A WEATHER MODEL, WHAT IS IT ?

Jean Oberson, © February 2010

Some pilots come to me and still ask some basic questions about models sometimes because they consider the models do not do prediction properly and therefore are disappointed of, laughs at or even are angry against models. The purpose of this paper is to try to diminish the misunderstanding about models by describing their limit and what they do exactly. Here is a summary and a free adaptation of DrJack point of view about model.

Dr Jack says:

A weather model produces forecasts by solving equations derived from fundamental physical laws for the fluids : conservation of mass (both of air and moisture), conservation of momentum (Newton's laws), and conservation of thermal energy (thermodynamics). These equations predict the change in variables such as temperature or velocity resulting from the physical phenomena which affect them. These equations strongly interact with each other - for example, a change in thermal energy (affecting temperature) will change atmospheric density (affecting mass), in turn changing pressure differences (affecting velocity). These feedback interactions tend to counter a forced change, e.g. to oppose an atmospheric heating by introducing a cooling effect. If forcing were to remain constant then eventually the feedbacks would produce an "equilibrium" in which changes with time would become increasingly smaller - but the forcing of the atmosphere is never constant, as solar heating is constantly changing, so the atmosphere is in a state of constantly adjusting "quasi-equilibrium".

To work properly, the atmosphere of the models is divided into grid points where an average of the weather variables (temperature, pressure, humidity, wind...) is distributed in these points. Generally points are regularly spaced in the horizontal but vary in the vertical, with vertical spacings becoming smaller near the surface since atmospheric conditions change more rapidly with height there. Similarly, vertical cell spacings in general are much smaller than horizontal spacings since conditions change much more rapidly in the vertical than in the horizontal (figure 1). Equations predict the time-change of a variable based upon conditions in each point and its horizontal/vertical neighbours. The equations are solved in a "marching-forward-in-time" fashion, starting from the assumed 3D initial conditions (which are usually based on available observations at that time), and predicting how the variables change at each time step at each grid point to give forecasts at a given time.

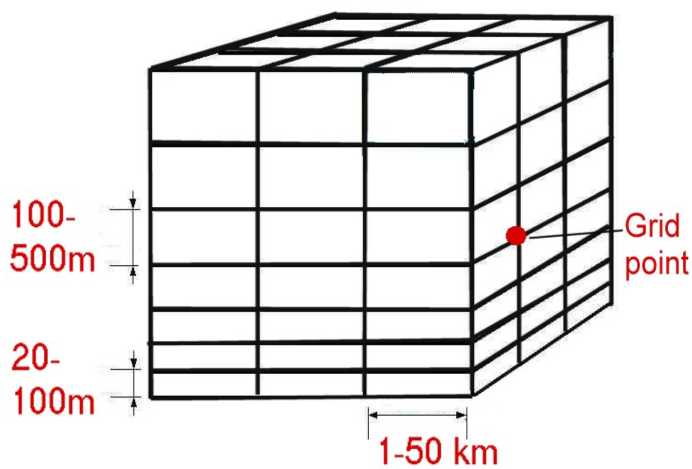

Figure 1: Schema of a grid for weather models.

Since models predict (simulate) changes of the atmosphere there must be an initially prescribed 3D atmosphere for them to start from. This is obtained from atmospheric observations (balloon, satellite, and aircraft data) at a limited number of points which are then interpolated to complete the 3D grid. This initialisation is also called assimilation and the resulting initial 3D grid is called analysis. There will of course be errors in the interpolated initial state. Assimilation must be done carefully while respecting the dynamic constraints of the equations, i.e. is not a matter of simple arithmetic interpolation of observations, since a large error introduced between observing points would cause large and unrealistic changes immediately after start-up as the equations tried to adjust to an unrealistic initial imbalance.

Now let me write this provocative sentence : Weather model do not predict the real weather !

They actually predict a schematic and coarsely simplified image of the atmosphere and do not forecast the real micro-infinitesimal (in fact probably molecular scale) atmosphere. So there is two separate worlds : the real molecular one and the finite one whose resolution is defined by its grid whose spaces between grid points are much larger than molecular scale.

Dr Jack says:

If the effect of a lake or mountain ridge or whatever upon the atmosphere is to be predicted, the model must adequately "know" about the existence of that lake or ridge or whatever. Realistic resolution requires a minimum of four grid points inside such a feature. Modelers keep trying, within the bounds of available computer power, to use finer and finer grid resolutions since with present grid spacings there is still much that is not being resolved, particularly if the forcing is controlled by topography. There are also many atmospheric features such as convergence-created upward motions which are smaller than can be resolved with present model grids and so are not well predicted. Real changes occur over an infinitesimally small distance whereas the model can only estimate changes over a finite distance. If a real change existing in the atmosphere occurs over a smaller distance than the grid can effectively resolve, the results of the model then cannot accurately represent this change. The difference between finite (models) and infinite (reality) worlds does not occur in the space only. Real world change over an "infinitesimal" time also. Conversely, model has to change by finite steps of several seconds. So the probability of errors is bigger with larger time steps and larger-spacing grid. The actual time step and grid-spacing is a compromise between the ideal and the practical.

Now let's imagine a simple 2D infinitesimal world which does not exist as on figure 2. There is only one parameter, the grey density. This “world” seems infinitesimal. In fact it is finite because it is digital with grey density steps and pixels but here both not visible by humans.

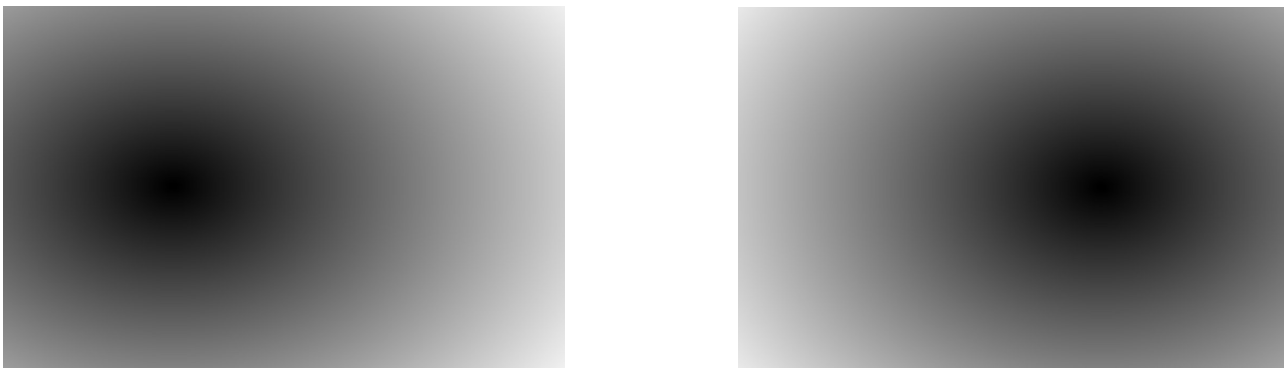

Figure 2: Imaginary 2D grey world at the beginning (on the left) and after some time (on the right).

Let's imagine that after some time and according to some mathematical laws the dark blurred spot on the left moves on the right. We would like to simulate this behaviour but your computer is not able to manage each pixel and each infinitesimal time step. The first thing to do is to take a few samples of grey density from the beginning state in some places and not exactly in the same time (fig. 3). Then with some other mathematics (assimilation) we have to interpolate these measurements and distribute numerical values in a finite coarse grid so that the coarse finite image (analysis) look about like the real greyscale image at an starting arbitrary but precise time.

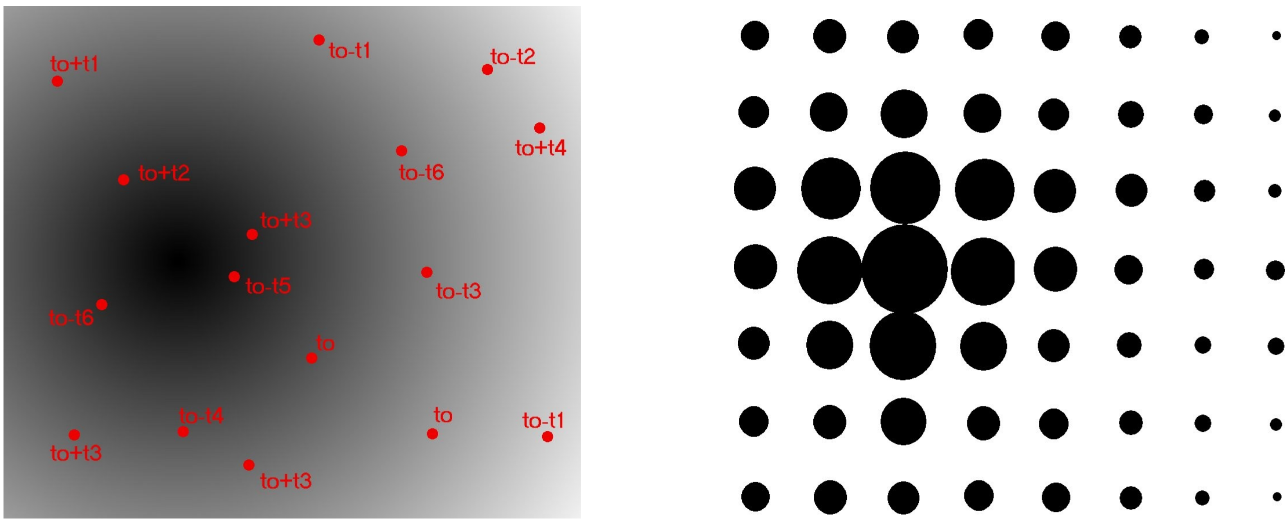

Figure 3 : sampling (red points) in some places and at some different times from the "real world" on the left. After assimilation the resulting coarse finite analysis at a precise time on the right. Of course, smaller is the grid resolution, more reliable is the analysis to the real image.

Once the analysis is performed, we can do the simulation only now, using the almost same mathematics for its time-change than the evolution laws of the real grey world. But the original image (analysis) is only not quite like the beginning reality to see the predictions become inaccurate, because a small dissemblance at the beginning amplifies and becomes big at the end. Assimilation is thus the Achilles heel of the models (figure 4).

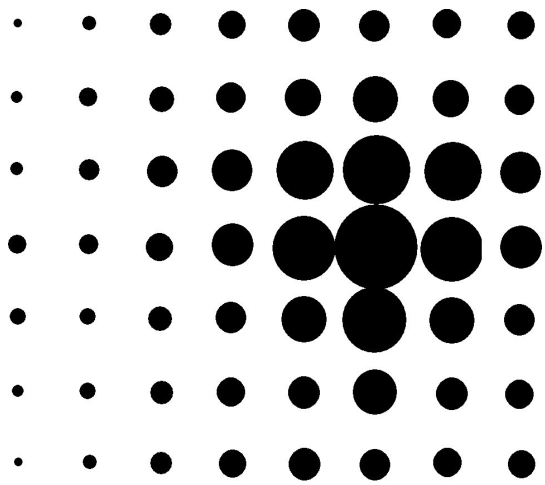

Figure 4 : finite prediction after simulation according to some mathematical rules.

Now the provocative sentence can be better understood. The simulating model does not know anything about the real infinitesimal atmosphere. It does know about the coarse finite image of atmosphere, the analysis, then its time-steps predictions, only. We just hope that the coarse image look the closest as possible like the real atmosphere.

To realize the importance of the grid resolution practically let's still examine the topography “seen” by two models with different grid (figure 5). The macroscale model “sees” the Alps topography like a wide, bald and not very high hill without any valley. The RASP topography is much closer to the real complex topography. The main valleys and main mountain massifs can be seen easily.

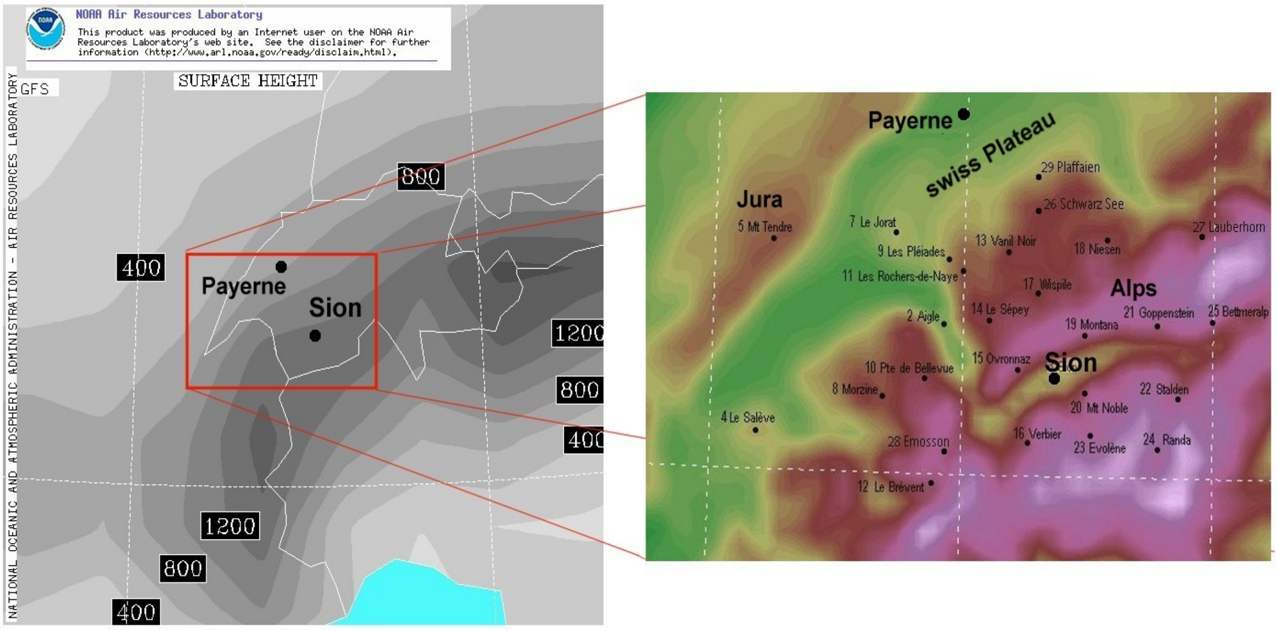

Figure 5: comparison between the topography of macroscale world US GFS model with about 50 Km resolution (on the left) and the one of RASP 4Km resolution (on the right).

It is then interesting to compare for example the aerological profile (sounding) on the same place (Payerne) and at the same time between GFS, RASP and the radiosounding (figure 6). RASP is clearly closer to the real measured profile than the GFS profile. RASP especially describes the exact CBL that GFS does not. Because GFS does not “see” the swiss Plateau between Jura (west) and Alps (East) the ground surface altitude seems to GFS too much high at Payerne and therefore the T and Td curves begin higher than the curves of RASP and radiosounding. We can conclude that fine-grid models are perhaps not better than coarse-grid models for general prediction of weather evolution but they specifically provide more realistic prediction for CBL with regard to the topography.

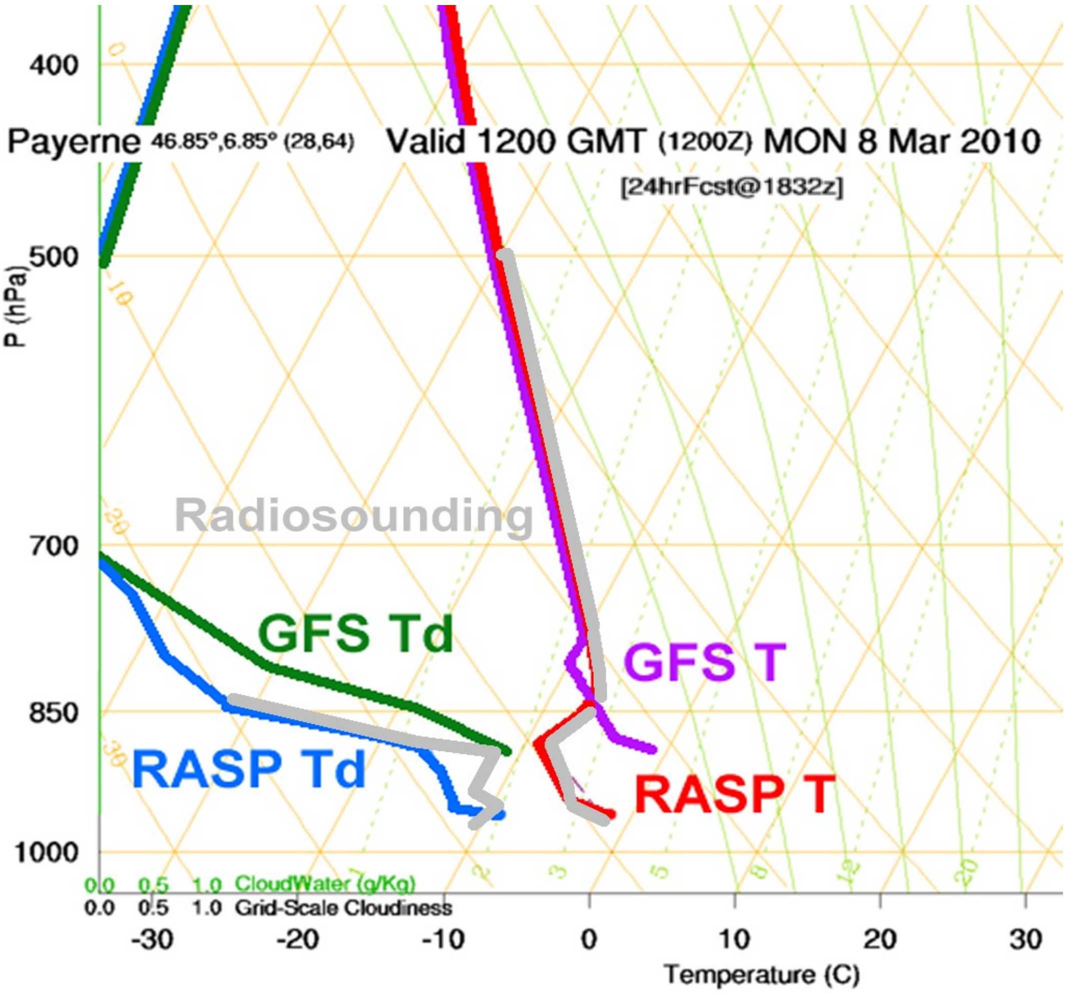

Figure 6: comparison between the aerological profile of macroscale world US GFS model with about 50 Km resolution, the one of RASP with 4Km resolution and the one from the radiosounding (measurements) above Payerne at the same time.

Dr Jack says:

Forecast accuracy of the many parameters predicted by a meteorological model can be generally ordered, from most accurate to least accurate, as: (1) Winds, (2) Thermal parameters, (3) Moisture parameters, (4) Cloud parameters, (5) Rainfall.

The computer power needed for improved model resolution increases as the fourth power of the resolution increase, e.g. halving the grid spacing requires the computer power to be 16 times larger! So doubling a model's resolution is a big accomplishment! This is because in addition to a factor of 8 increase corresponding to the increased number of horizontal and vertical grid points, since the finer resolution should occur in all directions, there is an additional factor of two because the time step must now be halved to accommodate the smaller grid size.

Human evaluation of RASP results together with other information should produce a superior forecast - but of course that depends on the correctness of the "added value" that the human *provides. One way that "human intelligence" comes into play is through knowledge of model strengths and weakness * particularly by recognizing when the latter are making a model forecast unlikely.*

* Personal note: and pilot's experience of the local topography and weather as well as his common sense, his sense of objectivity, his curiosity and his self-criticism, shortly involving some degree of modesty and intelligence.

Dr Jack says:

Thermal velocity varies greatly with the land surface type. Weather models try to incorporate the effect of difference surfaces, but must do so in a very crude manner by estimating the "average" surface type over the grid area. When you consider the wide variety of surfaces over such an area you can appreciate how inaccurate such an estimate can be. Moreover, surface type determinations are usually made on a much coarser scale and such determinations are usually based upon satellite-based estimates of surface type not on actual inspection of the surface itself. Seasonal adjustments are made using a monthly database of vegetative fraction but this considers only a limited number of seasonal effects (the effect of snow cover is also included in the model). This note came about because I was asked if the model takes account of the flooding of the rice fields in California's Central Valley around this time of year, which obviously has a big impact on the thermal strengths there - and the answer is that although I cannot actually examine the monthly database, the ratio of specific to latent surface heat fluxes forecast by the model indicates that the model surface moisture is much drier than the actual surface, so thermal strengths are being over-predicted.

Soil moisture greatly affects thermal predictions since solar energy which goes into evaporating (latent heat) surface moisture is not available to heat (sensible heat) the surface. All good atmospheric models include many soil moisture processes but these contributions can only be estimated crudely since including all the complexities of soil hydrology would require calculations as involved as those of the atmosphere itself! Based on limited reports, I've gotten the impression that the model tends to greatly underpredict soil moisture when there has been a previous heavy rain. Previous rainfall rates can be obtained from standard model reports, radar images, weather stations reports... Another clue can be obtained by comparing observed vs predicted surface dew point temperatures. That comparison is also be useful in determining whether the model is likely to over- or under-predict BL cloud formation.

Predicting clouds is always a challenge, with difficulties increasing as clouds decrease in size, vertically or horizontally, since clouds smaller than the grid spacing cannot be directly predicted by fundamental equations. Some ad hoc supplementary equations are used to estimate effects such as reduction of surface heating by unresolved clouds, but these cannot be very accurate. For RASP, thermal strength forecasts (W charts) do not include the contribution of condensation heating aloft produced by cloud formation (sometimes elegantly referred to as "cloudsuck") - so expect stronger than predicted thermals to occur below clouds when they are present in the BL.*

If thin cloud layers are present, then RASP predictions are particularly suspect. Models often fail to forecast cirrus and other thin cloud layers, largely due to the finite thickness of the model grid layers - and since grid vertical spacing increases with height, this problem exacerbates at upper levels. Unfortunately it does not take a very thick cloud layer to greatly reduce the solar radiation *reaching the ground, so thermal strengths and heights are often over-predicted when such layers are present. To allow for such clouds when they are not forecast by the model is a frequent challenge. Users can use satellite photos to spot the layers and anticipate their movement based upon upper level winds - but this works only for existing layers which are transported, not for those which develop later. One useful check is the model-predicted surface sunshine - if clouds are predicted patches of decreased sunshine will appear.*

Personal note: Another clue can be obtained by observing the soundings. If the blue dew point curve is close (about less than 5°C) to the red temperature curve above the CBL especially on a thick layer, you can expect some high clouds. It is a personal empirical deduction coming from many years of model sounding examination. A few months of RASP soundings examination with concomitant sky observations seem to confirm that fact.

Dr Jack says:

The models do not adequately allow for the reduction in surface solar radiation resulting from large "aerosol" concentrations such as dust or smoke. The model knows nothing about forest fires! Also, my impression is that the models do not adequately allow for the reduction in surface solar radiation created the haze associated with pollution (the model also knows nothing about pollution). Therefore, if visibility is poor, expect thermal strengths to be lower than predicted.

Dr Jack says:

There is a potential serious limitation of RASP about snow cover (figure 7). The forecast problem can be traced to input from the driving NCEP global GFS model, with too large snow region over the Alps at macroscale (GFS model view). Naturally if RASP is told there is snow cover it is not going to predict any thermals, and other predictions which depend upon surface heating will also be incorrect. The probable reason for the anomalously-predicted snow is that GFS uses "envelope topography" which for terrain values uses the maximum elevation in a grid cell rather than the average, which would produce a large area of higher-than-actual elevations and hence more snow than is actually the case. "Envelope topography" tends to produce better "dynamics", such as wind predictions, but at the cost of poorer thermodynamics, such as surface temperatures. And because the grid cell of macroscale GFS is around 50km, any such anomaly is spread over many points in the RASP grid.

It is an example of a case in which RASP forecasts can be invalid due to its dependence upon forecasts from the global model. To alleviate this anomaly I "tell" to my Alps RASP model before it runs that there no snow in winter and in the beginning of spring when there has been no new snow fall for a few day, because in this case I empirically notice that probably the heating effect of snow-free alpine pine forest is not negligible in the alpine valley. When just new snow falls, the pine forest is also covered by snow (it is of course beautiful) but there is no significant heating source, so I “tell” to the model to put the snow cover parameter on.

Figure 7 below, shows a concrete example of this problem. The south french Provence, famous for its warm climate, has a snow-free ground surface on march, what is very usual and what is seen on the satellite image. Nevertheless the GFS model considers that this area is covered by snow down to the mediterranean sea border !! For the broad and deep Bolzano valley and the large swiss Rhone valley (Valais) one can see the same discrepancy between the model snow cover chart and the satellite image. Moreover, even in the high small valleys, the pine forests during winter seem to be non negligible for the CBL thermodynamics, especially when they are not covered by new snow. In winter and at the beginning of spring, pilots usually do not fly on the high snow covered peaks but instead on the snow-free valley slopes. That is why I can empirically “cheat” and “tell” RASP there is no snow in these conditions.

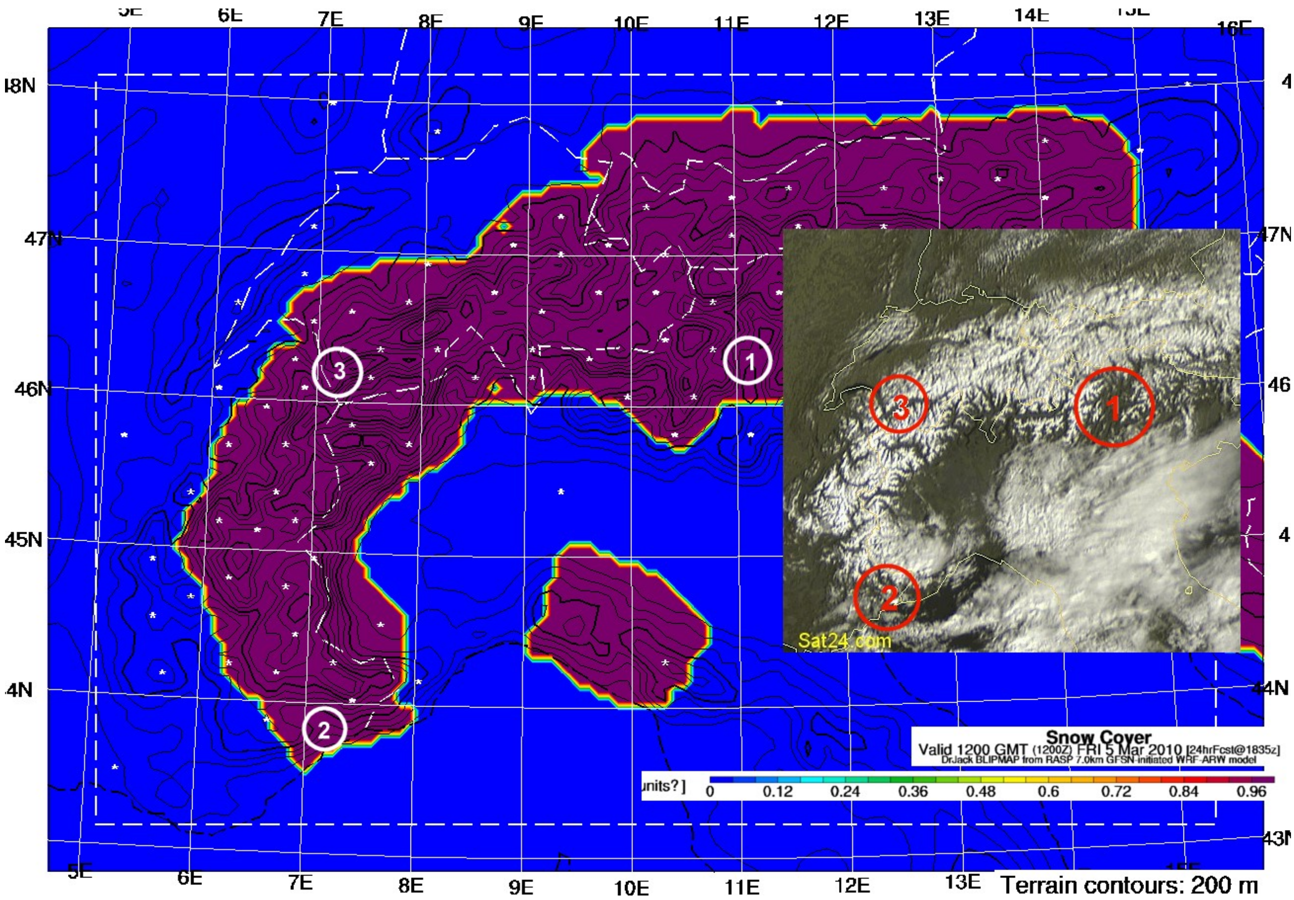

Figure 7 : discrepancy between macroscale RASP snow cover and real snow cover as seen on a sat image (on the right) at about the same time on the Alps (2010, 5th march). 1 = Bolzano valley. 2 = Provence. 3 = Valais. Purple areas mean the ground surface is simply covered with snow without taking account of the thickness of snow. Blue areas mean region without snow. There are still some superimposed numerous cumulus which increase the size of the white areas on the sat image. Therefore the real snow cover should be still less spread.