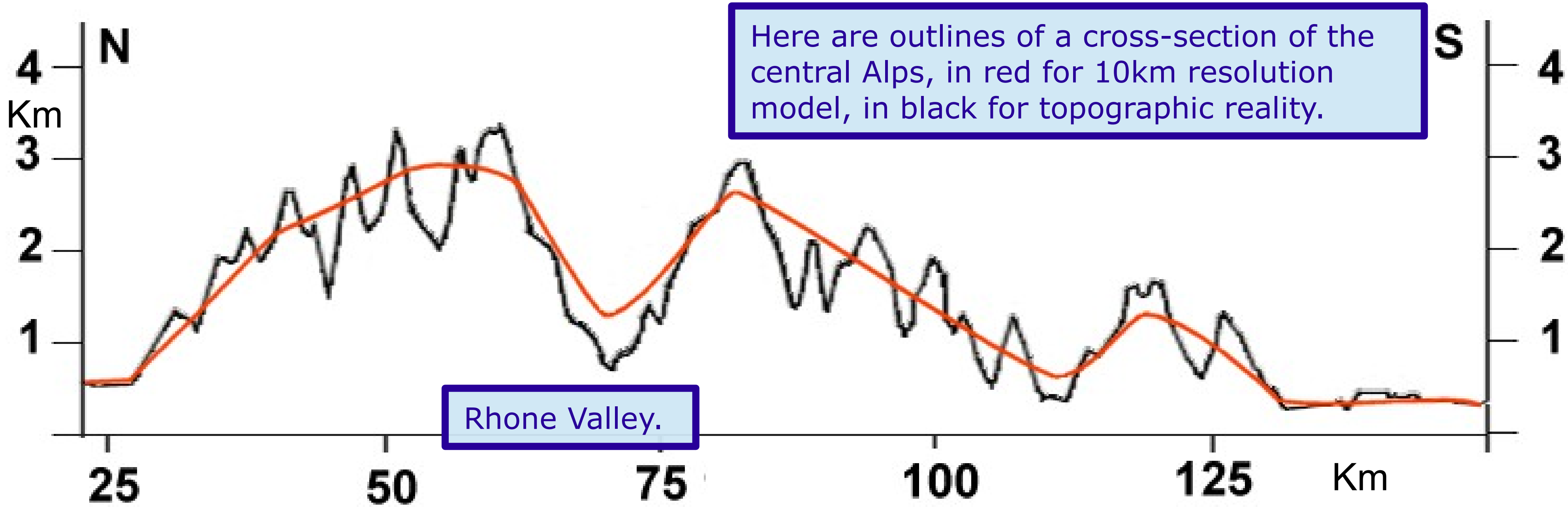
Here is the very complex real terrain of the Alps with many different peaks and valleys.



Here is the smoothed relief of a 10 km horizontal resolution model. Despite the smoothing, Jura from the Alps and a draft of the three main alpine valleys (Rhone, Rhine and Aosta) are distinguished.



Here are outlines of a cross-section of the central Alps, in red for 10km resolution model, in black for topographic reality.

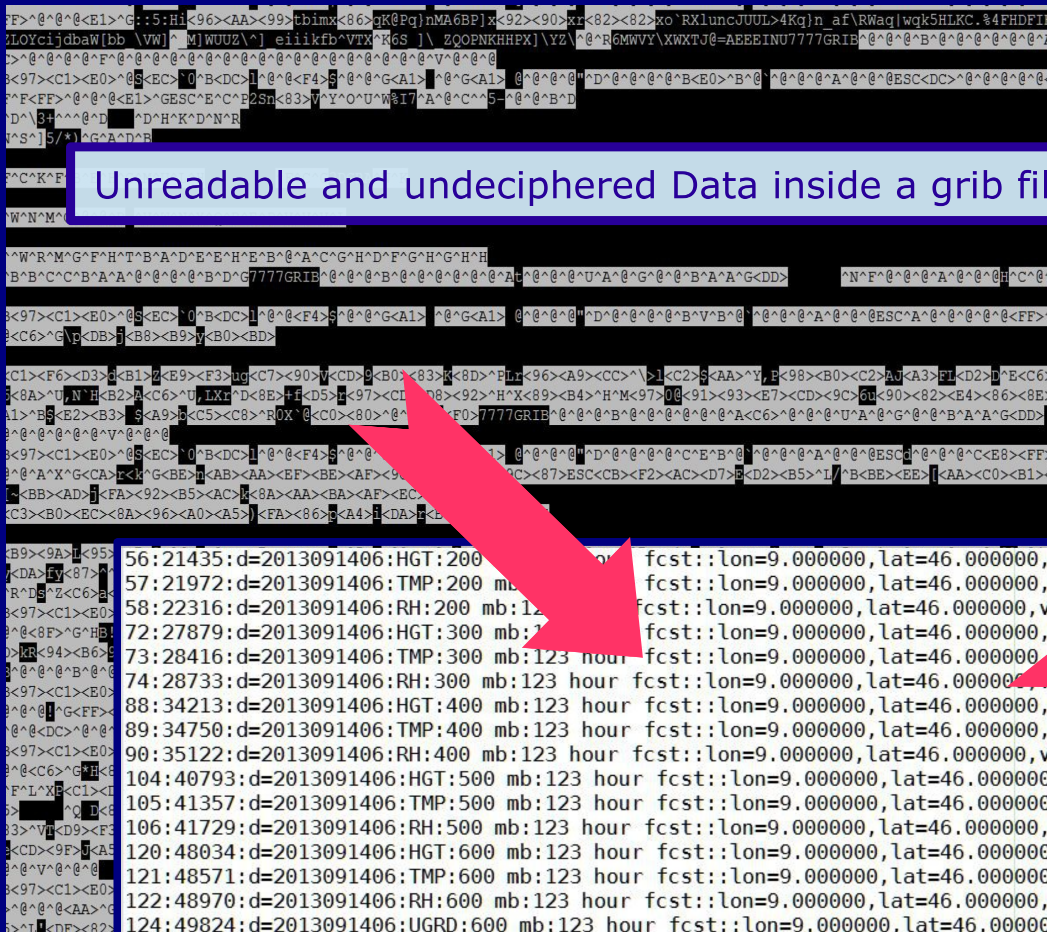


Rhone Valley.

There are many government and private models in the world. We speak here only about two American models: GFS, at synoptic scale and WRF, at mesoscale, both used in soaringmeteo.

Despite its large mesh, GFS (Global Forecast System) is useful for predicting thermal, provided that the outputs (results) are properly interpreted by the human. It is one of numerical weather prediction of the U.S. National Weather Service (NOAA-NCEP).

Performant and of a high level of technology, it is the only global model whose results are regularly freely and fully available to everyone. These results are found in the NCEP servers in the form of special computer files, officially recognized by the World Meteorological Organization (a subsidiary of the UN), called "grib" which needs to be decrypted before use.



Unreadable and undeciphered Data inside a grib file.

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56:21435:d=2013091406:HGT:200 ... fcst::lon=9.000000,lat=46.000000,val=12096
57:21972:d=2013091406:TMP:200 ... fcst::lon=9.000000,lat=46.000000,val=214
58:22316:d=2013091406:RH:200 mb:12... fcst::lon=9.000000,lat=46.000000,val=96
72:27879:d=2013091406:HGT:300 mb:1... fcst::lon=9.000000,lat=46.000000,va...
73:28416:d=2013091406:TMP:300 mb:123 hour fcst::lon=9.000000,lat=46.000000...
74:28733:d=2013091406:RH:300 mb:123 hour fcst::lon=9.000000,lat=46.00000...
88:34213:d=2013091406:HGT:400 mb:123 hour fcst::lon=9.000000,lat=46.000000,v...393.2
89:34750:d=2013091406:TMP:400 mb:123 hour fcst::lon=9.000000,lat=46.000000,v...=251.3
90:35122:d=2013091406:RH:400 mb:123 hour fcst::lon=9.000000,lat=46.000000,val=37
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... fcst::lon=9.000000,lat=46.000000,val=3641.
... fcst::lon=9.000000,lat=46.000000,val=273.2
... fcst::lon=9.000000,lat=46.000000,val=31
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140:57175:d=2013091406:UGRD:700 mb:123 hour fcst::lon=9.000000,lat=46.000000,val=2.28
141:57684:d=2013091406:VGRD:700 mb:123 hour fcst::lon=9.000000,lat=46.000000,val=-2.88
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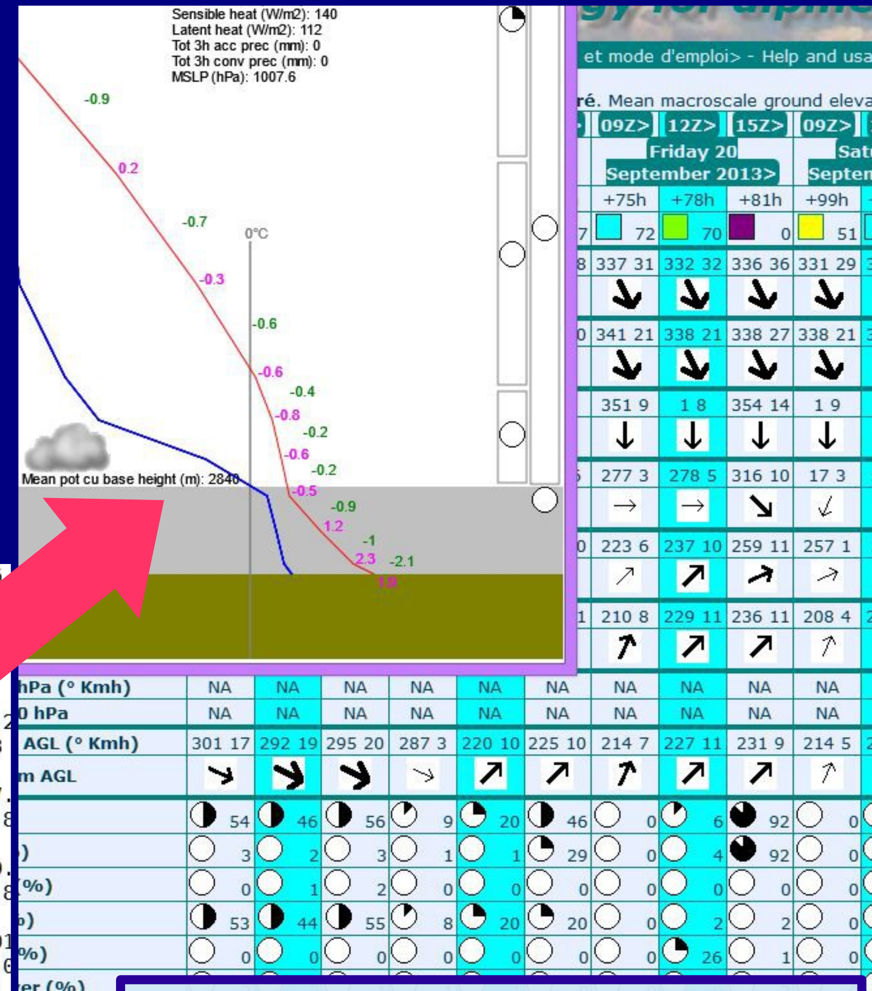
```

Decrypted but unusable data.

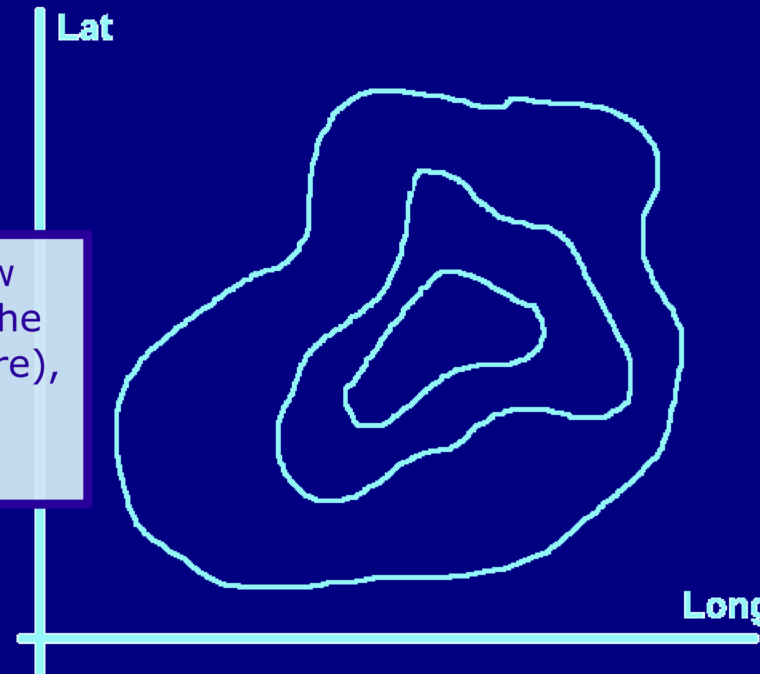


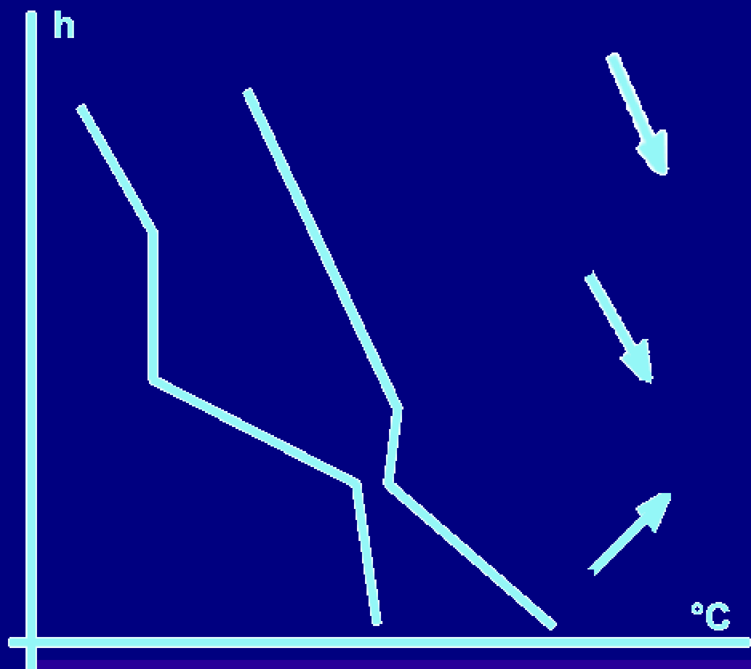
Graphical and user-friendly Data.

The raw data from these decrypted "grib" files already represent forecasts but are not yet usable. Calculations and additional tasks must be performed to make user-friendly and readable results. In general graphs are generated and are then distributed on a website accessible to all, in this case here soaringmeteo.ch

Usually there are three kinds of graphics: maps, meteograms and aerological profiles, the latter often drawn on emagrams.

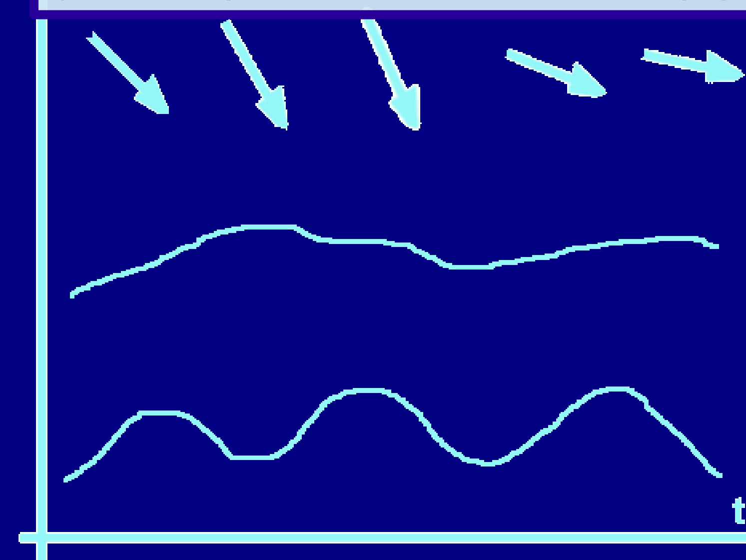
Maps are graphs on which are represented one or a few parameters over an entire region at a specific time in the form of pictograms or isovalue curves: isobars (pressure), isotherms (temperatures) isotachs (speeds)... Lat = latitude north-south. Long = longitude west-east.





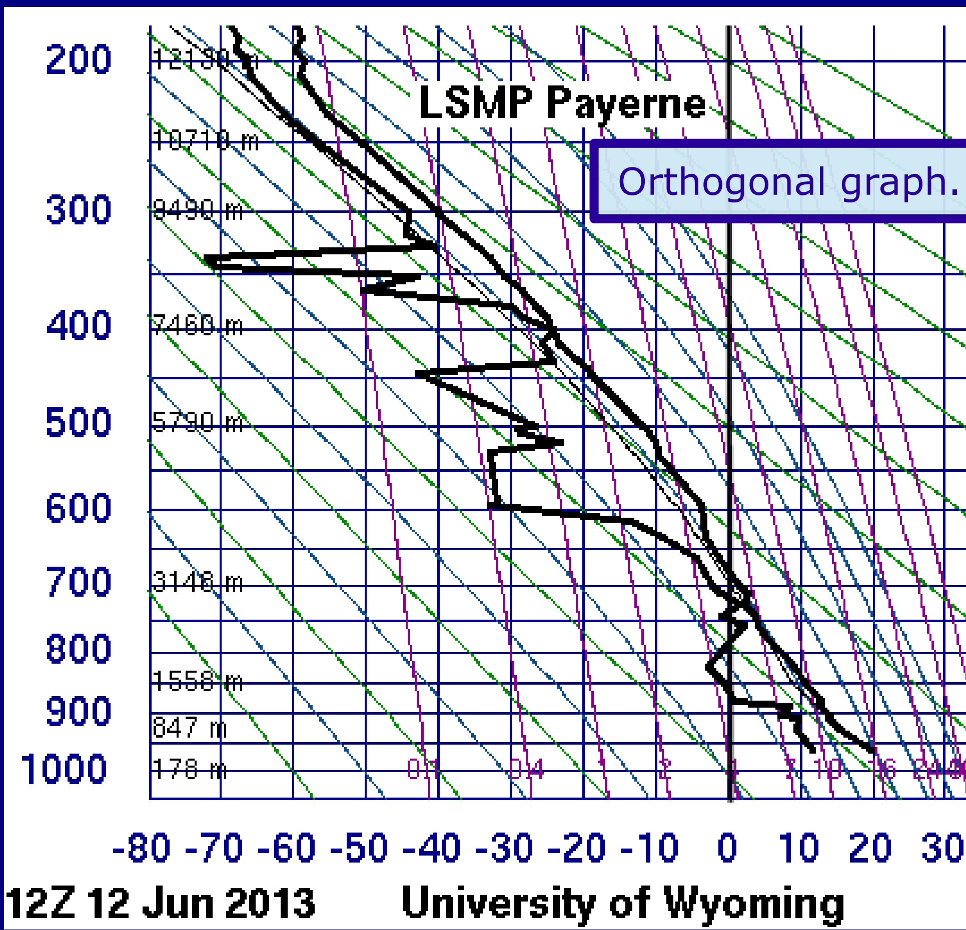
Aerological profiles are graphs on which are represented the temperature, humidity and winds at different altitudes h (called curves of state) in one precise place and at a specific time.

Meteograms are graphs on which are represented one or more parameters p at a specific location but during a period t (a few hours to a few days).

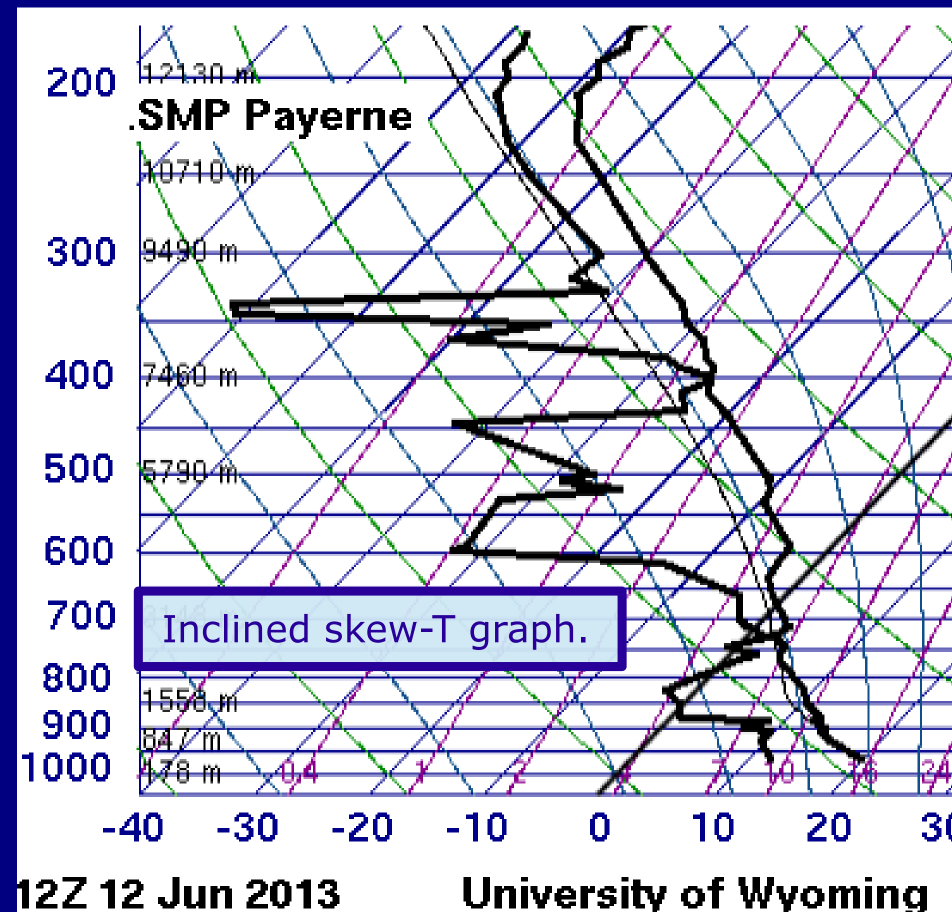


Aerological profiles can represent not only a forecast profile from a model but also measured profile from radiosounding.

Here are two strictly identical aerological profiles either on a conventional orthogonal graph or on a modern emagram (skew-T) graph.



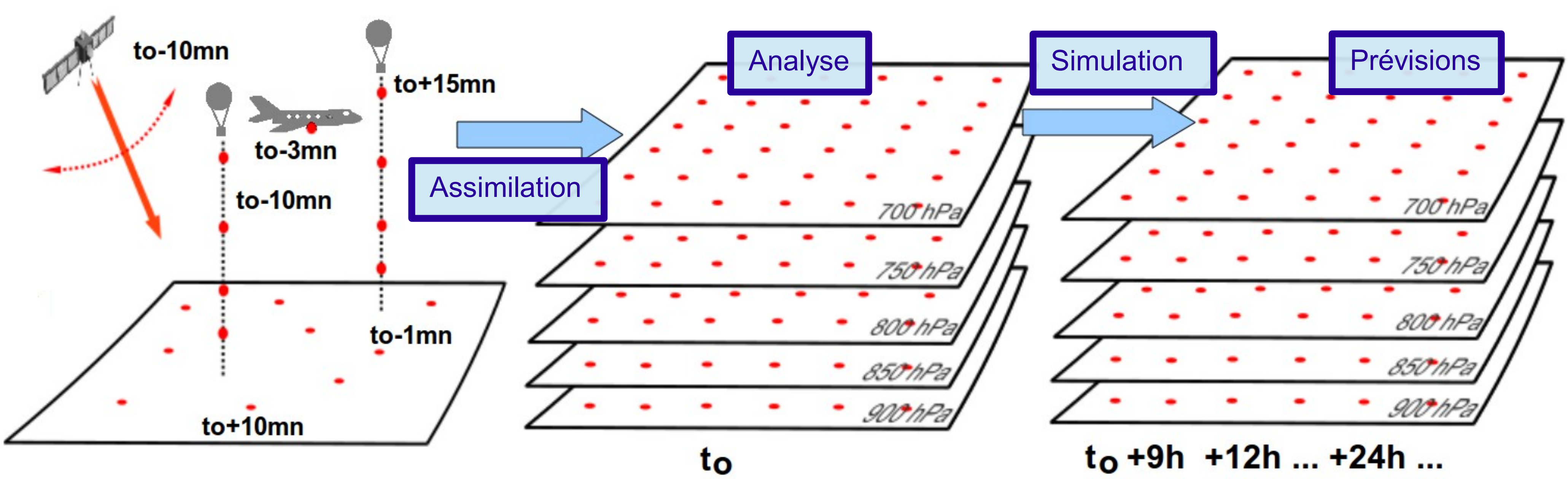
Orthogonal graph.



Inclined skew-T graph.

In this example, it is the same state curve from the radiosounding on June 12, 2013 at 12Z over Payerne but on the two different graphs.

The functionning principle of GFS 0.5° is as follows. Measured atmospheric data (ground stations, radiosoundings, satellites), irregularly distributed in time and space around the world are treated by complex calculations. Thanks to super-computers these data are assimilated on a regular three-dimensional virtual grid covering the whole Earth at a specific initialization time, also called analysis. Analyses are performed (this operation is called "assimilation") 4 times per day at 00Z, 06Z, 12Z and 18Z. Z = UTC = Universal Time or the UK time.



Assimilation is not a simple geometric interpolation but involves more complex calculations and methods with several steps including a very short forecast by simulation.

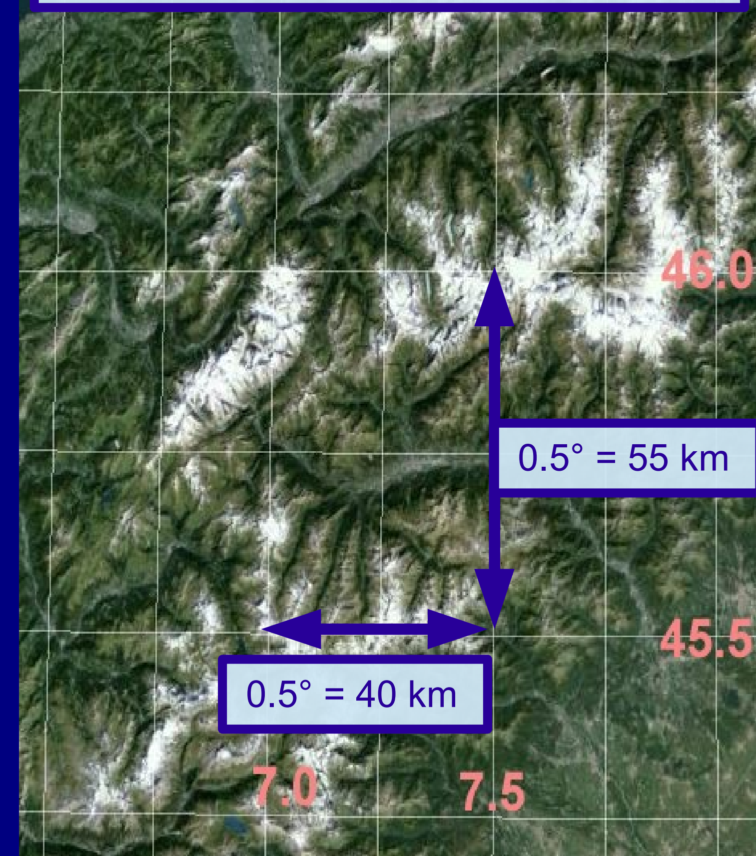
Then, with other supercomputers, GFS calculates and simulates the evolution of meteorological parameters, taking into account the laws of physics of fluids. He finally produced results every third hours over a period of seven days for each grid point spread over the globe. The results are contained in the grib files.

The GFS version of soarGFS (because there are a few versions) has a horizontal resolution of 0.5° i.e. mesh separated by about 40-60 km for the Alps and a vertical resolution of 64 levels. This is the latest version with the finer resolution. Nor all levels neither all meshes are represented in soarGFS. Since we only fly during the day, only the three daytime periods, i.e. 09Z, 12Z and 15Z (11h, 14h and 17h, summer time) over a period of seven days, which gives 21 times in all, are displayed in soarGFS presentation.

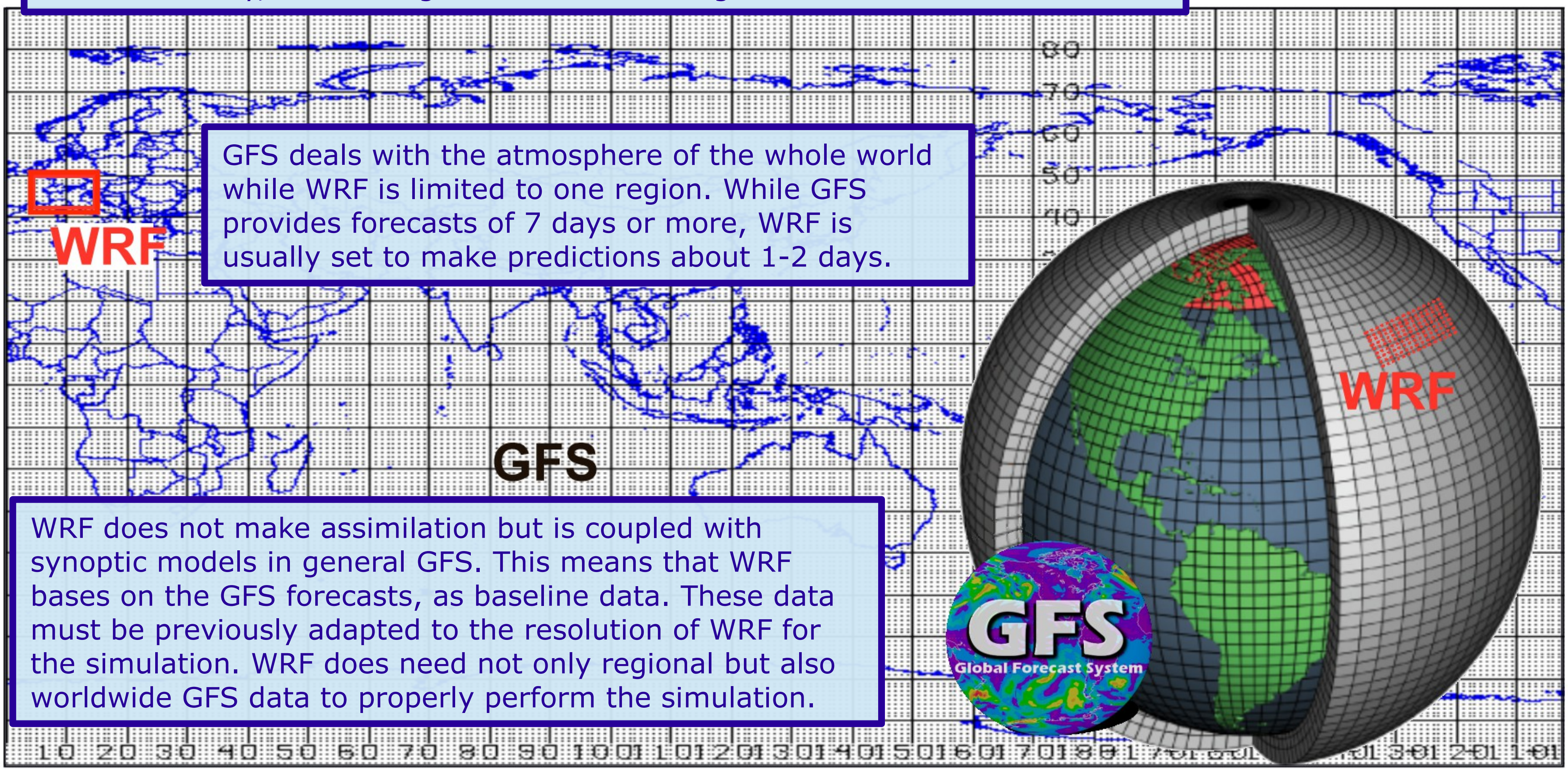
hPa	m
surface	variable
900	1000
850	1500
800	2000
750	2500
700	3000
600	4300
500	5500
400	7300
300	9300
200	12000

The vertical component of the GFS grid, with variable resolution according to the altitude, consists of a set of isobaric layers, whose height is measured in hPa. For soarGFS, only layers displayed on the table have been taken into account. The exact value of the altitude of the pressure layers varies constantly depending on the time of day, weather conditions and seasons.

The horizontal component of the GFS grid has a resolution of 0.5° in longitude and latitude which corresponds to 40 km in longitude and 55 km in latitude for the Alps.



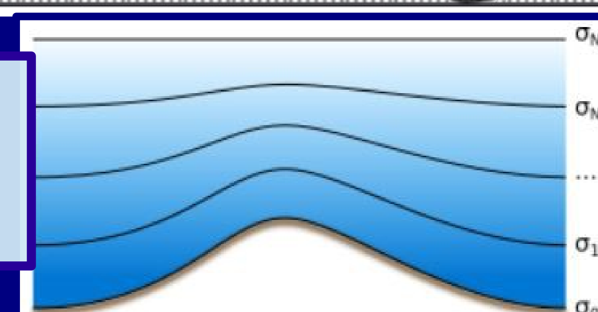
The functionning principle of WRF is similar to that of GFS. However there are some differences. The horizontal resolution is initially much finer, 2-12 km in general. The advantage is that the relief and forecast weather parameters is closer to reality, ie the image of time is less rough and smooth.



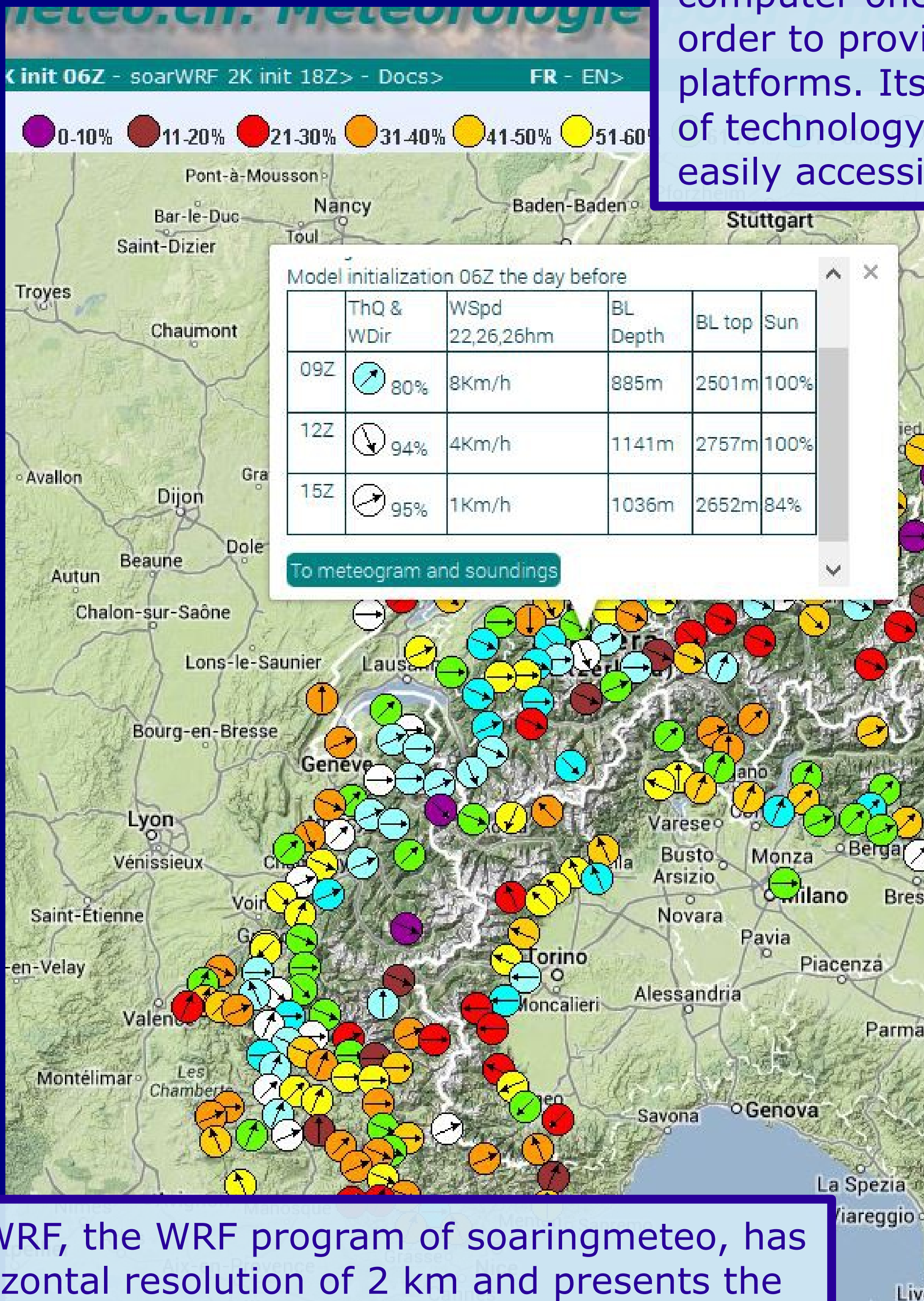
GFS deals with the atmosphere of the whole world while WRF is limited to one region. While GFS provides forecasts of 7 days or more, WRF is usually set to make predictions about 1-2 days.

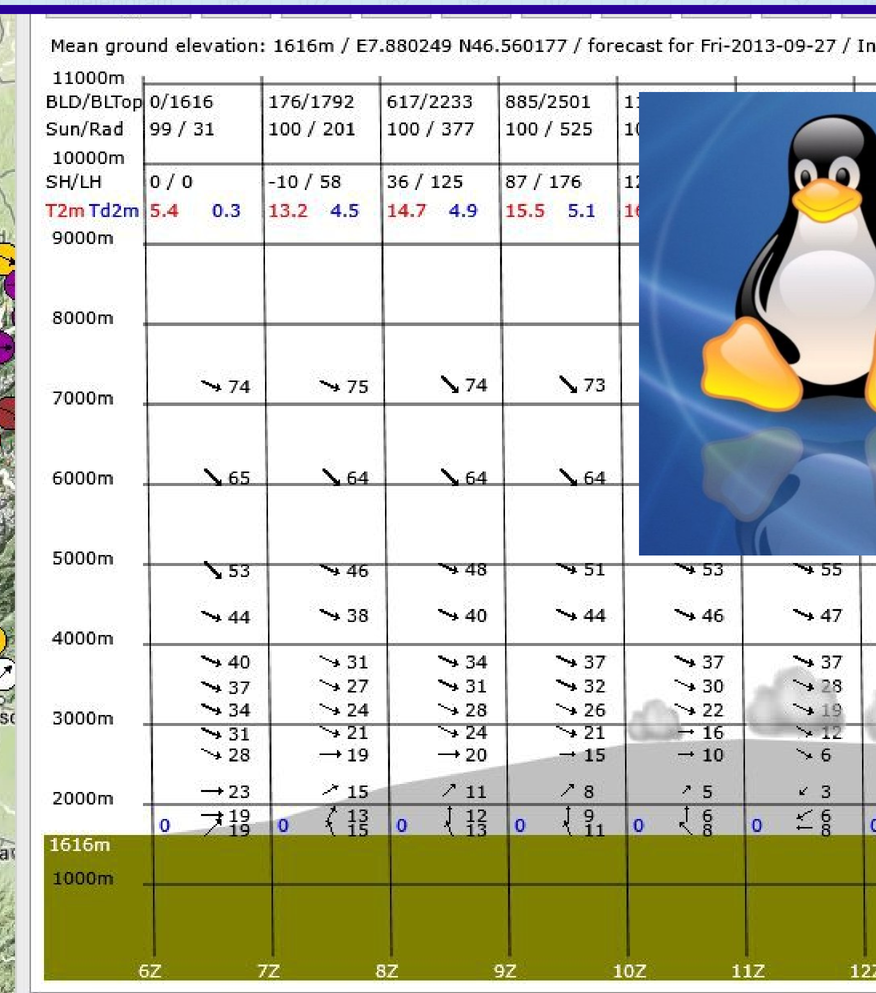
WRF does not make assimilation but is coupled with synoptic models in general GFS. This means that WRF bases on the GFS forecasts, as baseline data. These data must be previously adapted to the resolution of WRF for the simulation. WRF does need not only regional but also worldwide GFS data to properly perform the simulation.

The vertical resolution is almost identical to that of GFS. Instead pressure levels there are sigma σ layers following topography. These are layers of pressure normalized.



Finally, one has to compile, install, configure WRF on a private computer oneself and create a particular geographical domain in order to provide forecasts. WRF works only on Unix and Linux platforms. Its Use and even modification, despite its high level of technology, are free. The Fortran source code is freely and easily accessible on the Internet.

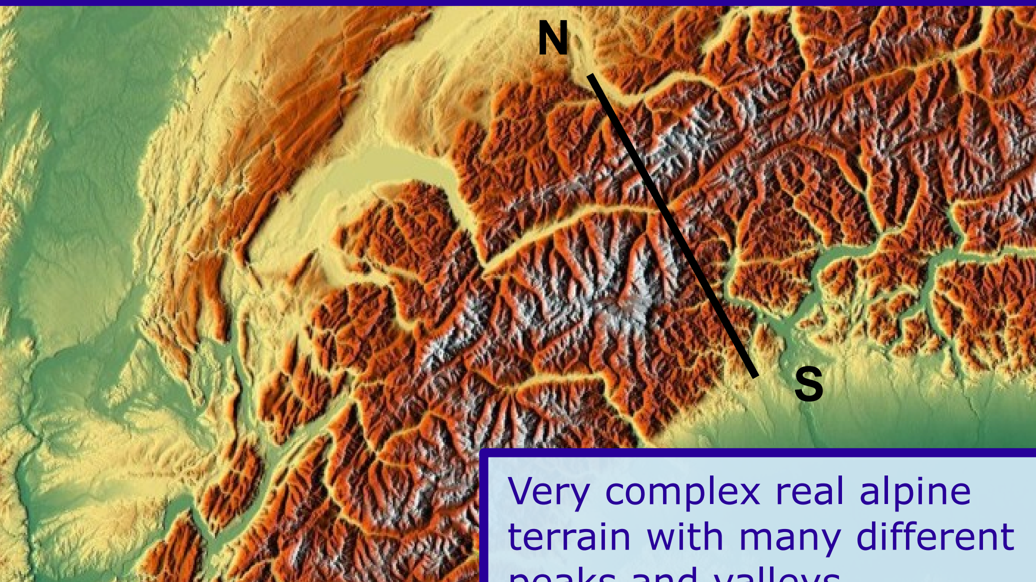




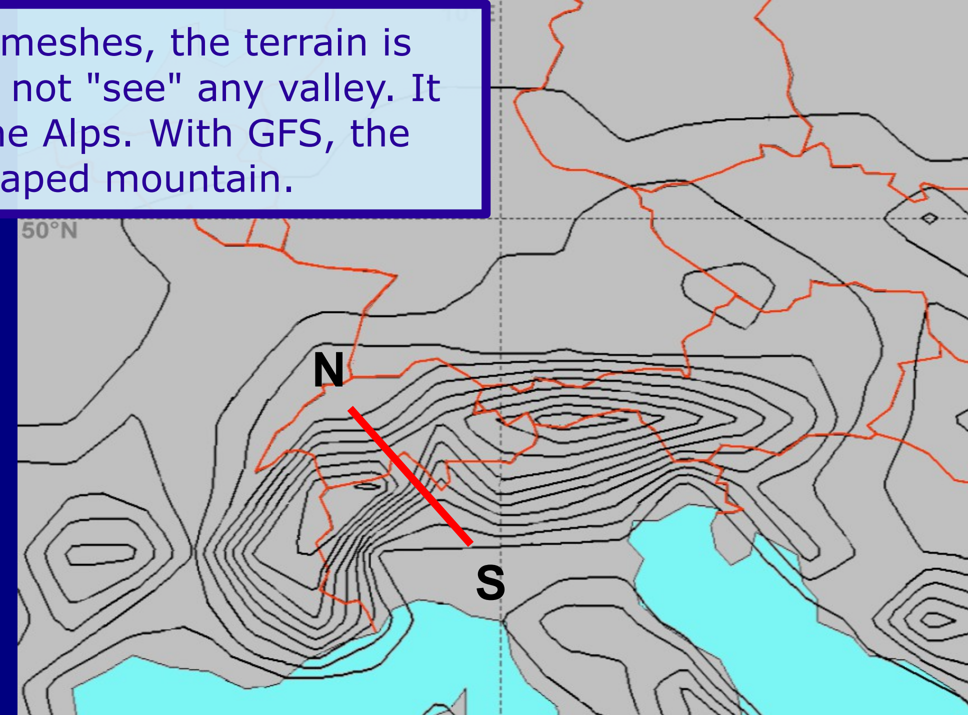
SoarWRF, the WRF program of soaringmeteo, has a horizontal resolution of 2 km and presents the results each hour from 6Z (8 am, summer time) to 15Z (17 hours, summer time).

Currently soarGFS and soarWRF only concern the Alps.

Since the GFS 0.5° model is a synoptic model with large meshes, the terrain is extremely simplified. For example for the Alps, GFS does not "see" any valley. It "guesses" just the Swiss Plateau between the Jura and the Alps. With GFS, the Alps presents itself as a huge smooth arcuate or bean-shaped mountain.

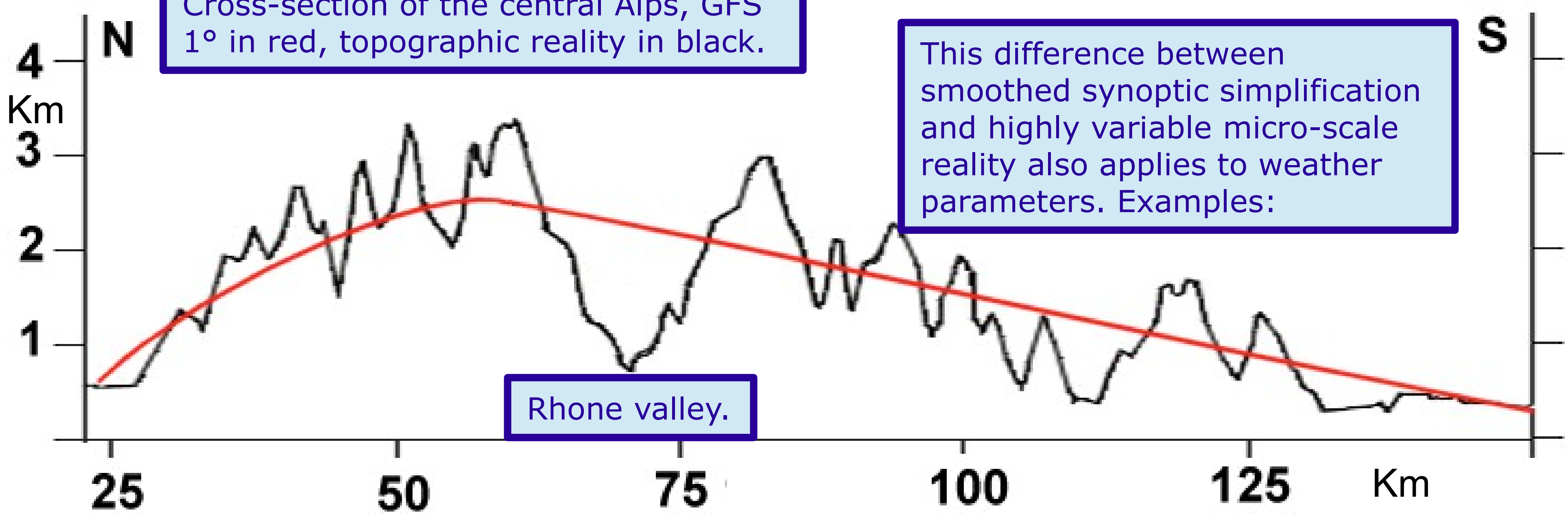


Very complex real alpine terrain with many different peaks and valleys.



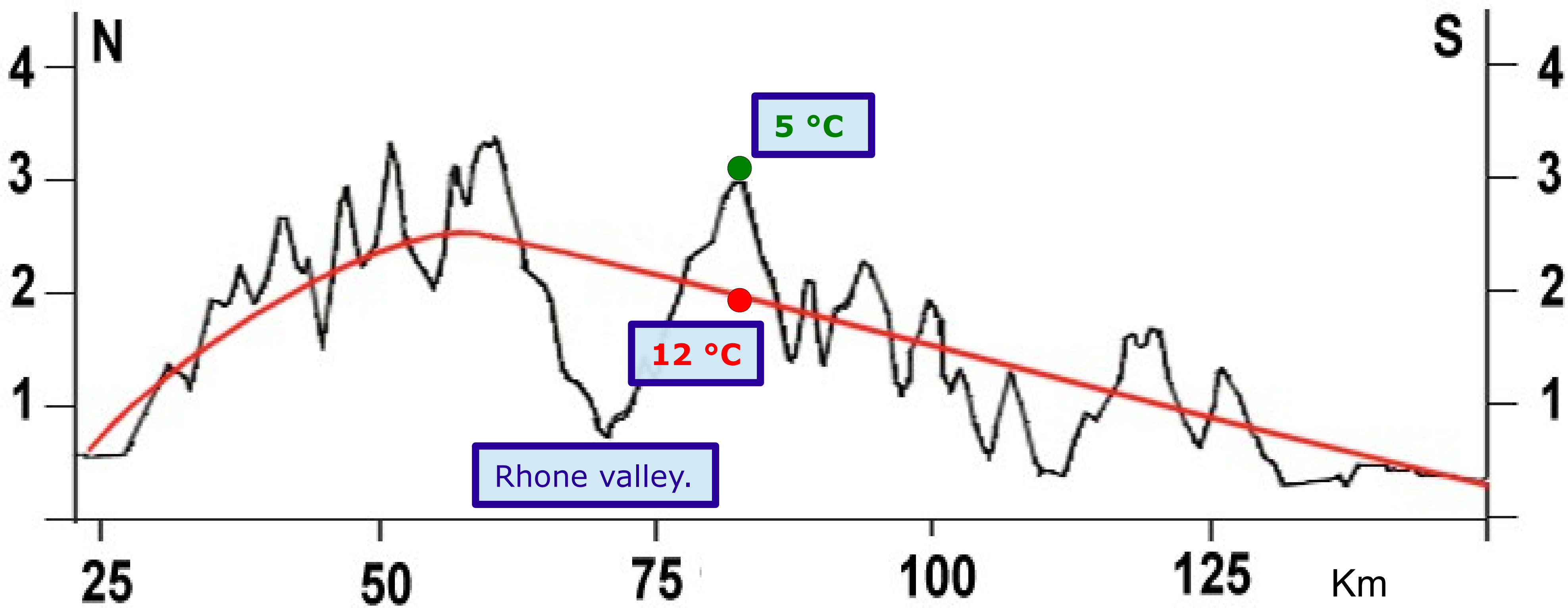
Very smooth relief of GFS 1°. On the GFS 0.5° relief, used by soarGFS, Jura from Alps are distinguished, not here. No GFS model sees a valley.

Cross-section of the central Alps, GFS 1° in red, topographic reality in black.

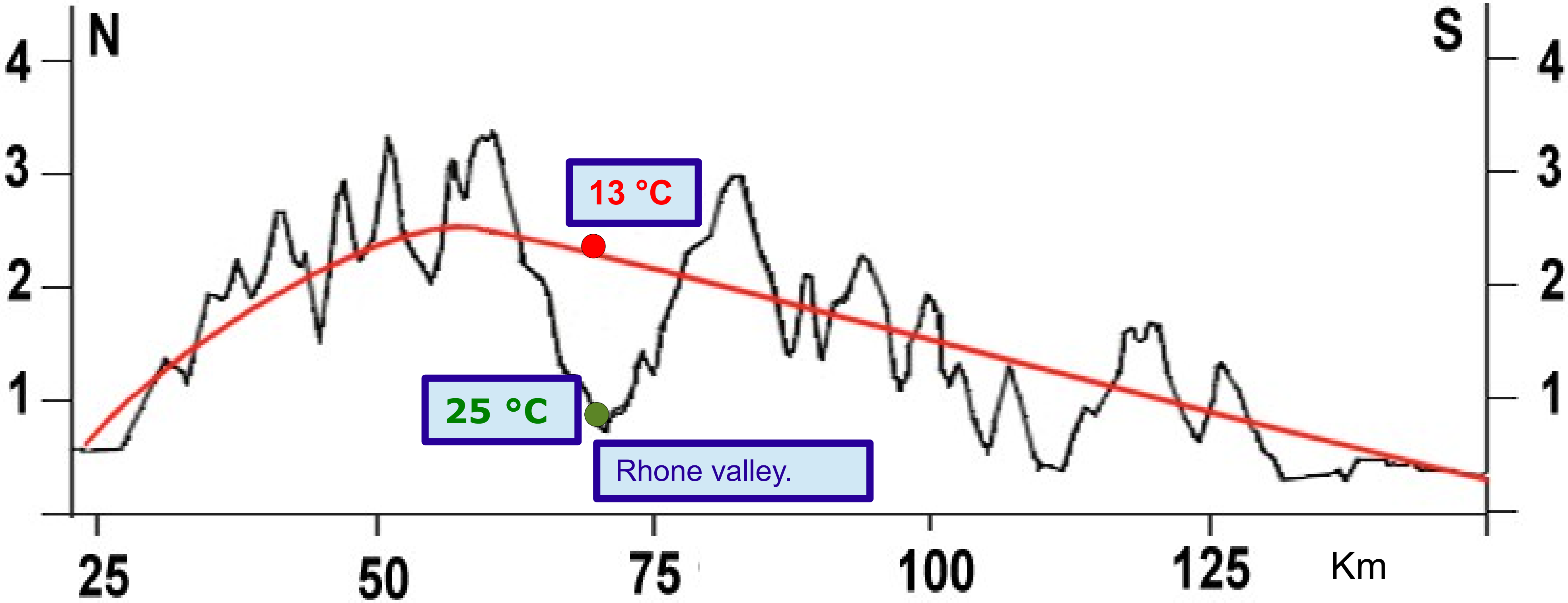


This difference between smoothed synoptic simplification and highly variable micro-scale reality also applies to weather parameters. Examples:

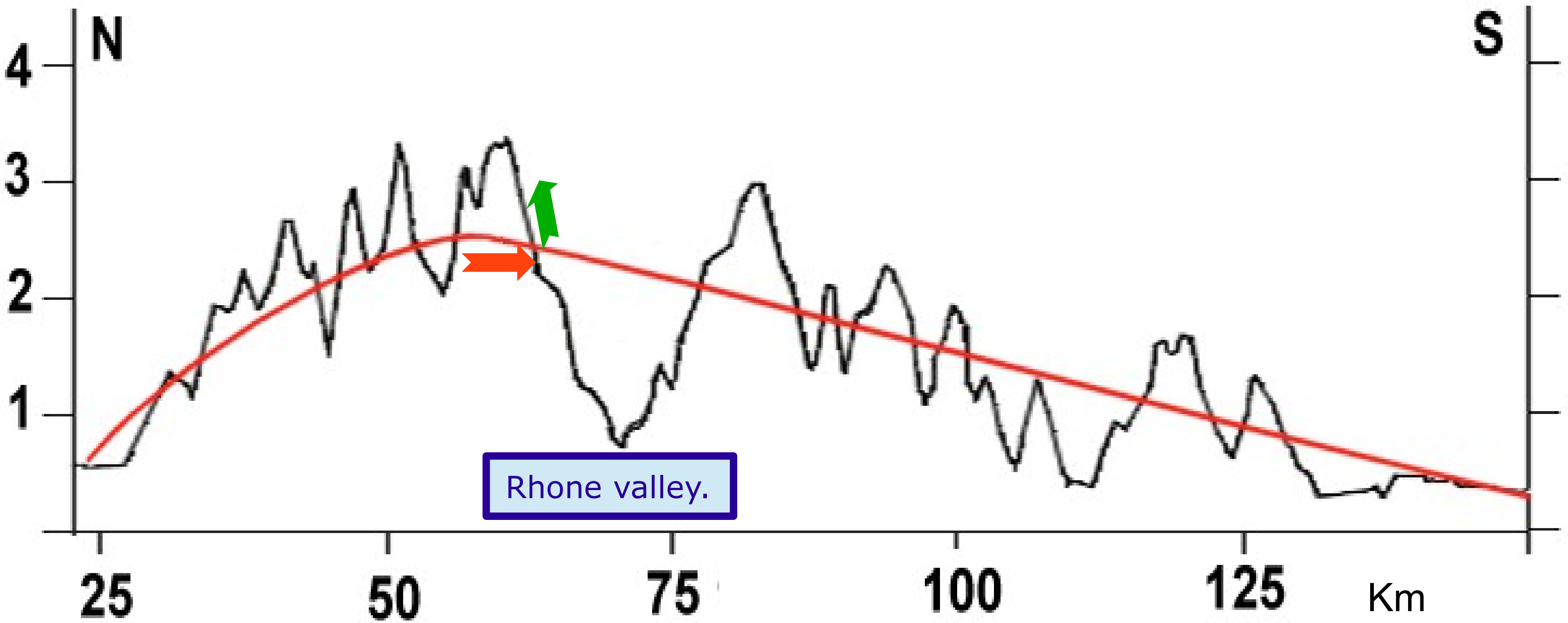
Let us imagine a predicted temperature of 12 ° C by GFS at a non-visible peak at macroscale. However, the actual temperature is, for example 5°C since the apex height of the latter, at real scale, is clearly higher than that of the model.



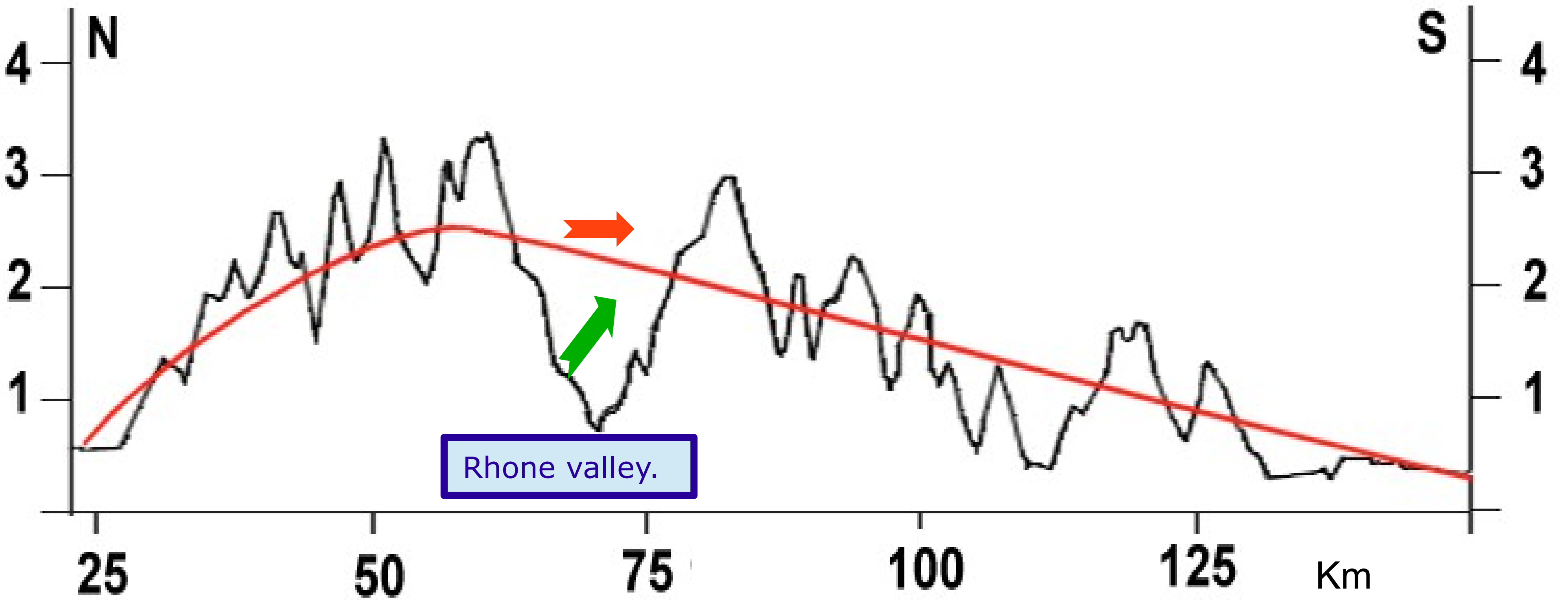
Conversely, at the bottom of the wide valley not seen by GFS, the model predicts, for example, a temperature of 13 ° C when in fact 25 ° C is measured as the actual altitude in this deep valley is lower than that of the model.



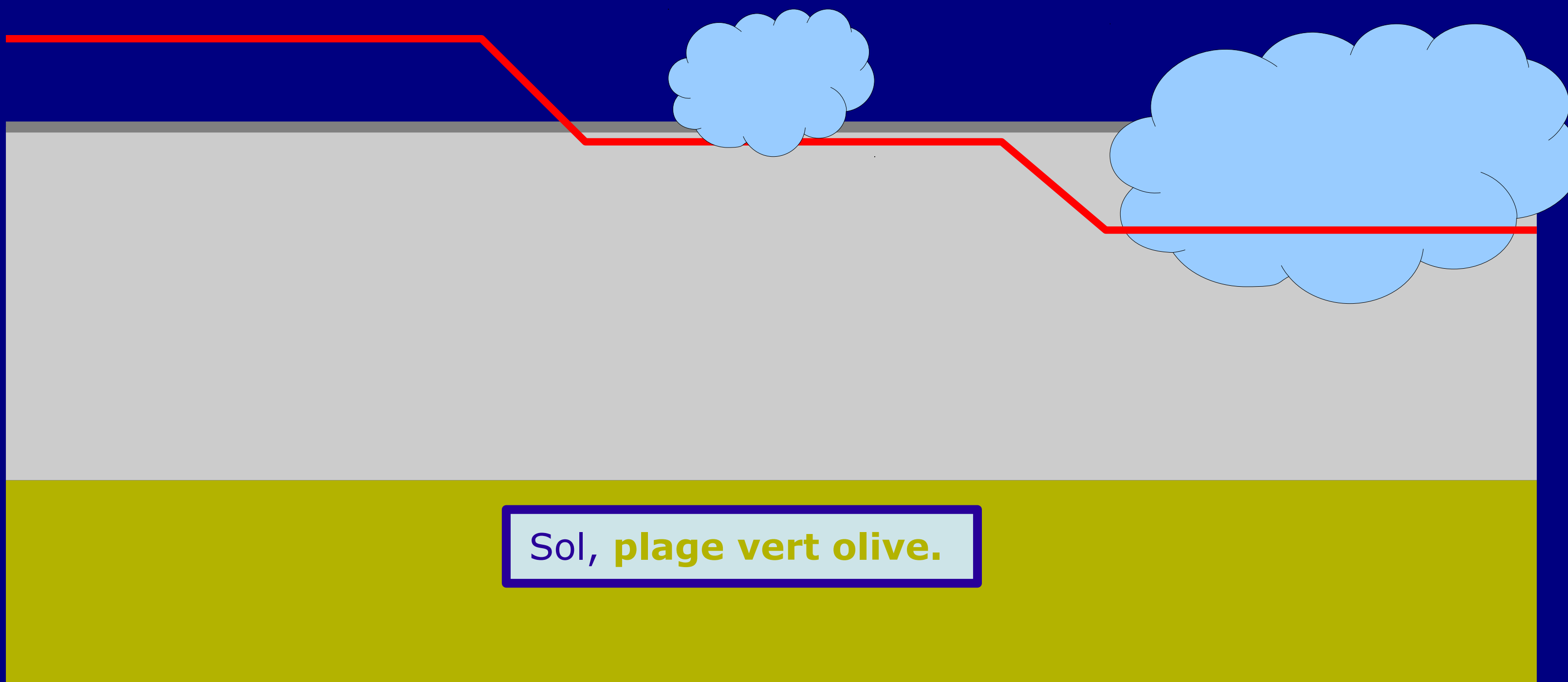
The reasoning is also valid with the wind. Let us suppose a little **north wind** predicted by GFS at a mountain peak. Actually, on the southern slope exposed to the sun, there is a small **local thermal wind ascending** from the south along the slope.



And at the bottom of the valley, instead of the **little north wind** predicted by GFS, a **moderate valley wind** (regional wind) is observed in the upstream direction of the valley.



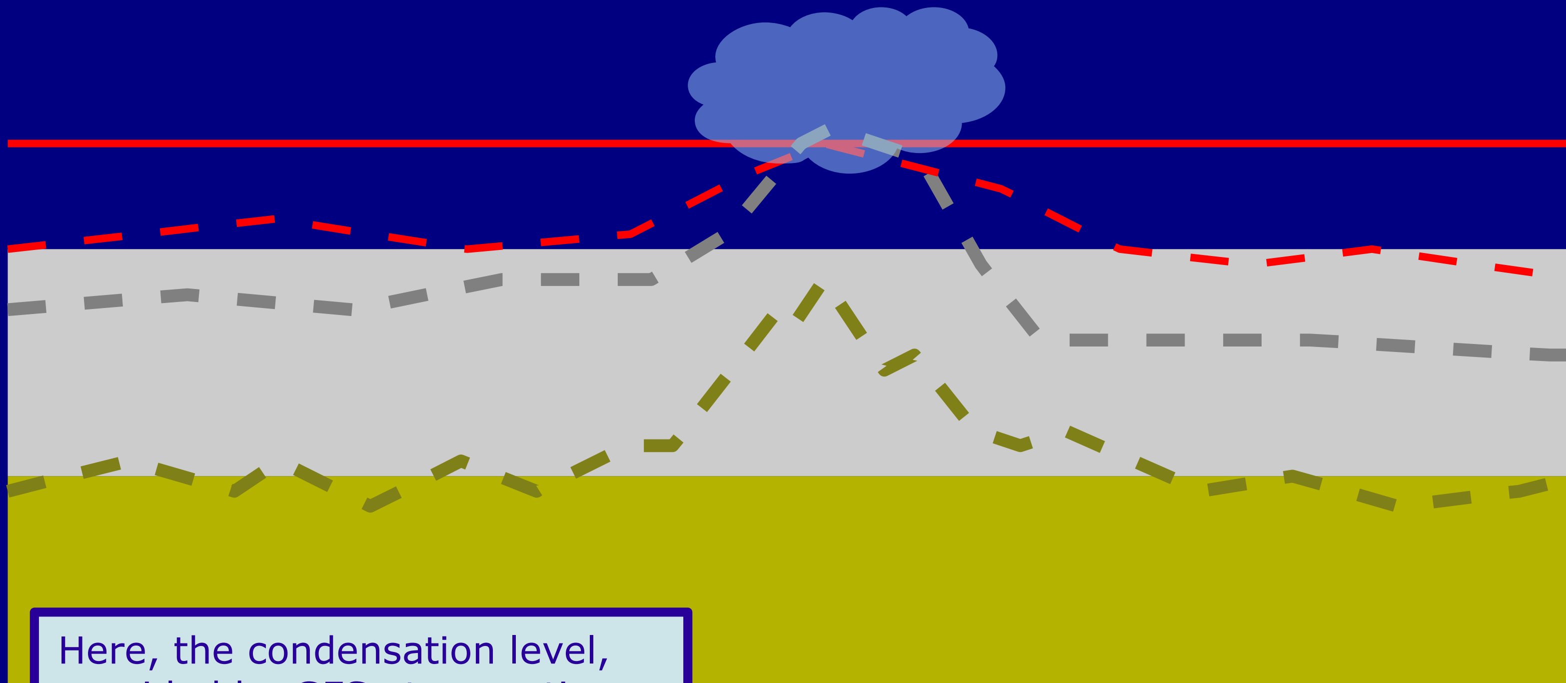
Here is another example of interpretation between the synoptic scale and the reality with the ceiling of the convective layer and the cumulus clouds condensation level.



But first, a quick reminder of the cumulus base is useful. The altitude of cumulus base, that is to say the level of vapor condensation of the convective layer, depends on the degree of air humidity on the ground. Wetter the air, less high the base of cumulus and vice versa. Recall that the concept of convective boundary layer at the lower troposphere is very important. In this layer the convections (thermals) are produced.

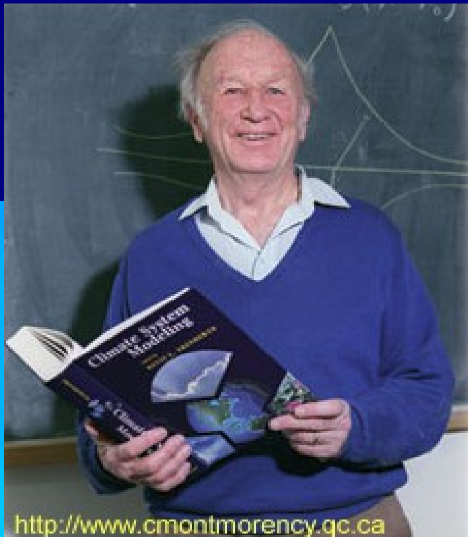
If the altitude of condensation level (**red line**) is above the top (**gray line**) of the convective boundary layer (**gray area**), the development of cumulus is not possible since the thermals that generate theses clouds do not climb up beyond the top of the convective layer (on the left of the figure). Conversely there are nice cumulus if the two lines are approximately at the same altitude (on the middle of the figure). If the condensation level is significantly lower than the top of the convective layer there is a risk of cumulus overdevelopment (on the right of the figure)..

For model as GFS one can find the following example:



Here, the condensation level, provided by GFS at synoptic scale, is well above the top of the convective layer. In reality, over a "not seen" mountain by GFS, the top of the convective layer can reach the level of condensation. Cumulus can therefore develop on this relief while GFS has not forecast cumulus on this place !

In continuous lines, the forecast weather and the smoothed relief seen by GFS. In dotted lines, the more variable reality. Soil and terrain in green. Condensation level in red. Convective layer in grey.



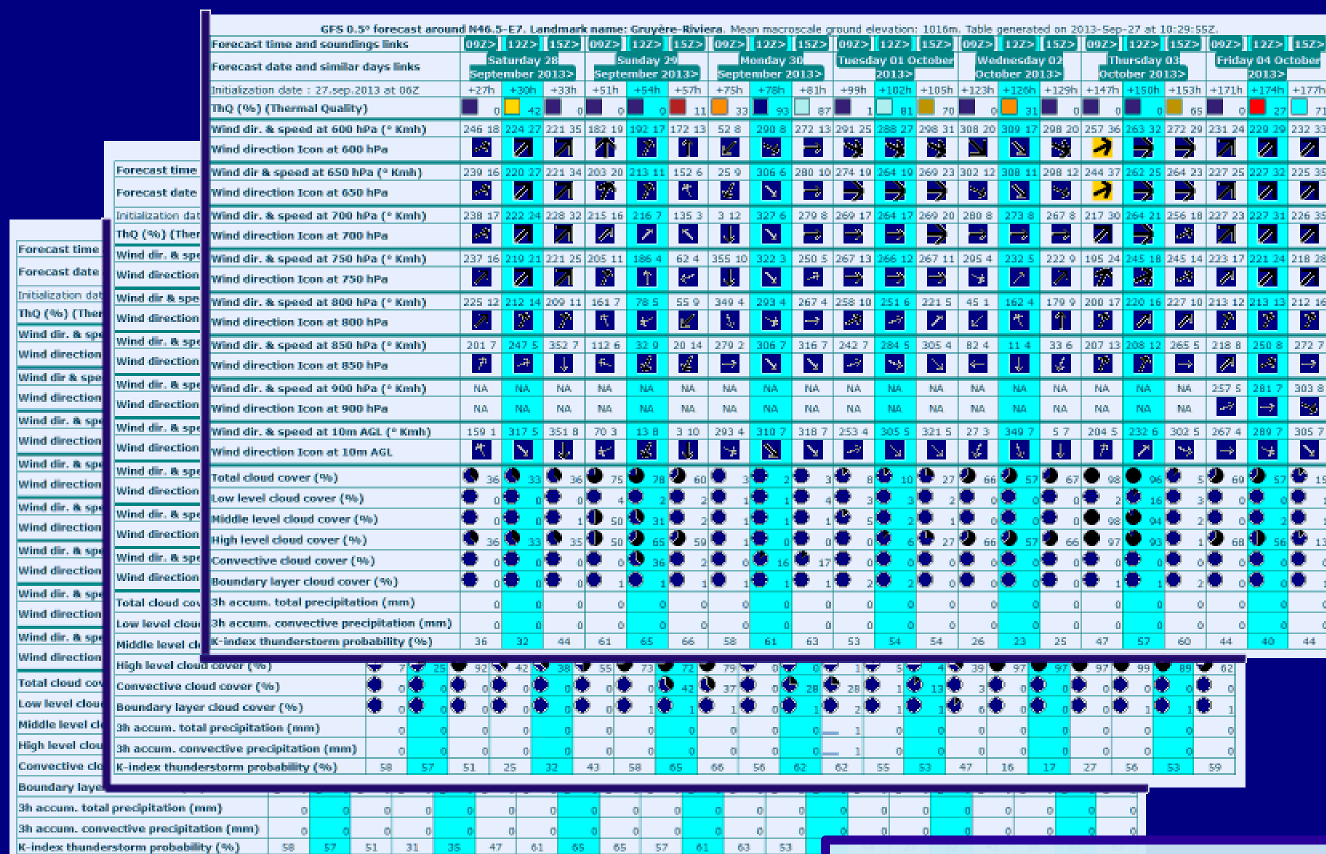
Lorenz, American meteorologist (1917-2008).

SoarGFS forecasts take place over 7 days. Obviously, from the 3rd and 4th day, the accuracy of the model decreases. You may be often disappointed with last days forecasts.

It is because, like all models, GFS undergoes the "butterfly effect" and the consequences of the chaos theory, described by Lorenz. The flapping wings of a butterfly can cause a storm several days later, at the other end of the planet. This is an image that is actually not entirely accurate. But more specifically, the smallest difference between two initial states can lead to diametrically opposite forecasts a few days after. A tiny difference between the initial states can grow exponentially with time. This is the inevitable limits of models predictability.

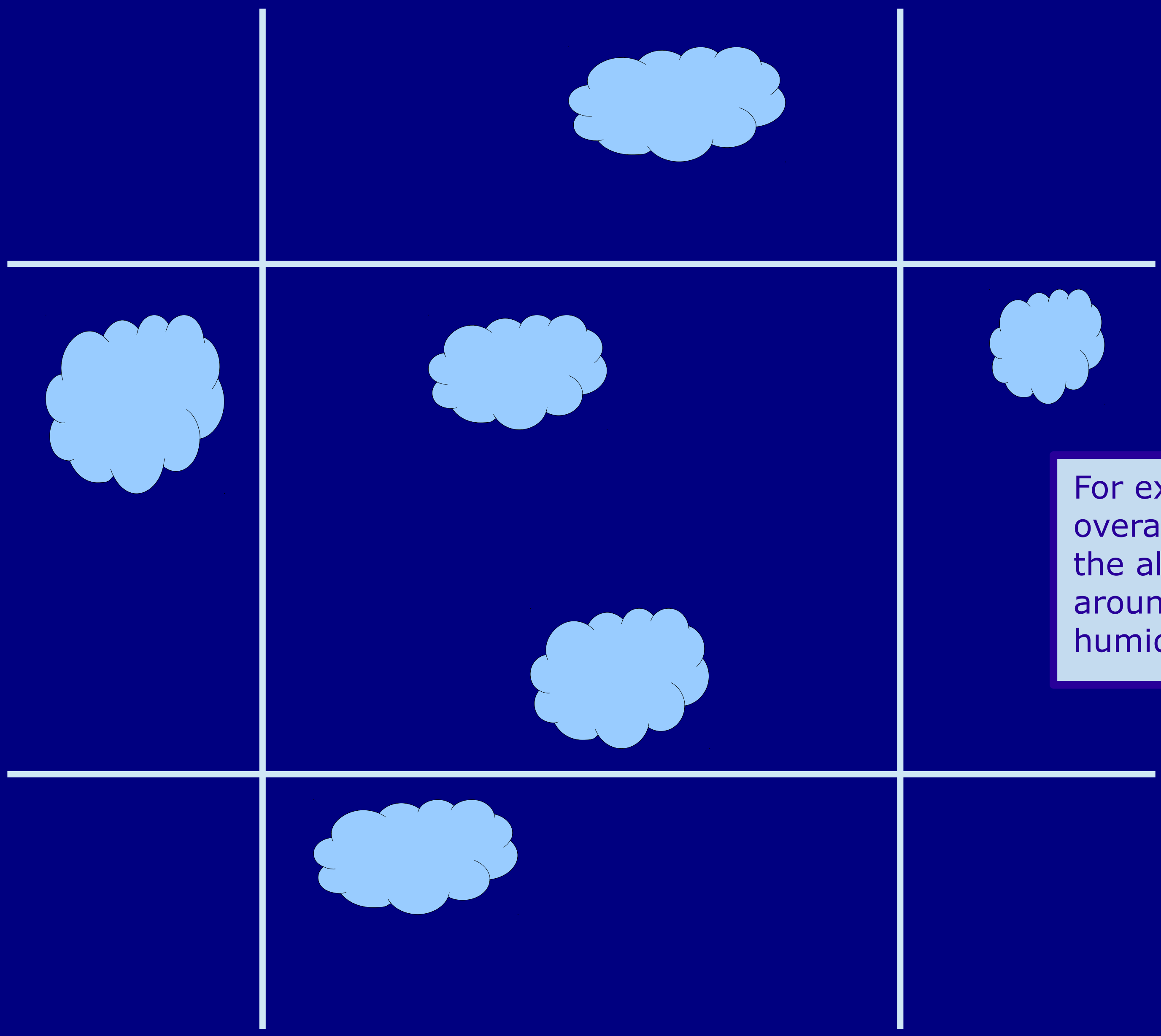
A fractal image, symbol of chaos theory.

However, there is a little empirical trick that seems natural and meaningful. Monday, for example, you want to evaluate flight conditions for the following weekend. You notice this sunny weekend with little wind. If the weather conditions are predicted without significant change the next days i.e. Tuesday and Wednesday for the same weekend, then the probability of reliable forecasts increases dramatically!

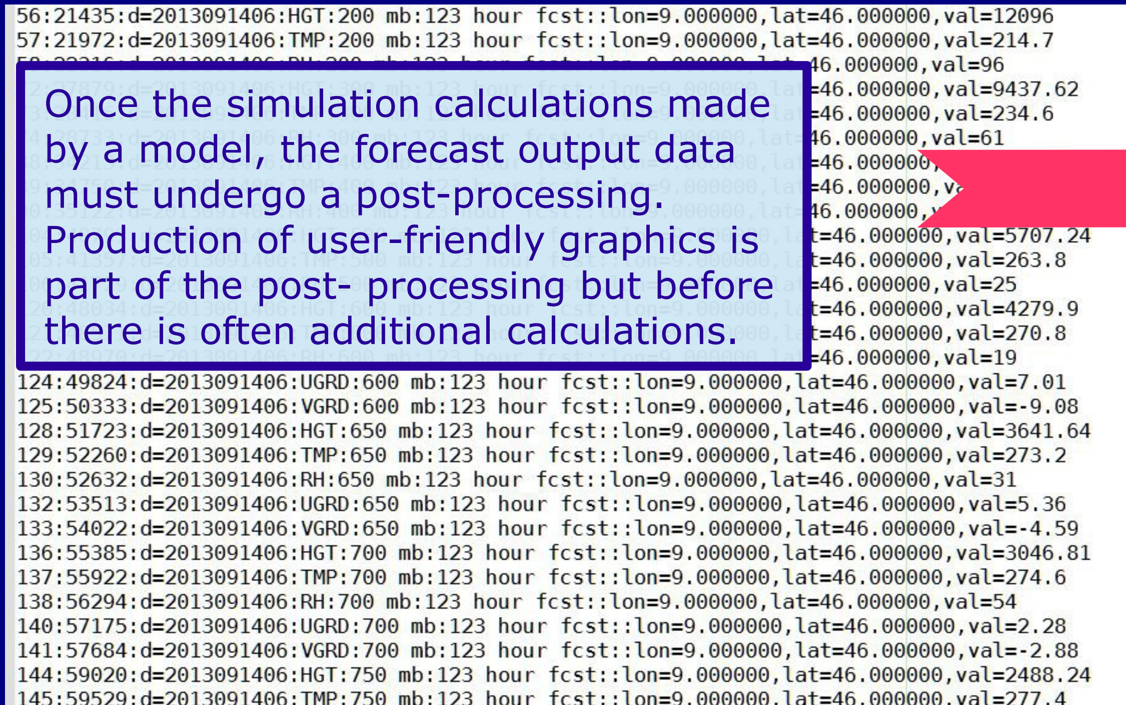


Conversely, if the forecast change greatly from day to day, it becomes very unreliable and unpredictable.

Some phenomena, such as thermals and cumulus, are smaller than the resolution of the model. We must give these "small" phenomena implicit existence within the model. Parameterization is a set of methods and calculations that predicts these phenomena. It is based on average values of certain parameters at grid point.



For example we can calculate an overall trend of the quantity and the altitude of the base of cumulus around the grid point from the air humidity value at this point.



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125:50333:d=2013091406:VGRD:600 mb:123 hour fcst::lon=9.000000,lat=46.000000,val=-9.08
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```
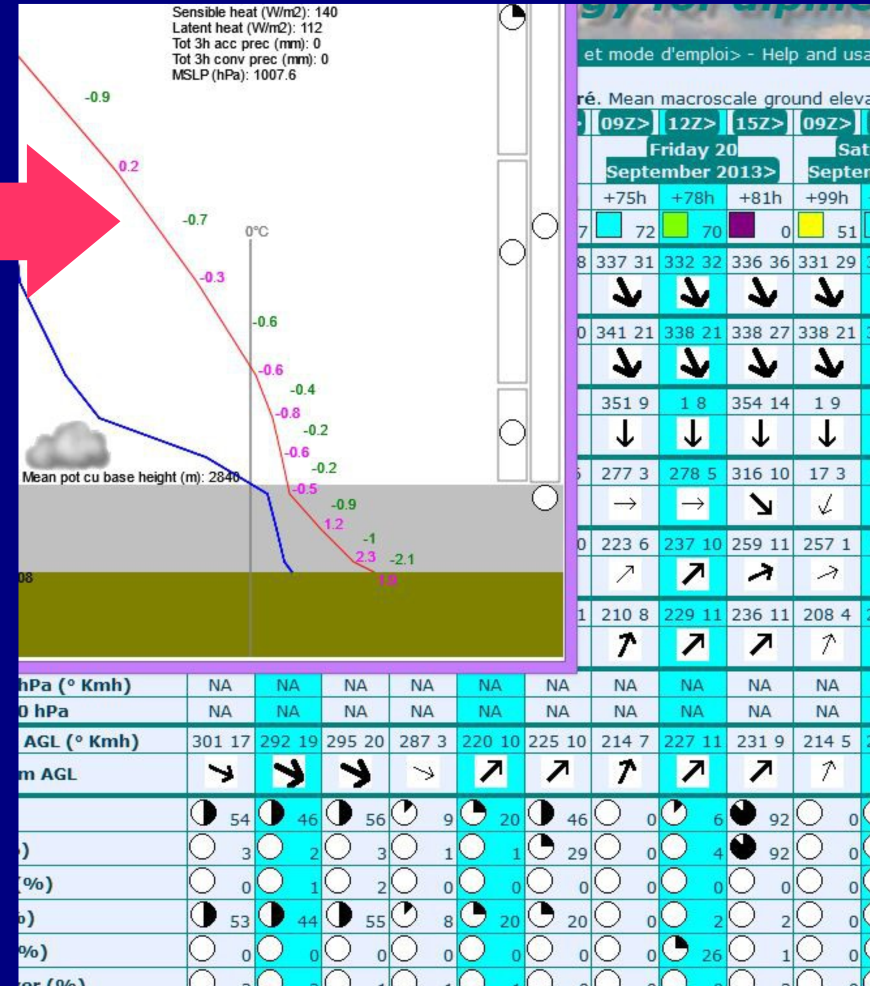
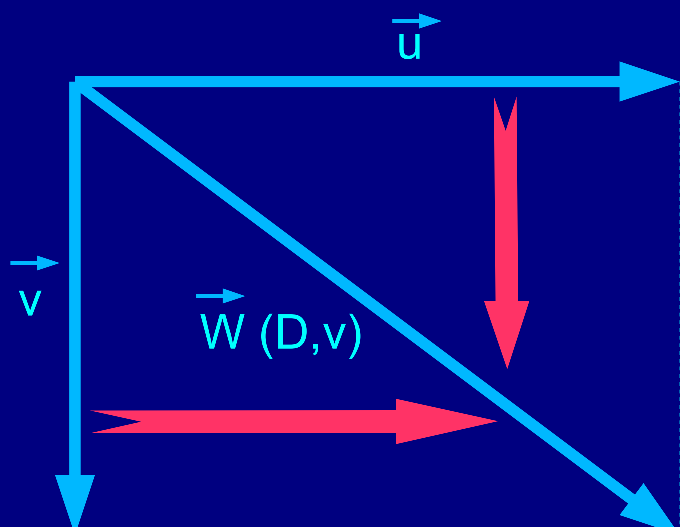

Once the simulation calculations made by a model, the forecast output data must undergo a post-processing. Production of user-friendly graphics is part of the post- processing but before there is often additional calculations.

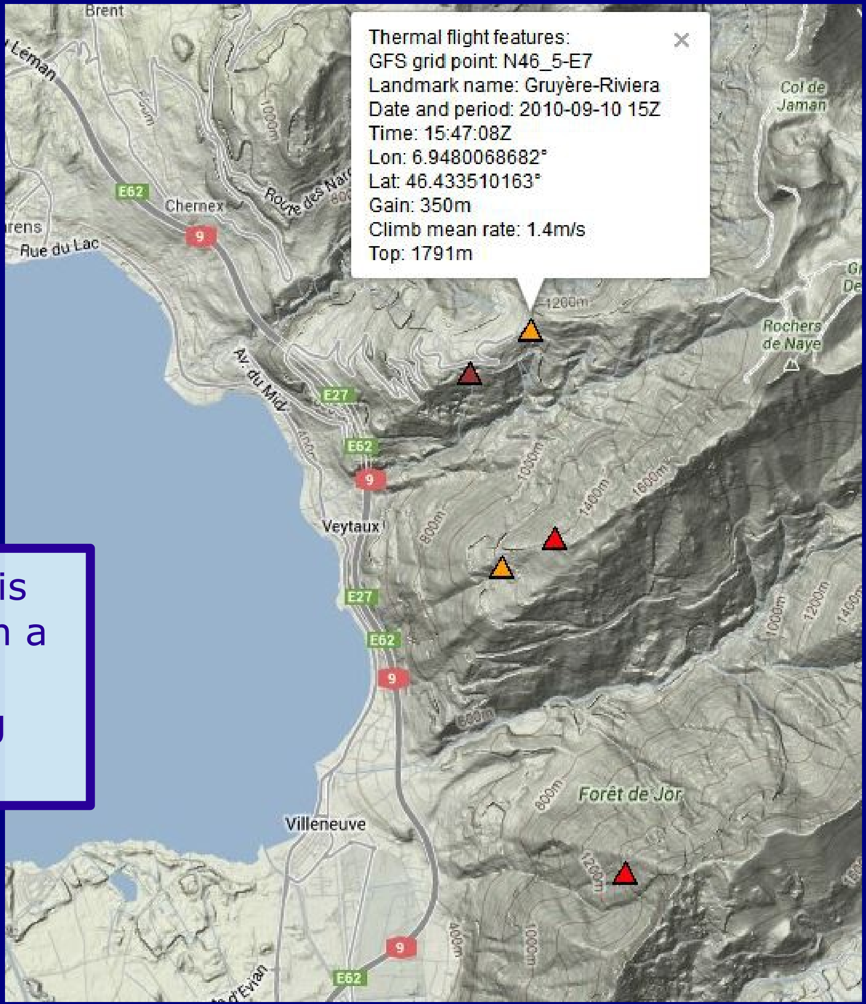




Post-processing parameterizations but also calculations of more accessible to users parameters can be achieved. For example, the winds are provided from models in the form of vector components u (east-west) and v (north-south). From u and v we can calculate the direction D in degrees and speed V of wind W. For moisture, one can calculate the dewpoint temperature from the air temperature, atmospheric pressure and relative humidity.

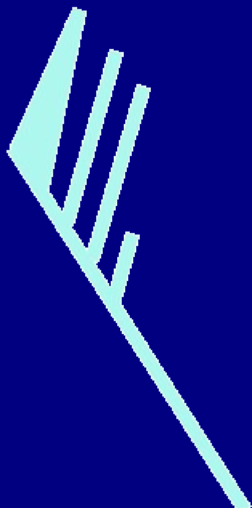
A particular and very useful post-processing is the MOS (Model Output Statistics). MOS attempts to correct the bias of model predictions. For example, the air temperature at the bottom of a valley not seen by the model can be corrected from predicted meteorological values and by statistics between the old measured temperatures of the valley bottom and the old archived predicted values.

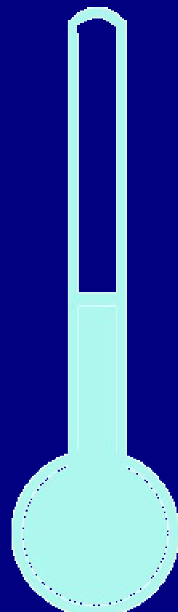
MOS also exists for the local wind, thunderstorm, frost risk, the probability of precipitation .. etc.. MOS allows models to be clearly more efficient.

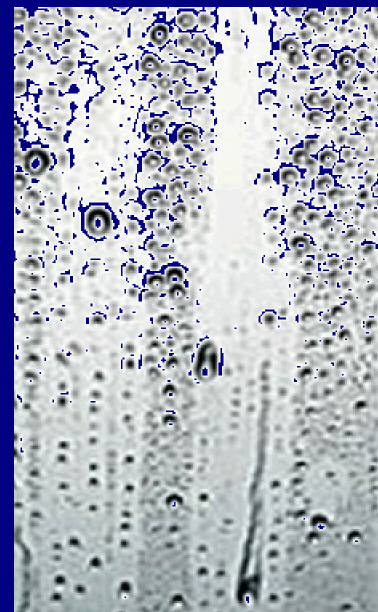


In soarGFS, there is an original MOS. This is to find the similar days to predicted days in a weather viewpoint, then search for GPS tracks of thermal soaring performed during competition flights in those old days.

Parameters predicted by a model can be ranked in descending order of accuracy: 1 / wind, 2 / temperature 3 / moisture, 4 / clouds, 5 / rain. Clouds and rain are therfore difficult to predict !





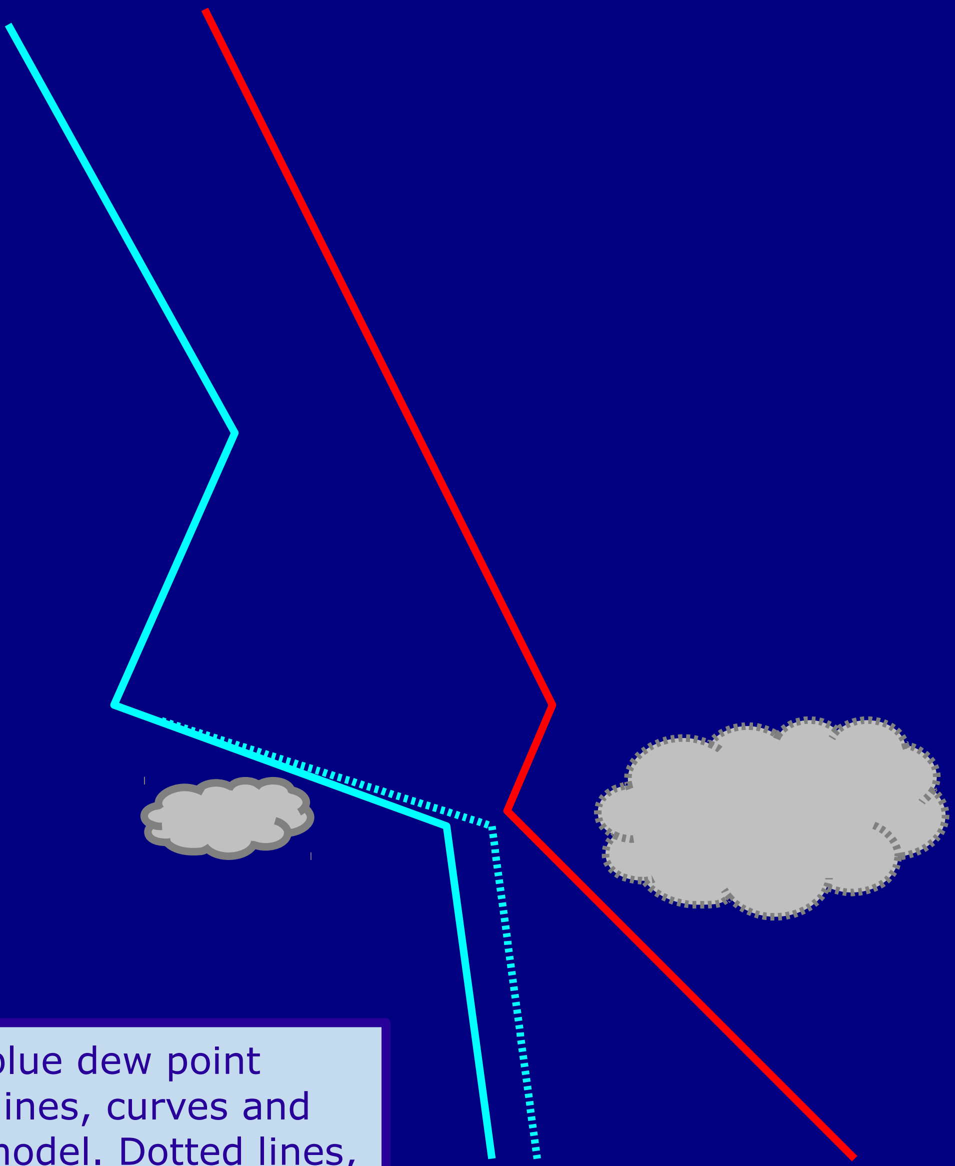


Increase the resolution of a model by a factor of 2 means an increase in computation time of 16 times. So there are serious limitations to improve model accuracy.

The human evaluation (pilot) of model results should be done taking into account the limits and flaws of the model, his flying experience and his memories of observations of the sky, with shades and modesty, especially when the model emits unlikely predictions.

Here are three examples of loopholes of some models:

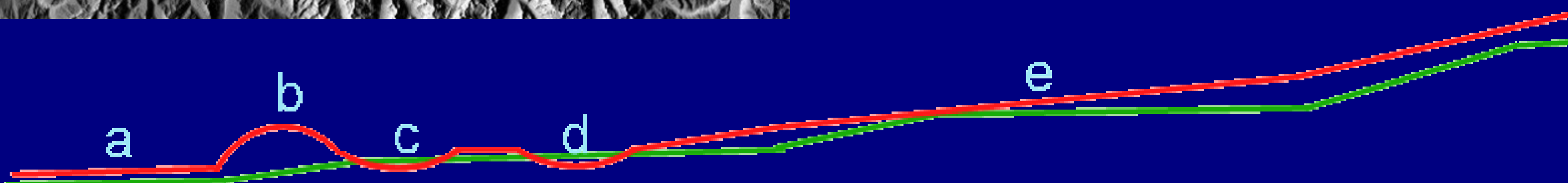
1 / The model tends to underestimate soil and air moisture in the lower layer especially when there has been previous heavy rainfall but also in autumn when the nights are long and it is therefore difficult for the soil moisture to escape. For this it is useful to consult the radar maps of the night and the previous day to estimate the amount of rainfall in the area of flight. Another clue is to compare the temperature dew point measured in the morning in various weather stations and dew point provided by the model. This underestimation of moisture leads to what cumulus clouds are more numerous and lower than expected.



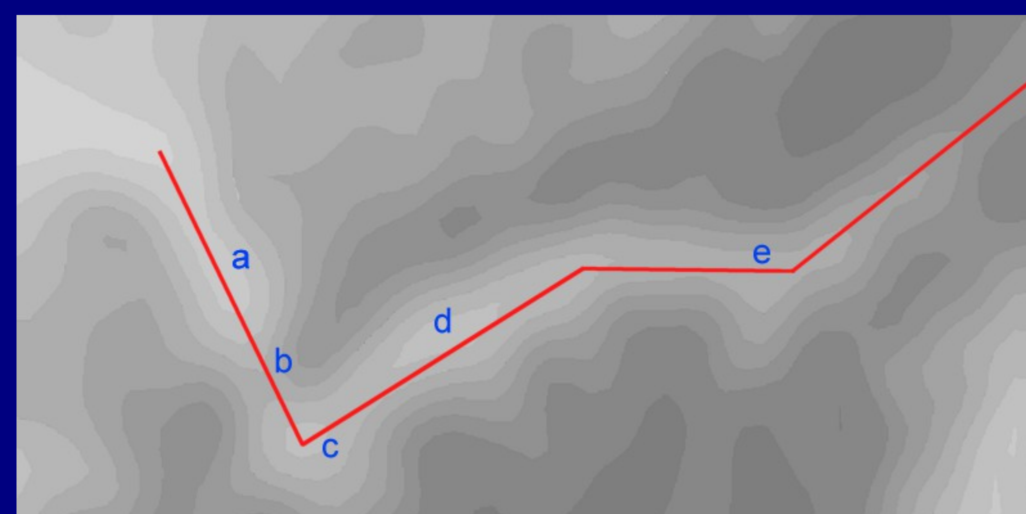
In red temperature curve. In blue dew point curve (humidity). Continuous lines, curves and cloud cover predicted by the model. Dotted lines, curves and the observed actual cloudiness.

2 / When a large valley, clearly visible to a mesoscale model, has a local narrowing, a false pass appears over the model's terrain while it does not exist in reality. This significantly distorts the prediction of valley upwind and probably therefore the other parameters.

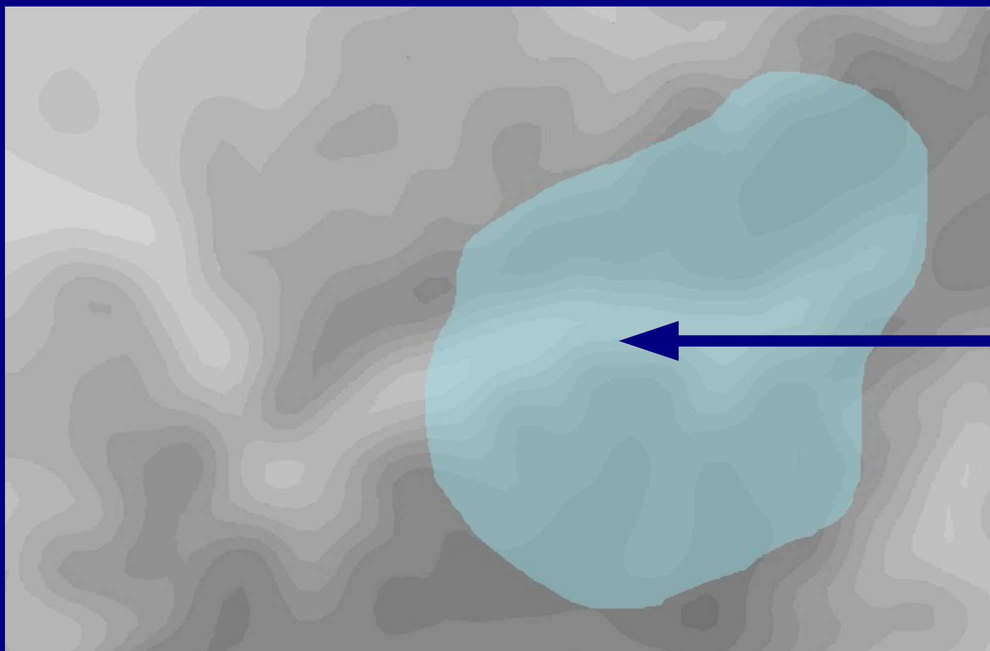
In red, bottom contour of the valley "seen" by the model. In green, real topographic profile of the bottom of the valley. Despite irregularities, the real bottom valley always rises from downstream to upstream.



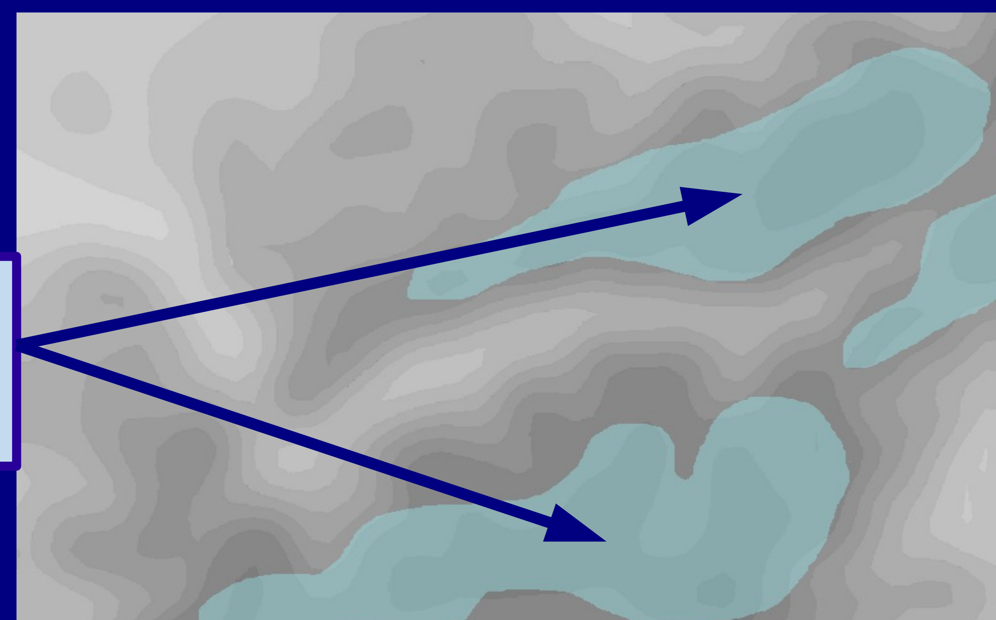
The valley bottom "seen" by the model climbs steadily in a and e. In b, there is a false pass due to local narrowing of the valley and c and d there is false basins due to local broadening of the valley.



3/ For an unclear reason, mesoscale models tend not to fit the snow cover on the ground at their mesoscale relief. Especially in spring, valleys are considered snow covered when in fact they are not. The thickness of the convective layer and the strength of the thermals in these valleys are therefore very underestimated.



Coarse snow cover falsely indicating that a portion of the broad valley is covered with snow.



Snow cover suitable for the terrain model. Unfortunately this configuration is not yet implemented in many high-resolution models.

Now you know the essentials of the numerical models for weather forecasting.