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Extracting statistical parameters of extreme precipitation from a NWP model

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Abstract

Precipitation simulations in an 8×8 km grid by the PSU/NCAR Mesoscale Model MM5 are used to find the M5 and C_i statistical parameters in order to support the M5 map used for flood estimates by Icelandic engineers. It is known a priori that especially wind anomalies do occur on a considerably smaller scale than 8 km. The simulation period used is 1962–2005 and 73 meteorological stations do have records long enough in this period to provide an observation value set. Of these only 1 is in the central highlands, so the highland values of the existing M5 map are estimations. The comparison between the simulated values and the observational value set show a M5 average difference (observed-simulated) of −5 mm/24 h with standard deviation 17 mm, 3 outliers excluded. This is within expected limits, computational and observational errors considered. Suggested correction procedure brings these values down to 4 mm and 11 mm.

1 Introduction

In this paper are presented the statistical parameters called M5 and C_i (Eliasson, 2000) for the annual precipitation extremes in Iceland. These are produced by a NWP model: The fifth-generation Pennsylvania State University-NCAR Mesoscale Model-MM5 (Grell et al., 1995). It has been widely used in forecasting and usually found reliable, e.g. in an investigation (Anders et al., 2007) of the small-scale spatial gradients in climatological precipitation on the Olympic peninsula, a geographical region even more mountainous than Iceland. They find good agreement between gauge precipitation and the cumulative MM5 precipitation forecasts for all seasons. The sum of all 10 large events compares well with the precipitation gauges, although some of the individual events are significantly over- or underforecast. In this paper we do just this, extract statistical parameters from MM5 computed annual extreme rainfalls, without considering discrepancies in the time histories of computed and observed data and then compare the results with available parameters based on observations.

Great care has to be taken in selecting the parameterization scheme used in MM5 simulations. Convective precipitation is one of the most difficult, here the Grell cumulus parameterization scheme (CPS) and the Reisner1 microphysics scheme (Reisner et al., 1998) is recommended by (Chien and Jou, 2004), but other combinations could cause a general underforecast. However, some investigations show that all microphysical schemes produce a similar precipitation field and none of them perform significantly better than the others (Serafin and Ferretti, 2007). CPS will be more closely discussed in the next chapter.

The danger of major precipitation errors for individual storms seems to exist even in model runs with excellent overall performance. (Minder et al., 2008) find the MM5 very good in simulating small-scale pattern of precipitation at seasonal time-scales while major errors exist for individual storms. Other analysis show clearly the tendency to form local precipitation maxima in the lee of individual mountain ridges (Zangl et al., 2008) while yet other research indicate the exact opposite (Rögnvaldsson et al., 2007a). This point will be closer examined in the second chapter.

The reason for this analysis is to review a M5 map presently used by Icelandic engineering hydrologists to estimate peak runoff[1]. The M5 – annual extreme 24 h rainfall with 5 years return period –, (Eliasson, 2000) is used as an index variable in these estimations so a good M5 map is needed. In reality another parameter is also needed for quantile estimation, the C_i parameter. Together these two replace the mean value and the standard deviation in the Gumbel distribution, but this distribution is found valid for the Icelandic data (Eliasson, 1997). The map is also used for PMP (Probable Maximum Precipitation) estimation (Eliasson, 1994) so the map is used in engineering design for a wide range of quantile estimates.

The North Atlantic experienced increased cyclonic activity from a relatively quiescent period from about 1930 to the early 1960s until the mid nineties with increased storminess (Hanna et al., 2008). The climatic stability and therefore the justification

[1] http://www2.verk.hi.is/vhi/vatnaverkfrstofa/Kort/1M5_Yfirlit.pdf

of using an index parameter extracted from the last 100 years of observation is an open question, still unanswered. It is therefore necessary to bear in mind the complex composition of precipitation extremes and significance of the individual precipitation components that is different in Iceland from central Europe. The main difference in extreme precipitation climatology is that orographic precipitation is more dominating in Iceland rather than the convective type (Hanna et al., 2004).

2 The MM5 model simulation for the period January 1961 to July 2006

This run was completed in 2006. General results are discussed in Rögnvaldsson et al. (2008). Prior to this, atmospheric flow over Iceland had been simulated for the period September 1987 through June 2003, using an older version of the PSU/NCAR MM5 mesoscale model driven by initial and boundary data from the European Centre for Medium-range Weather Forecasts (ECMWF) (Rögnvaldsson et al., 2007b).

An investigation of the seasonal and inter-annual variability of the precipitation results did reveal a negative trend in the winter precipitation in W-Iceland, but a positive trend in the ratio of lowland precipitation to mountain precipitation in E-Iceland and a substantial inter-annual variability in the ratio of lowland precipitation to precipitation in the mountains. It was also found that the mountains contribute to a total increase of precipitation in Iceland of the order of 40%. Because of the good experience with this preliminary run it was decided to extend the simulation period and try statistical analysis of the precipitation extremes. The calculations were done in an $8\times8\,\mathrm{km}^2$ net shown in Fig. 1.

If Fig. 1 is compared to a map of Iceland it reveals that the computational net is rather coarse compared to the landscape features. This can influence the results significantly; Fig. 2 shows the result of a storm incident 16 June 2008 (simulated with the AR-WRF model[2]). In the area encircled by red, local wind speed extremes and high

[2]http://www.wrf-model.org

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spatial gradients can clearly be seen on the south side of the landmass, which is the westward pointing peninsula on approximately 65° N in Fig. 1. Figure 2 is computed in a 1 km grid. Increasing the size to 3 km made the local features completely disappear. Calculation in a 9 km grid showed even less gradients than the 3 km grid but the difference was greatest between the 1 km and 3 km grid results. These grid-size dependent discrepancies cannot be mended by parameterization, but wrong parameterization can make them considerably worse. Therefore the possibility exists that spatial gradients in the 8 km MM5 grid are much too low to rely on the results in small catchment hydrology simulations. Never the less, results that do not depend upon a short time history in one point can be accurate enough.

Forecast skills of numerical weather prediction (NWP) models have improved considerably for many variables (e.g. geopotential height and temperature) over the past years and decades but precipitation has remained somewhat elusive (Bozart, 2003). One reason for this is that the physics governing the formation of precipitation are highly complicated, rendering parameterization difficult. Another reason is that the distribution of precipitation (particularly solid precipitation) over complex topography as simulated by NWP models is very sensitive to the dynamic and thermal characteristics of impinging winds (e.g. Chiao et al., 2004).

3 Estimation of M5 and C_i

The procedure for estimating M5 and C_i is set forth in (Eliasson, 2000). The stability of the M5 estimate is of great concern. The M5 estimates cannot be taken as scatter free but must have assigned an uncertainty value, just as the model values must be. The common practice is not to use M5 estimates with fewer than 20 annual extremes behind them. The reason for this is the previously mentioned long term fluctuations in the climate. The effect of this on the M5 estimate may be clearly seen in Fig. 3.

In the Fig. 3 example it is clearly seen that number of station years behind an M5 estimate should be greater than 40 in order to achieve stability. Only 32 meteorological stations do have more than 40 station years and of these only 11 have more than 60 years. The simulated M5 values have 44 station years behind them.

Another way of assessing the stability is to study the differences between a short and a longer period M5 in many points. Figure 4 shows how the differences in gauged M5 values in the 1990 and 2006 data, respectively. The difference is within 10 mm but depends strongly on the number of station years. Above 60 station years this difference seems to be within 5 mm. The average value of the difference is 1 mm but the standard deviation is 3.6 mm. It is therefore safe to assume that the M5 values in the meteorological stations are within ±4 mm for each location. In comparing observed and computed values, effects of spatial variability and model uncertainty will increase this number. The 4 mm value may then be taken as the uncertainty value of the M5 (gauge) estimate on top of the instrumental errors themselves. This must be kept in mind, as the simulation period is the 44 years from 1962–2005 in all points, but the observation period for individual gauges is normally different.

On the other hand the statistical distribution function of the pooled normalized annual maximum precipitation data in Iceland follows Gumbels probability distribution function very nicely (Eliasson, 1997). This function is therefore used to estimate the M5 and C_i values from the mean and the standard deviation of the station values used in the normalization.

The stability of the C_i estimate is also an issue, but the effect of a scatter in this value is much more limited than in the scatter of M5. Most station values of C_i in Iceland are below 0.2. The effect of a variability in C_i on a quantile estimate can be seen from the following equation (Eliasson, 2000):

$$MT/M5 = 1 + C_i(y - 1.5) \tag{1}$$

MT = 24 h annual precipitation maximum with return period T years

$$y = \text{Gumbels parameter} = -\ln(-\ln(1 - 1/T))$$

The biggest y used in engineering design is around 7 (T=1000). This will produce the greatest impact of a scatter in C_i, but a deviation of 10% in the C_i will only produce a

5% deviation in the MT estimate for y=7. For lower T values this effect is much less and disappears altogether around the 5 year value. This relatively little importance of the C_i value in practical quantile estimates is the main reason for replacing the mean value and the standard deviation in the Gumbel probability distribution function with M5 and C_i.

4 Comparison with existing mapped data

1650 of the 11 468 grid-cells only are on land. This is a great improvement though, as only 73 gauges exist that can be compared to this result. There is no doubt that great improvement can be gained in the model results using finer grid and shorter time step. Such simulations will undoubtedly be produced in the future. For the time being the when and how is unknown.

For qualitative comparison it is very instructive to study the surface map in Fig. 5.

Figure 5 shows clearly the very strong orographic effect in the precipitation. Areas with M5>120 are clearly seen to be on the glaciers, but they are the highest parts of the country, 1000–2000 m a.s.l. while the highland plateau around them is around 600 m a.s.l. Figure 5 shows that we are not having the biggest precipitation in the lee zones as in (Zangl et al., 2008) but directly on the mountain tops.

A qualitative comparison with the existing M5 map compiled from 1990 data is shown in Fig. 6. It too reveals unexpected results.

The two contour maps are not completely identical, but much closer than expected, especially the ungauged regions (punctuated lines on the M5 map). The main differences can be qualitatively described as follows:

- The channel between the high M5 values in the south and the lower values in the north is 60–80 mm/24 h in the existing map while the model values are 40–60 mm/24 h. The line through the high points is the main water divide between the north and the south parts of the country.

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- The 120 mm line does reach in between the two glaciers of the south in the map but not in the model.
- The low value areas in the north are bigger in the model.
- The largest area with gauges values (solid lines in the map) is very similar in both pictures.

The qualitative result of this comparison is that the model is producing the same values as the gauges where we have them, in the ungauged regions the estimated values in the map are higher than the model values and this difference is of the order of magnitude 10–20 mm or 20–30%.

The results for the C_i coefficients, described in the following, are very much along the same lines.

The computed C_i values range from 0.12–0.23, this is the same range as in the meteorological stations. It is impossible to compile an areal distribution comparable to Fig. 7 from the 73 observations because while the punctuated lines in the M5 map could be estimated from reliable M5 – AAR (annual average rainfall) relations, no such relation seems to exist for the C_i. It was therefore recommended to use the value C_i=0.19 with the map, or the value from the closest meteorological station.

Figure 7 nothing but justifies this recommendation. The average C_i value is closer to 0.17, but the recommended value to use with the map must be a little higher than the average.

In quantitative comparison between the met. stations and the simulation the 9 neighbor points (NP's) in Fig. 8 were considered. This is because simulated M5's are cell average values while the observations are point values. The NP0 is the closest neighbor point, NP0–NP3 the closes 4 points series, NP0–NP8 the cluster of the closest 9 points. The distance MS – NP0 can be up to 5.7 km and the differences in M5 between the NP points will show the spatial variation in the computational grid. On top of this spatial variation there is the precipitation effect due to landscape forms on the scale <8 km that are flattened out by the grid but felt by the meteorological stations. Various

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schemes to interpolate and estimate the "best computed value" in the meteorological station (red in Fig. 8) in order to compare that value to the observation M5 value may be suggested.

Now Fig. 9 shows the direct comparison between the NP0 points simulated M5 values and the M5 in the meteorological stations, no corrections applied.

The standard error of the estimate in Fig. 9 is 17 mm and the average M5 difference is −5 mm (model values higher than the gauges) the correlation coefficient is R=0.78. If the three red outliers are excluded the correlation improves somewhat (R=0.9). Of the 73 gauges 57 are in the range 40–80 mm and here 80% of these points (63% of the total) are within 10 mm which is the outer range for the scatter in Fig. 4. Resulting differences between the MS and MM5 are in Tables 3 and 4.

On top of the causes is then a general model error, caused by the model construction.

In particular, the magnitude of the measurement error Table 4 line a, depends on the wind-speed and the under-catch is more pronounced for solid (especially snow) than liquid precipitation (see review by Haraldsdottir et al., 2001, citing Førland et al., 1996). The Table 3 line a and Table 3 line b can be explained by Table 4 line a, Table 4 line b and Table 4 line c. But Table 3 line c, Table 3 line d, and Table 4 line d require a little closer examination. In Fig. 10 we examine the three red outliers in Fig. 9, together with the point directly above them. In all these points the gauge value is approximately the same, (103–106) so this value is represented by one thick green line in Fig. 10.

In Fig. 10 we see that the "normal" station 615 (yellow columns) has an average deviation within the 17 mm mark, but the spatial variation around the NP0 value is greater than in the other points. Same large spatial variation is seen in the 620 results, but here the simulated M5 value is only 60% of the gauge value. The two other points are less than 50% of the gauge value and the spatial variation is small with the exception of NP9 in 234 (red column). This shows that small spatial variation in the NP values by no means promises an accurate result. It is believed that hills in the landscape around 103 and 234 that are flattened out in the grid cause these deviations. This cannot be

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proved except by simulations in a finer grid and has therefore to be taken at face value. Nevertheless, this opens up the possibility that several grid points in the simulation, anywhere in the grid, can be rather inaccurate, and carefully interpolated values in the blue points in Fig. 8, statistical analysis of the differences and subsequent correction of all of the 1650 cell values does only have a minor chance in doing any good.

5 Discussion

The simulation has achieved M5 results for around 1500 locations in Iceland where no information was available before. Where we have information, the largest single group (63% of the total gauge values) NP0 and gauge values fall within 10 mm/24 h. Of these about 4 mm (Table 4 line c) may be due to different estimation periods, and effects of wind and MS and NP0 distance (Table 4 line a and Table 4 line b.) can easily explain the differences up to 10 mm.

The rest of the values (37%) show greater scatter. These discrepancies are presumably due to a combination of all errors listed in point 2 and errors in the precipitation measurements. Due to the strong orographic effect in the precipitation, local landscape features on length scales <8 km can be felt by the gauges without having any effect in the simulations. Three outliers show what could be this effect clearly, and in them simulated precipitation is only 50% of the gauge value so the total difference is 40–60 mm instead of the maximum 35 mm in the other points. There may be an unknown number of such points in the simulated data set; they can only be identified in more accurate simulations.

The line of general trend is $M5_{\text{sim}}=4+1.05\ M5_{MS}$ (outliers excluded), but this relation has very little effect and does not mend the real problems. The result of this discussion is therefore, that a general trend function that can be applied to the computed M5 values and used to correct them cannot be seen. This is merely the result of that the simulated values are already so good that differences between gauge values and simulated results falls within the combination of model inaccuracy and the accuracy of

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the estimation of the gauge M5's on one hand, and the general MM5 model inaccuracy on the other hand. Such differences are generally not randomly distributed.

In making a new M5 map the following policy is recommended to correct the simulation values

Gauged regions

1. Areas where the difference is <10 mm: No correction
2. Other areas (30 meteorological station points available): Correction by expert opinion.

For the ungauged regions following procedure is recommended

1. All regions where the original map and the $M5_{sim}$ value is <60 mm: No correction
2. Other regions, original map value up to 80 mm: Correction 0–20, linearly increasing.
3. In regions with original map value >80: Add 20.

The suggested procedure is believed to be more consistent than the flat trendline. It brings the overall differences down to the average −4 and rms 11 instead of the −5 and 17. This suggestion is presently in review.

6 Future research

The future research on the M5 and the basis of flood estimation in Iceland will be concentrated in 3 main areas:

1. Checking the probability distribution function of the annual precipitation maxima region for region in order to find if there are any discrepancies in the a priori assumption that they follow the 2-parameter General Extreme Value distribution as already found (Eliasson, 1997).

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2. Searching for statistically significant M5-AAR (Average annual rainfall) and C_i-AAR relations in the regions.

3. Working towards a new simulation 1961–2007 in as fine a grid as possible with the target grid size 1 km.

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Table 1. MM5 output results.

Run time	1961–2006	AD
Grid size	8×8	km
Number of cells North×West	122×94	
Output time step	6	h
Precipitation on boundary	0	mm/6 h
Output files produced	60.000	

Table 2. MM5 data transformation results.

Used data	1962–2005	AD
Number of 6 h time series	11 468	
Running average series	24 h	
Annual maxima isolated in each cell	44	
Precipitation on boundary	0	mm/6 h
Output files produced	60.000	
Number of M5 and C_i values computed	11 464	

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Table 3. Differences between meteorological station and NP0 values.

a. Average difference of meteorological stations and NP0	−5 mm
b. Standard error of the estimate, closest 63%	10 mm
c. Full standard error of the estimate (rms)	17 mm
d. Max error, outliers (total 3 or 4.1%) excluded	35 mm

Table 4. Order of magnitude values of possible causes of the differences in Table 1.

a. Wind effect in MS[3], average, (1/3 of ann. max. affected)	−5 mm
b. The MS[3] – NP0 distance effect, rms value	5 mm
c. Different estimation periods	4 mm
d. Course grid effect (0–50% in 4% of points) rms	10 mm

[3]Meteorological Station

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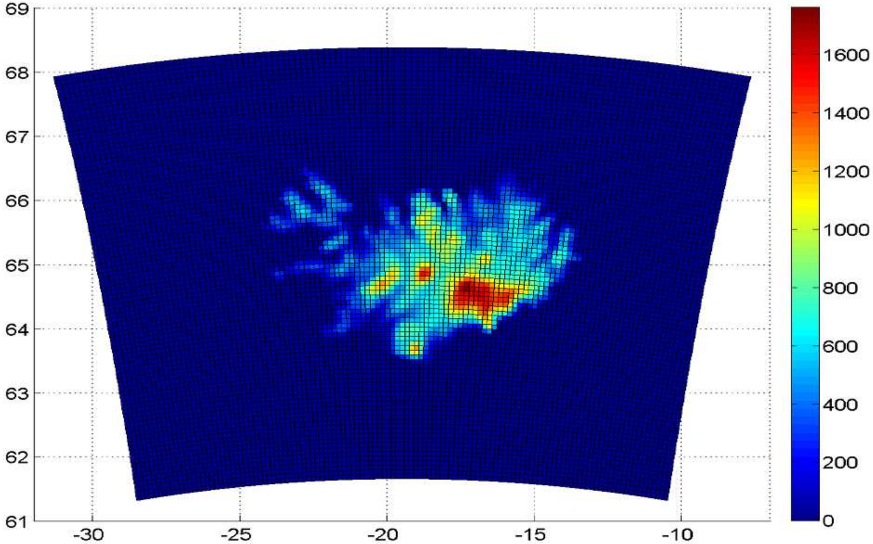

Fig. 1. Elevation data of the MM5 simulation area (color scale in meters), geographical longitude on horisontal axis, latitude on vertical axis.

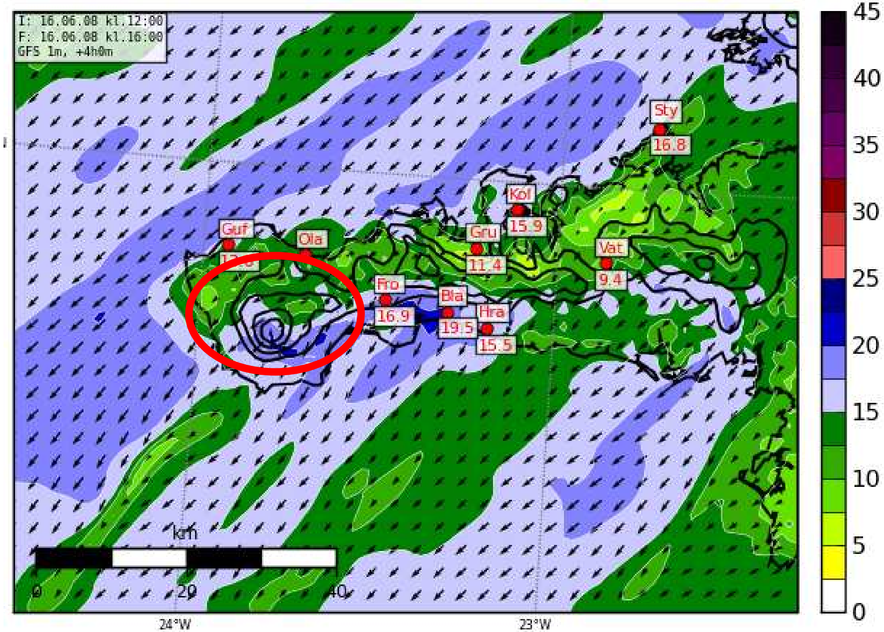

Fig. 2. Local wind anomalies in Snæfellsnes, only found in a 1 km grid, not 9 or 3 km.

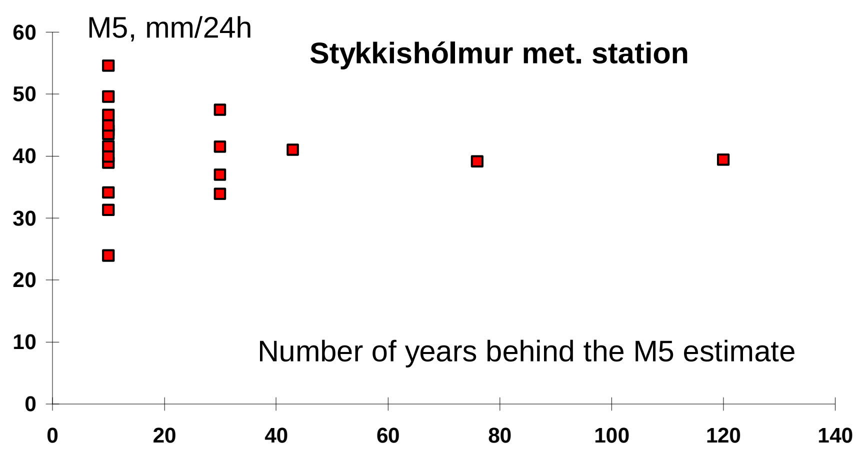

Fig. 3. Scatter of the M5 estimate and its dependence on station years, an example.

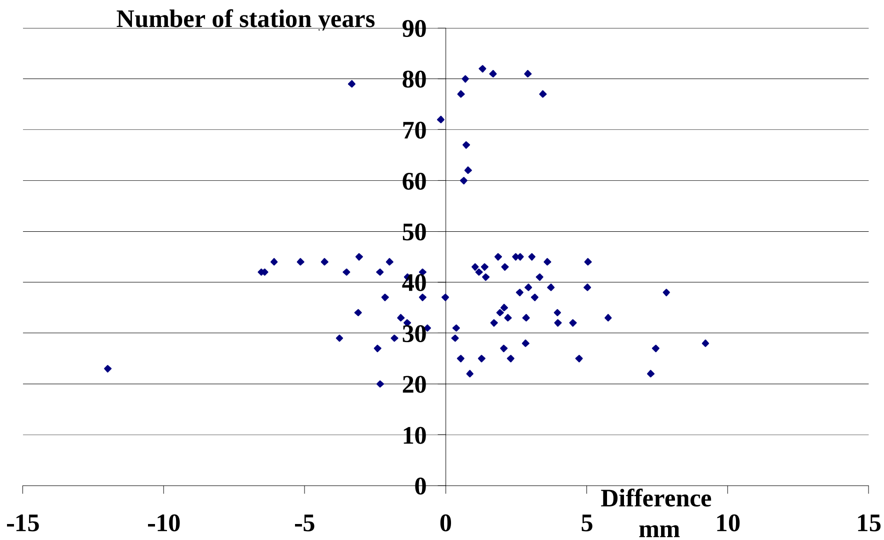

Fig. 4. The difference between M5 data in the 1990 and 2006 data sets.

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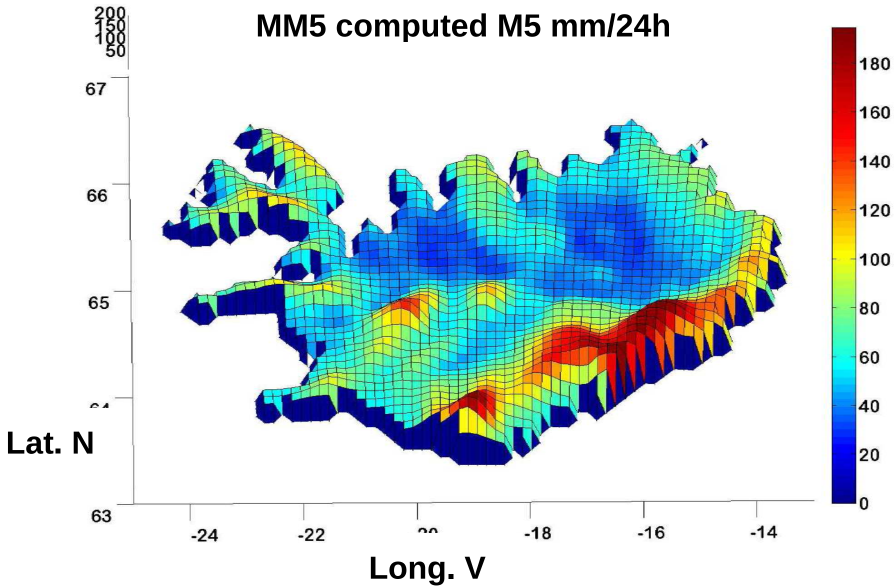

Fig. 5. Surface map of the MM5 model values for M5.

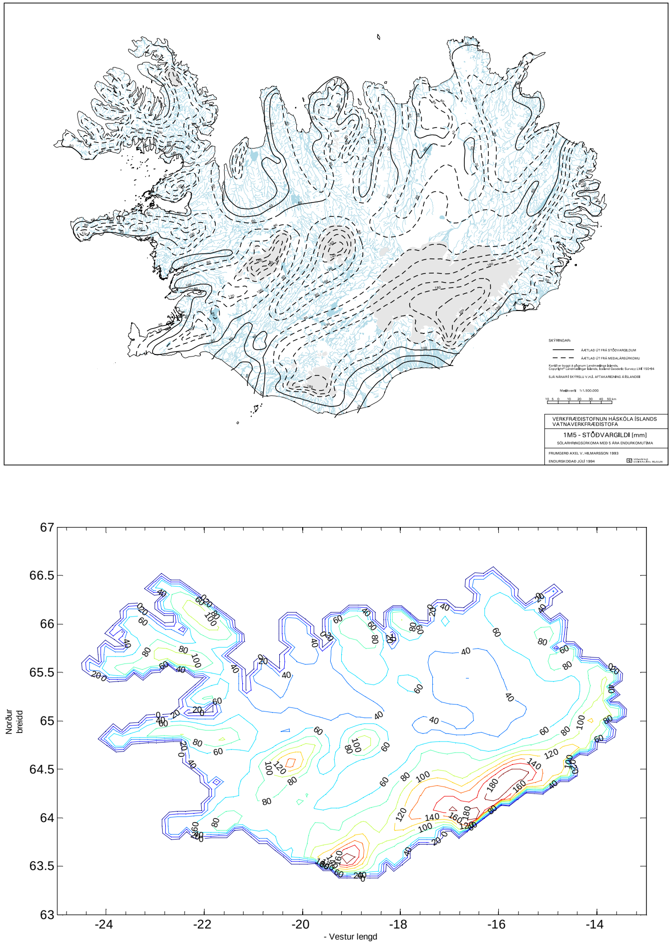

Fig. 6. Existing M5 map (punctuated lines estimated values) top, compared to MM5 model M5 (bottom). Contour lines for each 20 mm/24 h on both maps.

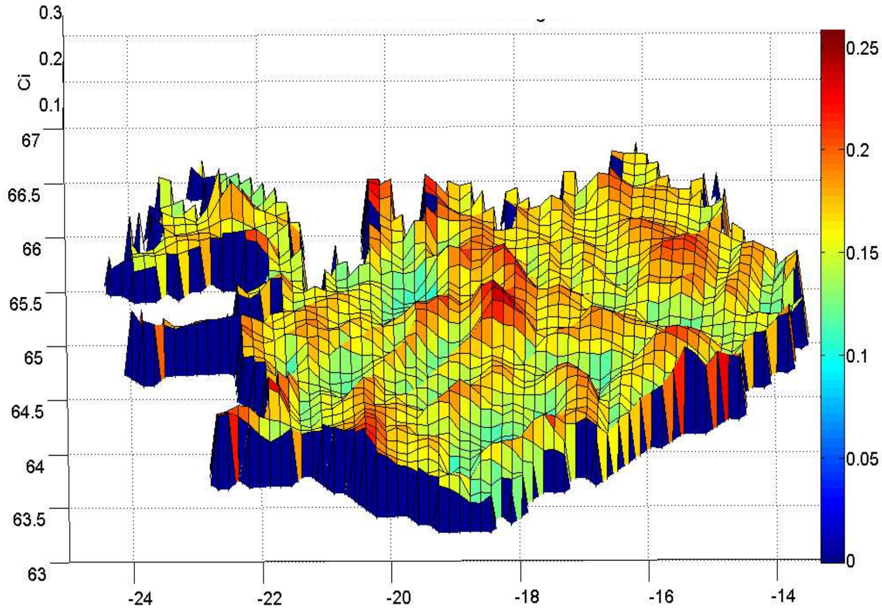

Fig. 7. Surface map of the C_i values from the MM5 run.

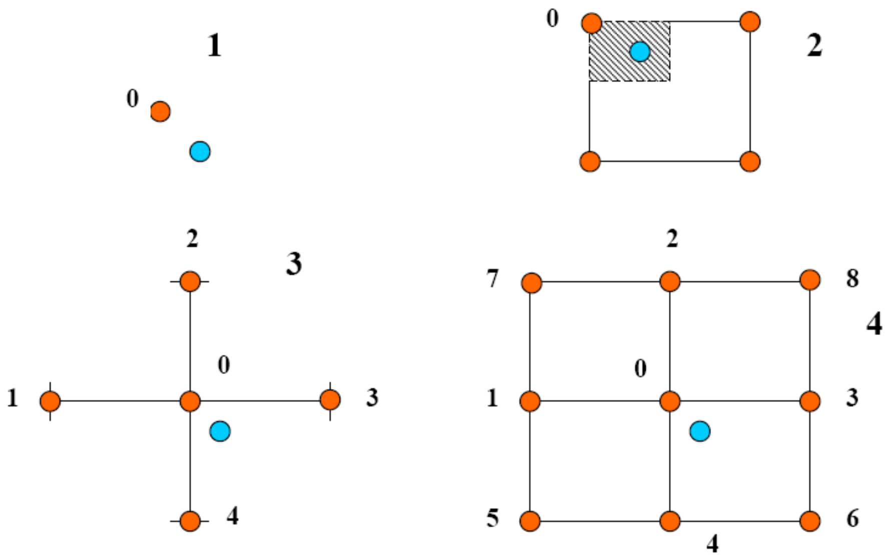

Fig. 8. Comparison schemes of a meteorological station (blue) and simulations (red) NP points.

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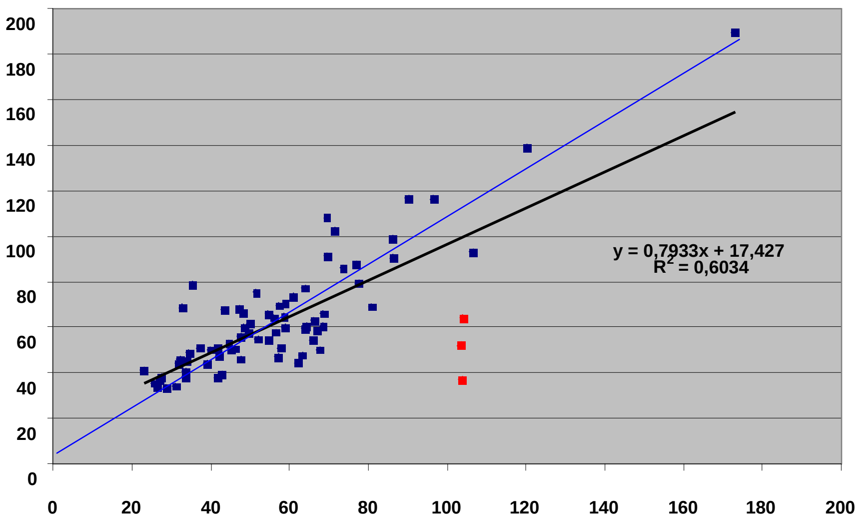

Fig. 9. Model M5 (vertial axis) in the 73 meteorological stations compared to NP0 point values (horizontal axis).

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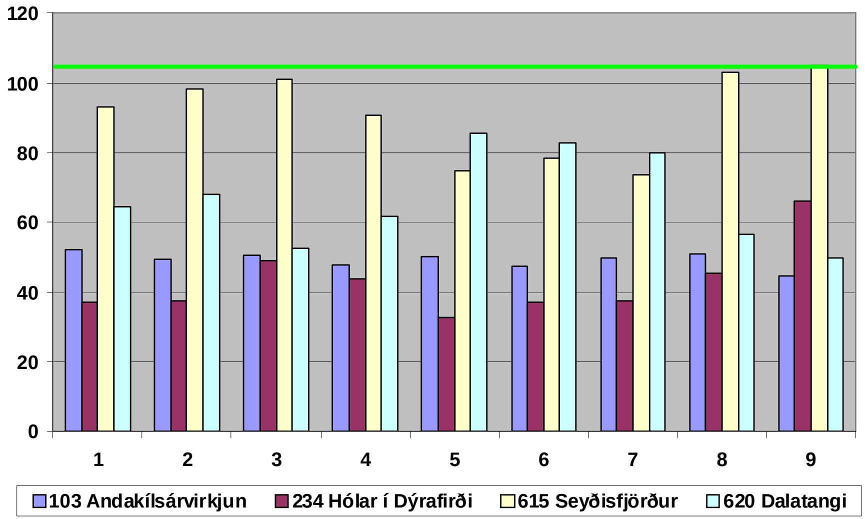

Fig. 10. Outlier points in Fig. 9. Meteorological stations number 103, 234 and 620 compared to "normal" difference station 615. Numbers on the horizontal axis are the NP point numbers.