VEÐURSTOFA ÍSLANDS

Report
02028

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A Linear Model for Mapping Precipitation in Iceland

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I) Introduction

Estimating the amounts of precipitation is of paramount importance for number of applications such as agricultural purposes, water management, hydrological models, climatic studies, global circulation models and for the validation of indirect estimation methods based on remote sensors such as radars or satellites and numerical prediction models.

The most common way to estimate ground precipitation is to interpolate scattered observations. There is not a unique solution and various interpolation methods are available for this purpose (see [1] to [3] for instance). Most of the time, these methods operate in 2D and rely only on the information based on the precipitation field itself. They usually work well if the precipitation network is dense enough with respect to the spatial variability of the precipitation field. In a country like Iceland, the use of such interpolation methods alone can be questionable in mountainous regions where strong 3D variability can be expected or in poorly monitored areas such as the highlands. It is thus necessary to pre-process the data and attempt to describe and remove any trend or non-stationarities before interpolating, see [4] for instance, [5] and earlier work from [6] and [7] who successfully describe relationships between precipitation amounts and topography. In this report, we propose to follow this general idea and study the influence of the topographical environment on the precipitation patterns in Iceland. It is part of the validation protocol developed for assessing the quality of the precipitation amounts produced by the MM5 numerical model in Iceland [8] and [9].

II) Relationship between precipitation and topographical environment

II-1) The predictors

The precipitation at each site is described by a linear model. The 9 selected predictors (p1) to (p9) give an information about the geographical and topographical features in the vicinity of each site.

$$P(x,y,k) = a_0 + a_1 x + a_2 y + a_3 d\min + a_4 \overline{h} + a_5 \overline{a} + a_6 \overline{s} + a_7 \sigma_h + a_8 \sigma_a + a_9 w \qquad (1)$$

Where:

$P(x,y,k)$ = Precipitation at location (x,y) and time k

and

(p0): a_0 = intercept term

(p1): x = x coordinate (in Lambert Conformal)

(p2): y = y coordinate (in Lambert Conformal)

(p3): d min = shortest distance to the ocean in km

(p4): $\overline{h}$ = average elevation (in metre) in the vicinity of point (x,y)

(p5): $\overline{a}$ = average orientation of the hillslope (in degree) in the vicinity of point (x,y).

(p6): $\overline{s}$ = average hillslope (in %) in the vicinity of point (x,y)

(p7): σ_h = standard-deviation of the elevation in the vicinity of point (x,y)

(p8): σ_a = standard-deviation of the hillslope orientation in the vicinity of point (x,y)

(p9): w = difference in metre between the highest elevation in the vicinity of point (x,y) and elevation at point (x,y).

The predictors (p1) and (p2) inform about the spatial location of the site in the plane, while predictor (p3) describes the location more dynamically, with respect to the Icelandic shoreline and accounts for the maritime influence on precipitation. Predictor (p4) describes the effect of the elevation around the site. Predictor (p5) integrates information about how exposed the site is in order to account for the dominant direction of the weather systems and possible shelter effects. Predictors (p6) to (p9) attempt to describe the complexity of the topographical environment and the degree of geographical isolation of the site being considered.

The 7 predictors (p3) to (p9) are estimated for each site once for all with the use of a digital elevation model (DEM) (figure 1). First, the original DEM (resolution of about 1 km) is resampled to a coarser resolution of about 2 km for computational purposes. From this coarser DEM, the elevation, hillslope and orientation are extracted at each grid point (figure 2). In the model presented here, the hillslope is taken positive downhill. The orientation (-180° , 180°) is positive clockwise from north (y-axis) towards east (x-axis) and negative anti-clockwise from north toward west. Then, the 7 predictors are estimated by considering a window of 5 km around each site. Further improvements in this first generation model will be considered later.

Figure 1: Digital Elevation Model

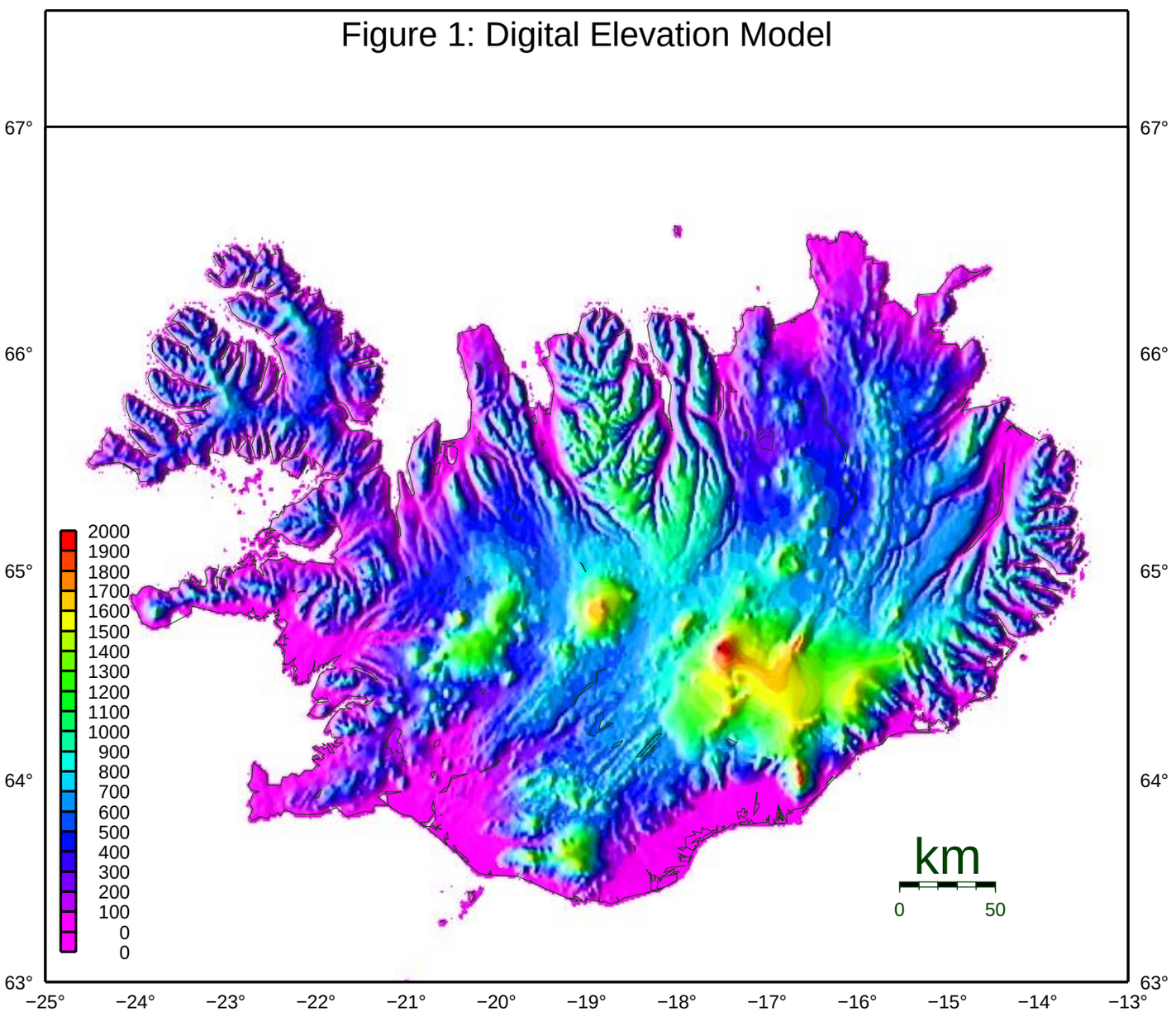
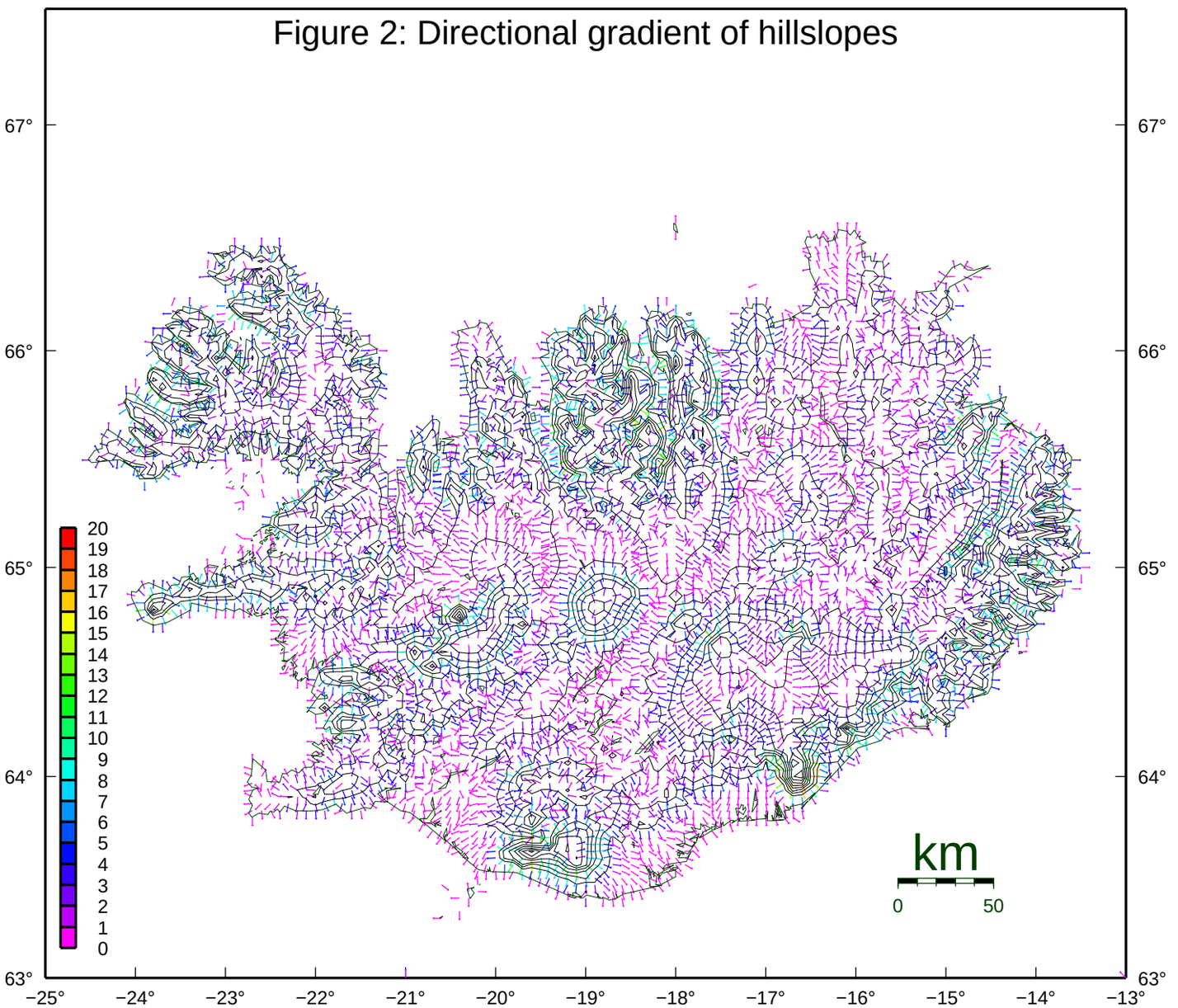


Figure 2: Directional gradient of hillslopes



II-2) Operational estimation procedure

The 9 predictors are not expected to have the same effect on the precipitation amounts all over Iceland nor from time to time. For this reason, the following procedure is defined and applied individually at each time step k:

The regression coefficients are estimated by a multiple linear regression (MLR). A set of 5 successive MLR is made over 3 sectors of 120° each, centered on the top of Hofsjökull glacier (figure 3). There is a rotation of 10° to 15° between one set to the next. There are several reasons that motivate this choice. As a matter of fact, we do not know for sure the best way to divide Iceland into homogeneous regions, and by making a set of 5 successive estimates, we expect the final estimation to be closer to the true value. The reason for dividing Iceland into 3 sectors is a compromise between having a reasonable number of stations per sector (greater than the number of predictors) and the definition of what we expect are homogeneous regions, i.e. regions under the influence of the same weather systems. Finally, in using this successive estimation method for mapping, we expect to avoid unpleasant sharp edge effects between the different sectors. This estimation procedure is not definitive and modifications might be considered later.

For each set, the method produces 3 series of regression coefficients, and the precipitation at site j is estimated by:

$$\begin{aligned} P^*(x_j, y_j, k, r) = {} & a_0(k, s[r,l]) + a_1(k, s[r,l])x_j + a_2(k, s[r,l])y_j + \\ & a_3(k, s[r,l])d\min_j + a_4(k, s[r,l])\overline{h}_j + a_5(k, s[r,l])\overline{a}_j + a_6(k, s[r,l])\overline{s}_j + \\ & a_7(k, s[r,l])\sigma_{h_j} + a_8(k, s[r,l])\sigma_{a_j} + a_9(k, s[r,l])w_j \end{aligned} \quad (2)$$

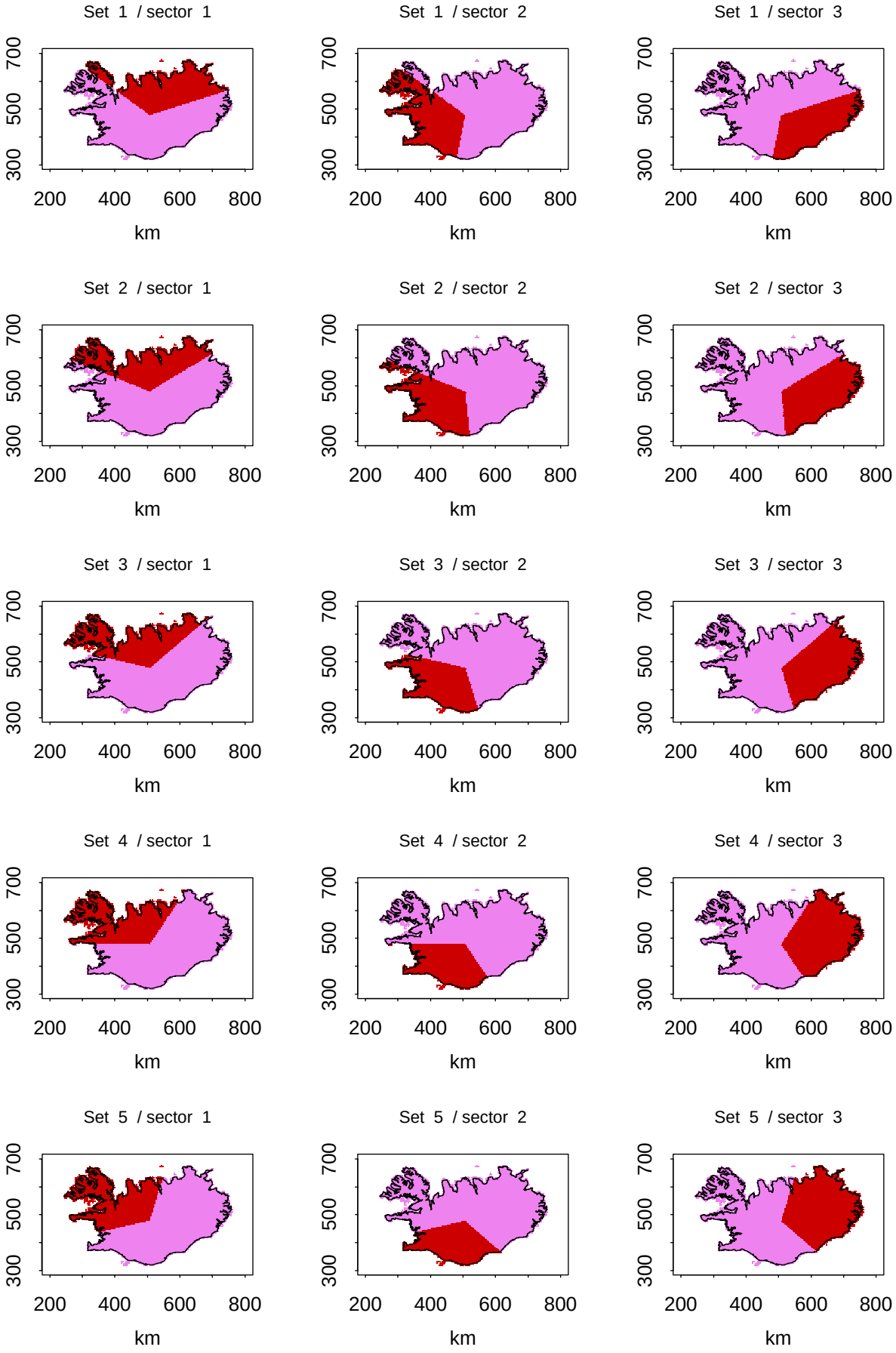
Where

$s[r,l]$ is the lth sector $[1 \le l \le 3]$ of the rth set $[1 \le r \le 5]$.

A given station belongs only to one sector at the time, and the final estimation is given by the mean of the 5 successive estimates:

$$P^*(x_j, y_j, k) = \frac{1}{5}\sum_{r=1}^{5} P^*(x_j, y_j, k, r) \quad (3)$$

Figure 3: The different sectors



III) Evaluation of the linear model in Iceland

III-1) The data

The data used in this study are daily precipitation measured at 122 sites from 1980 to 2001 (figure 4). These precipitation stations are manual. No correction is applied to account for any wind loss for instance. The monthly precipitation is computed if the station has been in operation for at least 25 days, and the annual precipitation is computed if the station has been in operation for at least 350 days. The number of stations used simultaneously in a given month is ranging from 60 to 122, with a mean of 84.

III-2) Annual precipitation

The model was evaluated for each year between 1980 to 2001. First the regression coefficients were estimated with the entire network and the model performance was judged by plotting the relationship between the estimated values $P^*(x,y,k)$ and observed values $P\ (x,y,k)$. Figure 5 presents the scatter plots between $P^*(x,y,k)$ and $P\ (x,y,k)$ for the year 2001. Appendix 1 gives the scatter plots for the period 1980-2000. The linearity of the relationship is good. The annual estimates are unbiased in average for each year (figure 6). The correlation coefficients are ranging between 0.903 and 0.976 with an average value of 0.947. However, systematic errors can occur punctually for some stations where the estimate can be systematically too high or too low (see appendix 2).

Figure 7 presents the histograms of the different regression coefficients. Large variations in both sign and magnitude are observed. This supports the previous assumption that there is not a unique relationship between the predictors and precipitation in both space and time. A numerical example is given with the annual precipitation in 1999 and 2000 (tables 1 and 2). The stepwise selection procedure (tables 3 and 4) gives the rank of the variable that gives the largest reduction of the residual sum of squares. It is obvious that a given predictor does not influence the estimation in the same manner , both in space and time. The results tend to show that the topography "captures" long term accumulated precipitation features but the complexity of the relationships cannot be easily described by one single model.

Figure 4: precipitation network

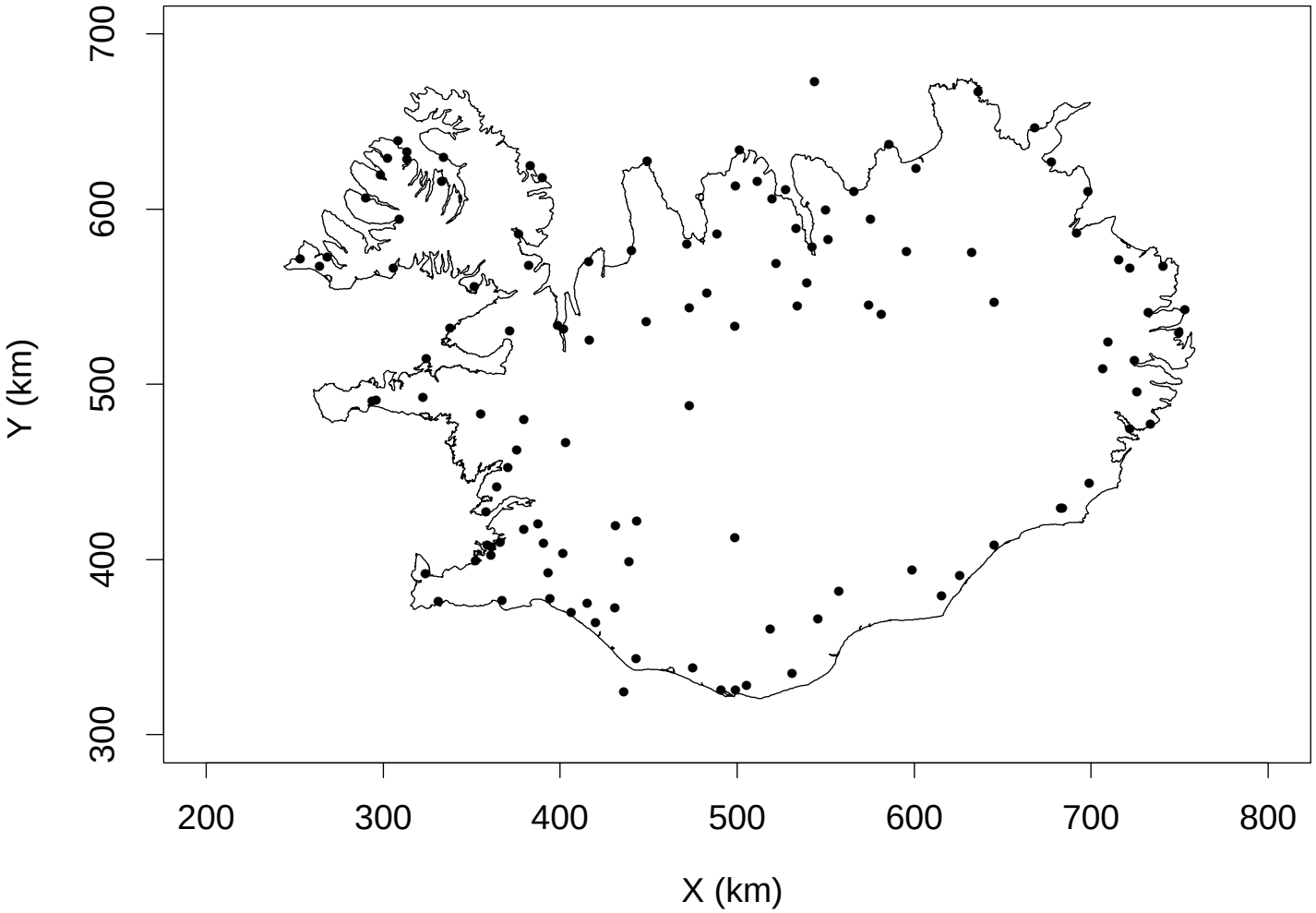


Figure 5: Annual precipitation in 2001

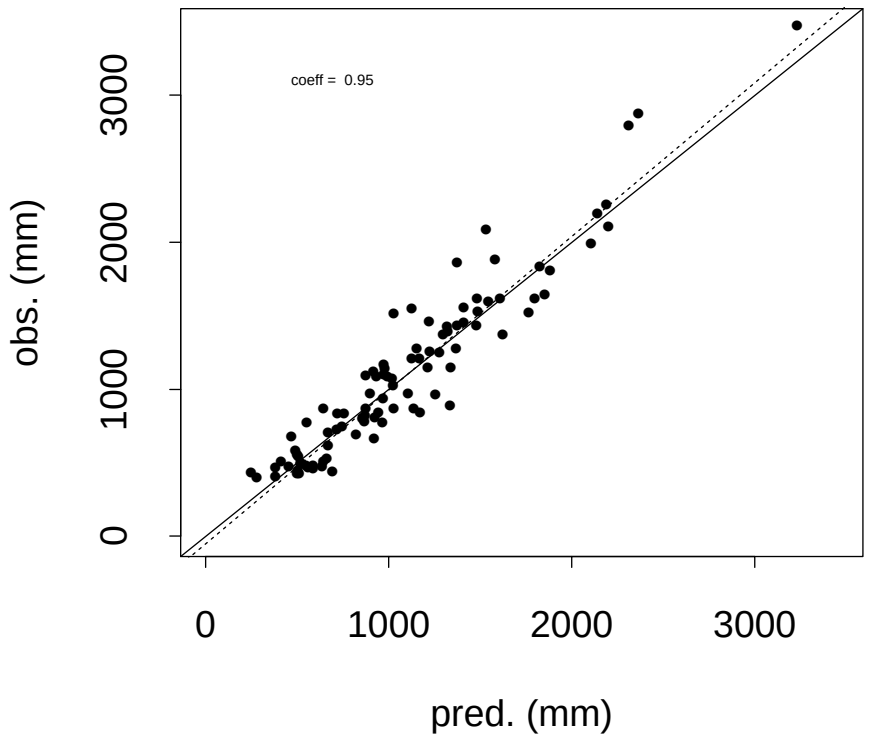
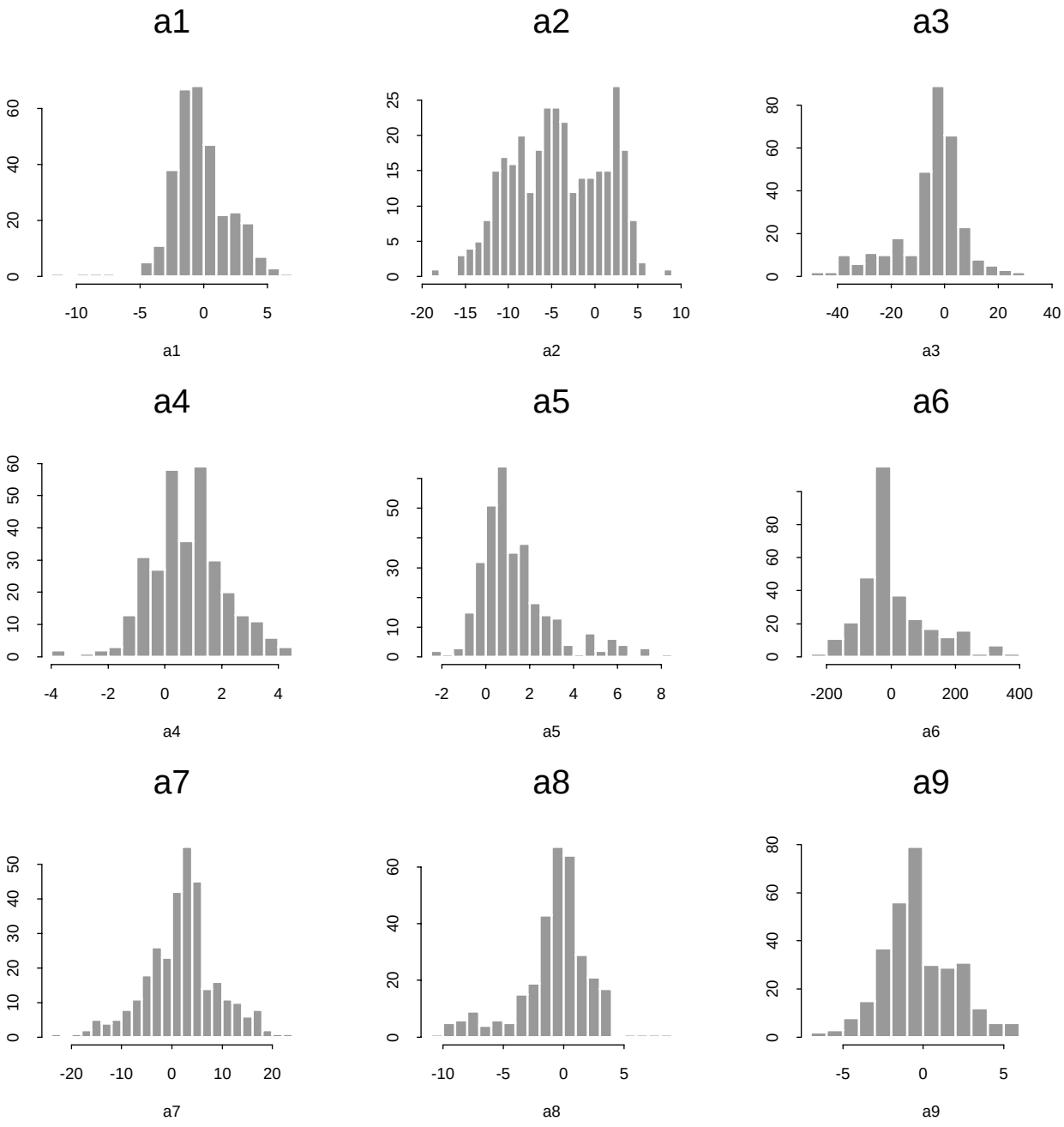


Figure 6: Annual precipitation : mean error

Figure 7: Annual precipitation (1980-2000): Histograms of the regression coefficients



In order to assess the quality of the model in a more consistent manner, a validation procedure was considered by defining two independent samples (figure 8):

- A calibration sample (95 stations) was used to estimate the model coefficients.

- A reference sample (27 stations independent from the calibration sample) was used to estimate precipitation with the model defined with the calibration sample.

The scatter plots between $P^*(x_{ref}, y_{ref}, k)$ and $P(x_{ref}, y_{ref}, k)$ for the years 1980 to 2000 are given in appendix 3. As expected, the correlation coefficients are not as high as those estimated in the first place, i.e. when the calibration and validation are made with the entire network. These results represent somehow the lower limit of what can be expected in reality when using the model for mapping purposes in poorly monitored areas. The entire network hardly reaches 122 stations in total and any reduction in this number will most likely have a dramatic consequence on the estimation of the model coefficients and the robustness of the method. When using the method for mapping purposes, all the available information will be used and any additional information such as ice core data for instance will be of great value.

Figure 8 : Validation network (red) and calibration network (black)

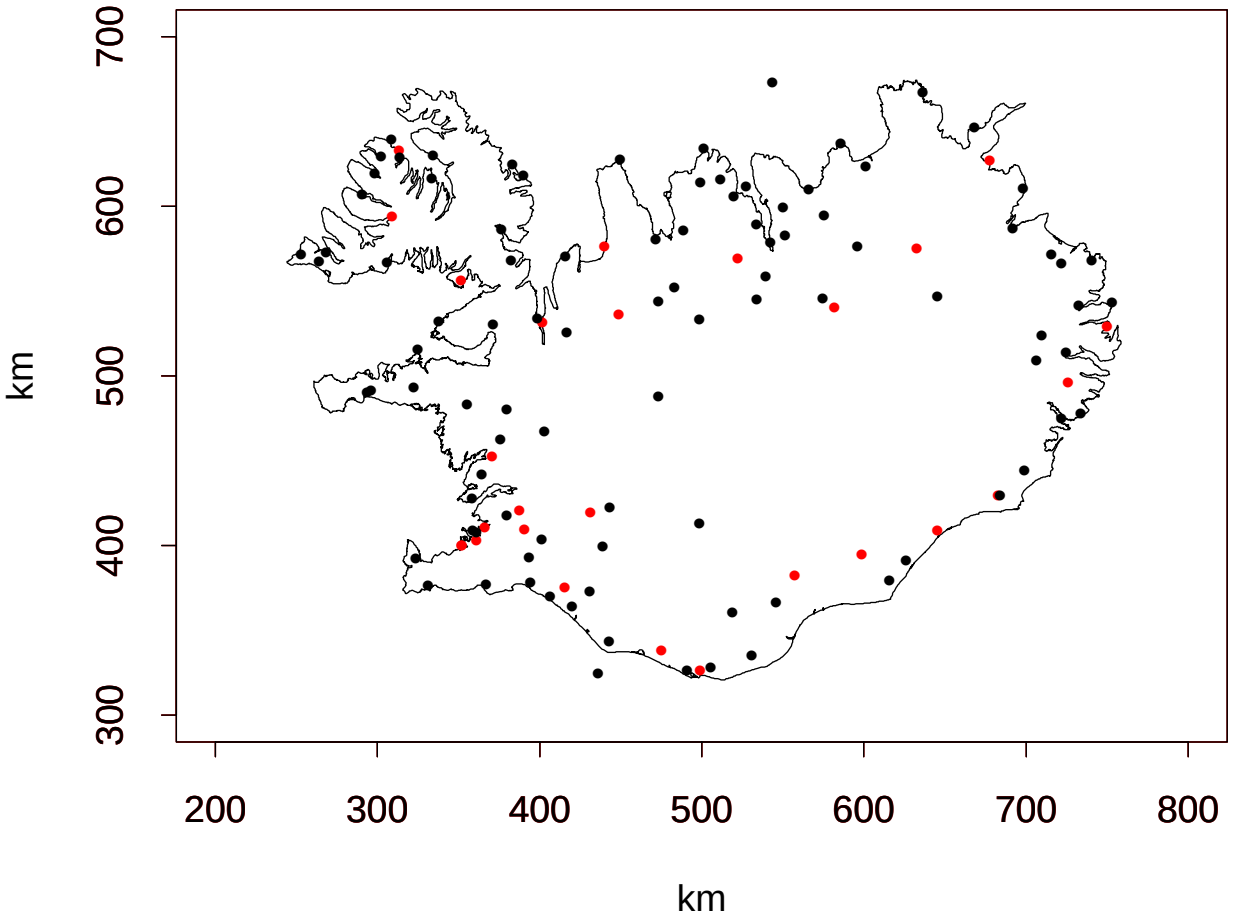


Table 1: Year 1999: regression coefficients for the 3rd set

	a_0	$a1$	$a2$	$a3$	$a4$	$a5$	a_6	$a7$	$a8$	a_9
S1	-108	-1.24	2.36	-8.68	0.84	0.115	-6.11	-0.648	0.304	-0.02
S2	2173	2.47	-5.12	-2.79	0.16	1.57	51.47	4.47	-0.002	-0.695
S3	3759	-0.143	-5.39	-19.6	1.91	1.77	-3.95	9	-1.26	-3.48

Table 2: Year 2000: regression coefficients for the 3rd set

	a_0	$a1$	$a2$	$a3$	$a4$	$a5$	a_6	$a7$	$a8$	a_9
S1	-230	-0.802	2.09	-11.41	1.08	0.155	7.84	-0.003	0.598	-0.448
S2	1410	3.61	-4.47	-8.83	0.135	1.566	94.18	2.27	0.259	-0.019
S3	1199	2.15	-3.28	-15.16	1.483	3.2	48.38	5.88	-1.23	-2.83

Table 3: Year 1999: rank of predictors in the stepwise selection for the 3rd set

	1	2	3	4	5	6	7	8	9
S1	x	y	$\overline{h}$	d min	σ_h	σ_a	$\overline{s}$	$\overline{a}$	w
S2	x	σ_h	y	$\overline{a}$	$\overline{s}$	d min	w	$\overline{h}$	σ_a
S3	y	d min	$\overline{h}$	$\overline{a}$	$\overline{s}$	w	σ_h	σ_a	x

Table 4: Year 2000: rank of predictors in the stepwise selection for the 3rd set

	1	2	3	4	5	6	7	8	9
S1	d min	$\overline{h}$	x	y	w	σ_a	$\overline{a}$	$\overline{s}$	σ_h
S2	y	w	$\overline{a}$	$\overline{s}$	d min	x	σ_h	σ_a	$\overline{h}$
S3	d min	$\overline{a}$	$\overline{s}$	y	x	w	σ_h	$\overline{h}$	σ_a

III-3) Application to monthly precipitation

The model was evaluated for each month from 1980 to 2001. First, the entire network was used both to derive the regression coefficients and to check the model performances. Figure 9 presents the scatter plots between $P^*(x,y,k)$ and $P\ (x,y,k)$ for each month of the year 2001, and appendix 4 the scatter plots for the period 1980-2000. The linearity of the relationships between $P^*(x,y,k)$ and $P\ (x,y,k)$ is usually high. The correlation coefficients are ranging between 0.736 and 0.976 with an average value of 0.915 (figure 10). In average, the proposed model is able to produce unbiased estimates of monthly precipitation (figure 11), but systematic errors can occur punctually for some stations where the estimate can be systematically too high or too low (see appendix 5). Here too, the different regression coefficients display large spatio-temporal variations in both sign and magnitude (figure 12).

Then, the same validation procedure defined for the annual precipitation in section III-2 was considered. The scatter plots are presented in appendix 6. The relationships are usually rather linear but the performances are lower, as expected.

In conclusion, the developed model is quite suitable for estimating monthly precipitation in Iceland, but the quality of the estimation will depend on the number of available sites for calibrating the model parameters.

Figure 9: Monthly precipitation in 2001

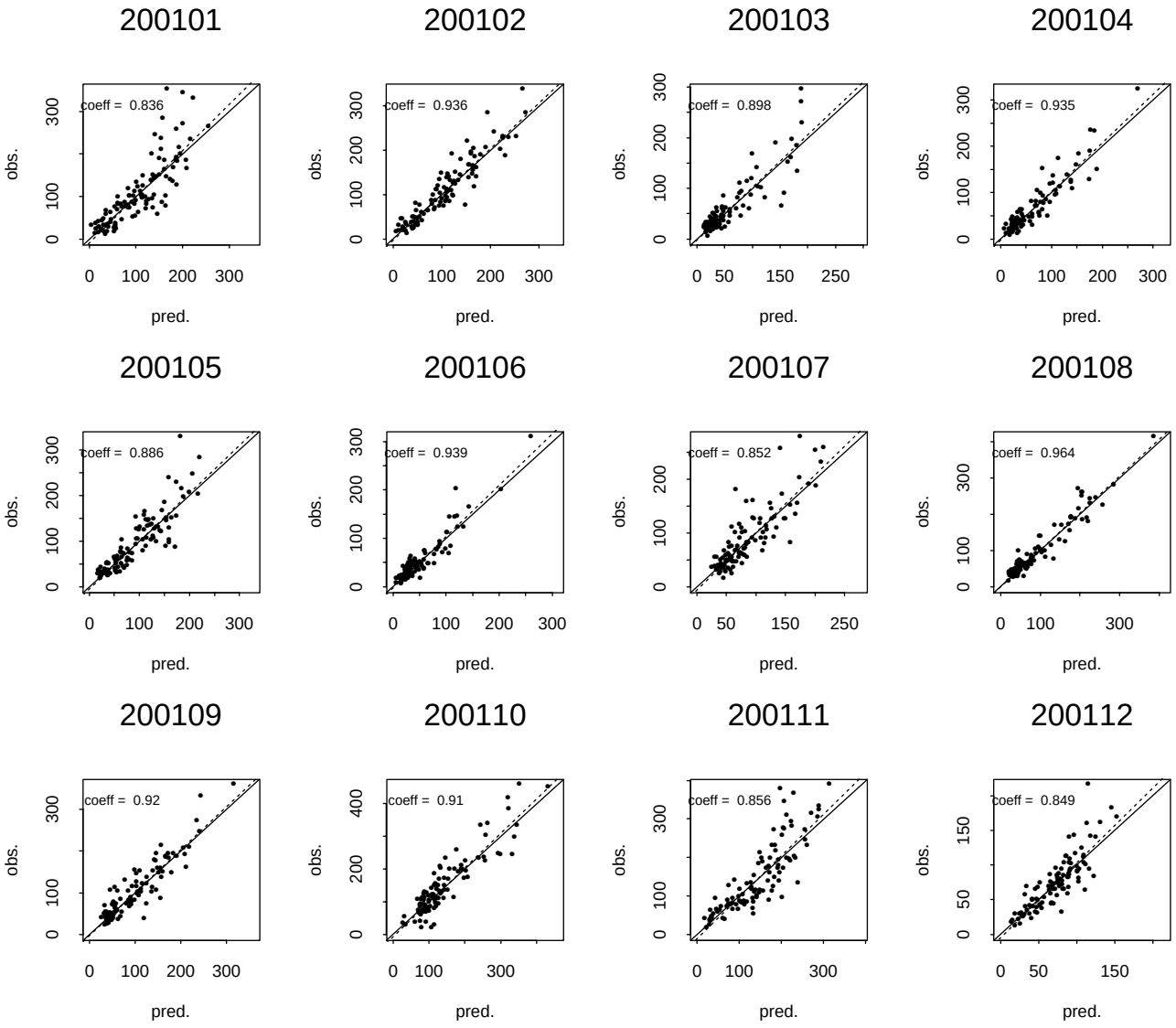


Figure 10: Monthly precipitation : correlation coefficients

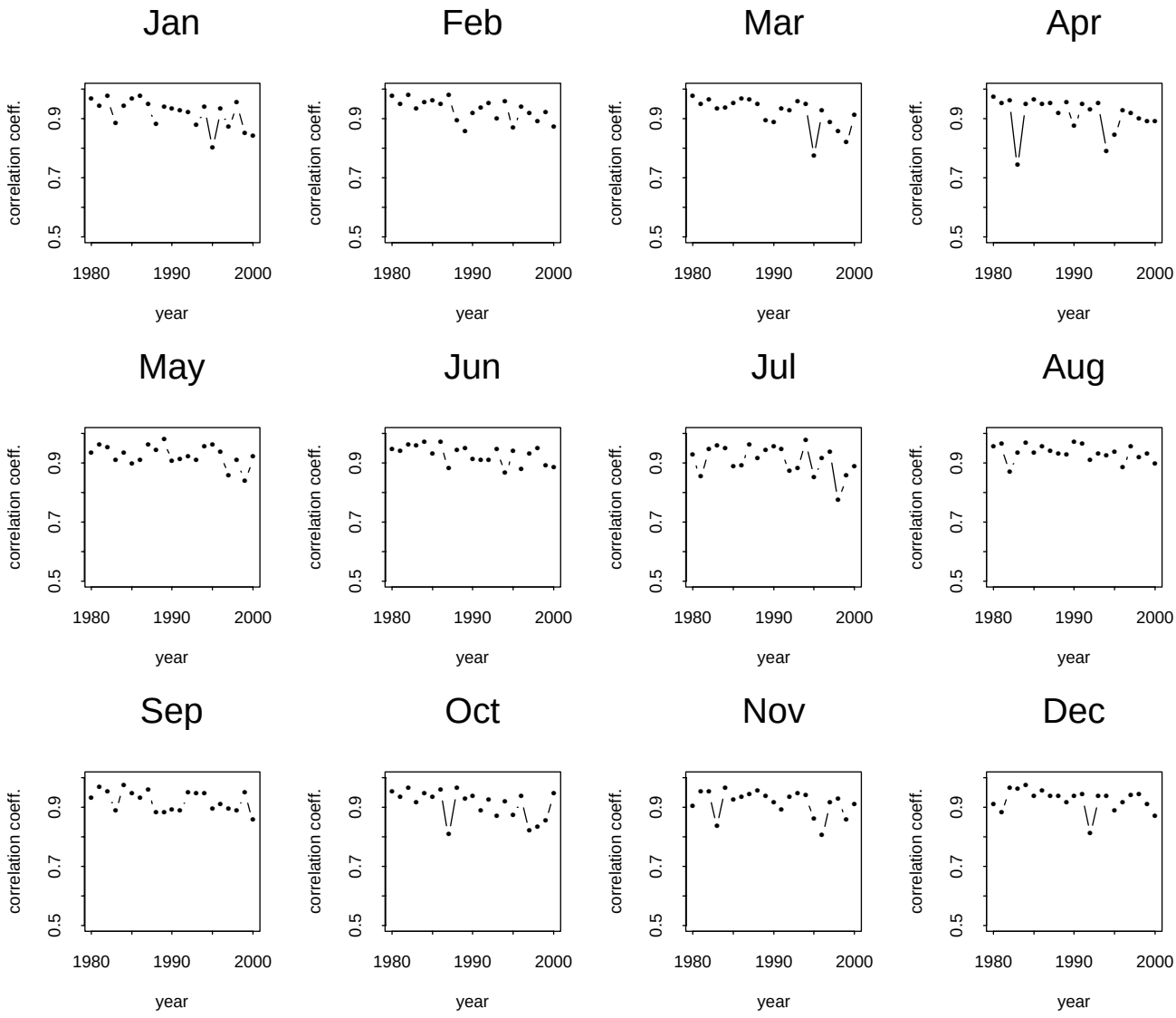


Figure 11: Monthly precipitation : mean error

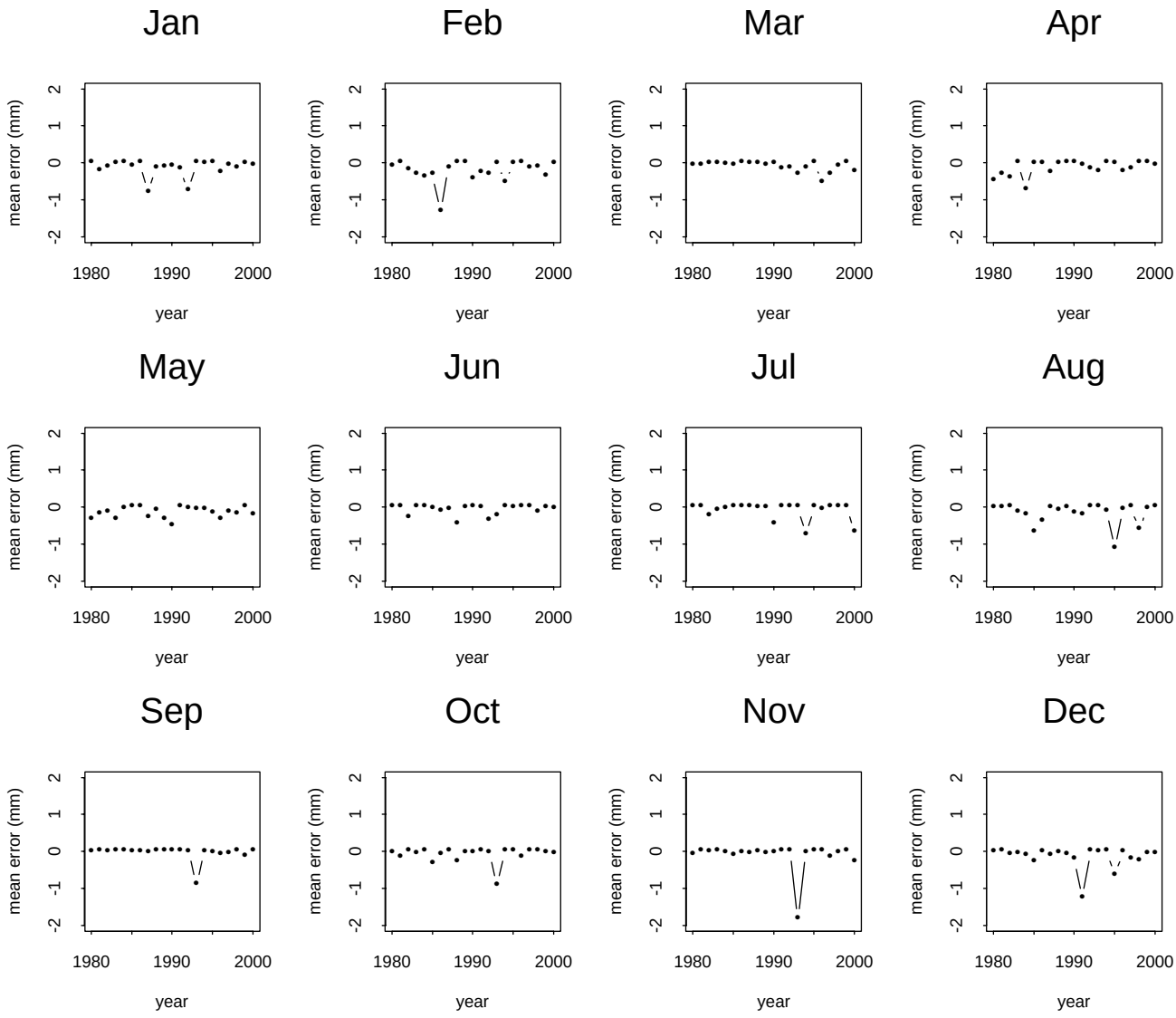
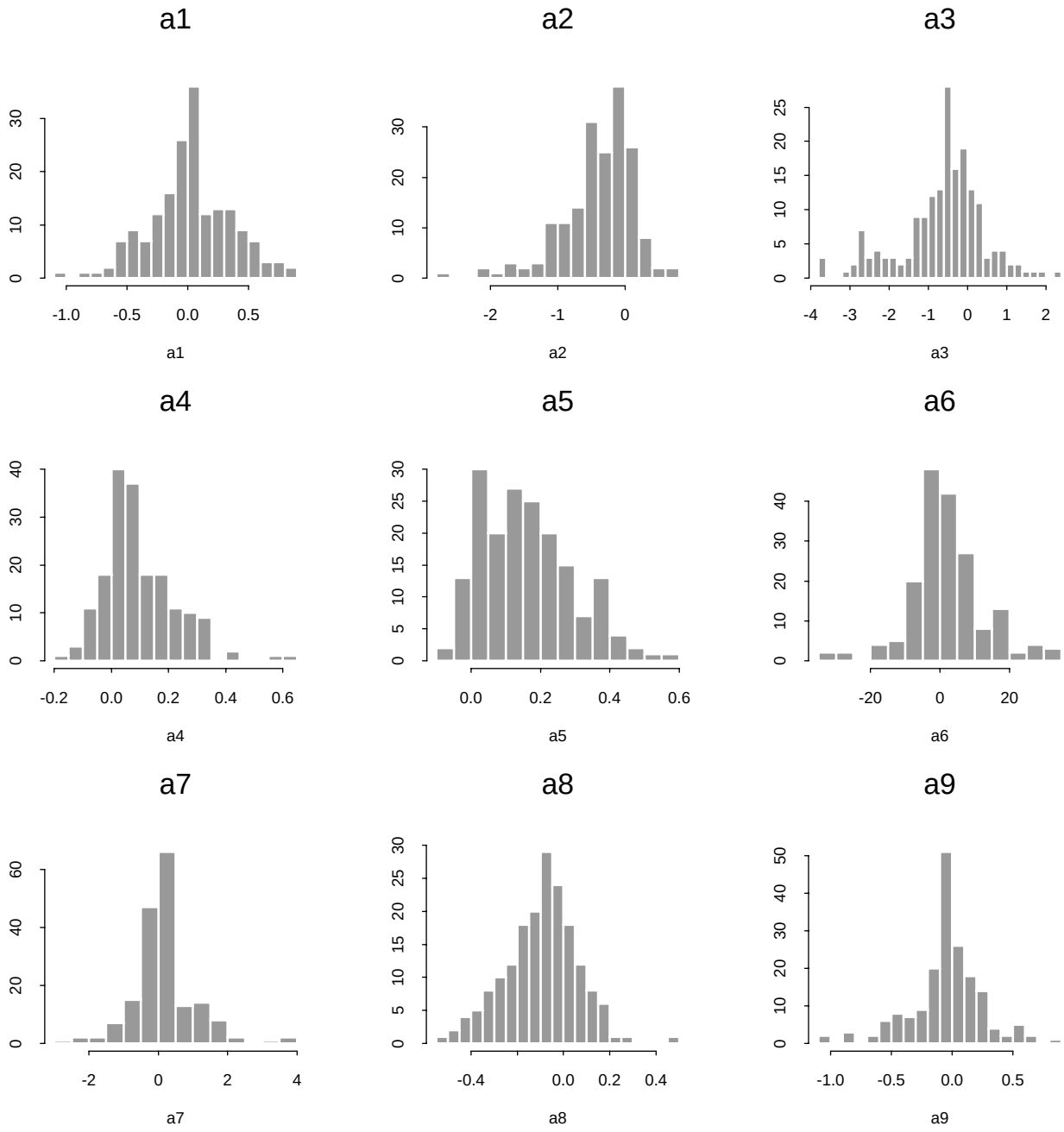


Figure 12: Monthly precipitation in 2001: Histogram of the regression coefficients



III-4) Spatial structure of residuals

The residuals of the regression are defined as follows:

$$e(x,y,k) = \mathrm{P}(x,y,k) - P^{*}(x,y,k) \tag{4}$$

If the residuals exhibit any spatial structure, then an interpolation procedure can be considered. The spatial structure of the residuals is defined by the climatological semi-variogram, see [10] for instance.

First a scaled residual is defined for each field k:

$$e_s(X,k) = \frac{e(x,y,k)}{\sigma_k[e(x,y,k)]} \tag{5}$$

where

X denotes the spatial location (x,y)

and

$\sigma_k[e(x,y,k)]$ denotes the spatial standard-deviation of $e(x,y,k)$ for the field k

The experimental climatological semi-variogram is computed as

$$\gamma(h) = \frac{1}{2m(h)} \sum_{k=1}^{n} \sum_{i=1}^{m(h,k)} \left(e_s(X_i,k) - e_s(X_i+h,k)\right)^2 \tag{6}$$

where h is the separation distance between two stations i and j:

$$h = \left\| X_i - X_j \right\| \tag{7}$$

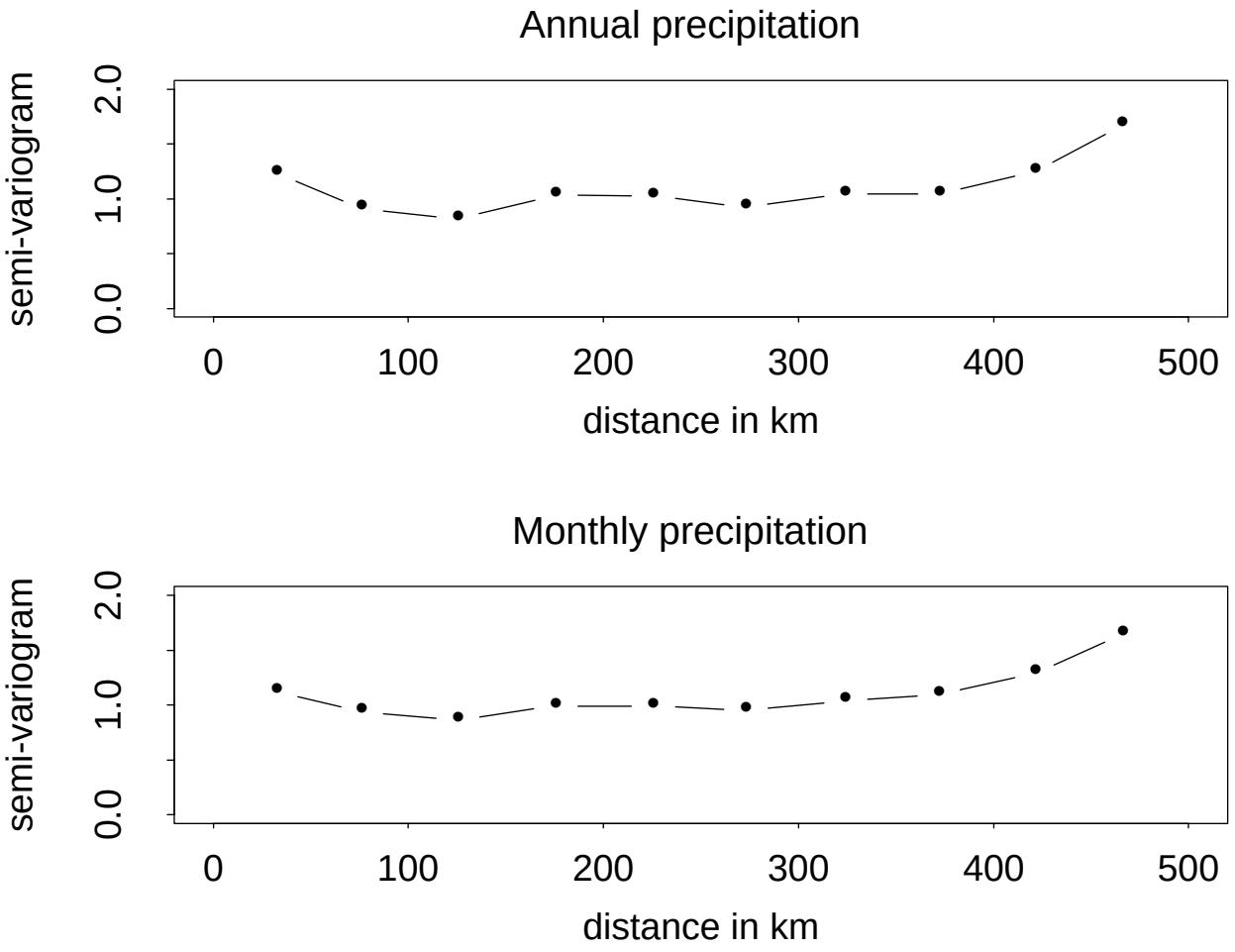
$m(h,k)$ is the number of pairs of stations having an inter-distance of of $h \pm \Delta h$ for the field k, $m(h)$ is the total number of pairs of stations having an inter-distance of $h \pm \Delta h$, and n is the number of fields.

As figure 13 suggests, the monthly and annual residuals do not present any spatial structure and can be considered as decorrelated. Thus, the attempt to define an estimation procedure based on the kriging interpolation of the residuals:

$$\mathrm{P}^{\mathrm{k}}(x,y,k) = e^{k}(x,y,k) + P^{*}(x,y,k) \tag{8}$$

will not be considered in this study.

Figure 13: Climatological semi-variogram of residuals



III-5) Mapping precipitation in Iceland with the linear model

The linear model was used to map monthly and annual precipitation in Iceland. The maps have a spatial resolution of 2 km or 4 km. The predictors are defined at each grid point with the DEM (figures 14 and 15).

Figure 16 presents the annual precipitation map for 2001 (2 km resolution) and figure 17 the sum of the 12 monthly precipitation maps from January to December 2001. The two maps display a rather similar pattern, with some discrepancies over the glaciers where the second estimation produces larger values over Vatnajökull but lower values over Hofsjökull. The annual precipitation maps from 1980 to 2000 (4 km resolution) are given in appendix 7 and the monthly precipitation maps for 2001 (2 km resolution) in appendix 8.

The method is able to produce more detailed information than any classical interpolation procedure, especially in the regions poorly or not monitored such as the highlands, the glaciers and the west and east fjords. It is also quite interesting to see that the average ratio between the maximum estimated precipitation and the maximum observed precipitation is 1.7 (min = 1, max = 2.45) for the annual precipitation (period 1980-2000) and 1.95 (min = 0.9, max = 4.6) for monthly precipitation (period 1990-2000). These results contribute to show how unrepresentative the network probably is, and a simple interpolation procedure will not be able to capture this detailed pattern and will give estimates ranging only between the minimum and maximum observed values.

Figure 14: grid 2 km resolution : predictors (p3) to (p6)

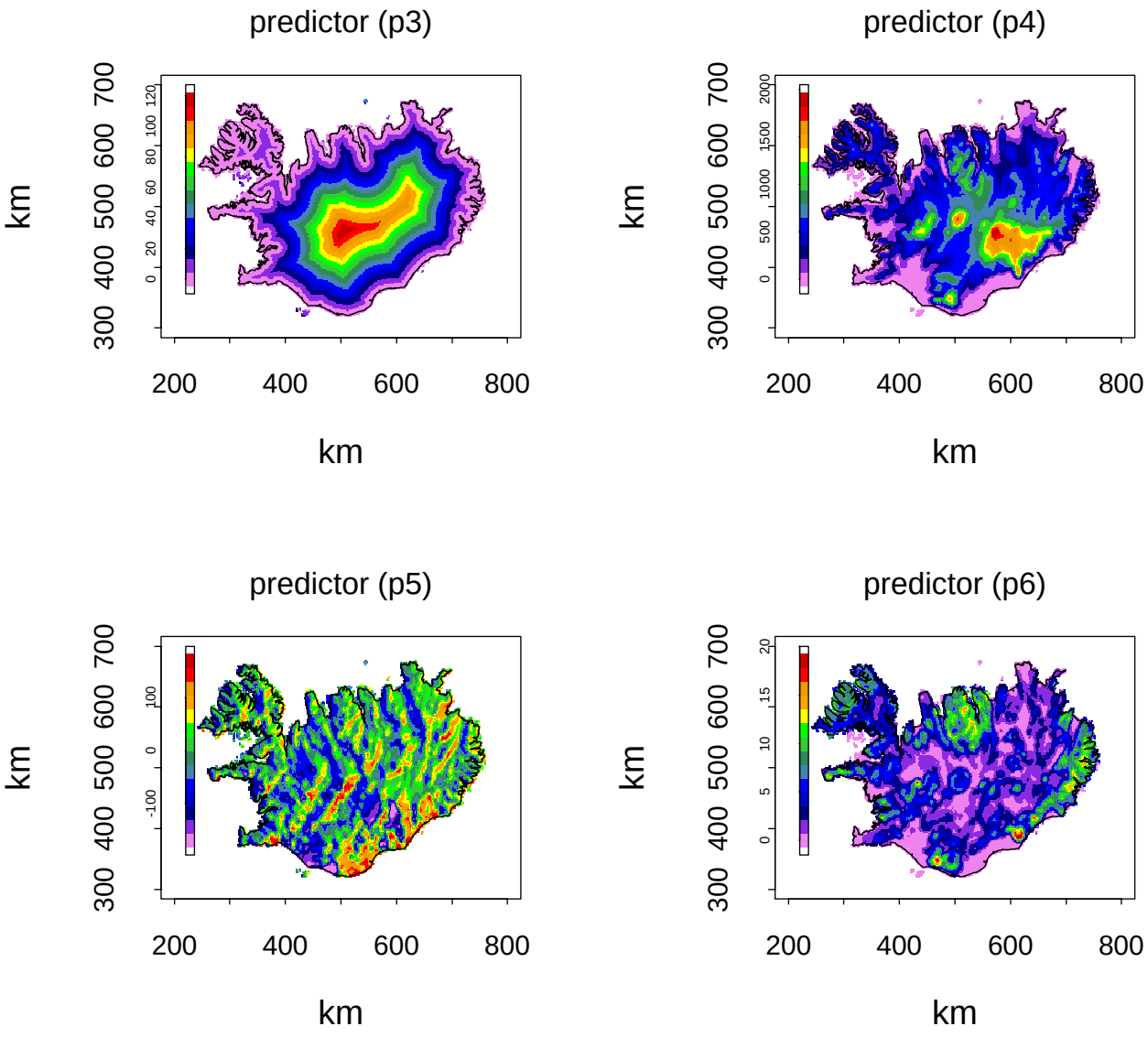


Figure 15: grid 2 km resolution : predictors (p7) to (p9)

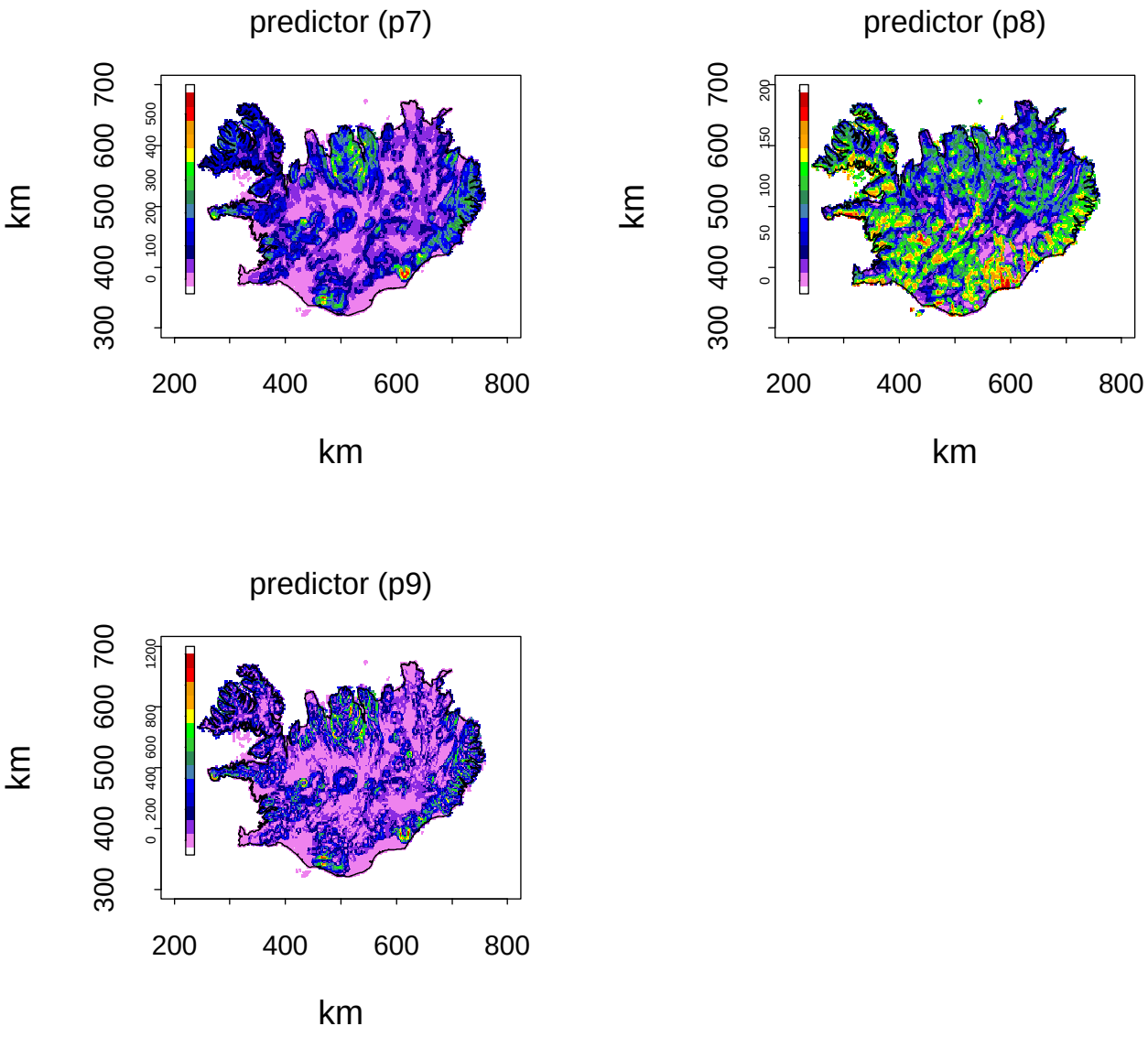


Figure 16: Annual precipitation in 2001

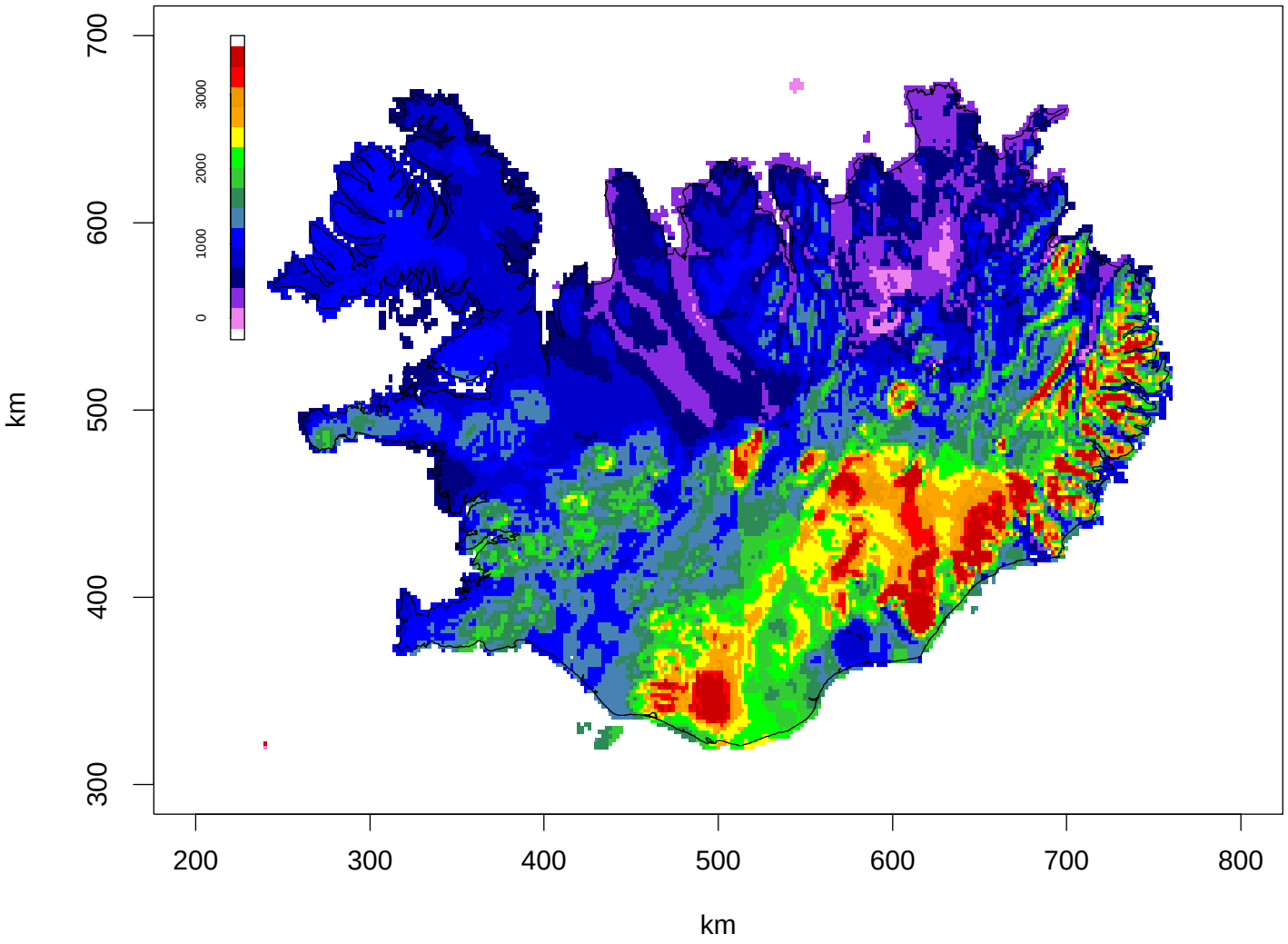
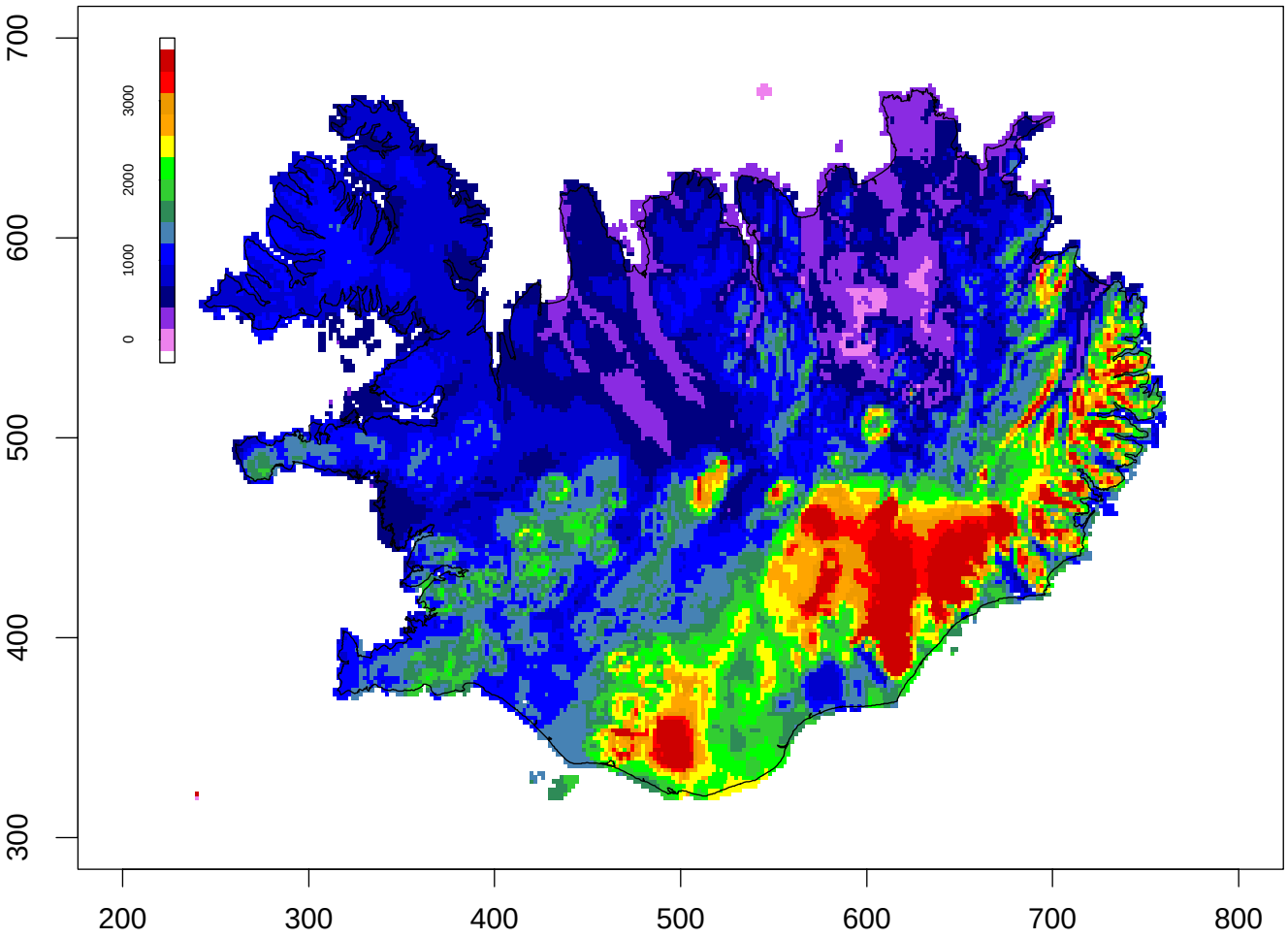


Figure 17: Annual precipitation in 2001 (sum of 12 months)



IV) Conclusion

In this work, a model has been developed for studying the influence of geographical and topographical factors on precipitation. According to the model characteristics, it is observed that a large part of the spatial variability of monthly and annual precipitation in Iceland is explained by the geographical and topographical environment in the vicinity of the considered locations. The results suggest that the predictors do not contribute to precipitation in the same manner in space and time. The systematic errors observed at some locations show that a more detailed division of Iceland will most likely improve the quality of the estimation. In the future, the model will hopefully gain in accuracy when information over the glaciers such as ice core data will be available. The main range of application of this model is to produce high resolution precipitation maps. For the near future, it is intended to be used in order to assess the quality of the precipitation amounts generated by the MM5 numerical prediction model. Further work in both the selection of the model parameters and the estimation procedure will be considered later, as well as the extension of the method to shorter time steps and other variables such as statistical parameters and other weather parameters such as the temperature.

Acknowledgements

This work was supported by the Icelandic Research Council (RANNÍS) and the Nordic Climate Water and Energy (CWE) project. It is part of the validation protocol developed for assessing the quality of the precipitation amounts produced by the MM5 model in Iceland. I wish to thank Thomas Jóhannesson and Haraldur Ólafson for involving me in this research project, and Trausti Jónsson for the interesting discussions concerning the work presented in the present report.

References

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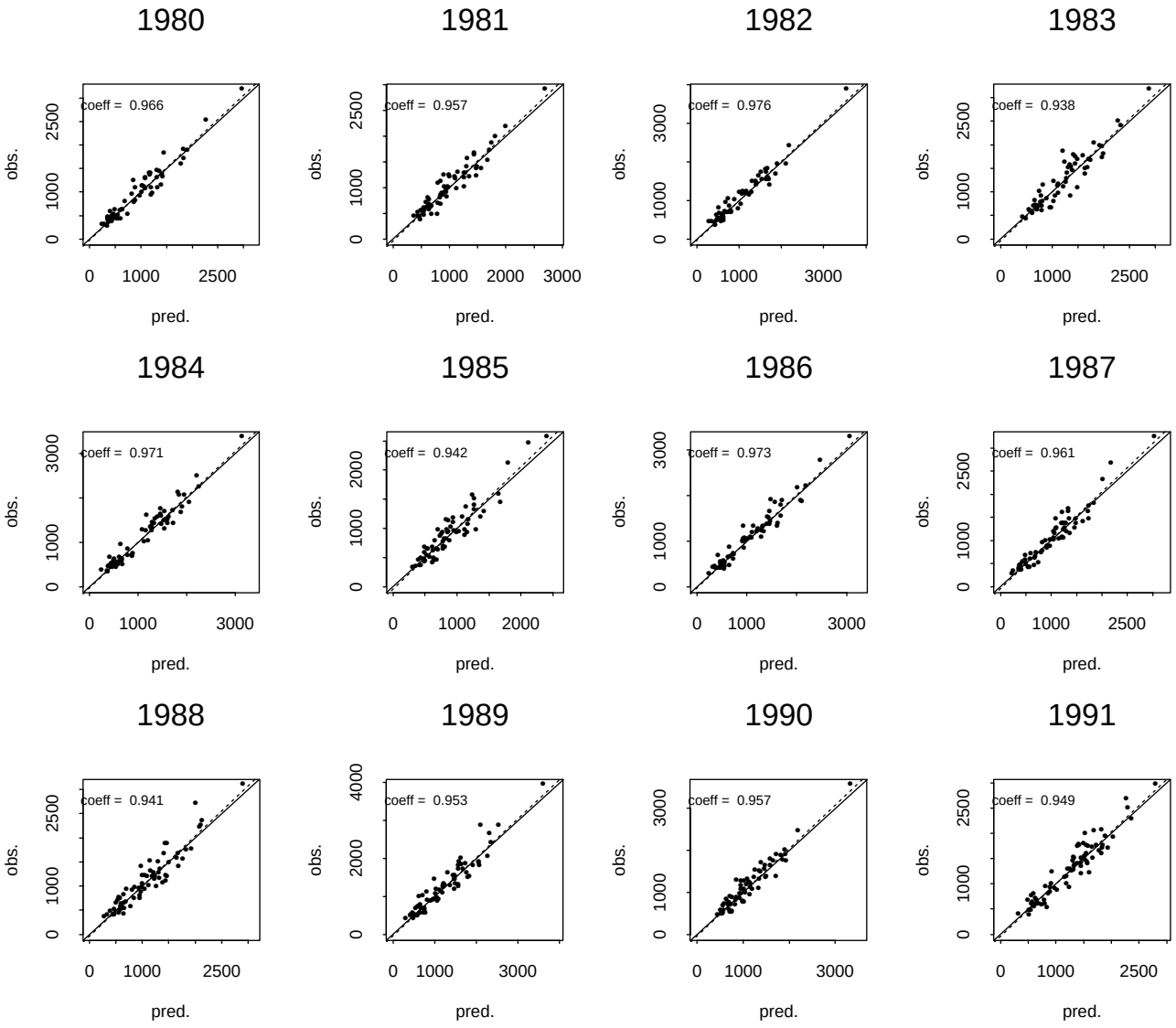
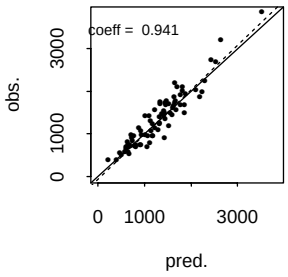
Appendix 1

Annual precipitation

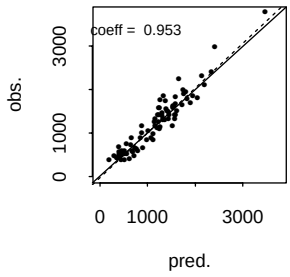
Scatter plots for the period 1980-2000


1980
coeff = 0.966
1981
coeff = 0.957
1982
coeff = 0.976
1983
coeff = 0.938
1984
coeff = 0.971
1985
coeff = 0.942
1986
coeff = 0.973
1987
coeff = 0.961
1988
coeff = 0.941
1989
coeff = 0.953
1990
coeff = 0.957
1991
coeff = 0.949
obs.
pred.

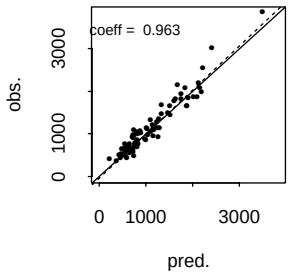
1992



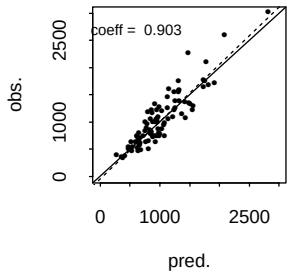
1993



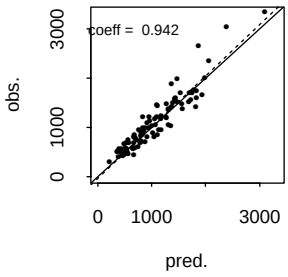
1994



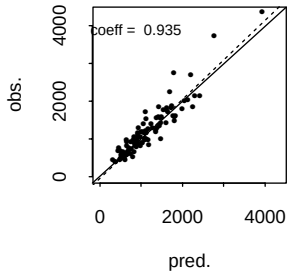
1995



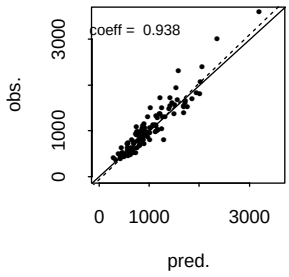
1996



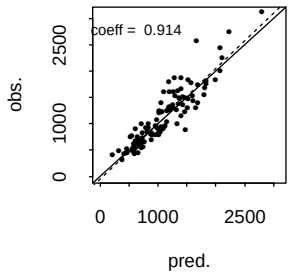
1997



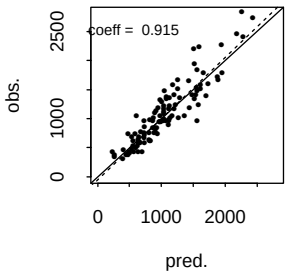
1998



1999



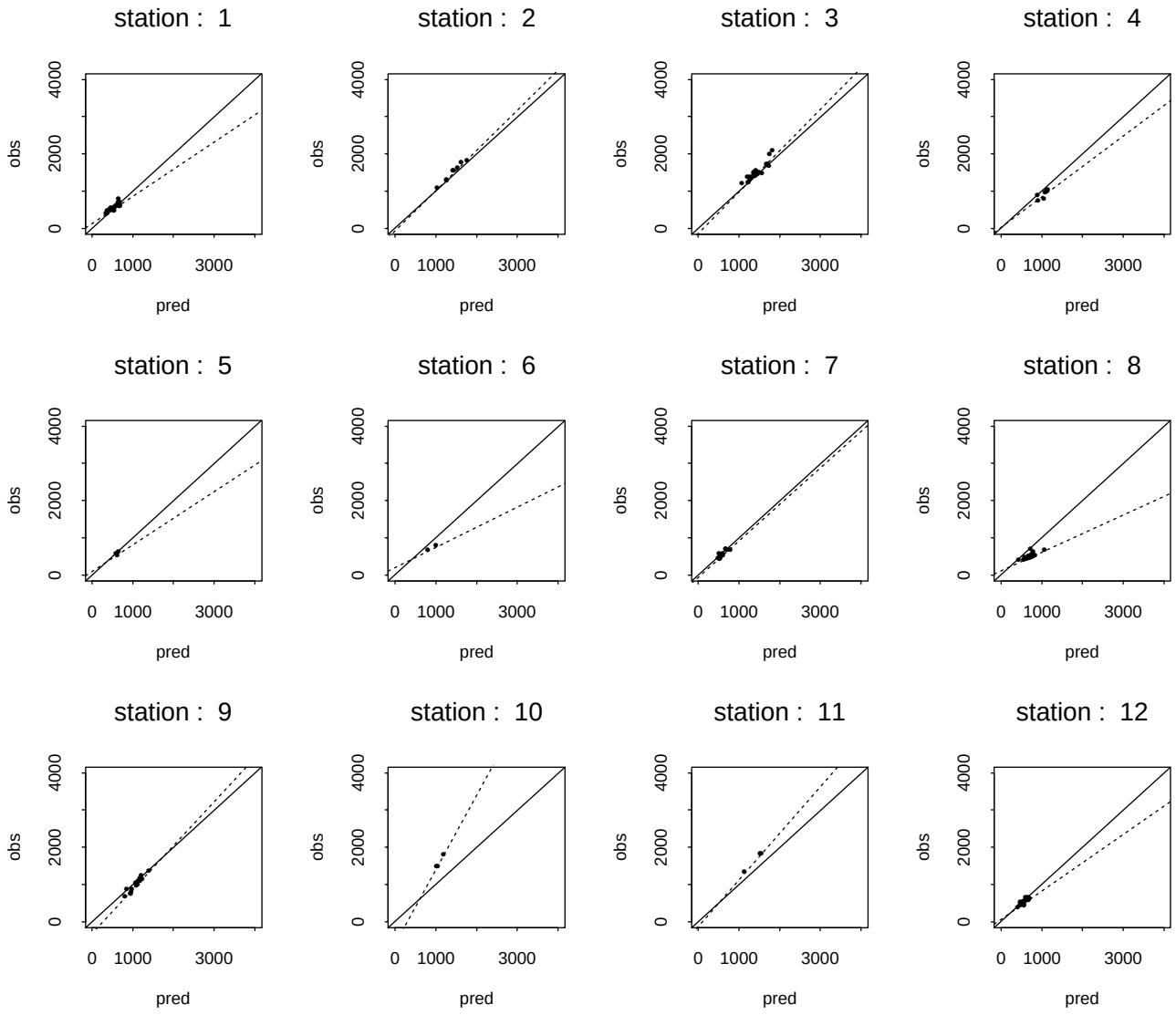
2000

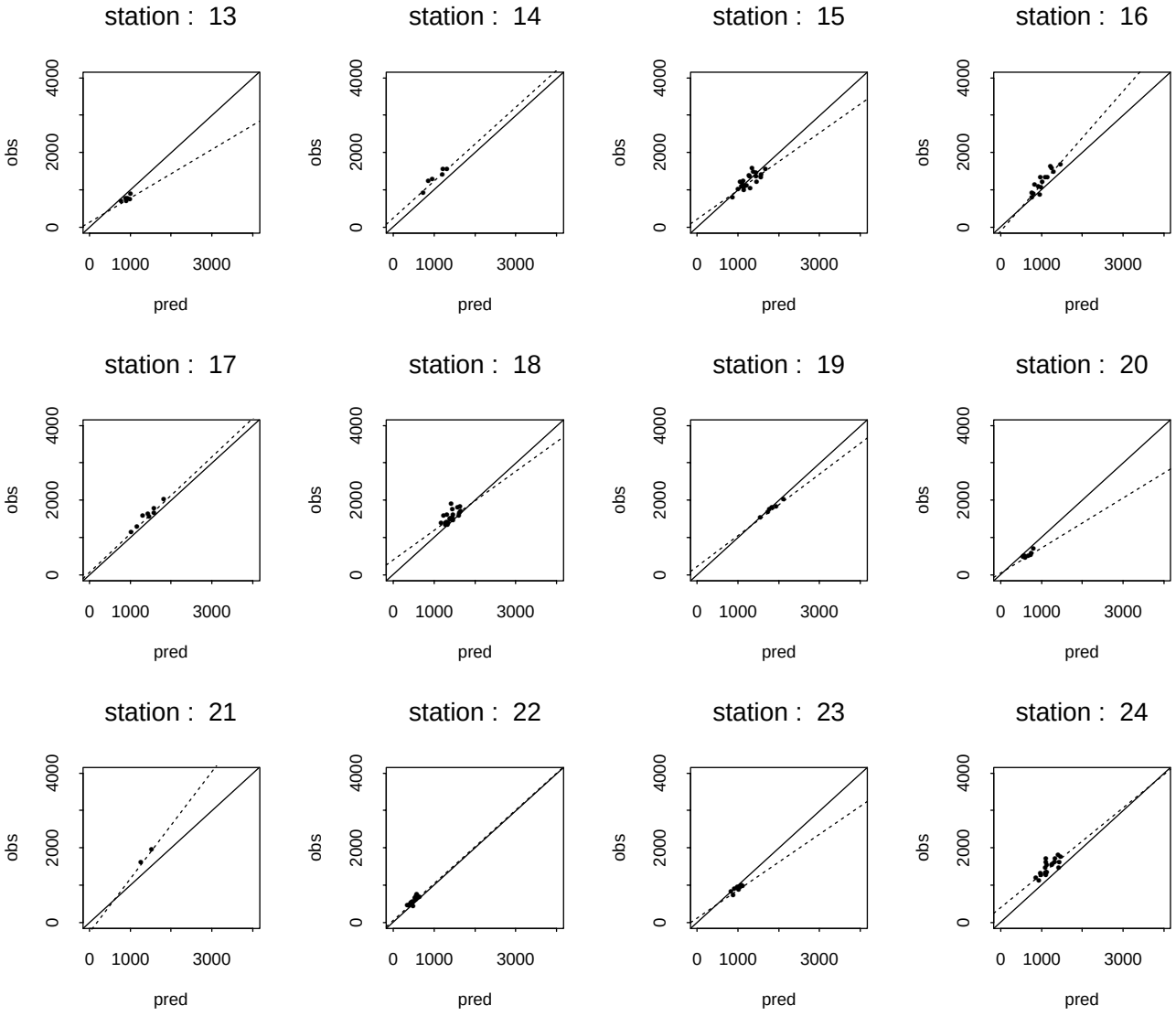


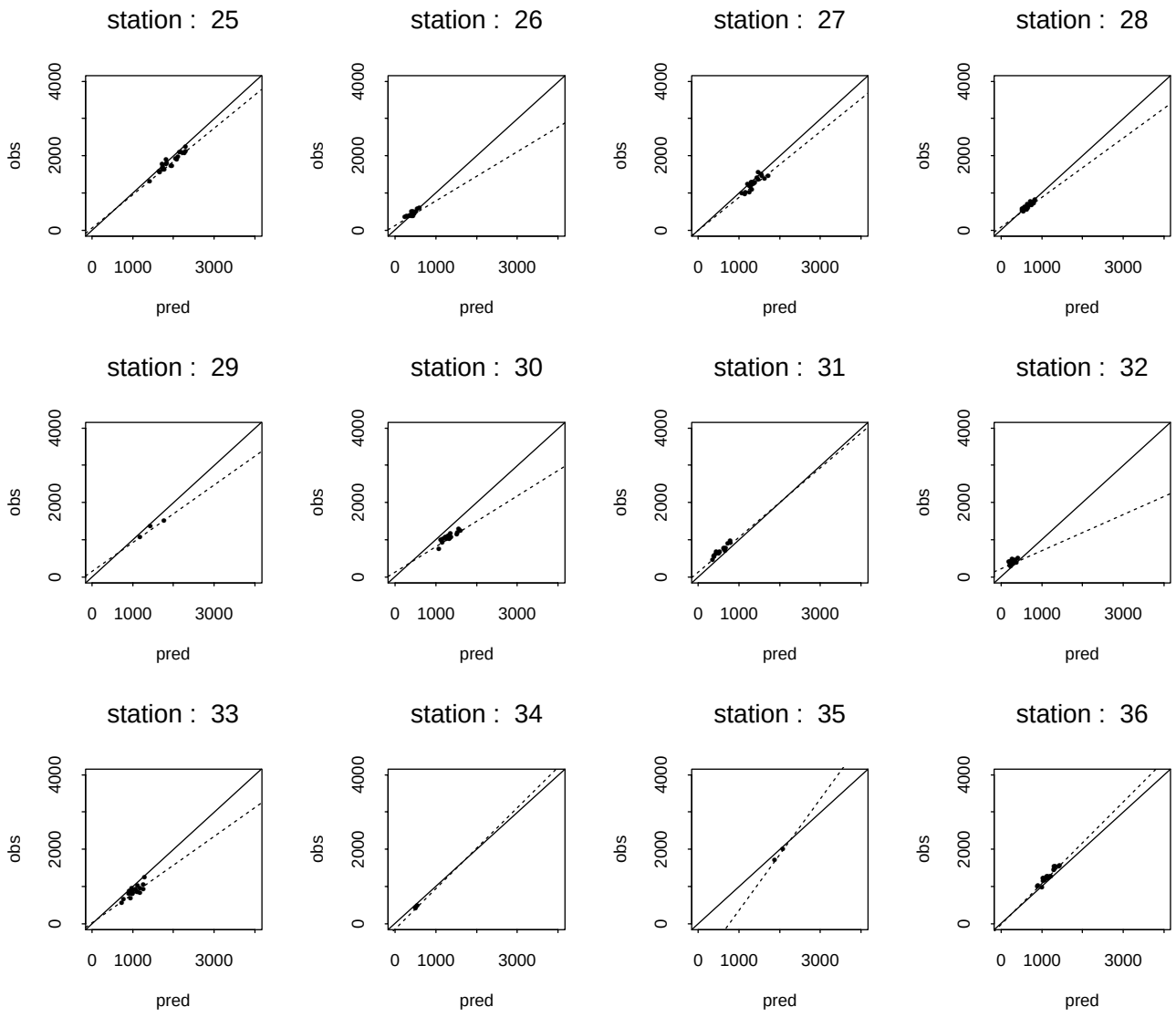
Appendix 2

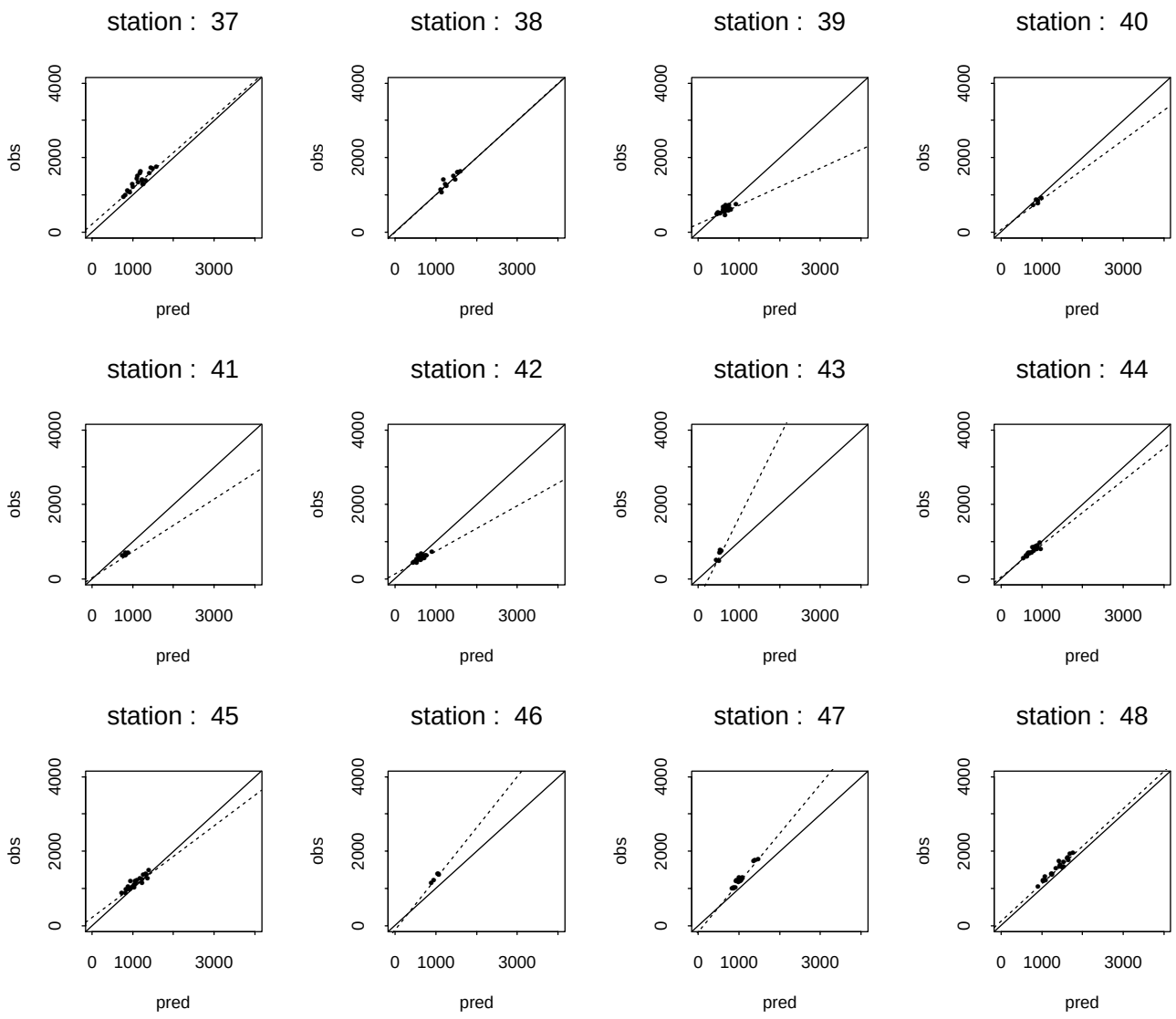
Annual precipitation

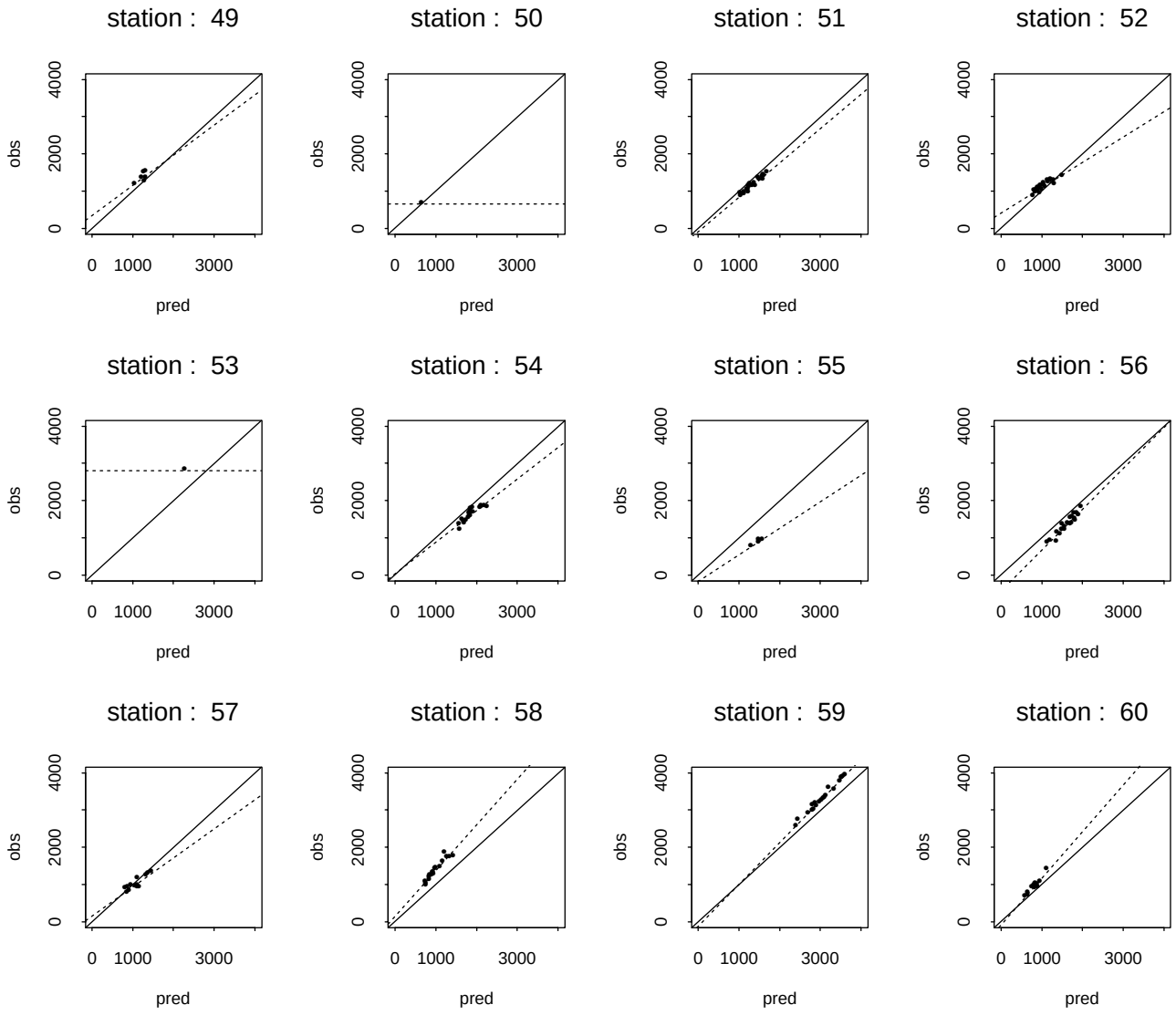
Scatter plots for each station (period 1980-2000)

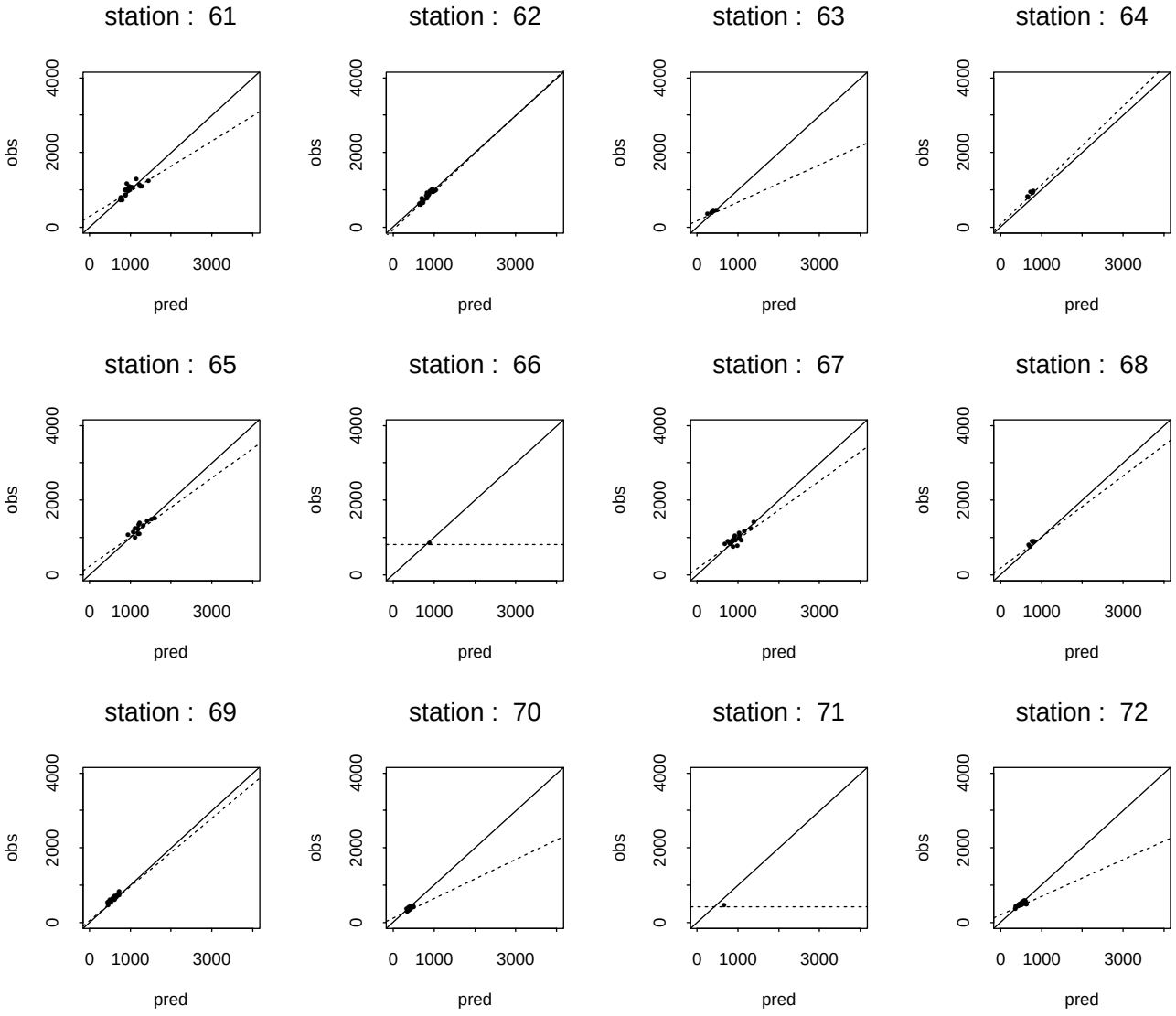

station : 1
station : 2
station : 3
station : 4
station : 5
station : 6
station : 7
station : 8
station : 9
station : 10
station : 11
station : 12
obs
pred
0
2000
4000
1000
3000

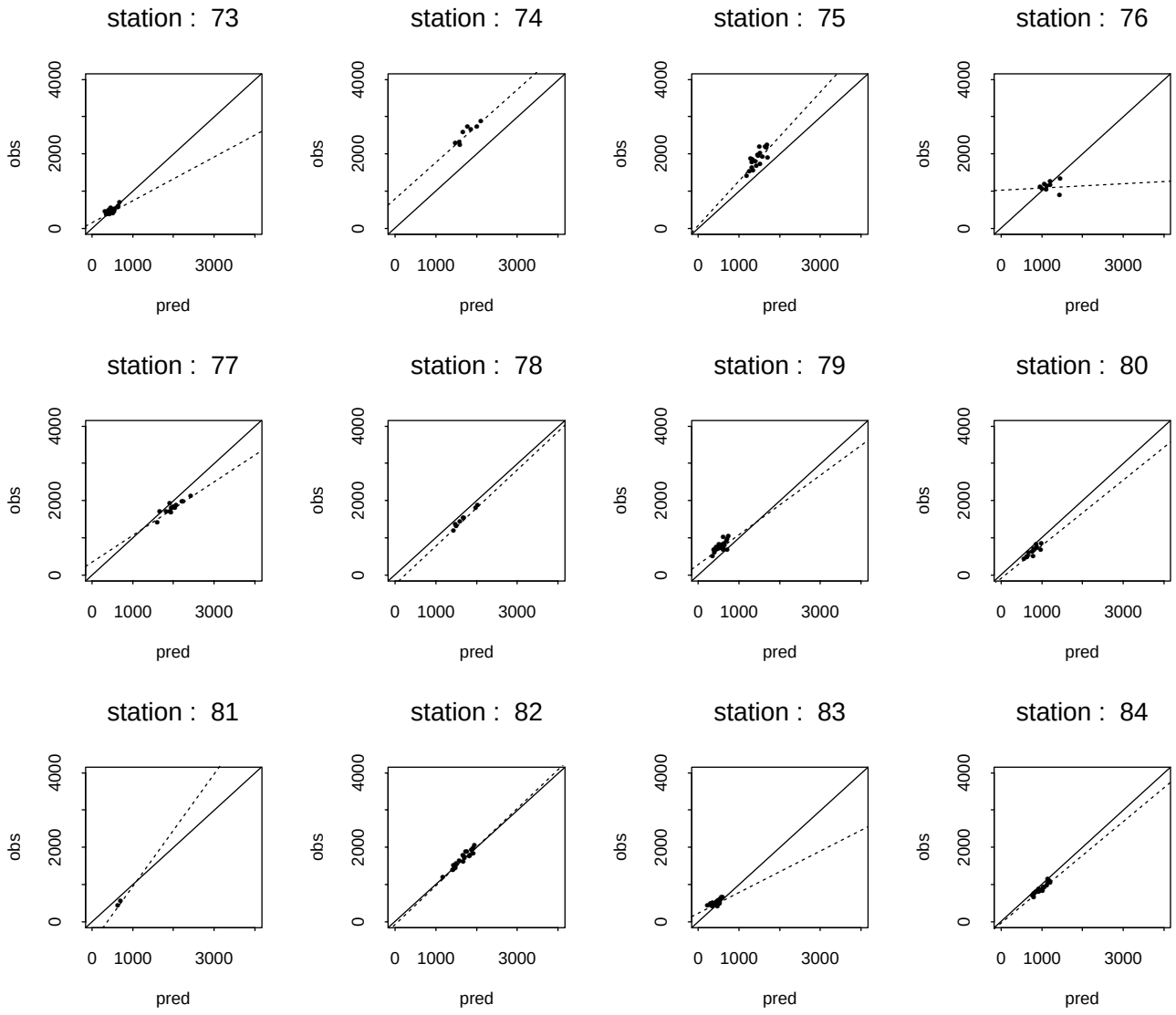

station : 13
station : 14
station : 15
station : 16
station : 17
station : 18
station : 19
station : 20
station : 21
station : 22
station : 23
station : 24
obs
pred
0
2000
4000
1000
3000

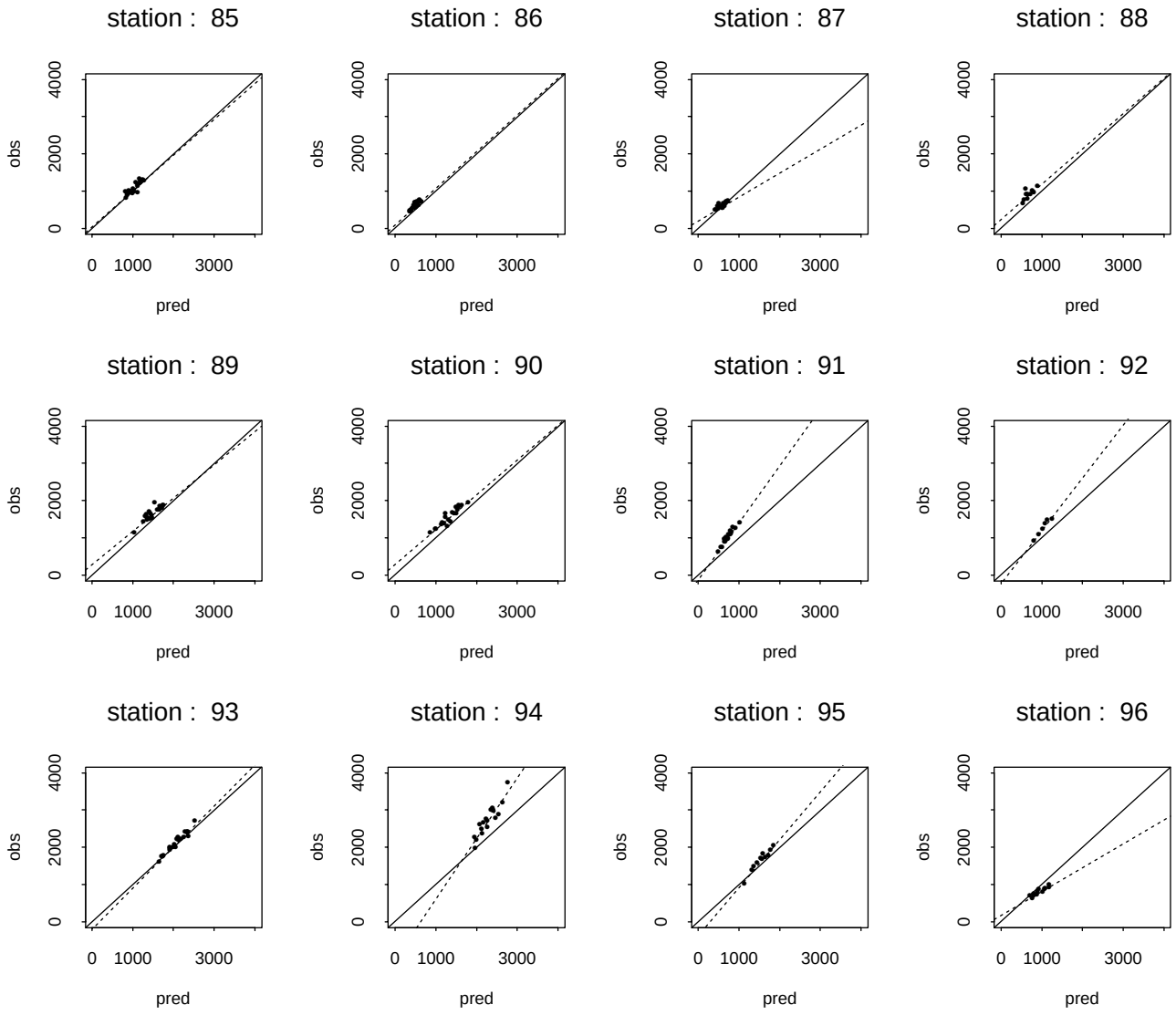

station : 25
station : 26
station : 27
station : 28
station : 29
station : 30
station : 31
station : 32
station : 33
station : 34
station : 35
station : 36
obs
pred
0
2000
4000
1000
3000

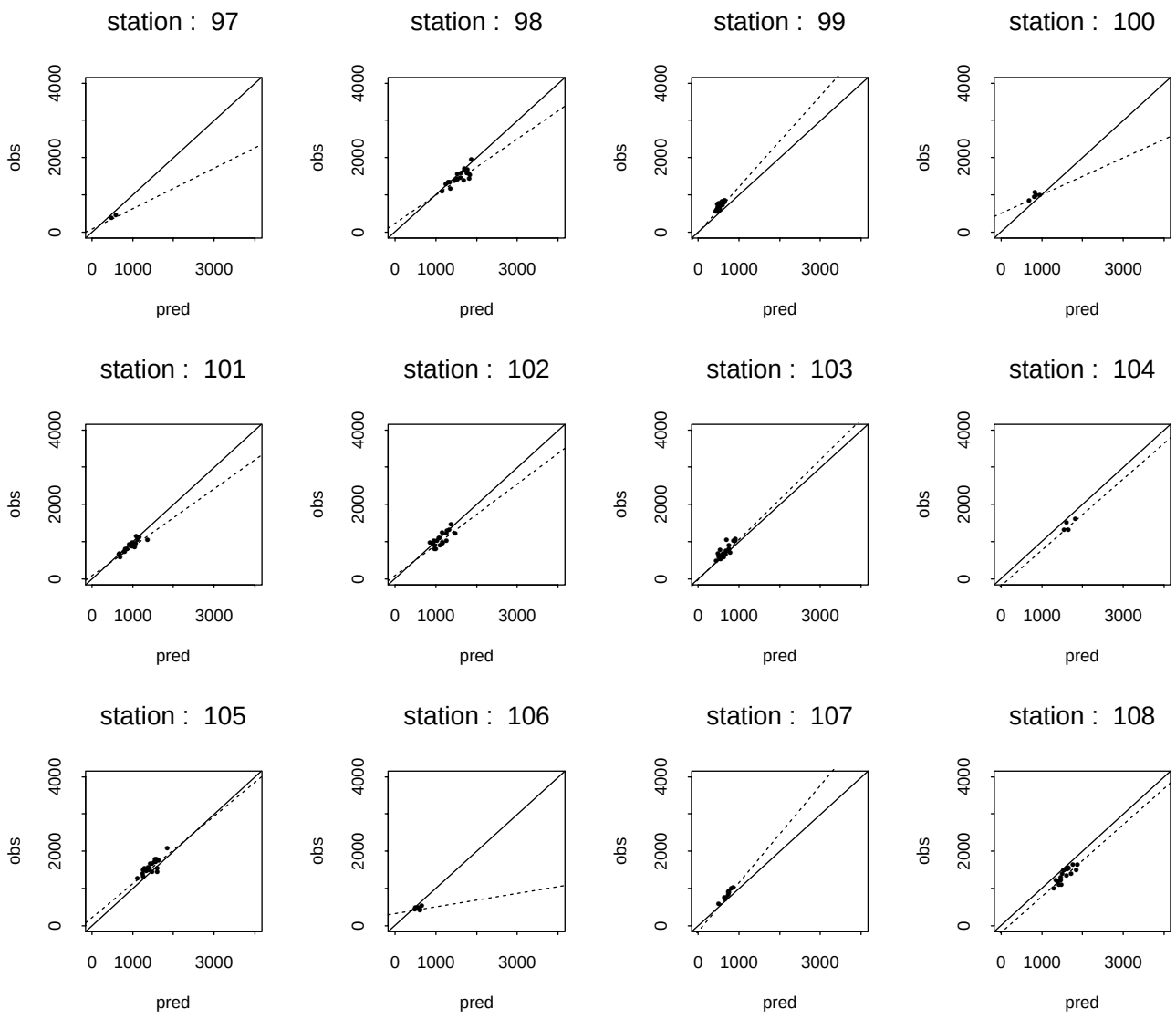

station : 37
station : 38
station : 39
station : 40
station : 41
station : 42
station : 43
station : 44
station : 45
station : 46
station : 47
station : 48
obs
pred
0
2000
4000
1000
3000

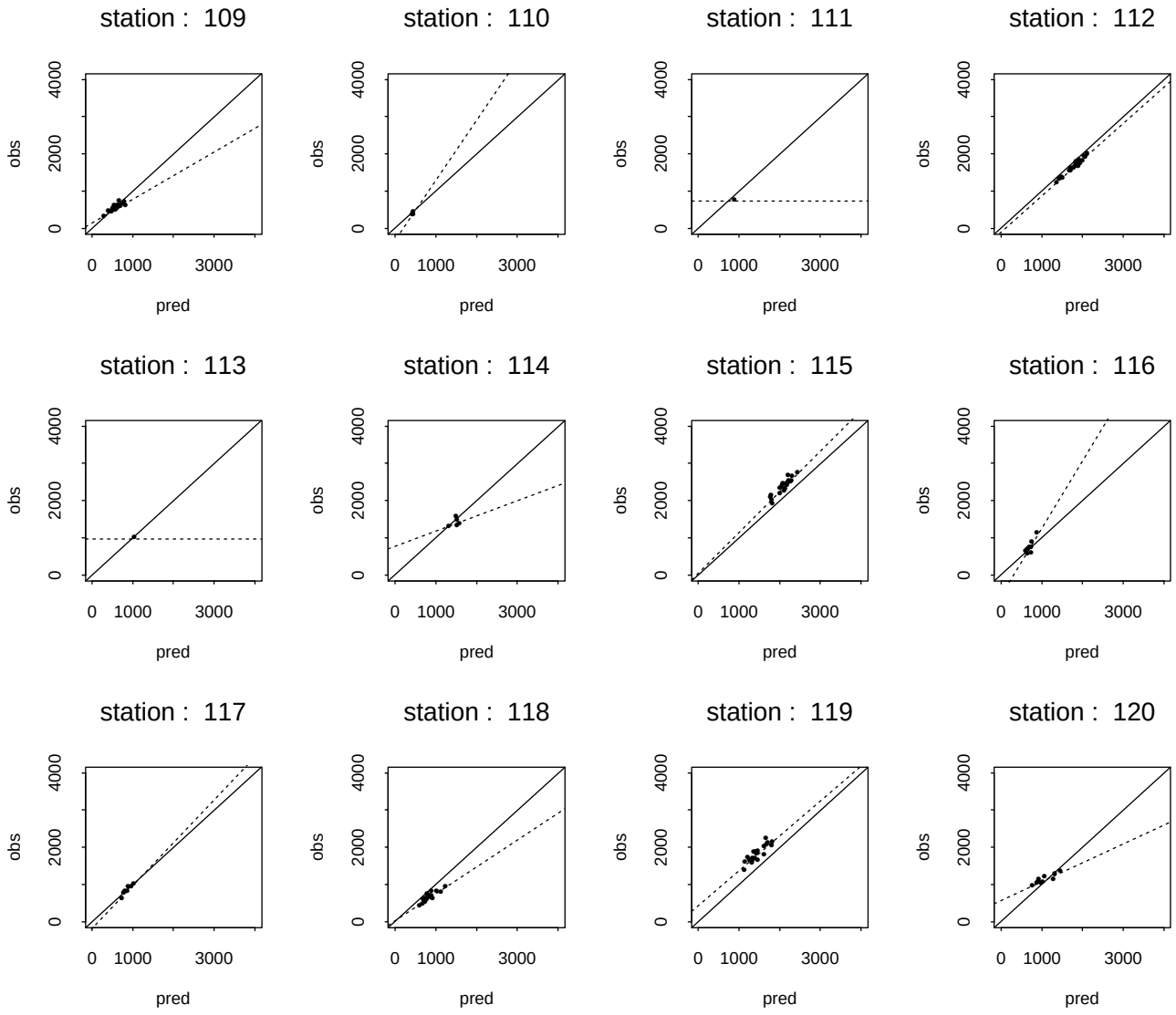

station : 49
station : 50
station : 51
station : 52
station : 53
station : 54
station : 55
station : 56
station : 57
station : 58
station : 59
station : 60
obs
pred
0
2000
4000
0
1000
3000

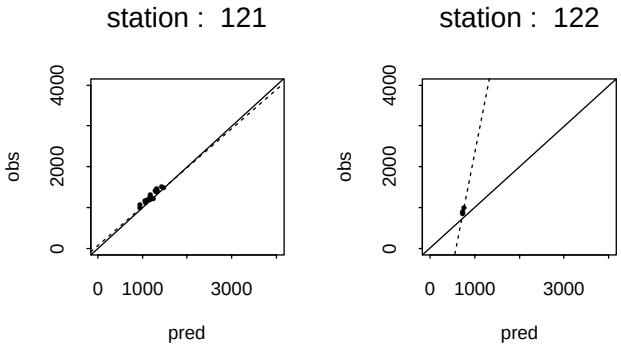

station : 61
station : 62
station : 63
station : 64
station : 65
station : 66
station : 67
station : 68
station : 69
station : 70
station : 71
station : 72
obs
pred
0
2000
4000
0
1000
3000


station : 73
station : 74
station : 75
station : 76
station : 77
station : 78
station : 79
station : 80
station : 81
station : 82
station : 83
station : 84
obs
pred
0
2000
4000
0
1000
3000


station : 85
station : 86
station : 87
station : 88
station : 89
station : 90
station : 91
station : 92
station : 93
station : 94
station : 95
station : 96
obs
pred
0
2000
4000
1000
3000


station : 97
station : 98
station : 99
station : 100
station : 101
station : 102
station : 103
station : 104
station : 105
station : 106
station : 107
station : 108
obs
pred
0
2000
4000
1000
3000


station : 109
station : 110
station : 111
station : 112
station : 113
station : 114
station : 115
station : 116
station : 117
station : 118
station : 119
station : 120
obs
pred
0
2000
4000
1000
3000

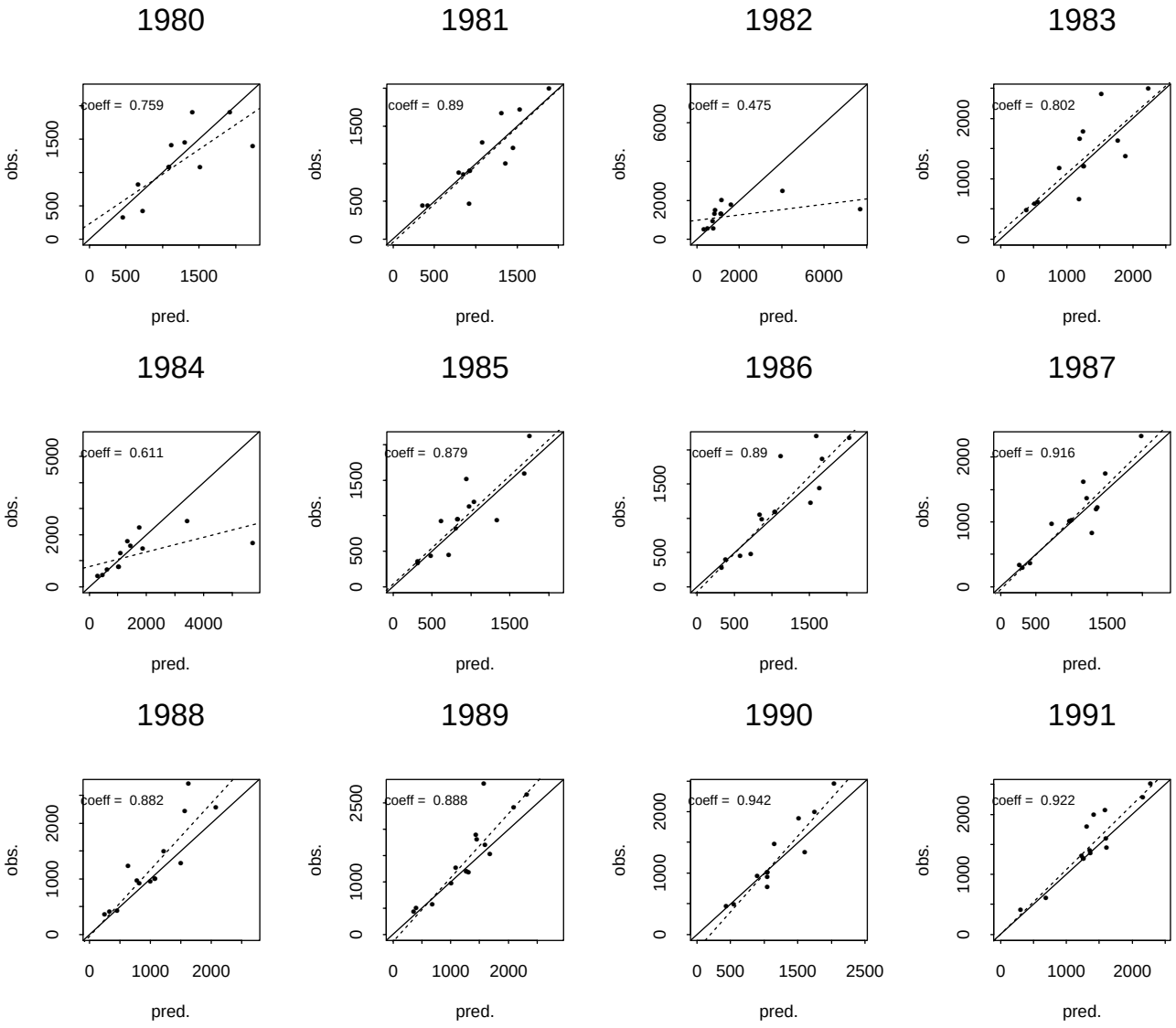

station : 121
station : 122
obs
pred
0
2000
4000
0
1000
3000

Appendix 3

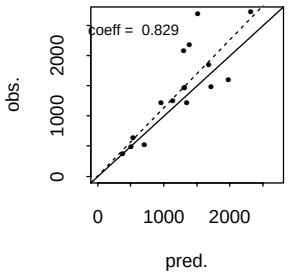
Annual precipitation

Validation procedure

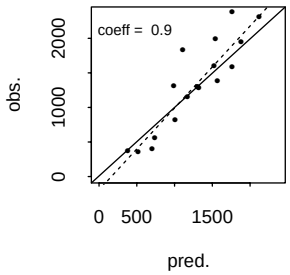
Scatter plots for the period 1980-2000


1980
coeff = 0.759
1981
coeff = 0.89
1982
coeff = 0.475
1983
coeff = 0.802
1984
coeff = 0.611
1985
coeff = 0.879
1986
coeff = 0.89
1987
coeff = 0.916
1988
coeff = 0.882
1989
coeff = 0.888
1990
coeff = 0.942
1991
coeff = 0.922
obs.
pred.

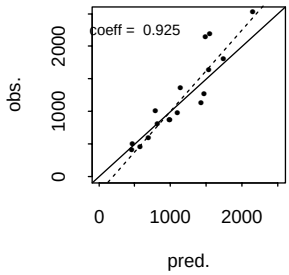
1992



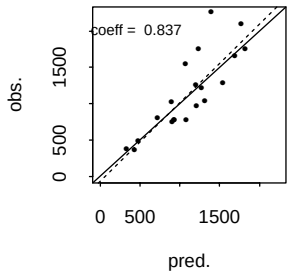
1993



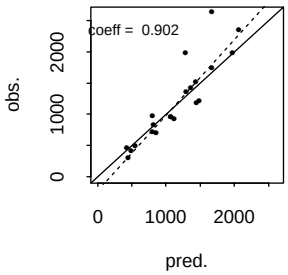
1994



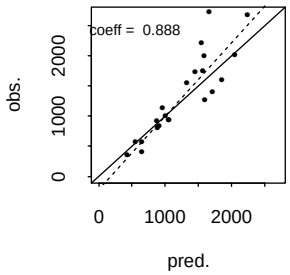
1995



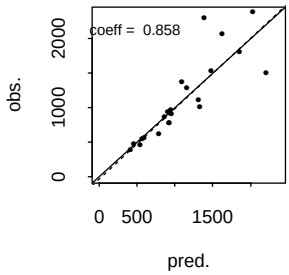
1996



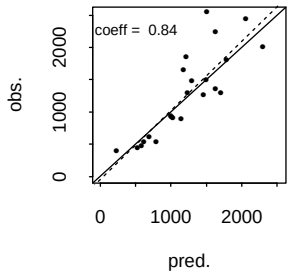
1997



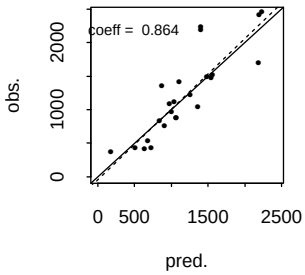
1998



1999



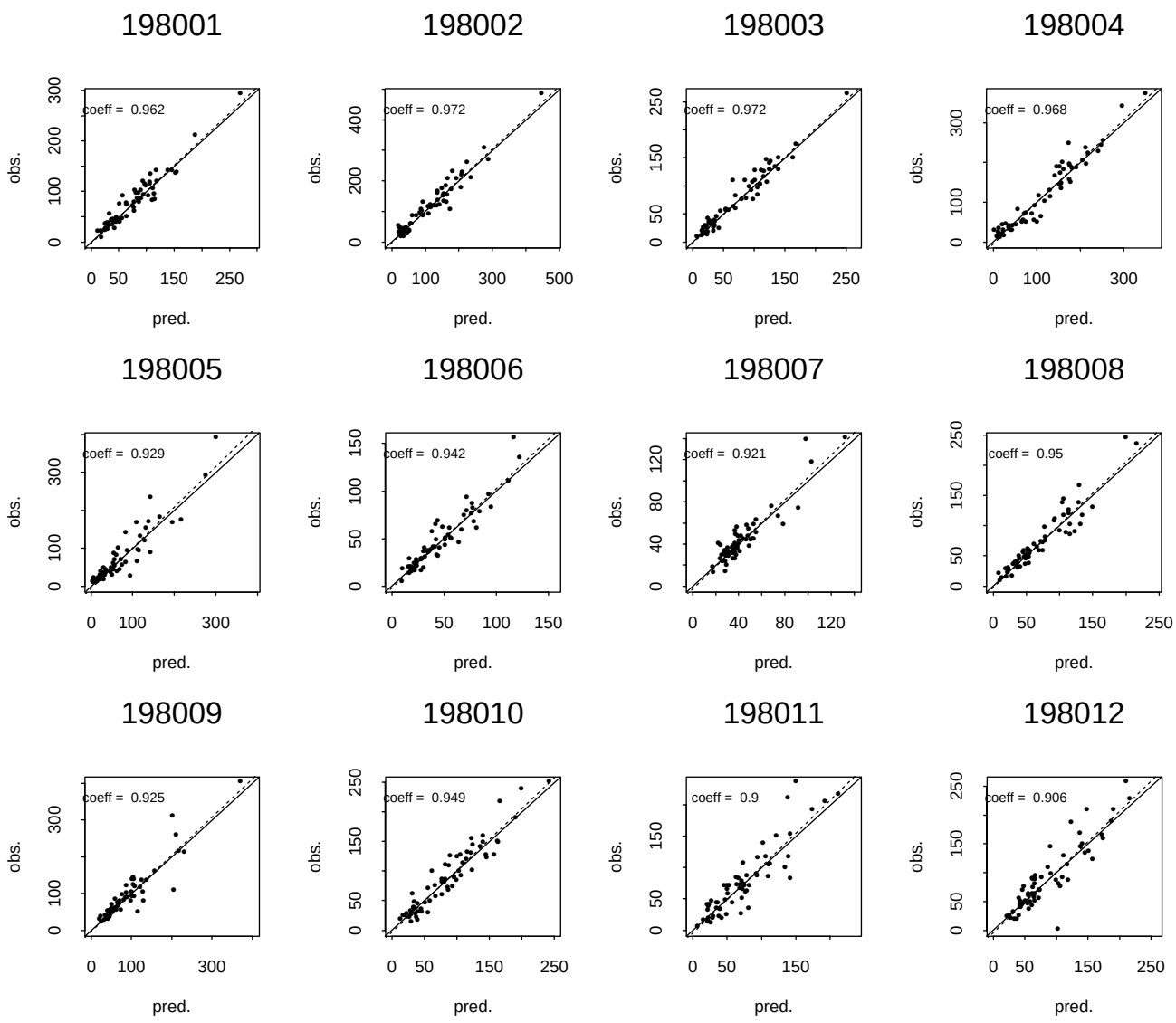
2000

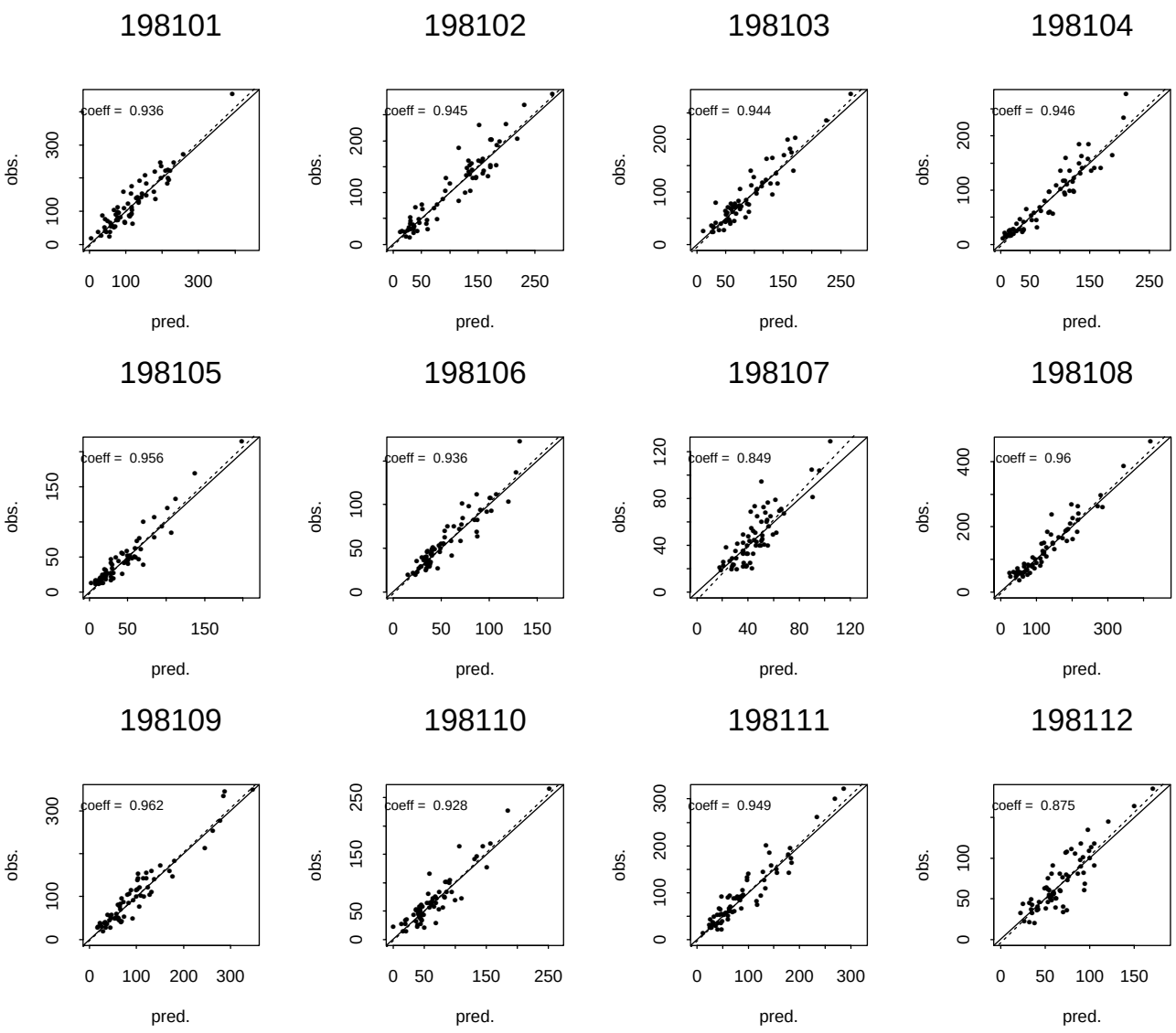


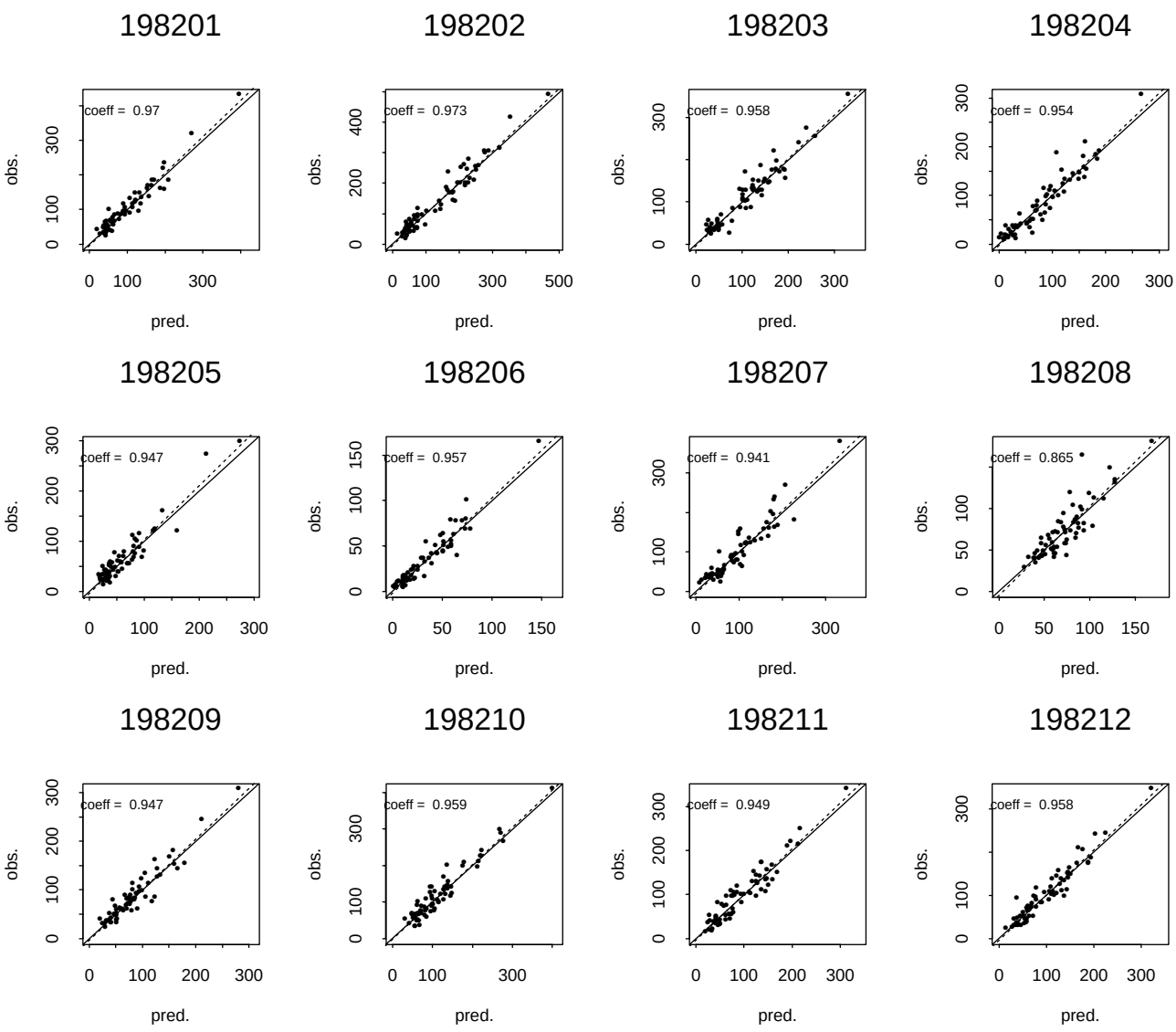
Appendix 4

Monthly precipitation

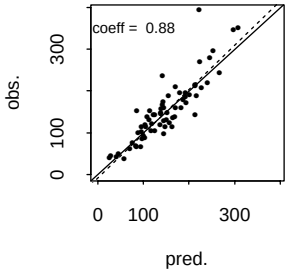
Scatter plots for the period 1980-2000


198001
coeff = 0.962
198002
coeff = 0.972
198003
coeff = 0.972
198004
coeff = 0.968
198005
coeff = 0.929
198006
coeff = 0.942
198007
coeff = 0.921
198008
coeff = 0.95
198009
coeff = 0.925
198010
coeff = 0.949
198011
coeff = 0.9
198012
coeff = 0.906
obs.
pred.

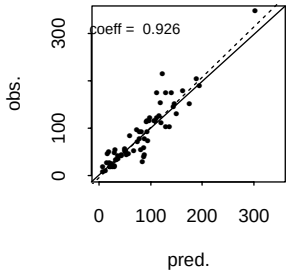

198101
coeff = 0.936
198102
coeff = 0.945
198103
coeff = 0.944
198104
coeff = 0.946
198105
coeff = 0.956
198106
coeff = 0.936
198107
coeff = 0.849
198108
coeff = 0.96
198109
coeff = 0.962
198110
coeff = 0.928
198111
coeff = 0.949
198112
coeff = 0.875
obs.
pred.


198201
coeff = 0.97
198202
coeff = 0.973
198203
coeff = 0.958
198204
coeff = 0.954
198205
coeff = 0.947
198206
coeff = 0.957
198207
coeff = 0.941
198208
coeff = 0.865
198209
coeff = 0.947
198210
coeff = 0.959
198211
coeff = 0.949
198212
coeff = 0.958
obs.
pred.

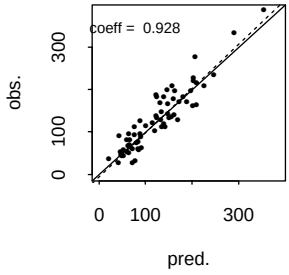
198301



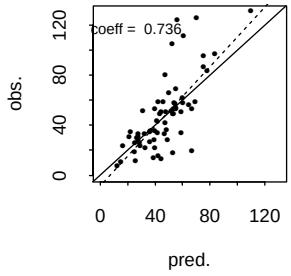
198302



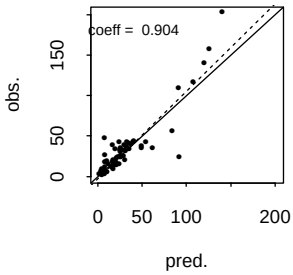
198303



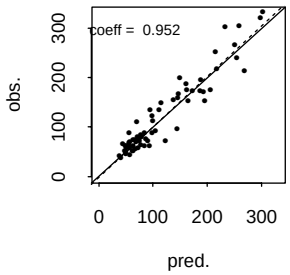
198304



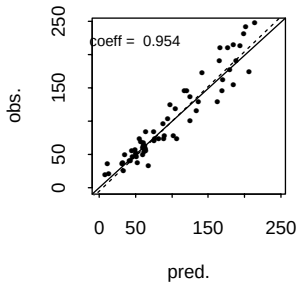
198305



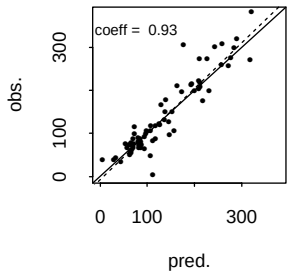
198306



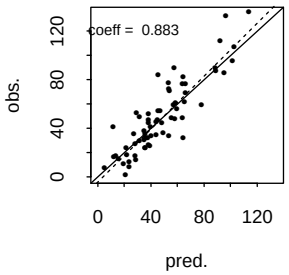
198307



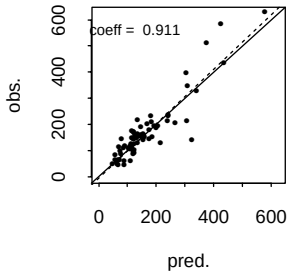
198308



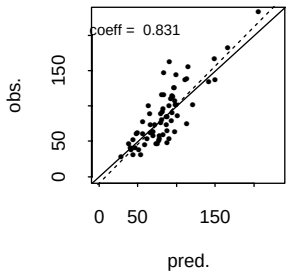
198309



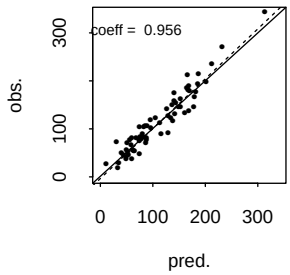
198310

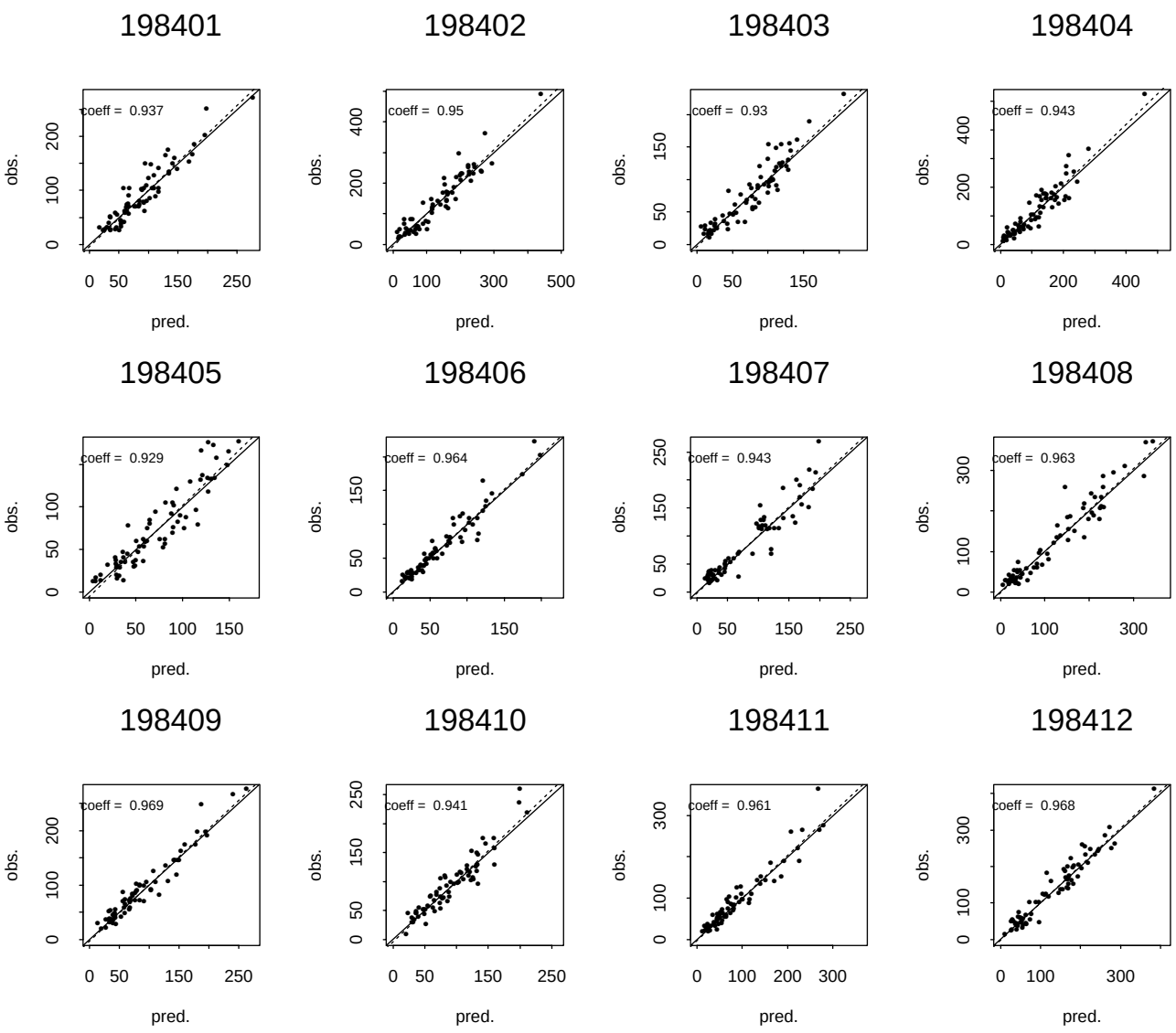


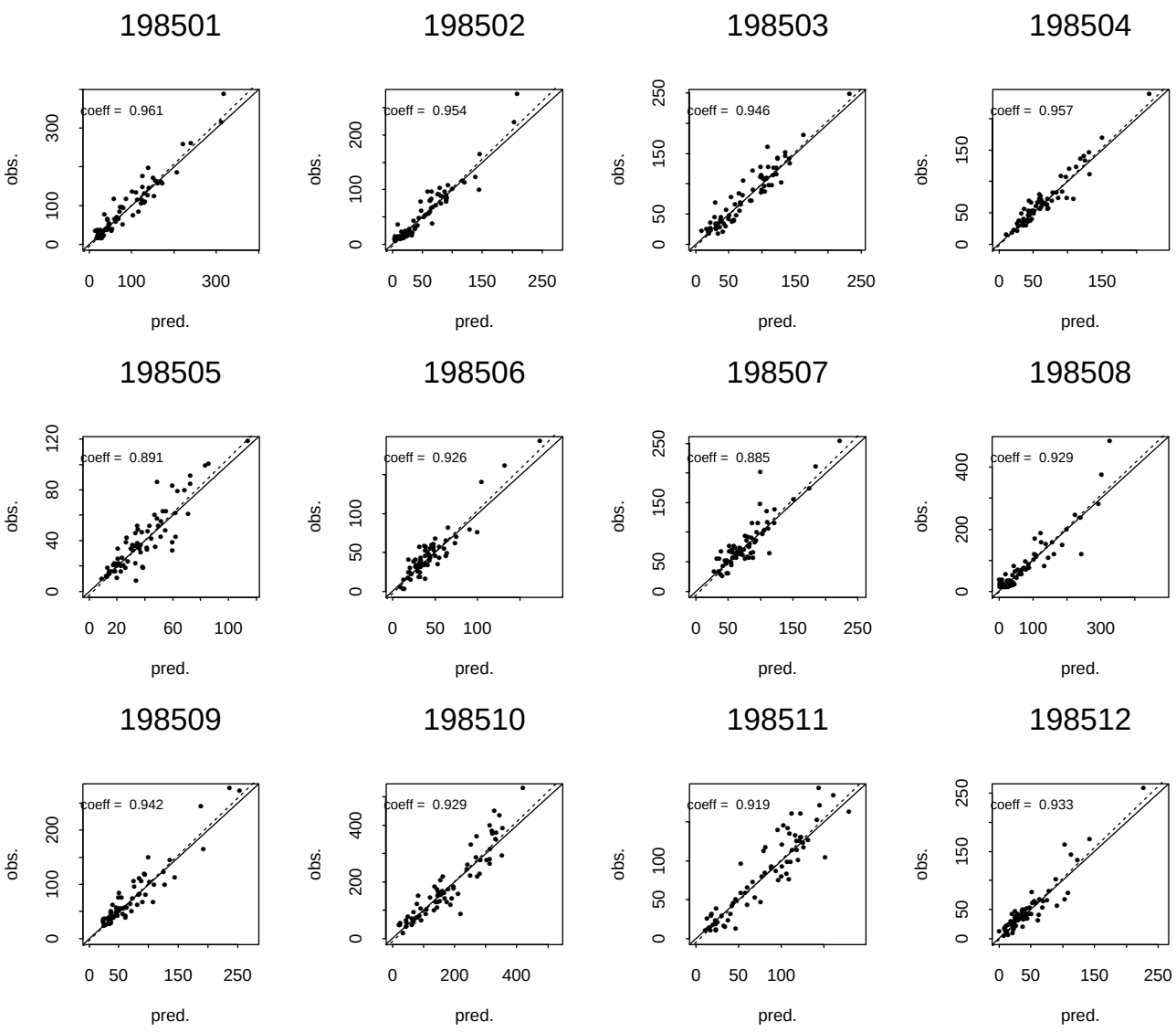
198311

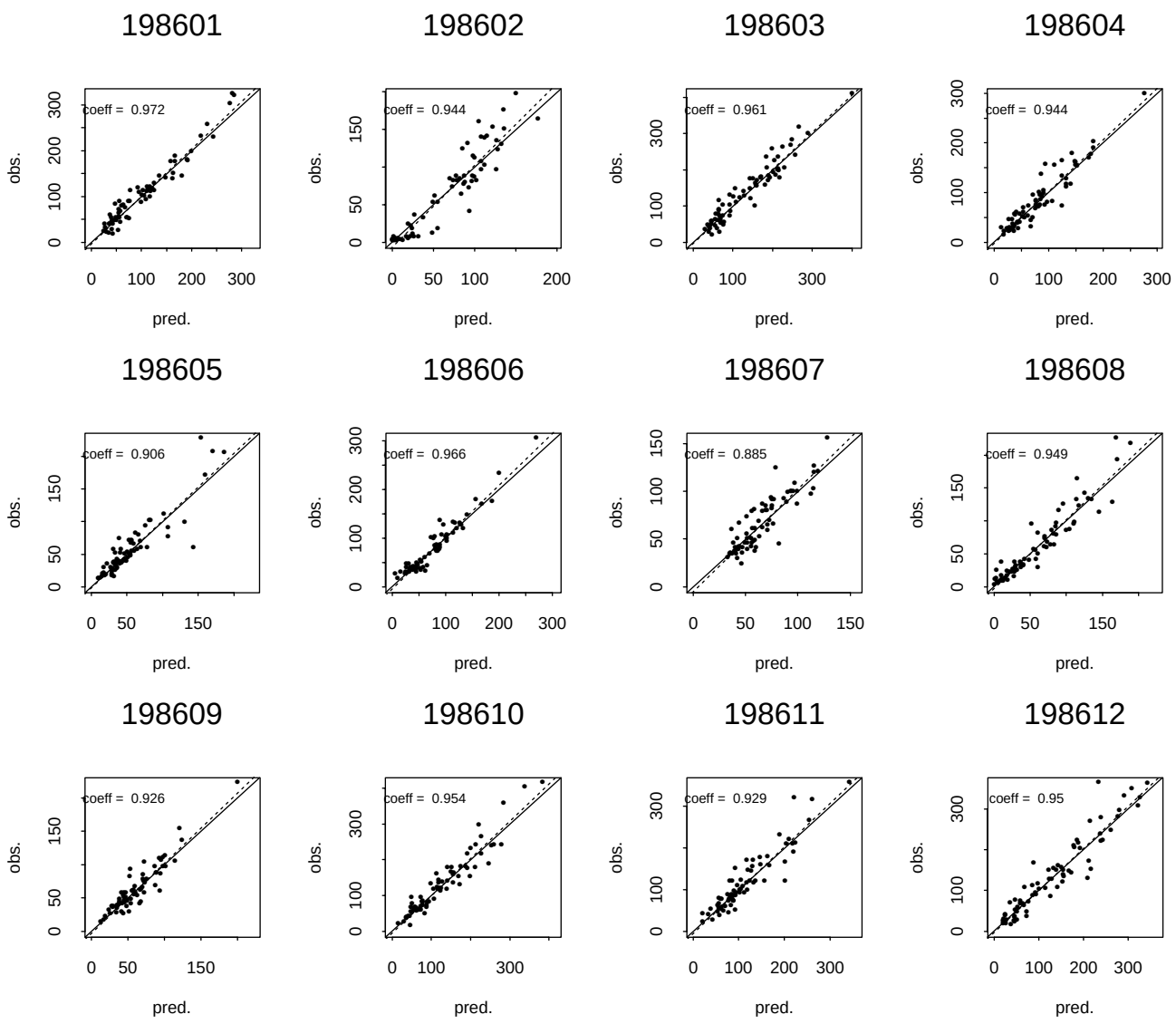


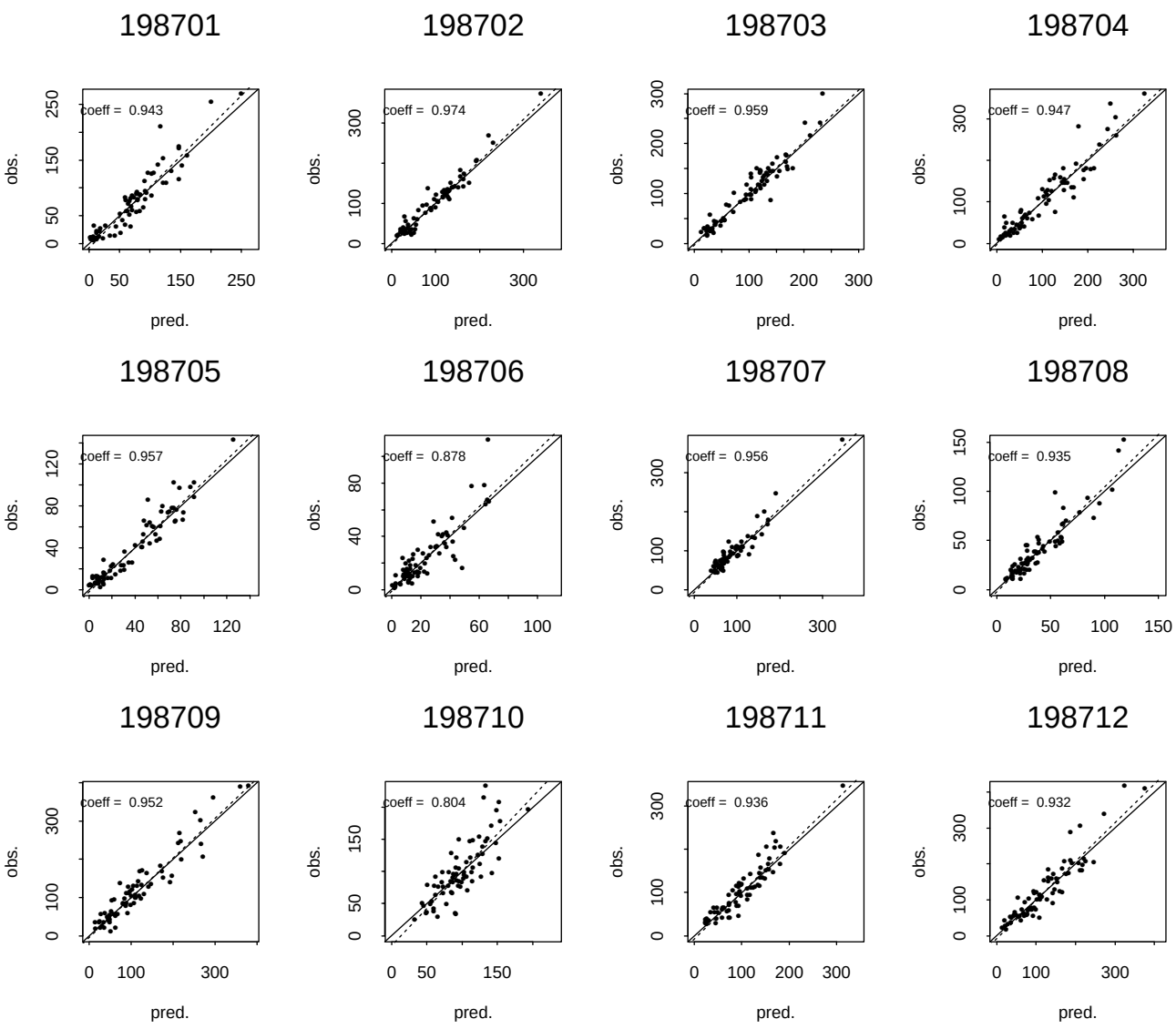
198312

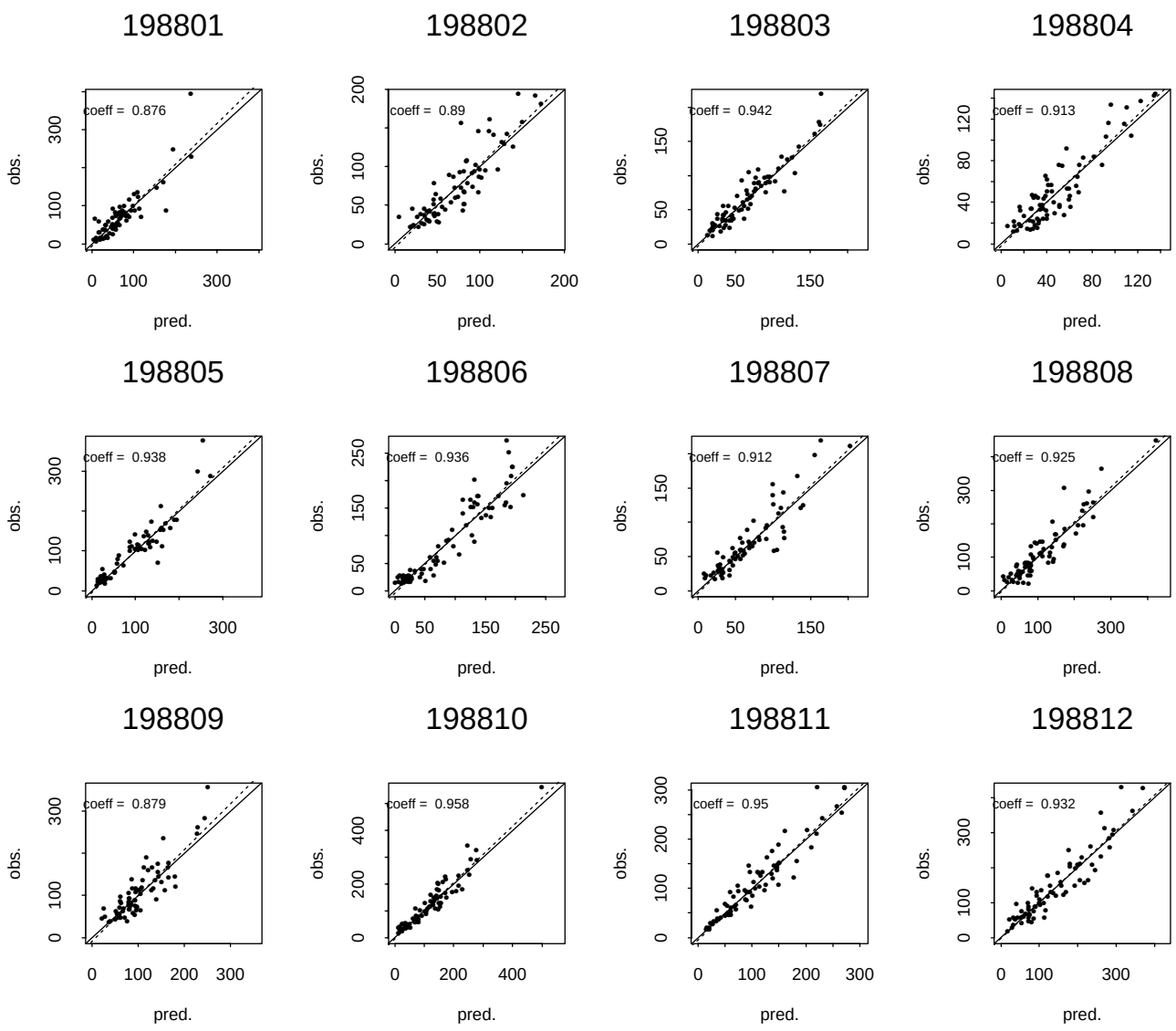


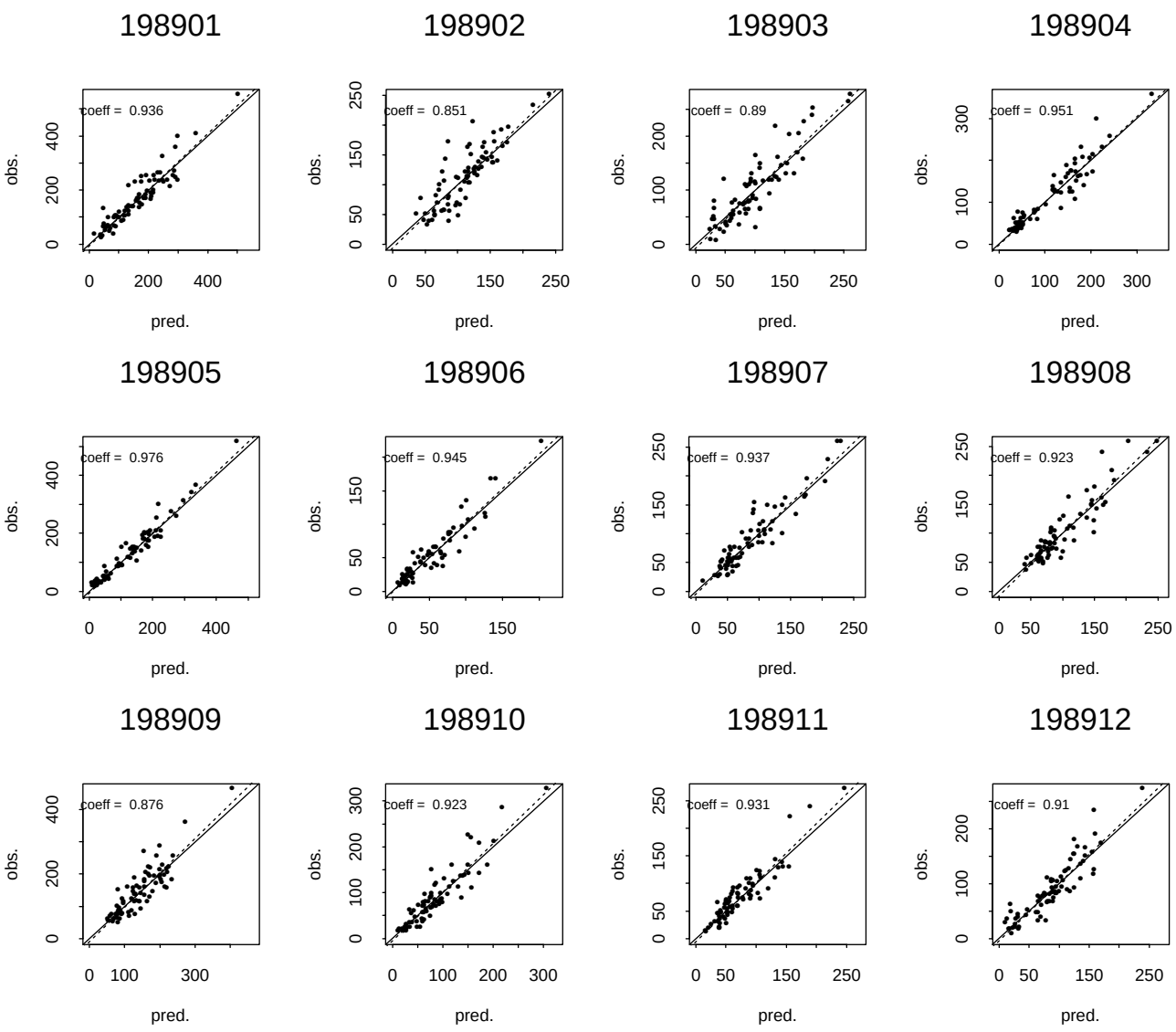

198401
coeff = 0.937
198402
coeff = 0.95
198403
coeff = 0.93
198404
coeff = 0.943
198405
coeff = 0.929
198406
coeff = 0.964
198407
coeff = 0.943
198408
coeff = 0.963
198409
coeff = 0.969
198410
coeff = 0.941
198411
coeff = 0.961
198412
coeff = 0.968
obs.
pred.

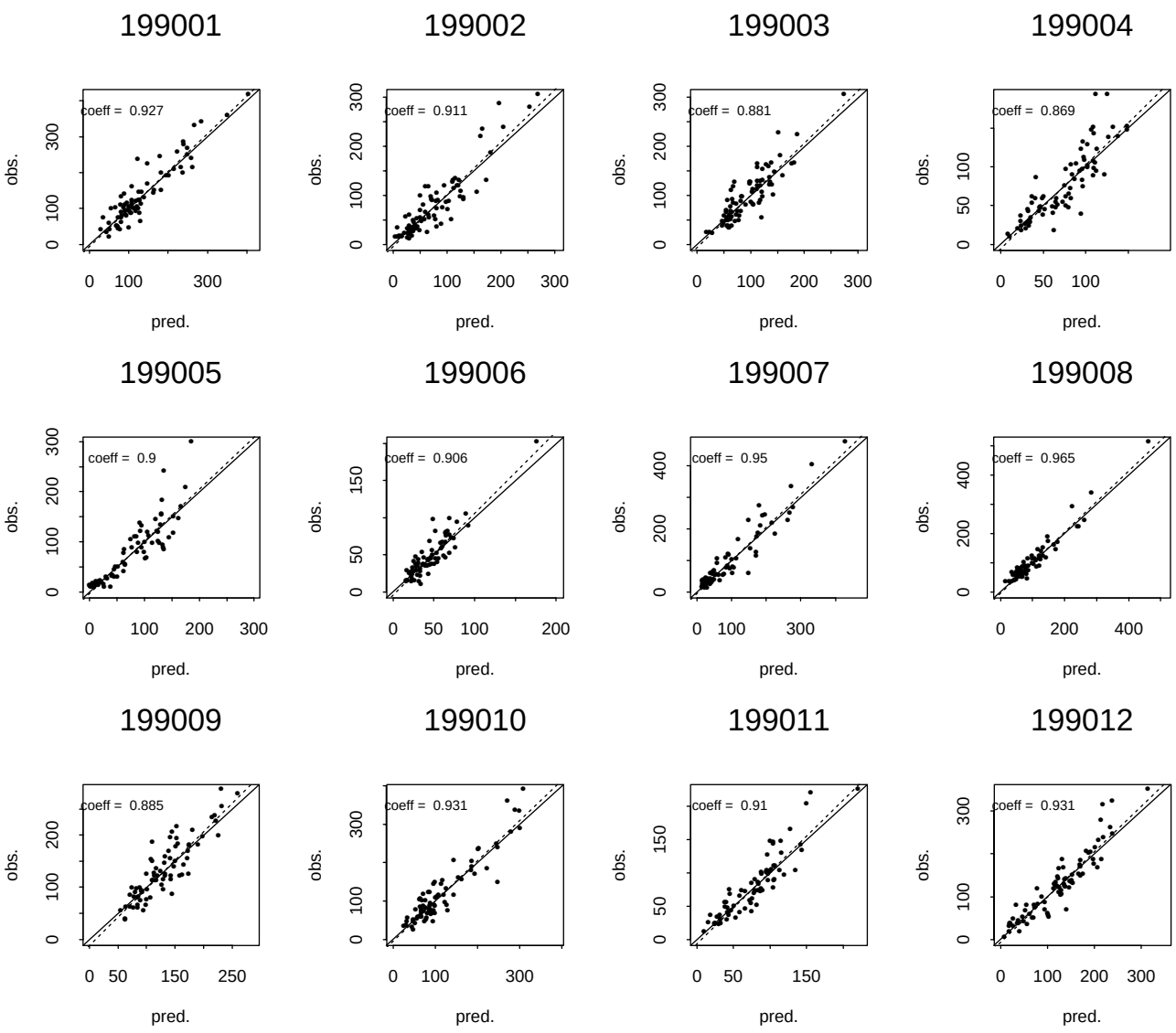

198501
coeff = 0.961
198502
coeff = 0.954
198503
coeff = 0.946
198504
coeff = 0.957
198505
coeff = 0.891
198506
coeff = 0.926
198507
coeff = 0.885
198508
coeff = 0.929
198509
coeff = 0.942
198510
coeff = 0.929
198511
coeff = 0.919
198512
coeff = 0.933
obs.
pred.

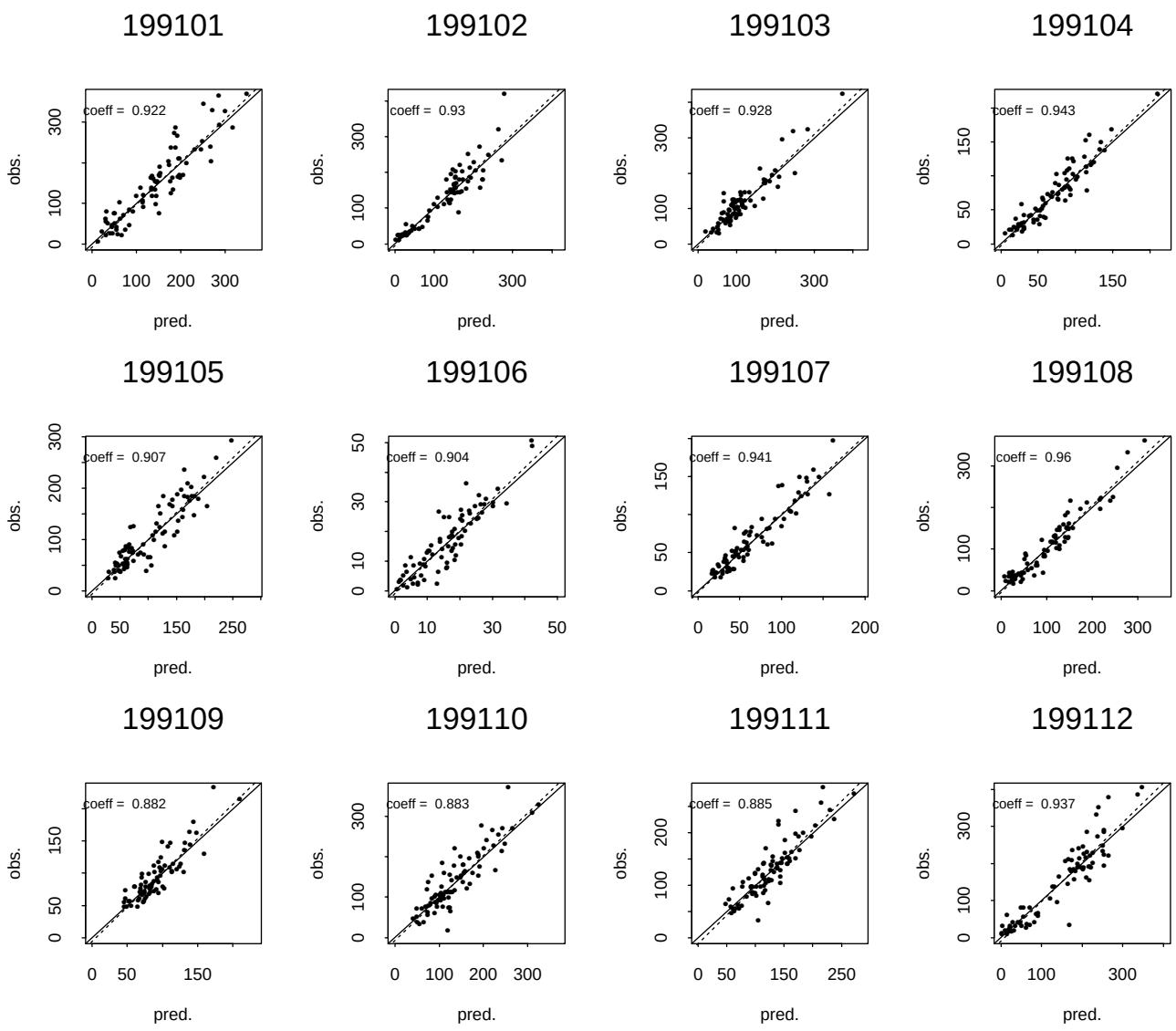

198601
coeff = 0.972
198602
coeff = 0.944
198603
coeff = 0.961
198604
coeff = 0.944
198605
coeff = 0.906
198606
coeff = 0.966
198607
coeff = 0.885
198608
coeff = 0.949
198609
coeff = 0.926
198610
coeff = 0.954
198611
coeff = 0.929
198612
coeff = 0.95
obs.
pred.

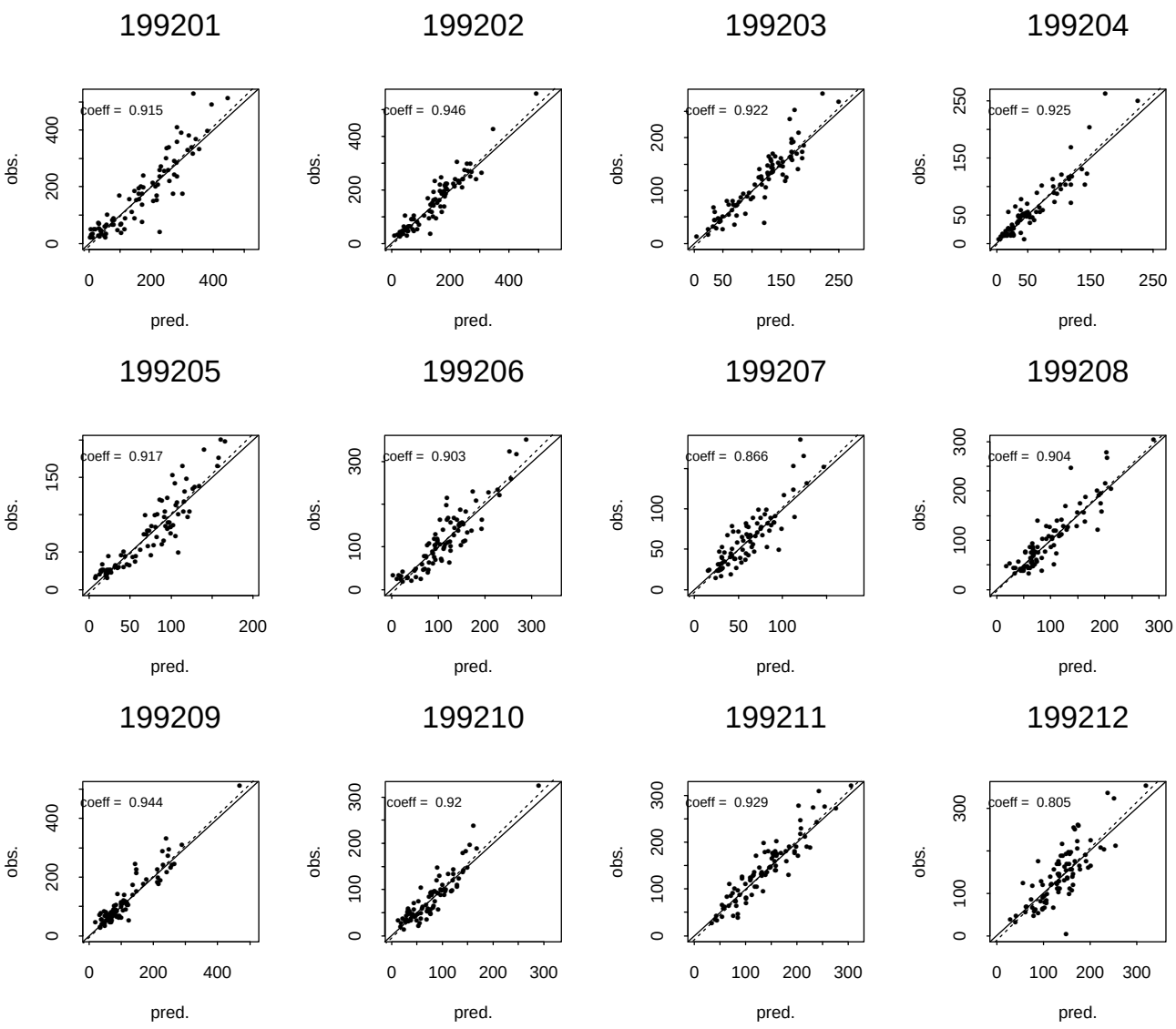

198701
coeff = 0.943
198702
coeff = 0.974
198703
coeff = 0.959
198704
coeff = 0.947
198705
coeff = 0.957
198706
coeff = 0.878
198707
coeff = 0.956
198708
coeff = 0.935
198709
coeff = 0.952
198710
coeff = 0.804
198711
coeff = 0.936
198712
coeff = 0.932
obs.
pred.

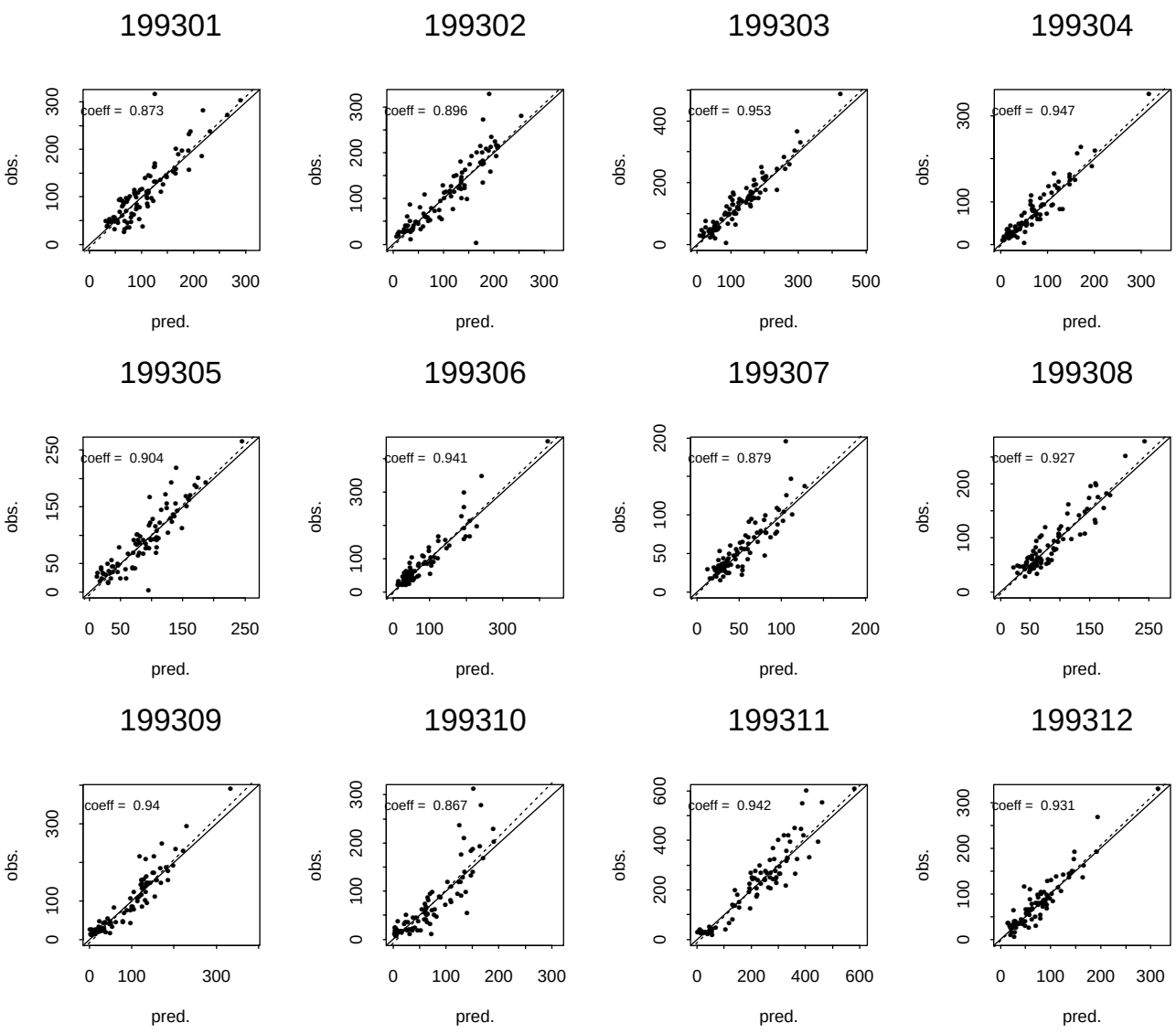

198801
coeff = 0.876
198802
coeff = 0.89
198803
coeff = 0.942
198804
coeff = 0.913
198805
coeff = 0.938
198806
coeff = 0.936
198807
coeff = 0.912
198808
coeff = 0.925
198809
coeff = 0.879
198810
coeff = 0.958
198811
coeff = 0.95
198812
coeff = 0.932
obs.
pred.

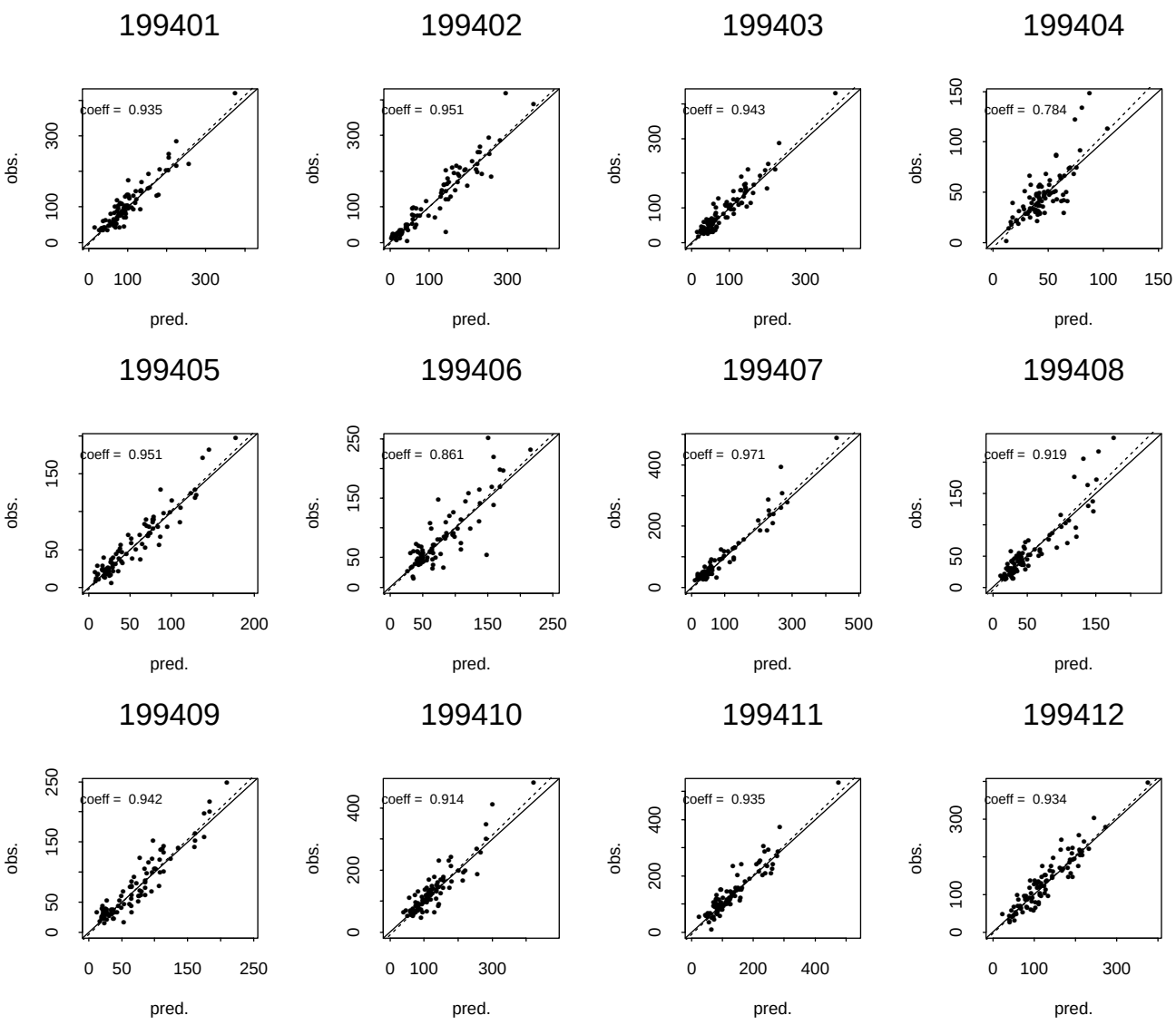

198901
coeff = 0.936
198902
coeff = 0.851
198903
coeff = 0.89
198904
coeff = 0.951
198905
coeff = 0.976
198906
coeff = 0.945
198907
coeff = 0.937
198908
coeff = 0.923
198909
coeff = 0.876
198910
coeff = 0.923
198911
coeff = 0.931
198912
coeff = 0.91
obs.
pred.

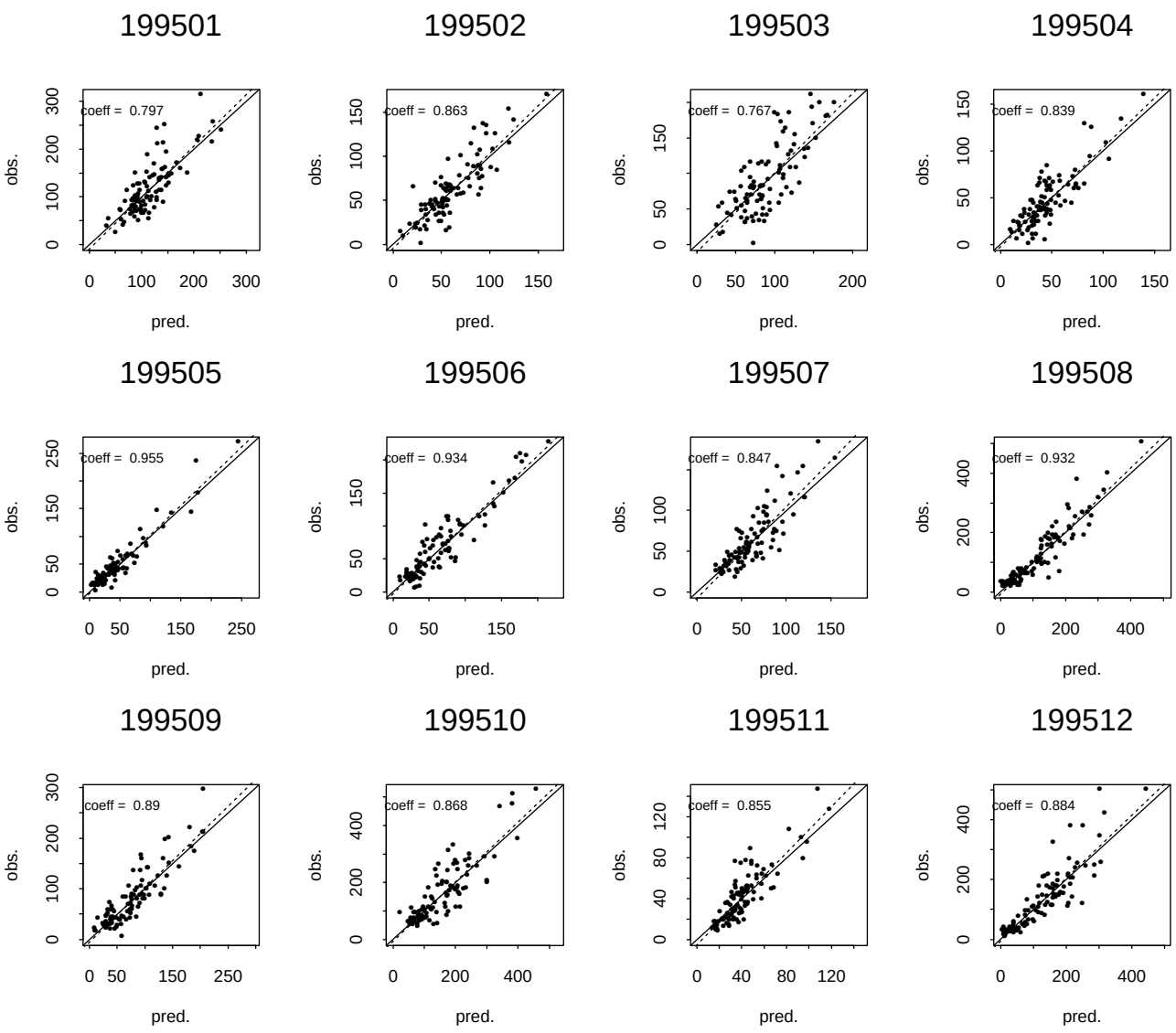

199001
coeff = 0.927
199002
coeff = 0.911
199003
coeff = 0.881
199004
coeff = 0.869
199005
coeff = 0.9
199006
coeff = 0.906
199007
coeff = 0.95
199008
coeff = 0.965
199009
coeff = 0.885
199010
coeff = 0.931
199011
coeff = 0.91
199012
coeff = 0.931
obs.
pred.

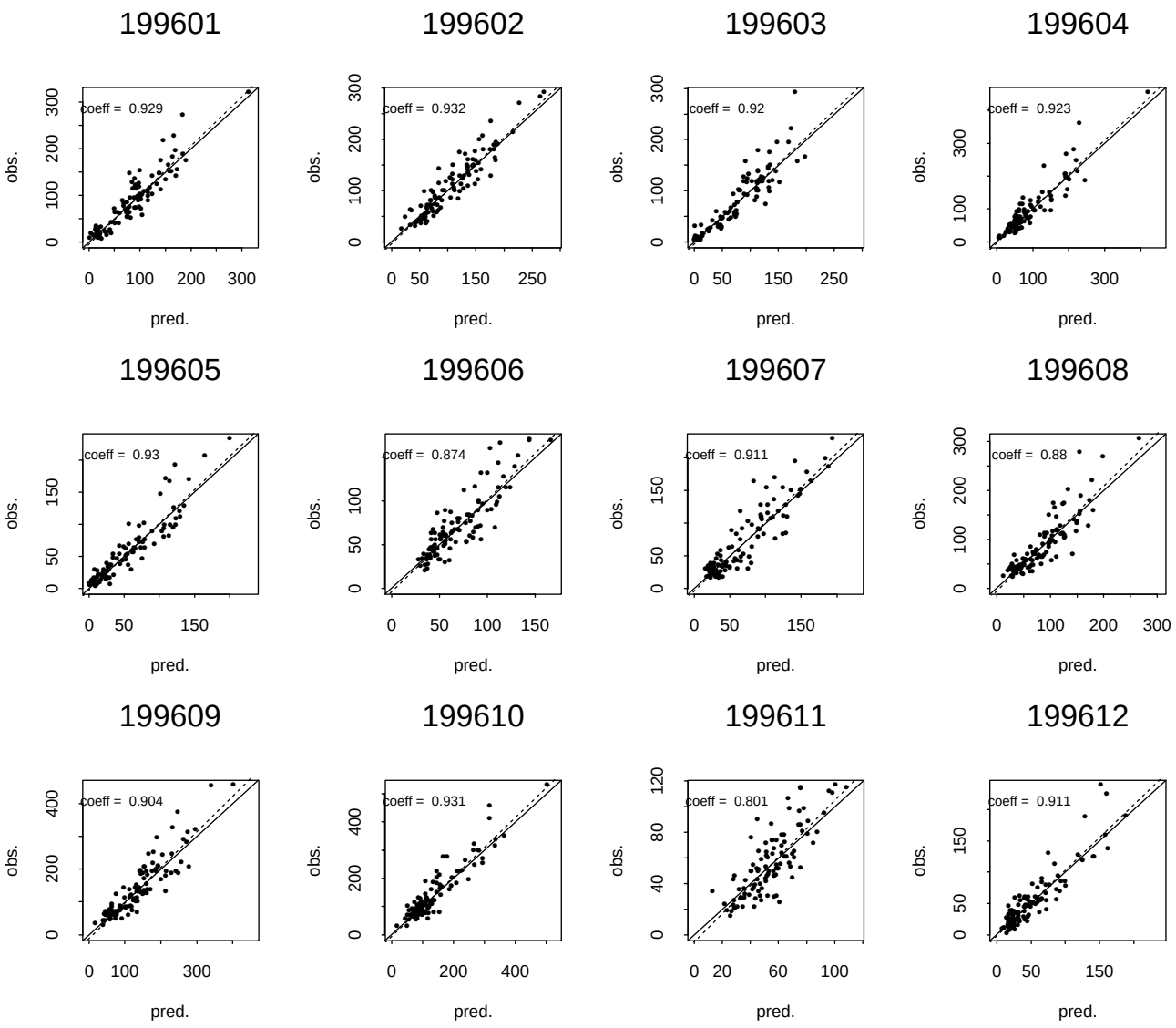

199101
coeff = 0.922
199102
coeff = 0.93
199103
coeff = 0.928
199104
coeff = 0.943
199105
coeff = 0.907
199106
coeff = 0.904
199107
coeff = 0.941
199108
coeff = 0.96
199109
coeff = 0.882
199110
coeff = 0.883
199111
coeff = 0.885
199112
coeff = 0.937
obs.
pred.

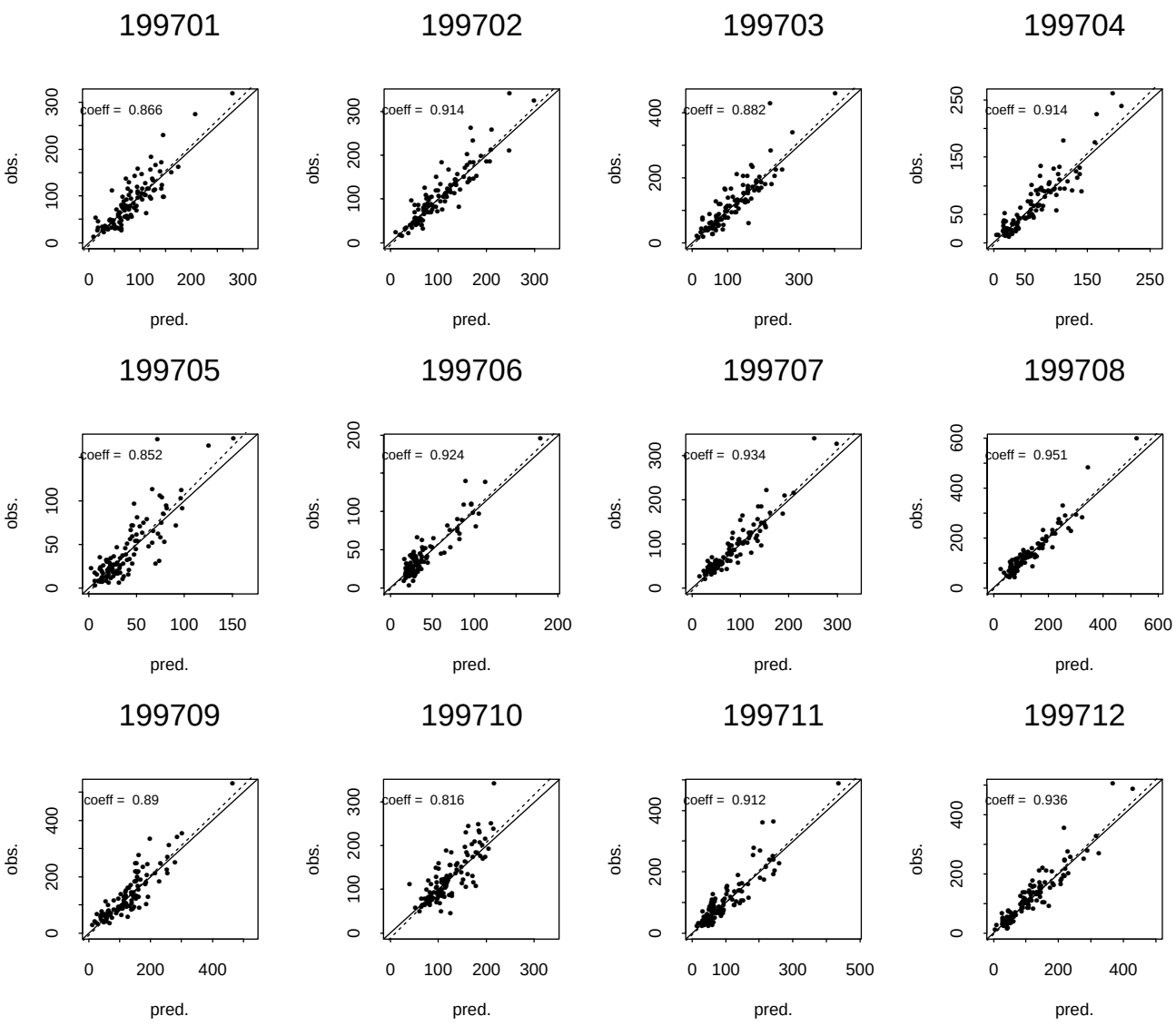

199201
coeff = 0.915
199202
coeff = 0.946
199203
coeff = 0.922
199204
coeff = 0.925
199205
coeff = 0.917
199206
coeff = 0.903
199207
coeff = 0.866
199208
coeff = 0.904
199209
coeff = 0.944
199210
coeff = 0.92
199211
coeff = 0.929
199212
coeff = 0.805
obs.
pred.

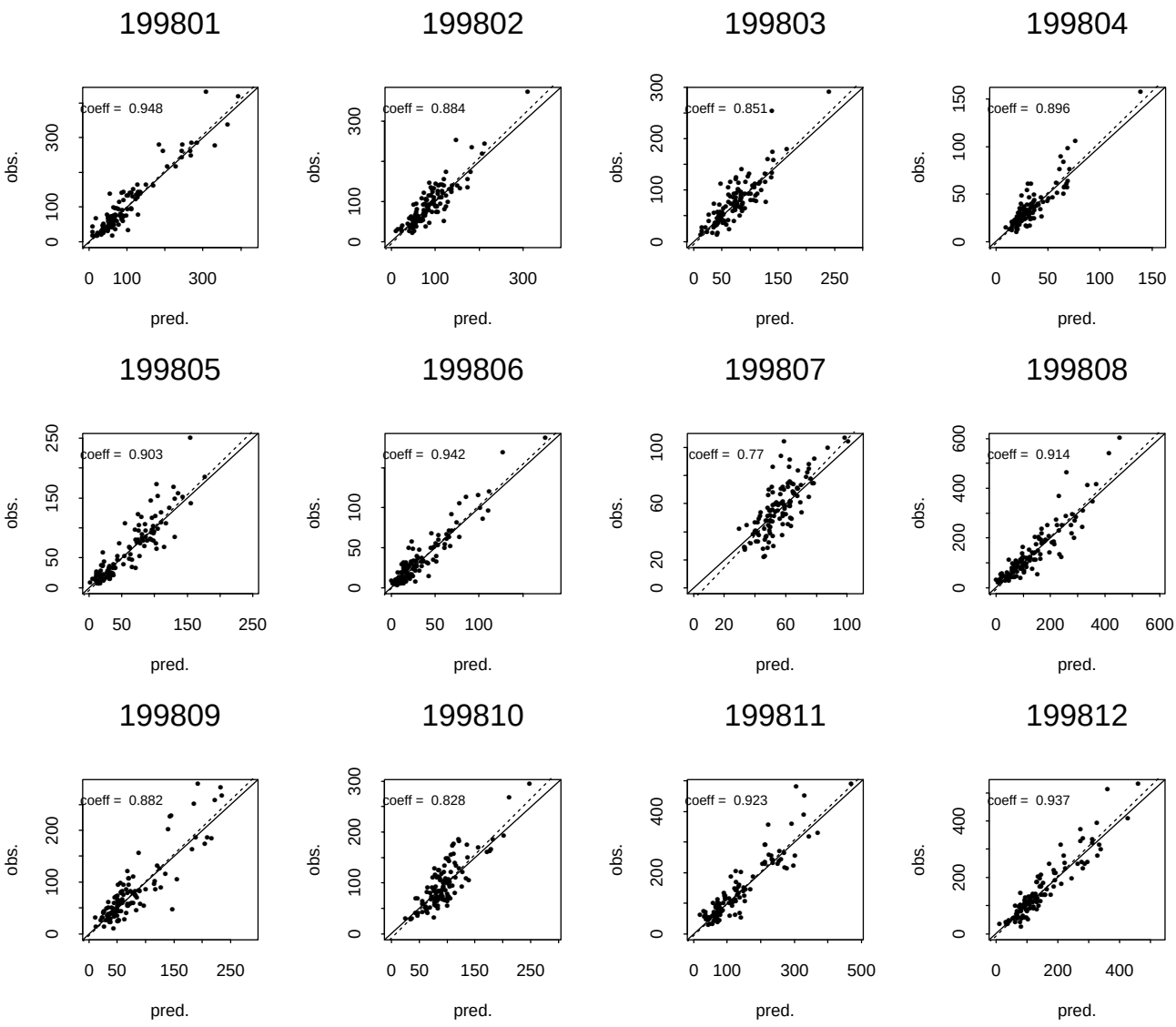

199301
coeff = 0.873
199302
coeff = 0.896
199303
coeff = 0.953
199304
coeff = 0.947
199305
coeff = 0.904
199306
coeff = 0.941
199307
coeff = 0.879
199308
coeff = 0.927
199309
coeff = 0.94
199310
coeff = 0.867
199311
coeff = 0.942
199312
coeff = 0.931
obs.
pred.

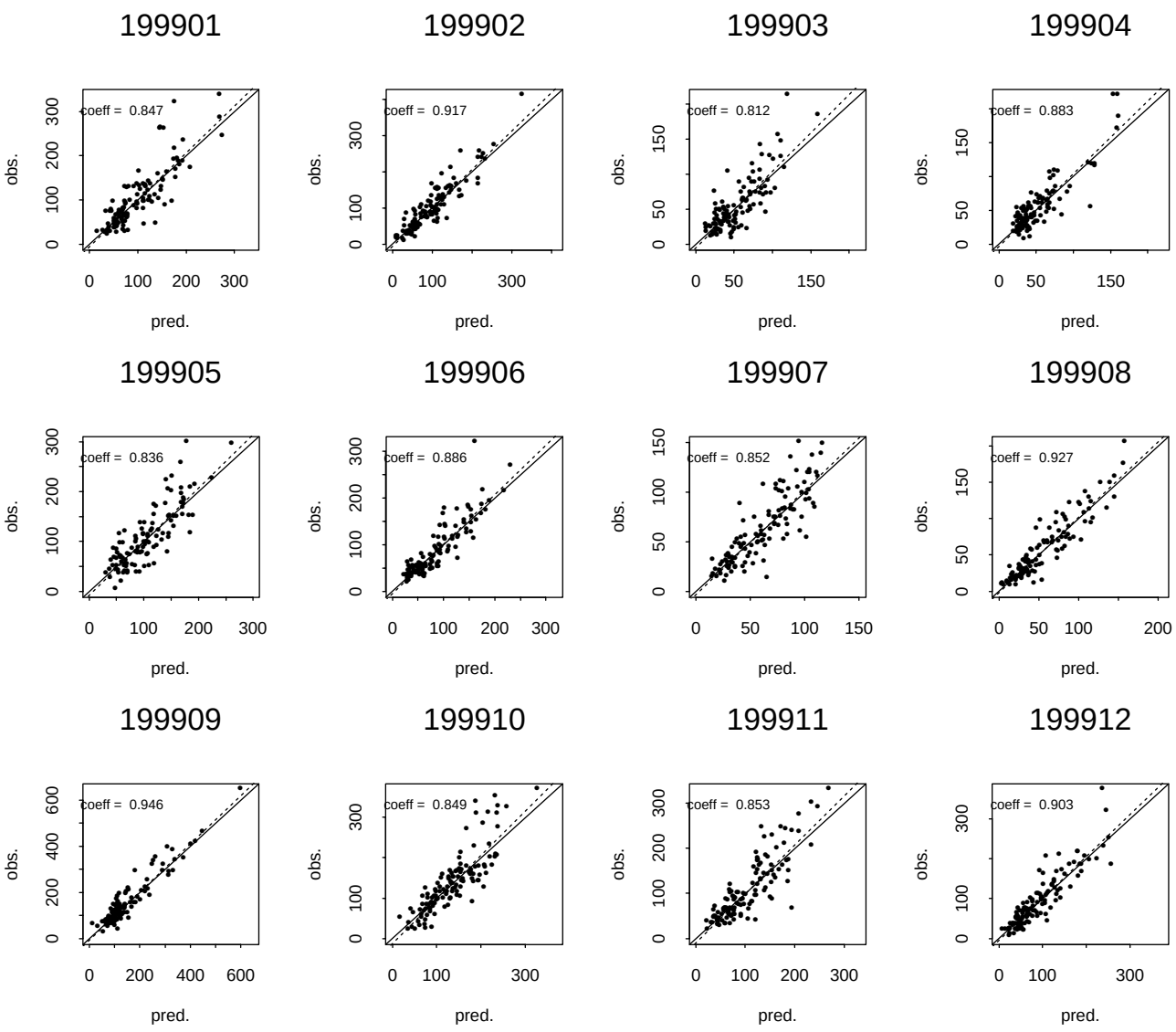

199401
coeff = 0.935
199402
coeff = 0.951
199403
coeff = 0.943
199404
coeff = 0.784
199405
coeff = 0.951
199406
coeff = 0.861
199407
coeff = 0.971
199408
coeff = 0.919
199409
coeff = 0.942
199410
coeff = 0.914
199411
coeff = 0.935
199412
coeff = 0.934
obs.
pred.

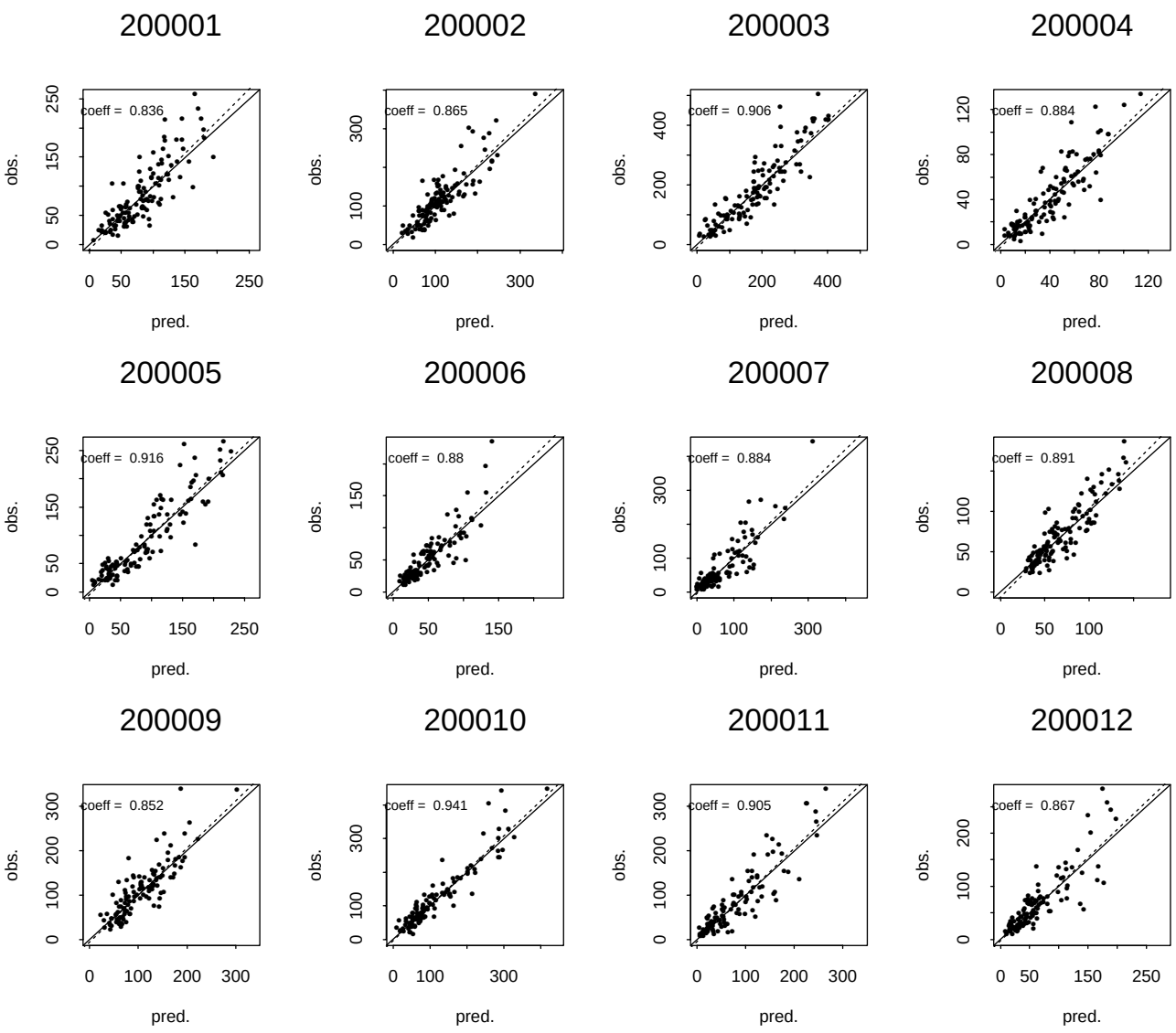

199501
coeff = 0.797
199502
coeff = 0.863
199503
coeff = 0.767
199504
coeff = 0.839
199505
coeff = 0.955
199506
coeff = 0.934
199507
coeff = 0.847
199508
coeff = 0.932
199509
coeff = 0.89
199510
coeff = 0.868
199511
coeff = 0.855
199512
coeff = 0.884
obs.
pred.


199601
coeff = 0.929
199602
coeff = 0.932
199603
coeff = 0.92
199604
coeff = 0.923
199605
coeff = 0.93
199606
coeff = 0.874
199607
coeff = 0.911
199608
coeff = 0.88
199609
coeff = 0.904
199610
coeff = 0.931
199611
coeff = 0.801
199612
coeff = 0.911
obs.
pred.


199701
coeff = 0.866
199702
coeff = 0.914
199703
coeff = 0.882
199704
coeff = 0.914
199705
coeff = 0.852
199706
coeff = 0.924
199707
coeff = 0.934
199708
coeff = 0.951
199709
coeff = 0.89
199710
coeff = 0.816
199711
coeff = 0.912
199712
coeff = 0.936
obs.
pred.


199801
coeff = 0.948
199802
coeff = 0.884
199803
coeff = 0.851
199804
coeff = 0.896
199805
coeff = 0.903
199806
coeff = 0.942
199807
coeff = 0.77
199808
coeff = 0.914
199809
coeff = 0.882
199810
coeff = 0.828
199811
coeff = 0.923
199812
coeff = 0.937
obs.
pred.

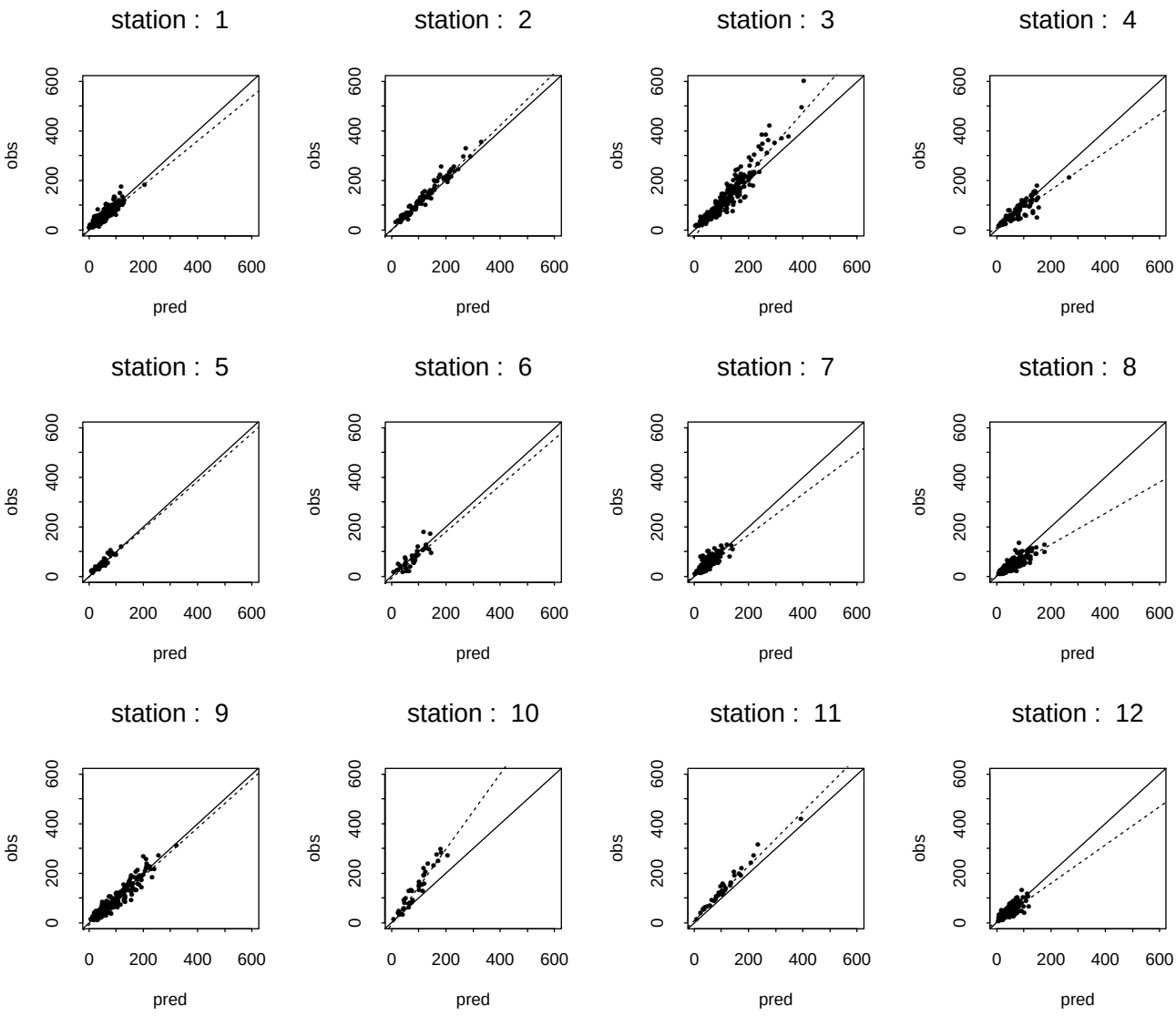

199901
coeff = 0.847
199902
coeff = 0.917
199903
coeff = 0.812
199904
coeff = 0.883
199905
coeff = 0.836
199906
coeff = 0.886
199907
coeff = 0.852
199908
coeff = 0.927
199909
coeff = 0.946
199910
coeff = 0.849
199911
coeff = 0.853
199912
coeff = 0.903
obs.
pred.

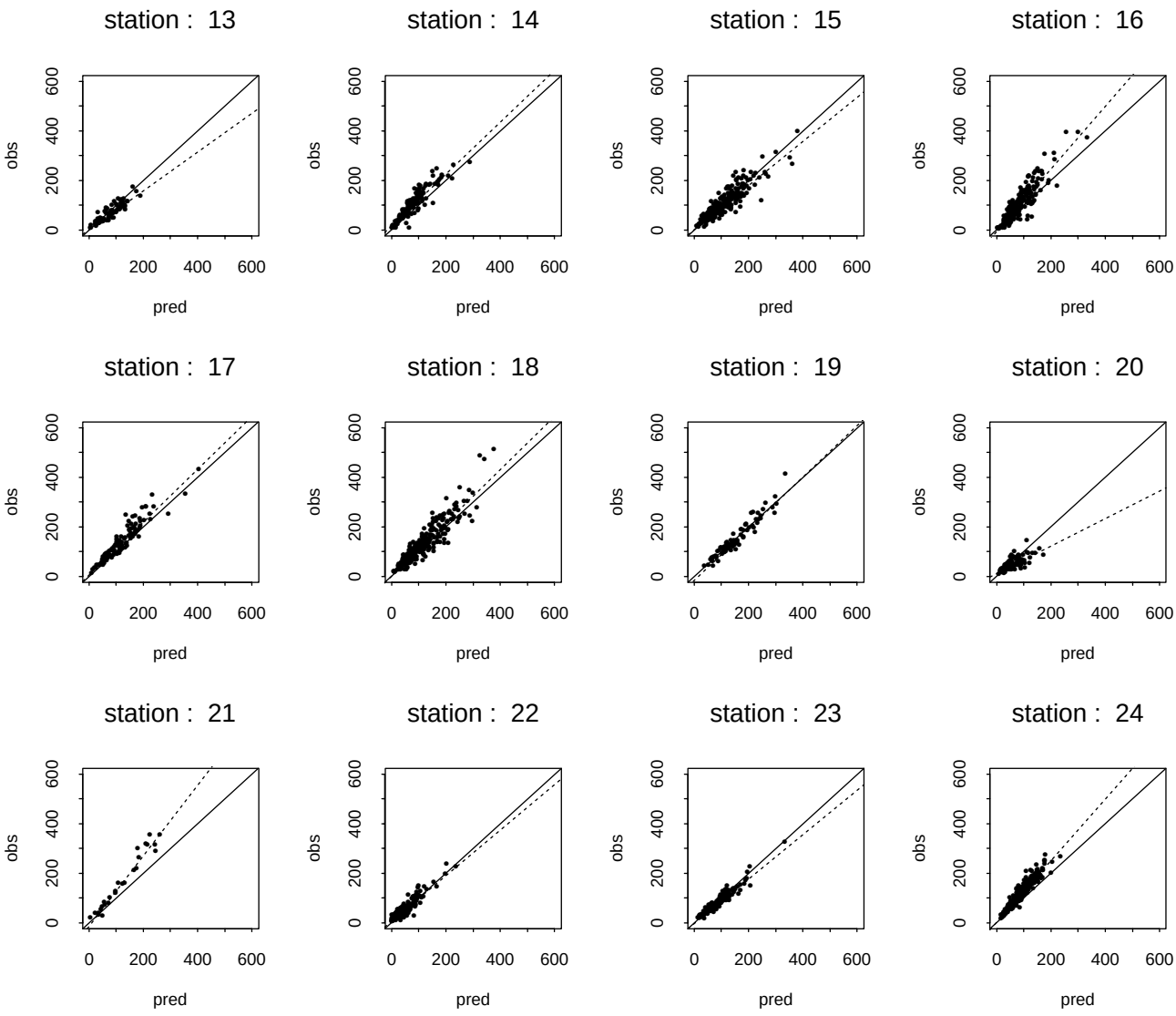

200001
coeff = 0.836
200002
coeff = 0.865
200003
coeff = 0.906
200004
coeff = 0.884
200005
coeff = 0.916
200006
coeff = 0.88
200007
coeff = 0.884
200008
coeff = 0.891
200009
coeff = 0.852
200010
coeff = 0.941
200011
coeff = 0.905
200012
coeff = 0.867
obs.
pred.

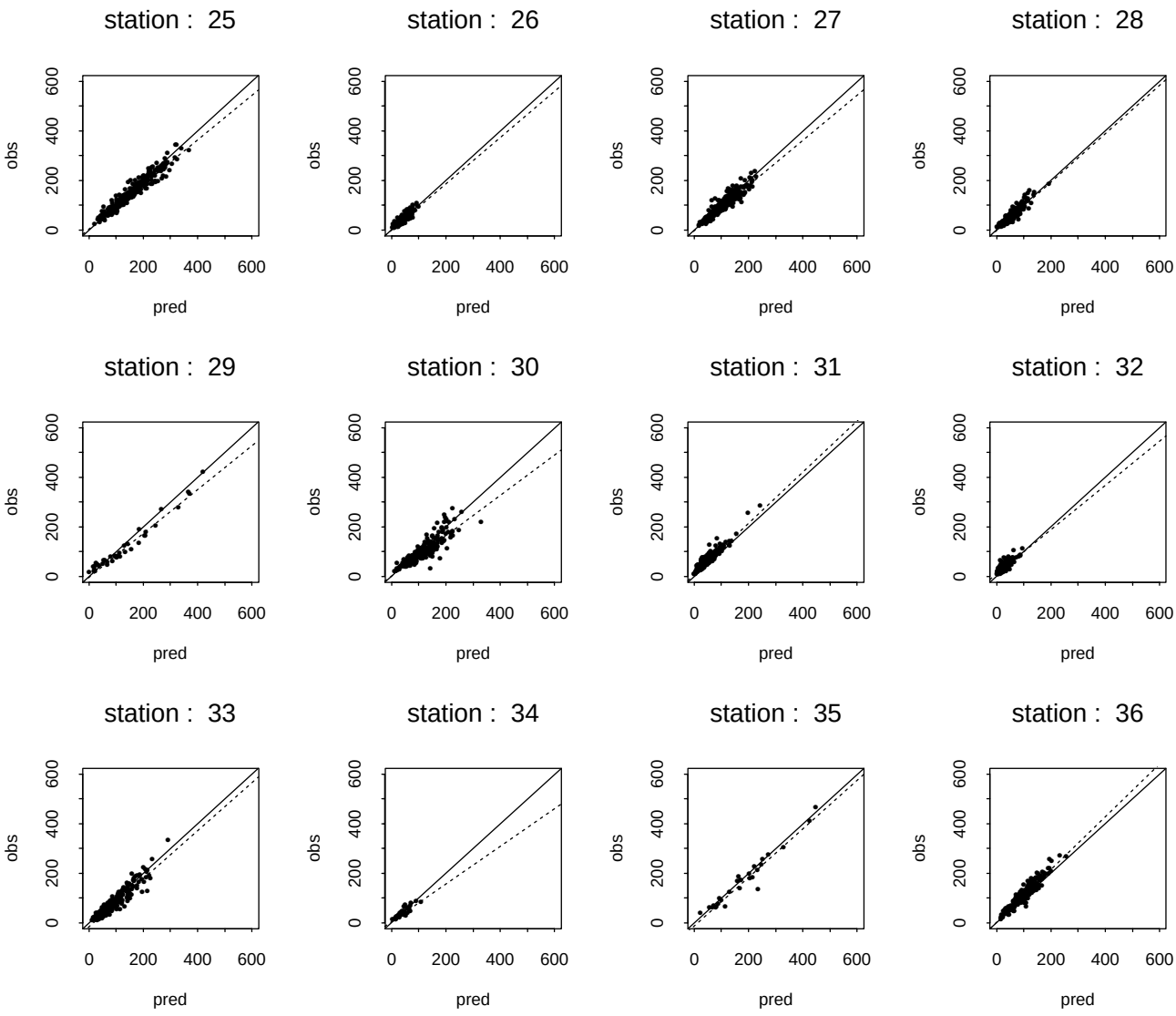
Appendix 5

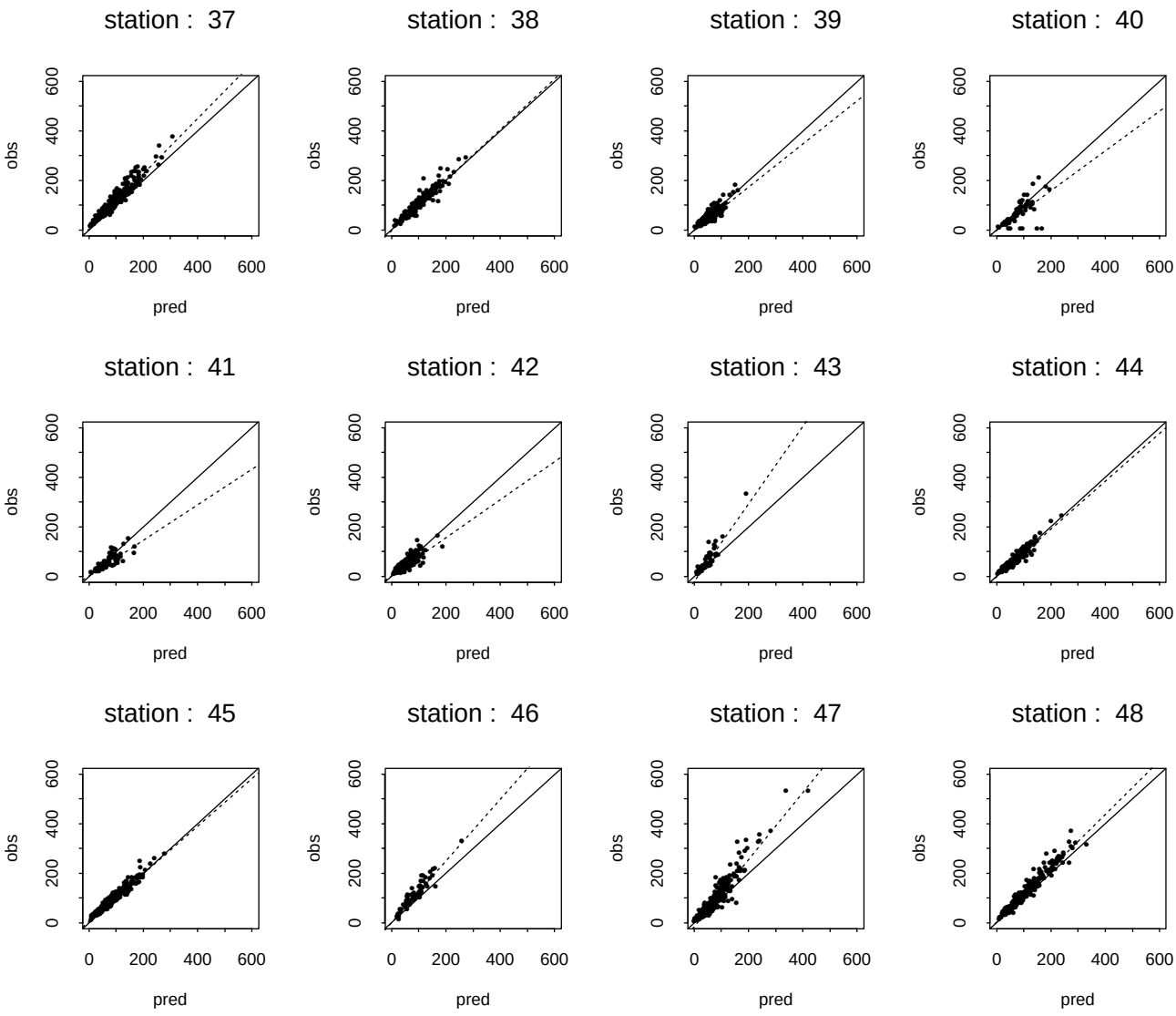
Monthly precipitation

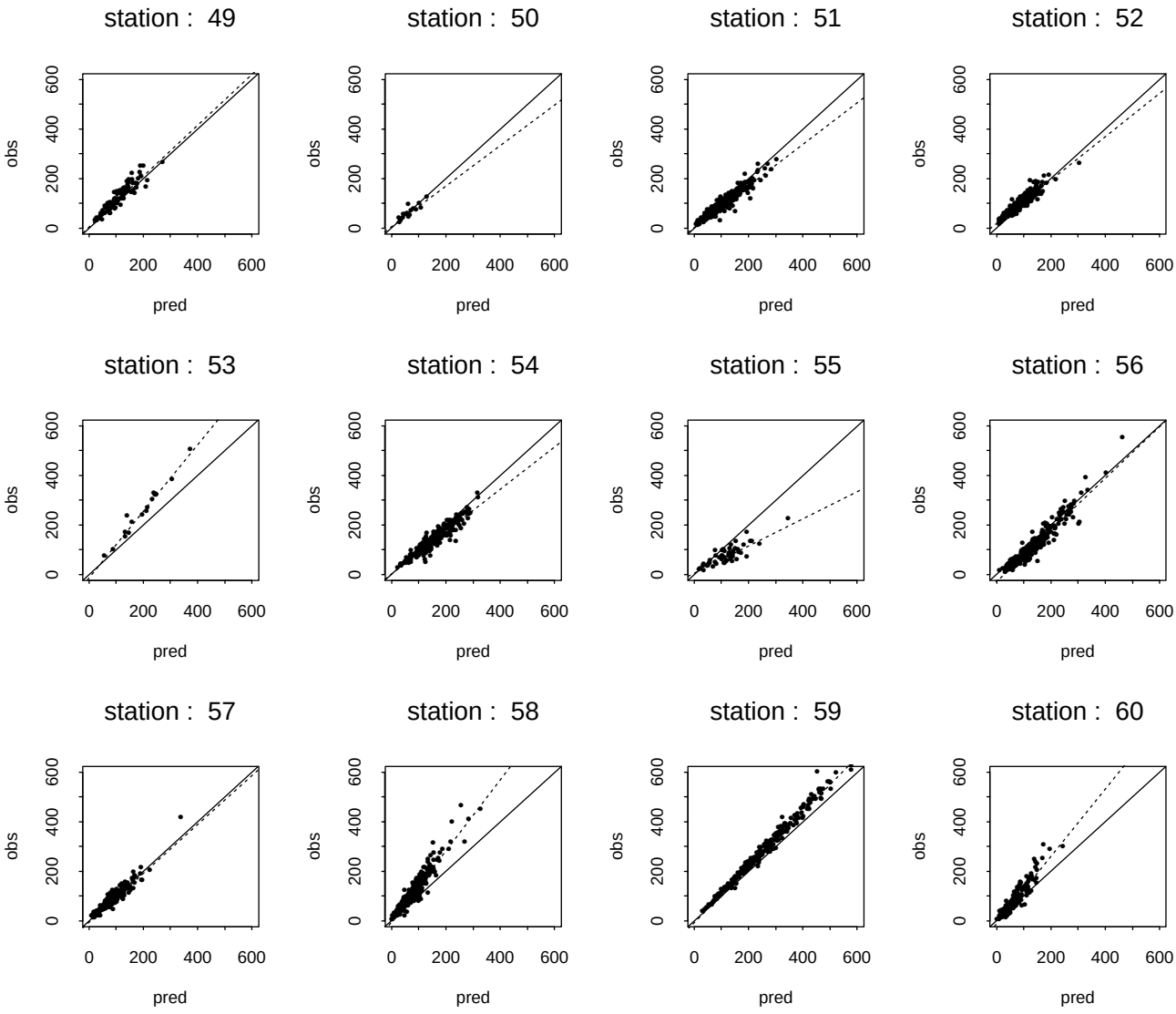
Scatter plots for each station (period 1980-2000)

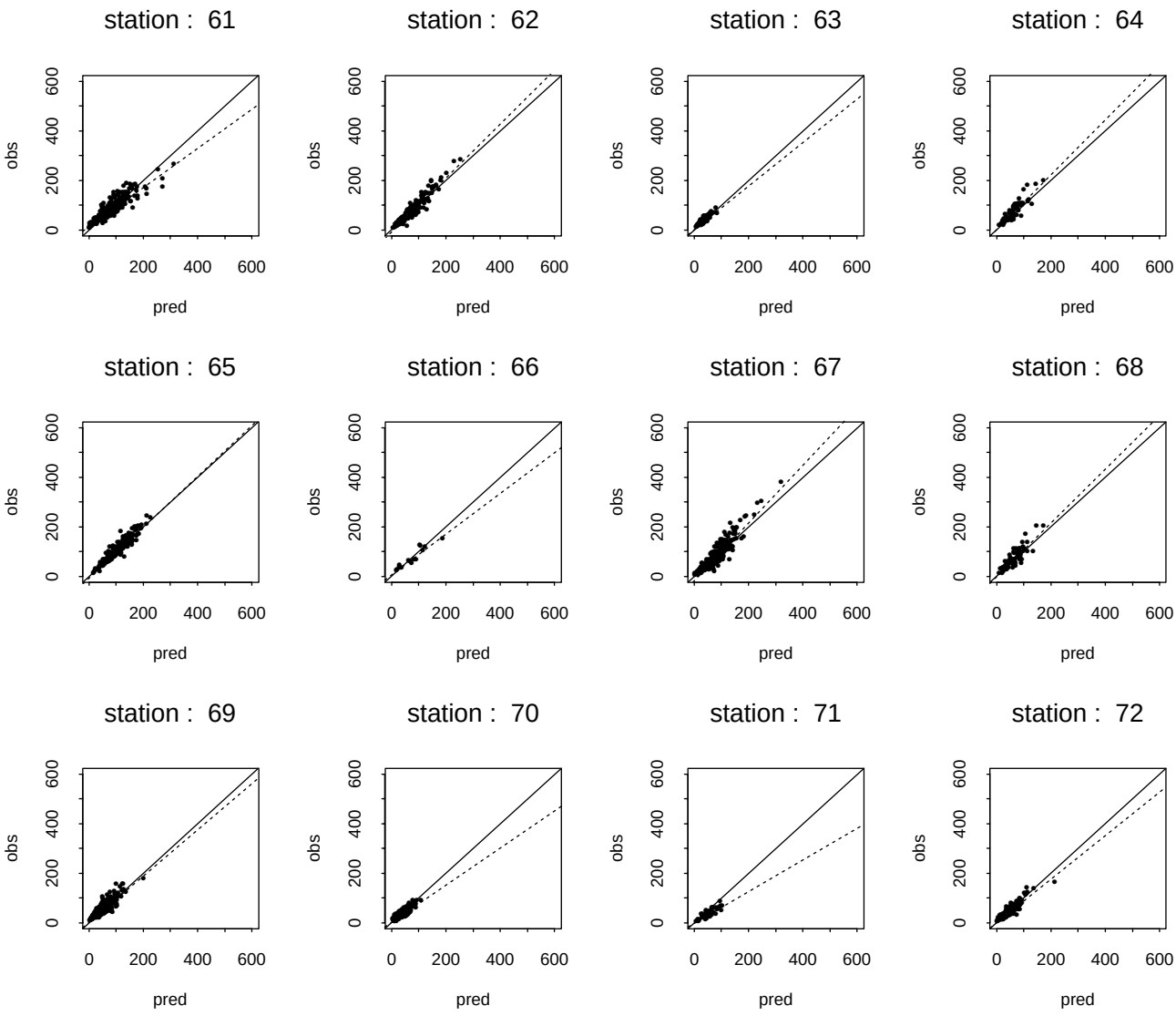

station : 1
station : 2
station : 3
station : 4
station : 5
station : 6
station : 7
station : 8
station : 9
station : 10
station : 11
station : 12
obs
pred
0
200
400
600

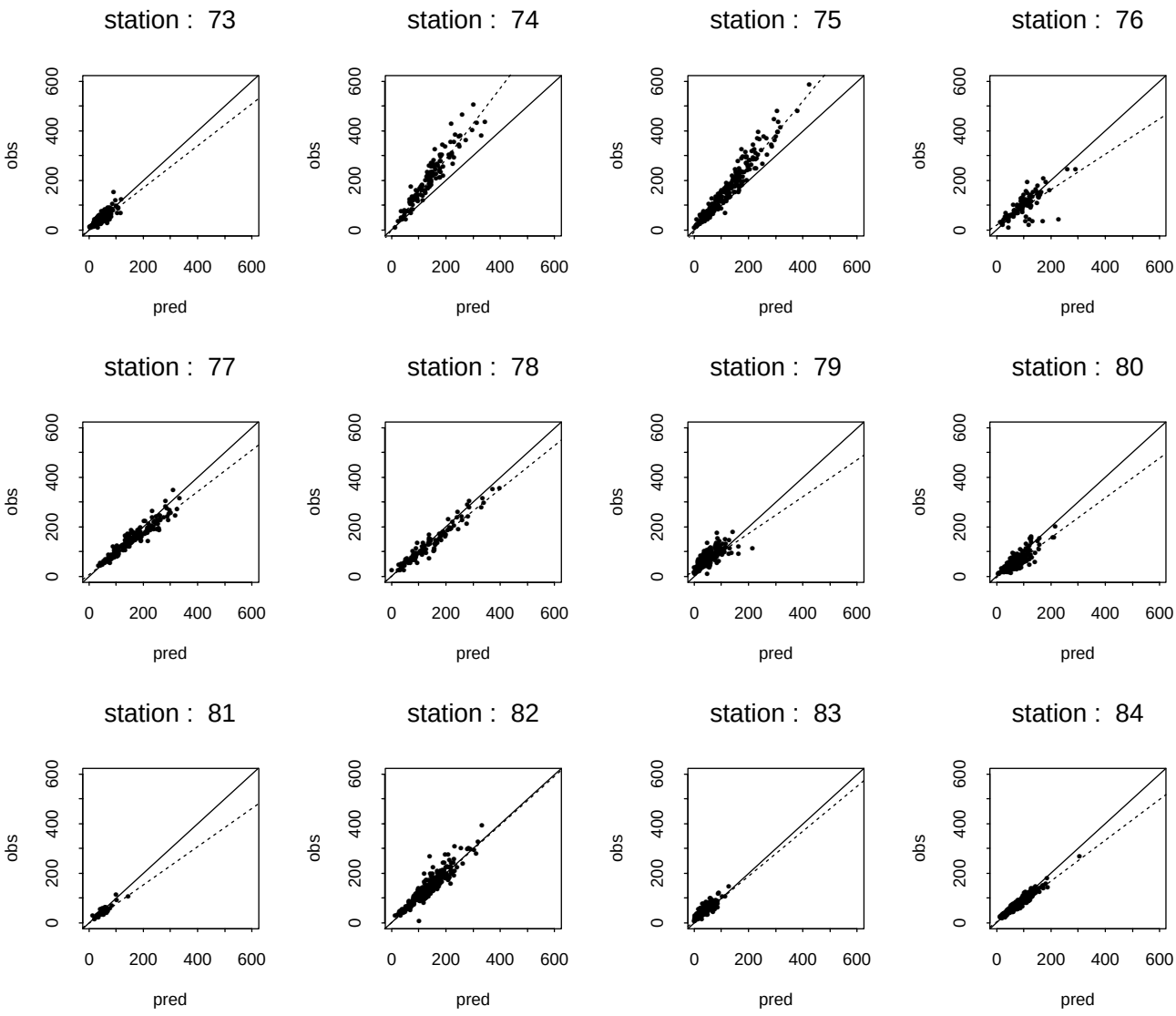

station : 13
station : 14
station : 15
station : 16
station : 17
station : 18
station : 19
station : 20
station : 21
station : 22
station : 23
station : 24
obs
pred
0
200
400
600

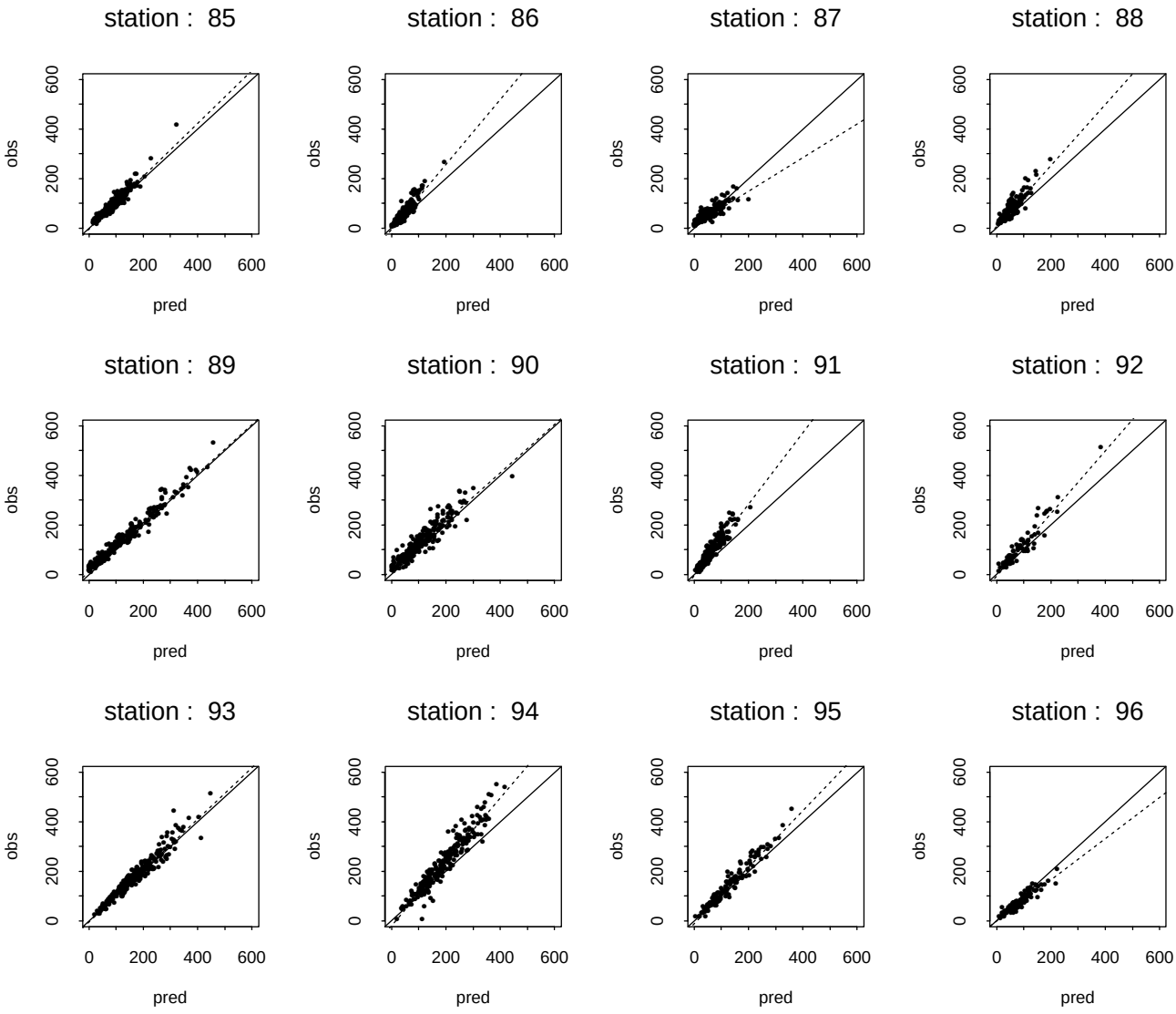

station : 25
station : 26
station : 27
station : 28
station : 29
station : 30
station : 31
station : 32
station : 33
station : 34
station : 35
station : 36
obs
pred
0
200
400
600

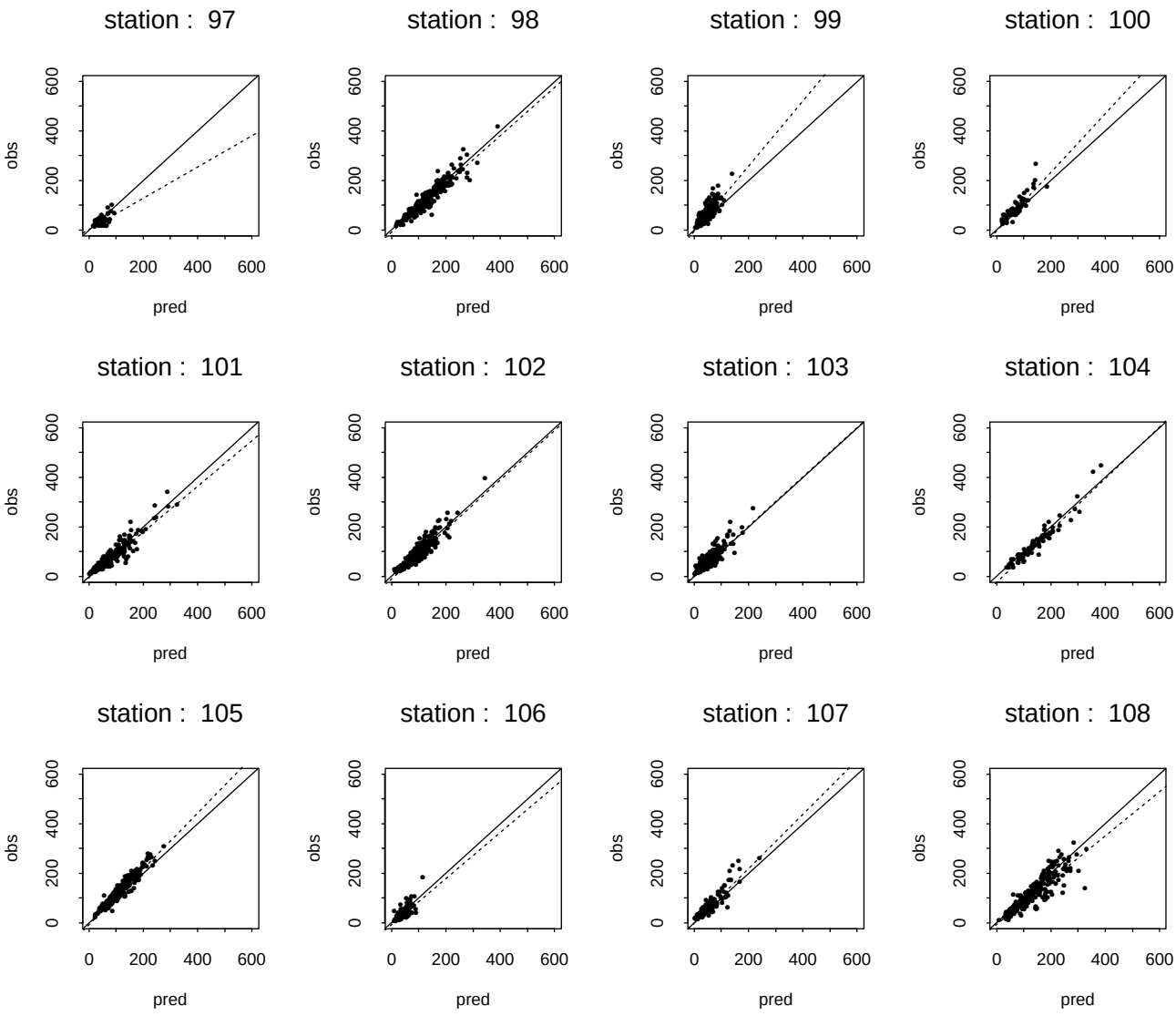

station : 37
station : 38
station : 39
station : 40
station : 41
station : 42
station : 43
station : 44
station : 45
station : 46
station : 47
station : 48
obs
pred
0
200
400
600

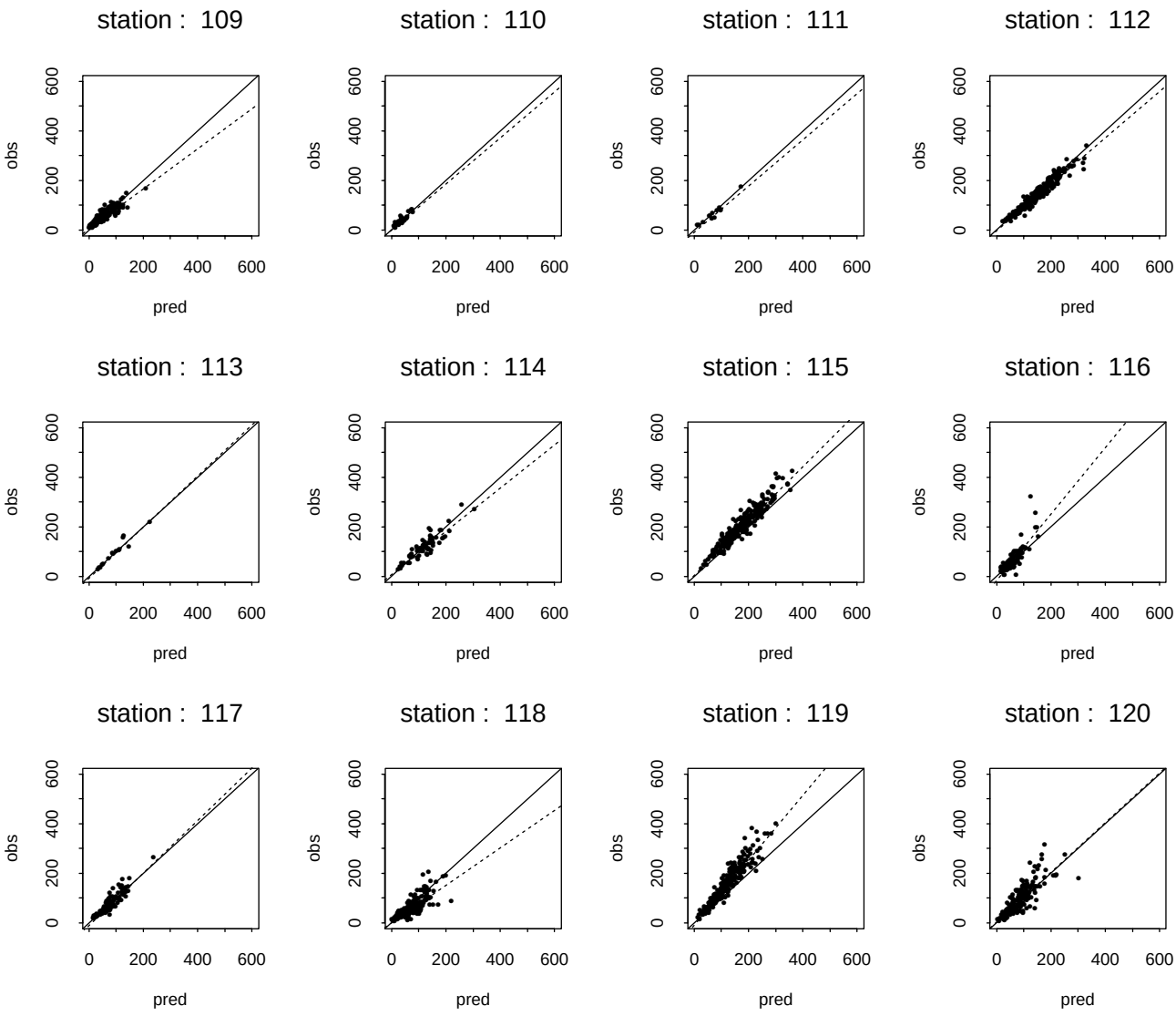

station : 49
station : 50
station : 51
station : 52
station : 53
station : 54
station : 55
station : 56
station : 57
station : 58
station : 59
station : 60
obs
pred
0
200
400
600

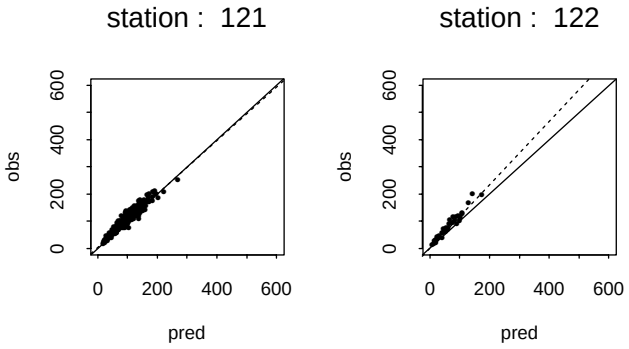

station : 61
station : 62
station : 63
station : 64
station : 65
station : 66
station : 67
station : 68
station : 69
station : 70
station : 71
station : 72
obs
pred
0
200
400
600


station : 73
station : 74
station : 75
station : 76
station : 77
station : 78
station : 79
station : 80
station : 81
station : 82
station : 83
station : 84
obs
pred
0
200
400
600


station : 85
station : 86
station : 87
station : 88
station : 89
station : 90
station : 91
station : 92
station : 93
station : 94
station : 95
station : 96
obs
pred
0
200
400
600


station : 97
station : 98
station : 99
station : 100
station : 101
station : 102
station : 103
station : 104
station : 105
station : 106
station : 107
station : 108
obs
pred
0
200
400
600


station : 109
station : 110
station : 111
station : 112
station : 113
station : 114
station : 115
station : 116
station : 117
station : 118
station : 119
station : 120
obs
pred
0
200
400
600

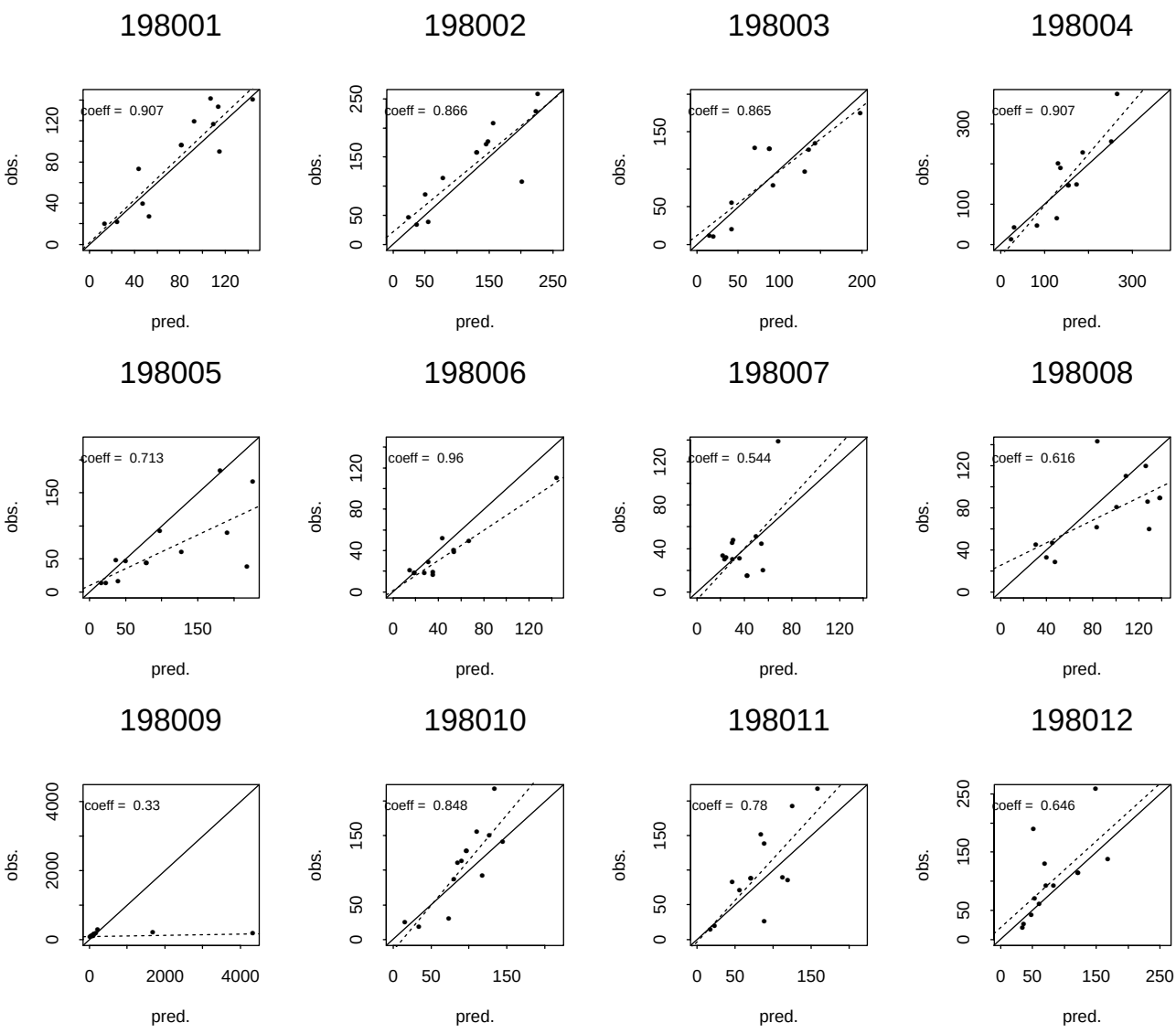

station : 121
station : 122
obs
pred
0
200
400
600

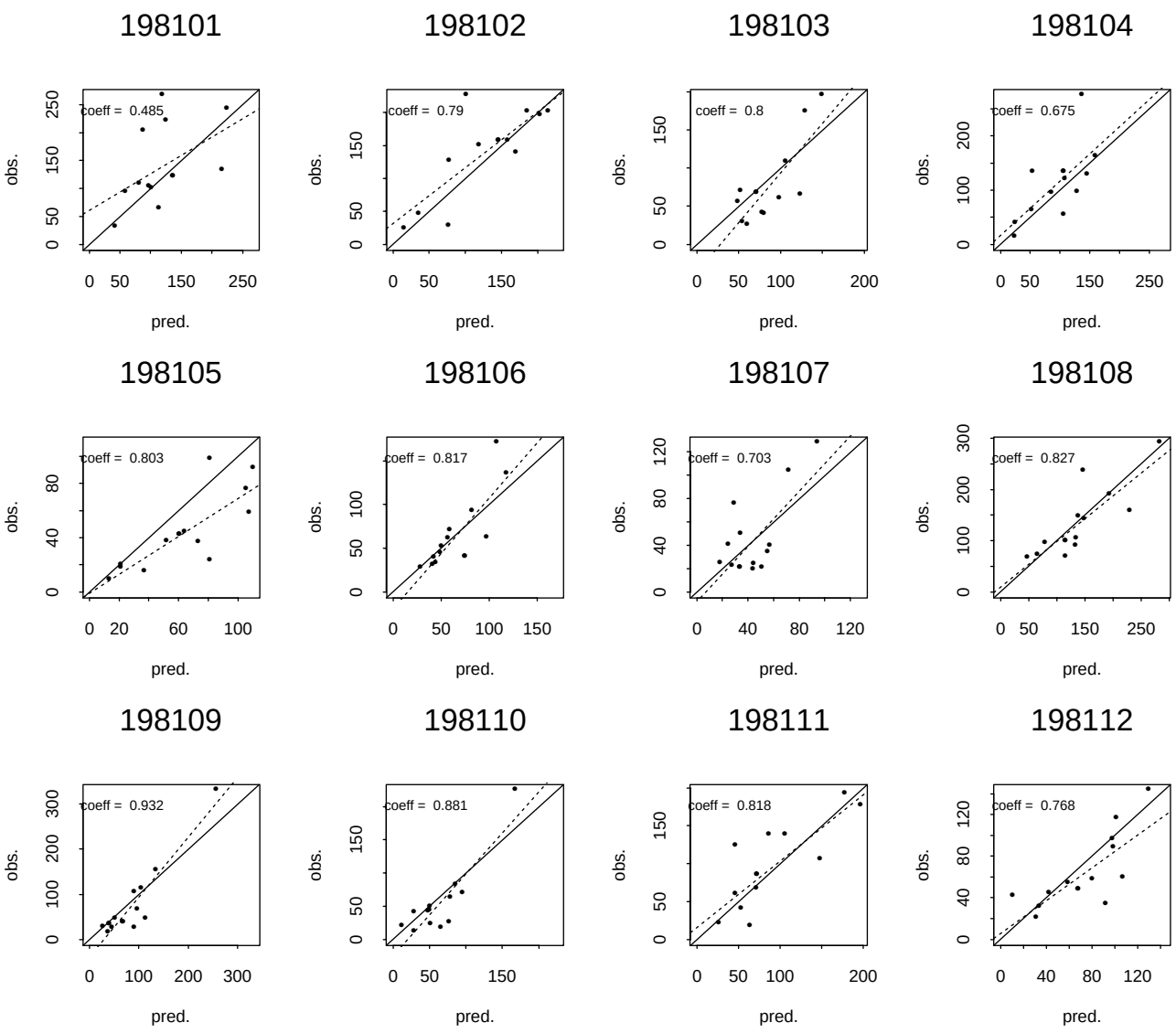
Appendix 6

Monthly precipitation

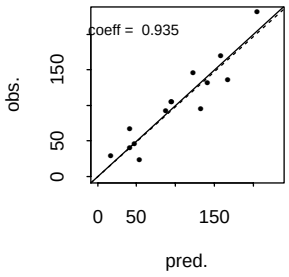
Validation procedure

Scatter plots for the period 1980-2000

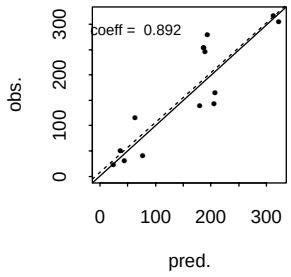

198001
coeff = 0.907
198002
coeff = 0.866
198003
coeff = 0.865
198004
coeff = 0.907
198005
coeff = 0.713
198006
coeff = 0.96
198007
coeff = 0.544
198008
coeff = 0.616
198009
coeff = 0.33
198010
coeff = 0.848
198011
coeff = 0.78
198012
coeff = 0.646
obs.
pred.


198101
coeff = 0.485
198102
coeff = 0.79
198103
coeff = 0.8
198104
coeff = 0.675
198105
coeff = 0.803
198106
coeff = 0.817
198107
coeff = 0.703
198108
coeff = 0.827
198109
coeff = 0.932
198110
coeff = 0.881
198111
coeff = 0.818
198112
coeff = 0.768
obs.
pred.

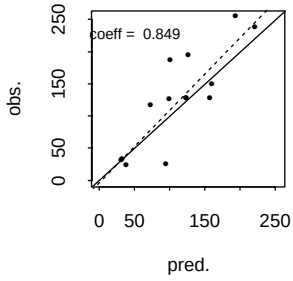
198201



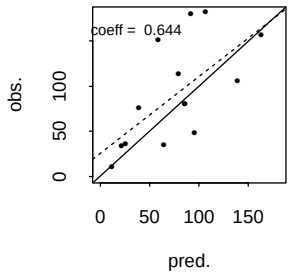
198202



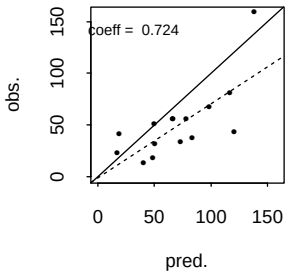
198203



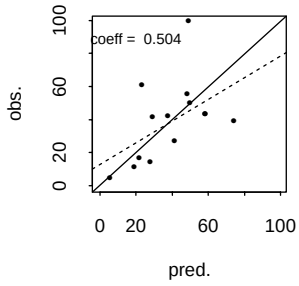
198204



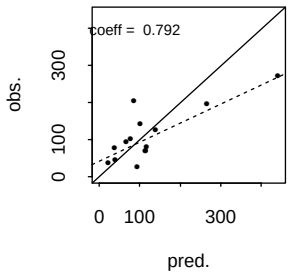
198205



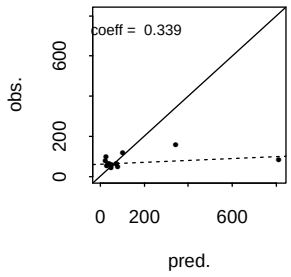
198206



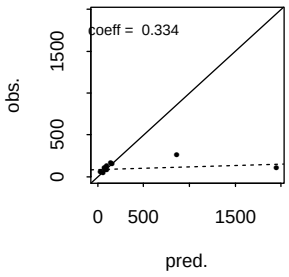
198207



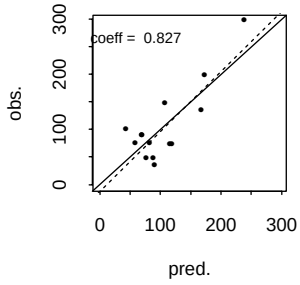
198208



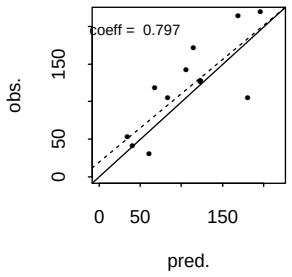
198209



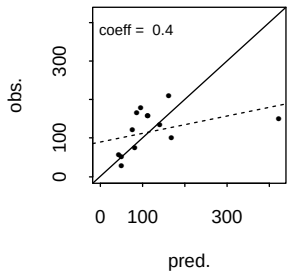
198210



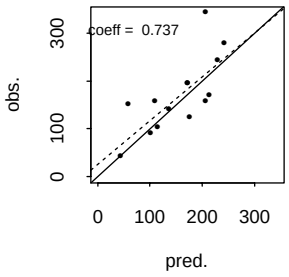
198211



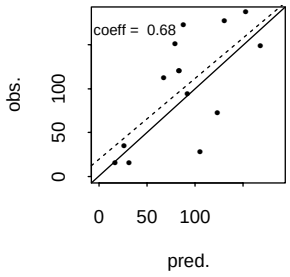
198212



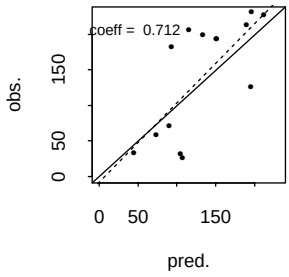
198301



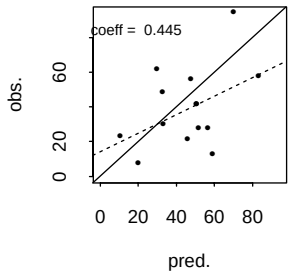
198302



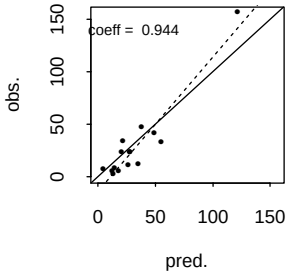
198303



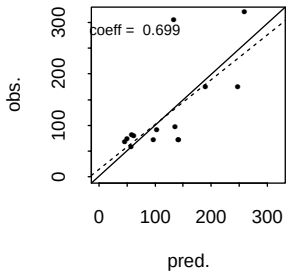
198304



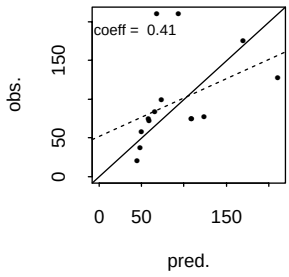
198305



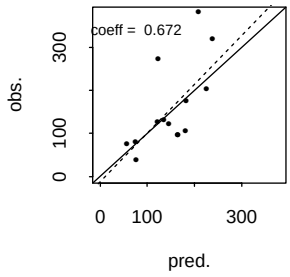
198306



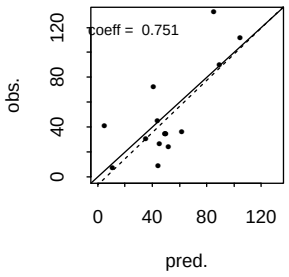
198307



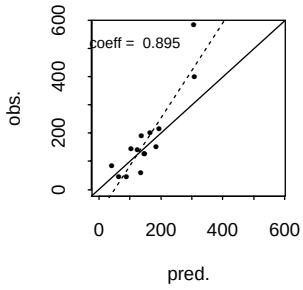
198308



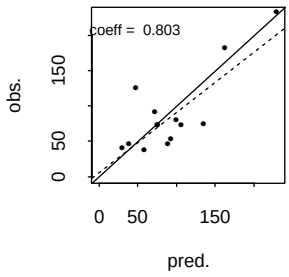
198309



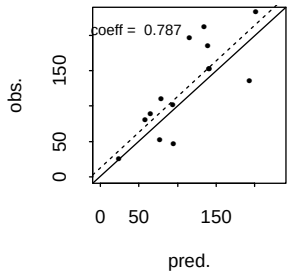
198310

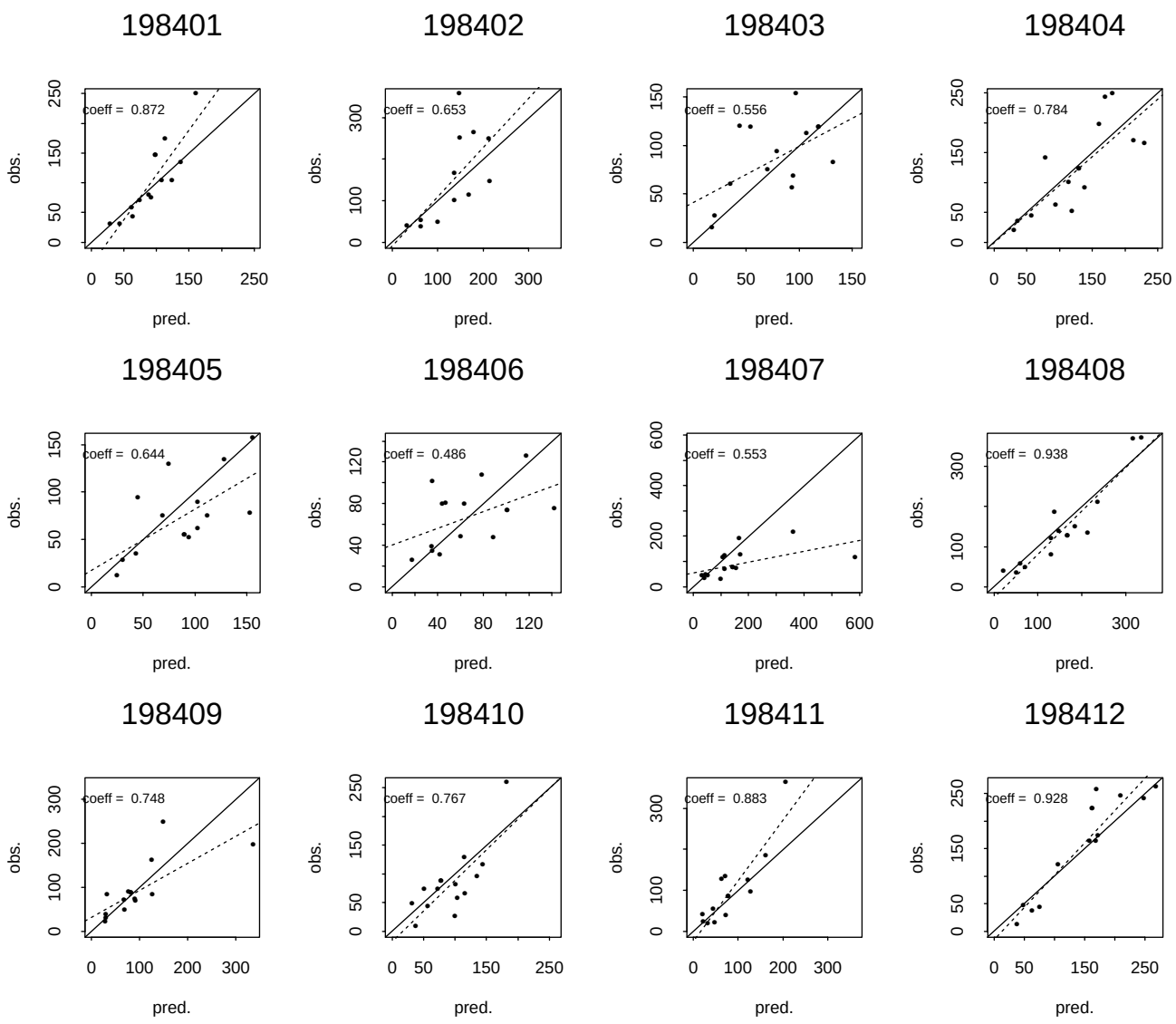


198311

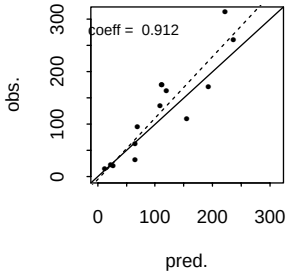


198312

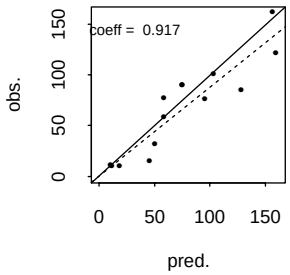



198401
coeff = 0.872
198402
coeff = 0.653
198403
coeff = 0.556
198404
coeff = 0.784
198405
coeff = 0.644
198406
coeff = 0.486
198407
coeff = 0.553
198408
coeff = 0.938
198409
coeff = 0.748
198410
coeff = 0.767
198411
coeff = 0.883
198412
coeff = 0.928
obs.
pred.

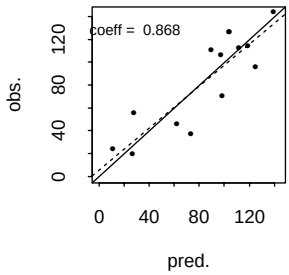
198501



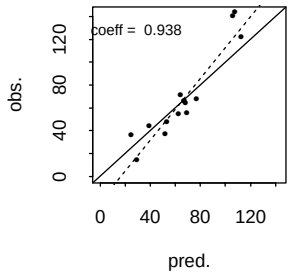
198502



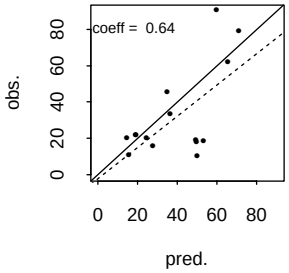
198503



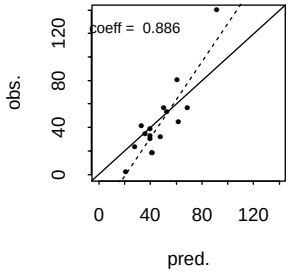
198504



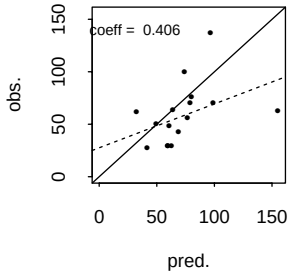
198505



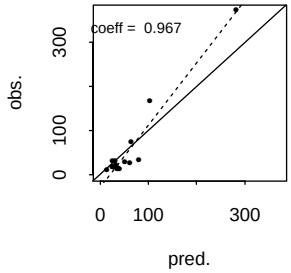
198506



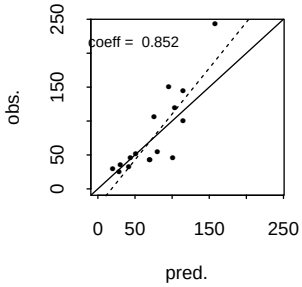
198507



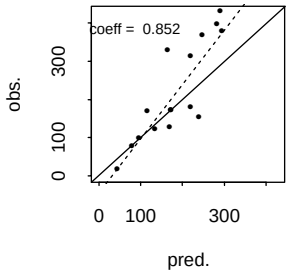
198508



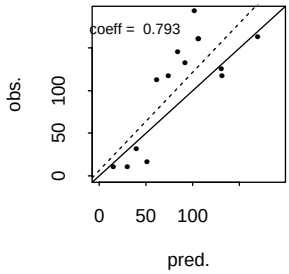
198509



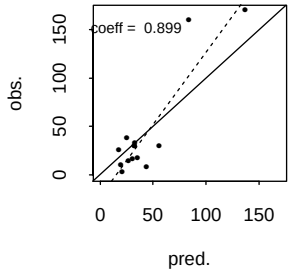
198510

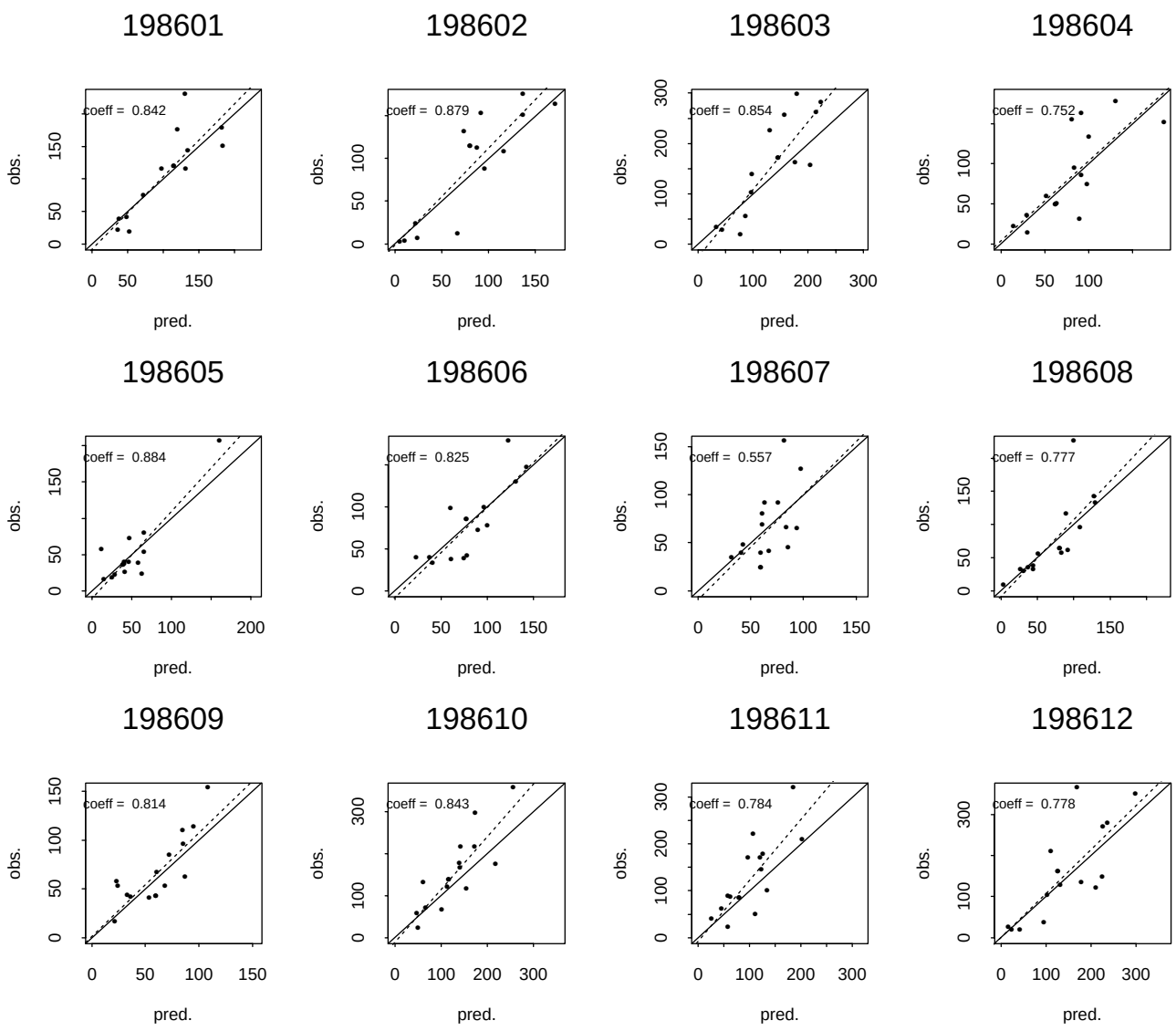


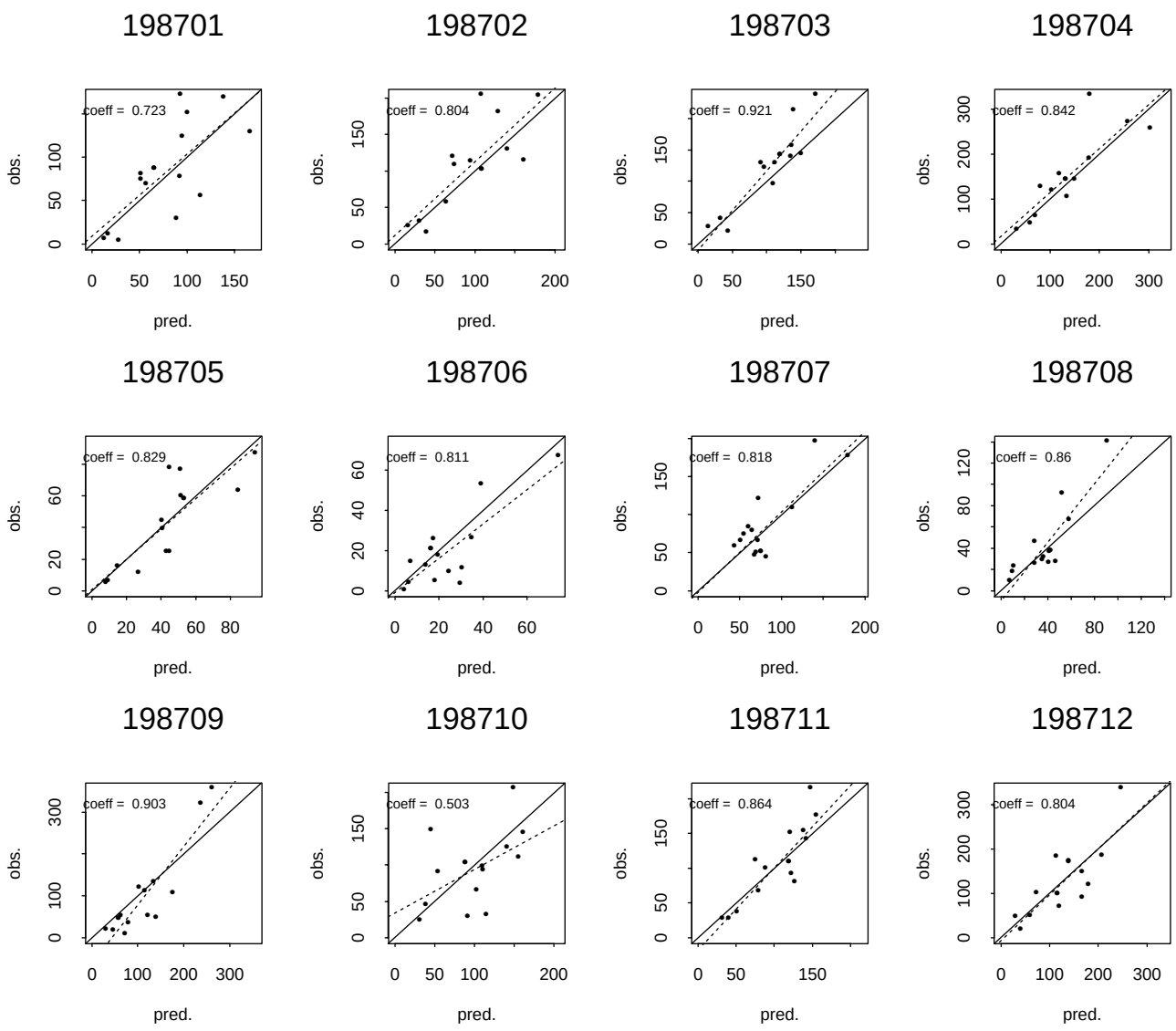
198511

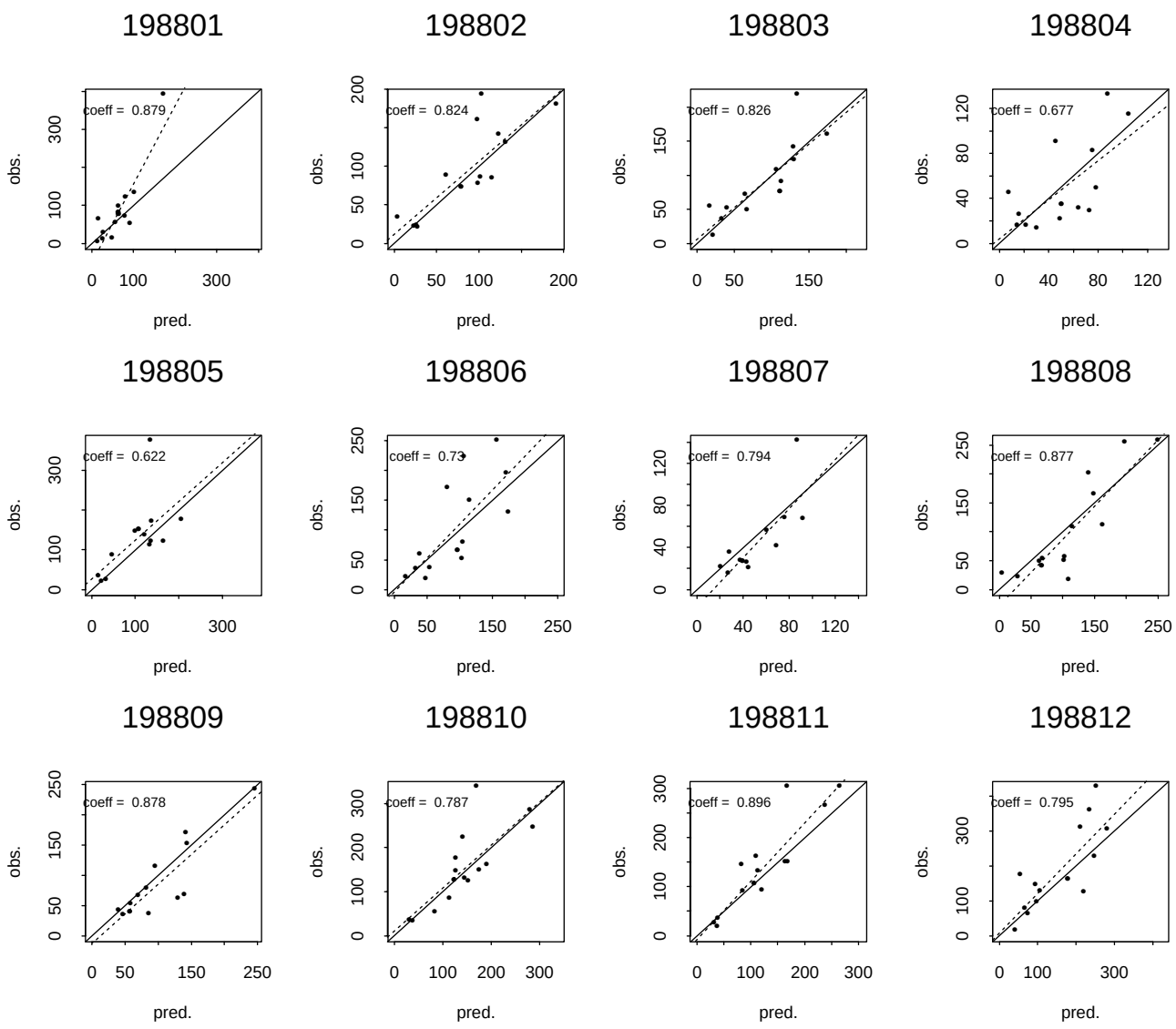


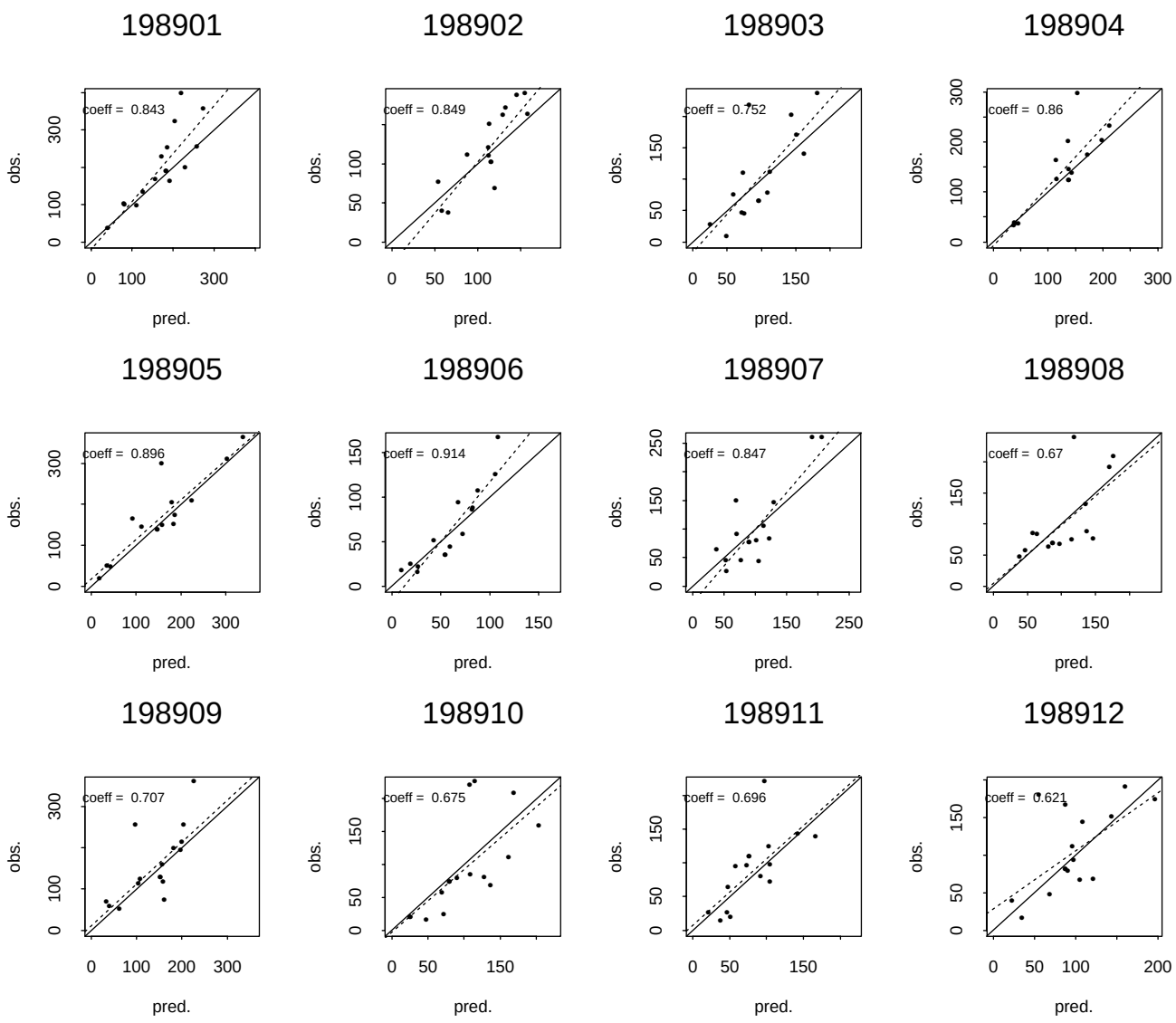
198512

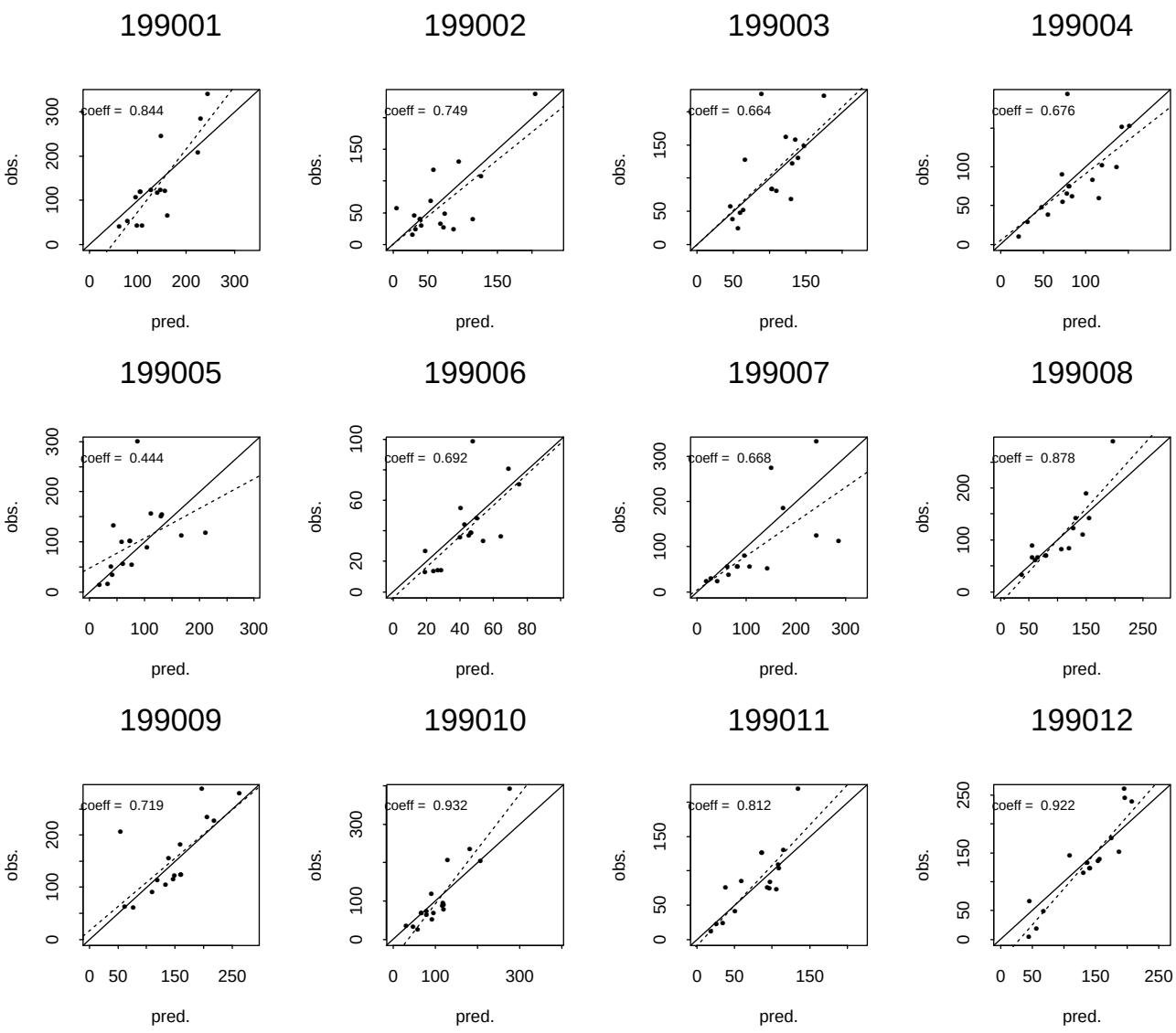


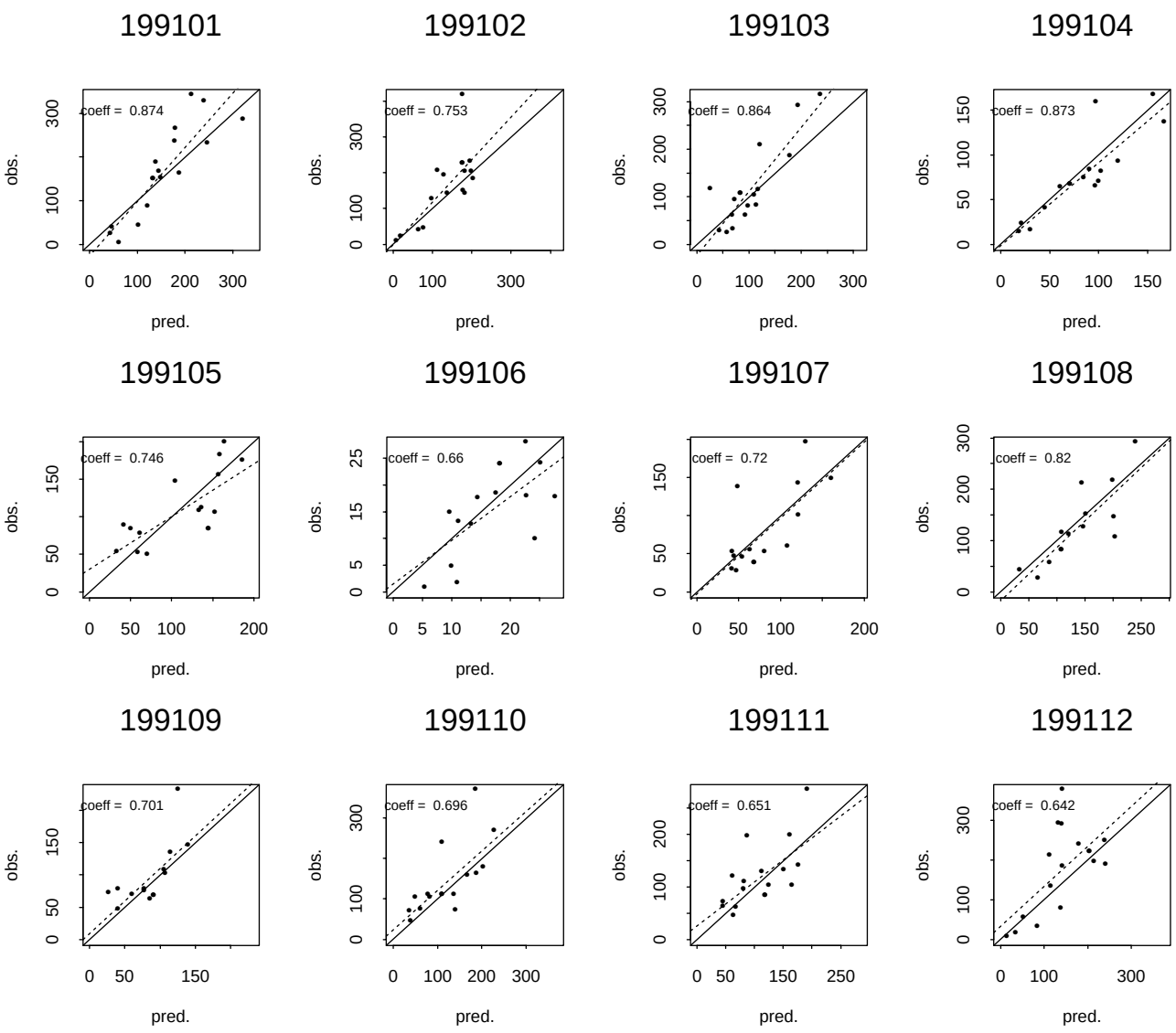

198601
coeff = 0.842
198602
coeff = 0.879
198603
coeff = 0.854
198604
coeff = 0.752
198605
coeff = 0.884
198606
coeff = 0.825
198607
coeff = 0.557
198608
coeff = 0.777
198609
coeff = 0.814
198610
coeff = 0.843
198611
coeff = 0.784
198612
coeff = 0.778
obs.
pred.

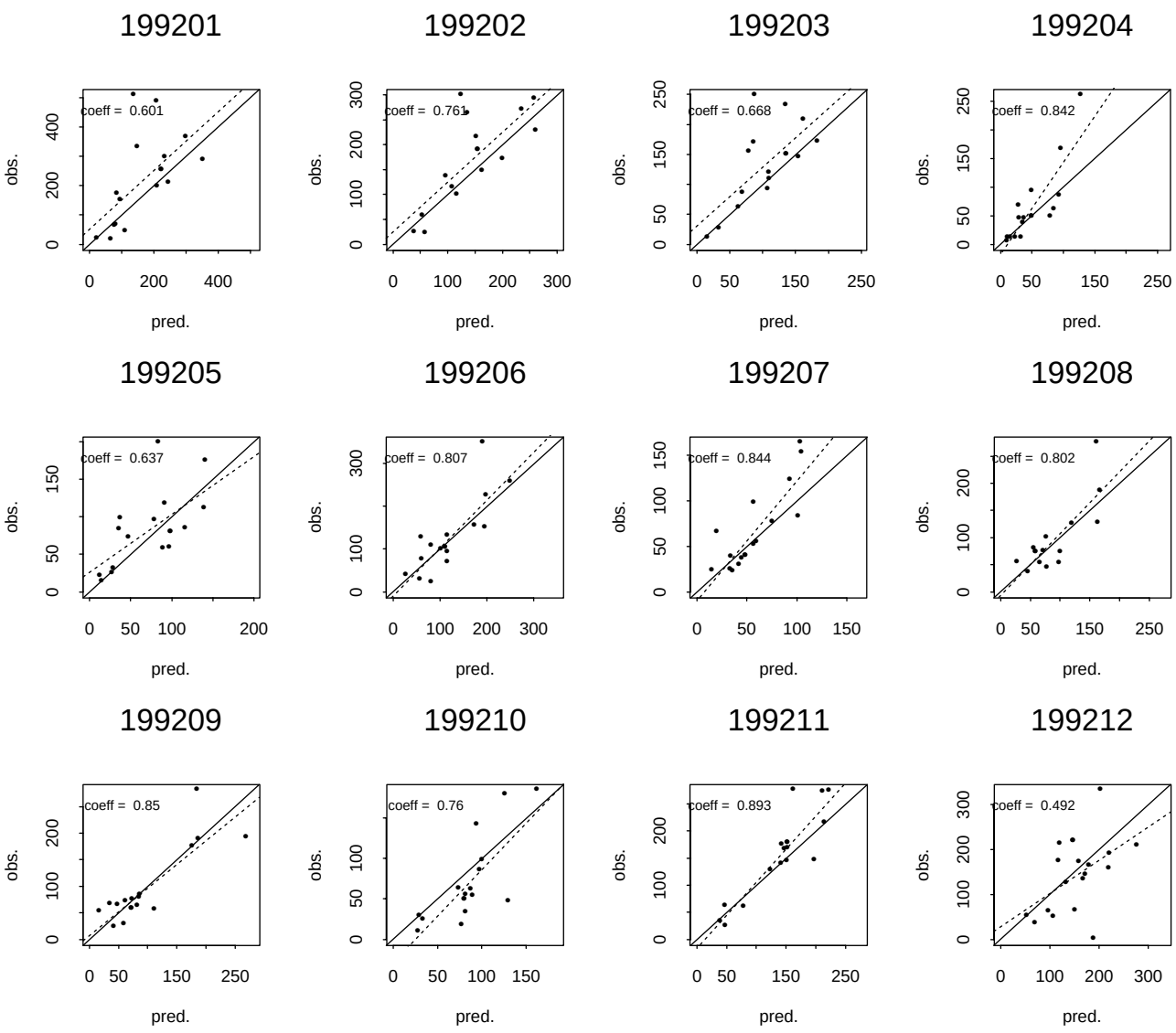

198701
coeff = 0.723
198702
coeff = 0.804
198703
coeff = 0.921
198704
coeff = 0.842
198705
coeff = 0.829
198706
coeff = 0.811
198707
coeff = 0.818
198708
coeff = 0.86
198709
coeff = 0.903
198710
coeff = 0.503
198711
coeff = 0.864
198712
coeff = 0.804
obs.
pred.

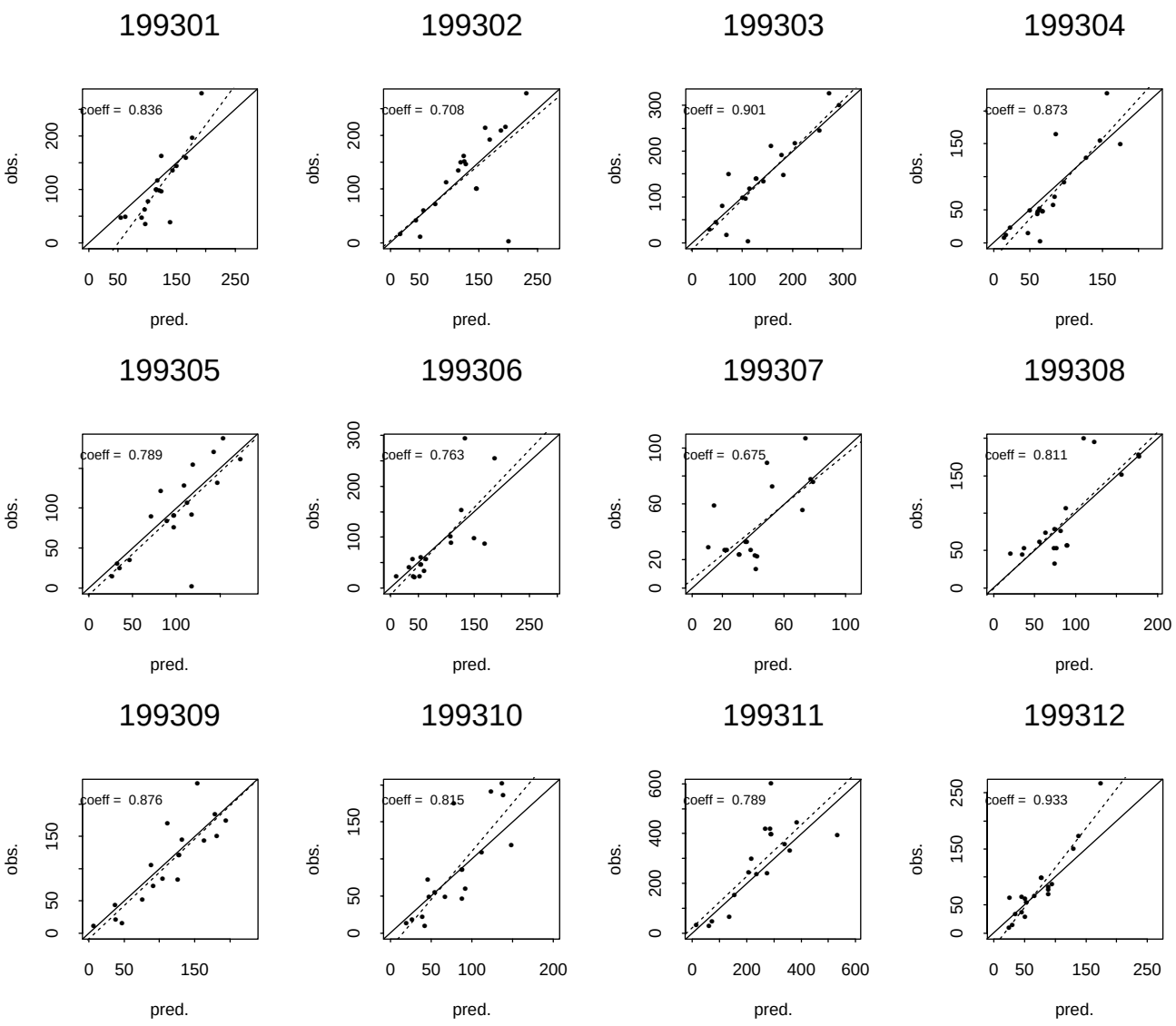

198801
coeff = 0.879
198802
coeff = 0.824
198803
coeff = 0.826
198804
coeff = 0.677
198805
coeff = 0.622
198806
coeff = 0.73
198807
coeff = 0.794
198808
coeff = 0.877
198809
coeff = 0.878
198810
coeff = 0.787
198811
coeff = 0.896
198812
coeff = 0.795
obs.
pred.


198901
coeff = 0.843
198902
coeff = 0.849
198903
coeff = 0.752
198904
coeff = 0.86
198905
coeff = 0.896
198906
coeff = 0.914
198907
coeff = 0.847
198908
coeff = 0.67
198909
coeff = 0.707
198910
coeff = 0.675
198911
coeff = 0.696
198912
coeff = 0.621
obs.
pred.


199001
coeff = 0.844
199002
coeff = 0.749
199003
coeff = 0.664
199004
coeff = 0.676
199005
coeff = 0.444
199006
coeff = 0.692
199007
coeff = 0.668
199008
coeff = 0.878
199009
coeff = 0.719
199010
coeff = 0.932
199011
coeff = 0.812
199012
coeff = 0.922
obs.
pred.


199101
coeff = 0.874
199102
coeff = 0.753
199103
coeff = 0.864
199104
coeff = 0.873
199105
coeff = 0.746
199106
coeff = 0.66
199107
coeff = 0.72
199108
coeff = 0.82
199109
coeff = 0.701
199110
coeff = 0.696
199111
coeff = 0.651
199112
coeff = 0.642
obs.
pred.


199201
coeff = 0.601
199202
coeff = 0.761
199203
coeff = 0.668
199204
coeff = 0.842
199205
coeff = 0.637
199206
coeff = 0.807
199207
coeff = 0.844
199208
coeff = 0.802
199209
coeff = 0.85
199210
coeff = 0.76
199211
coeff = 0.893
199212
coeff = 0.492
obs.
pred.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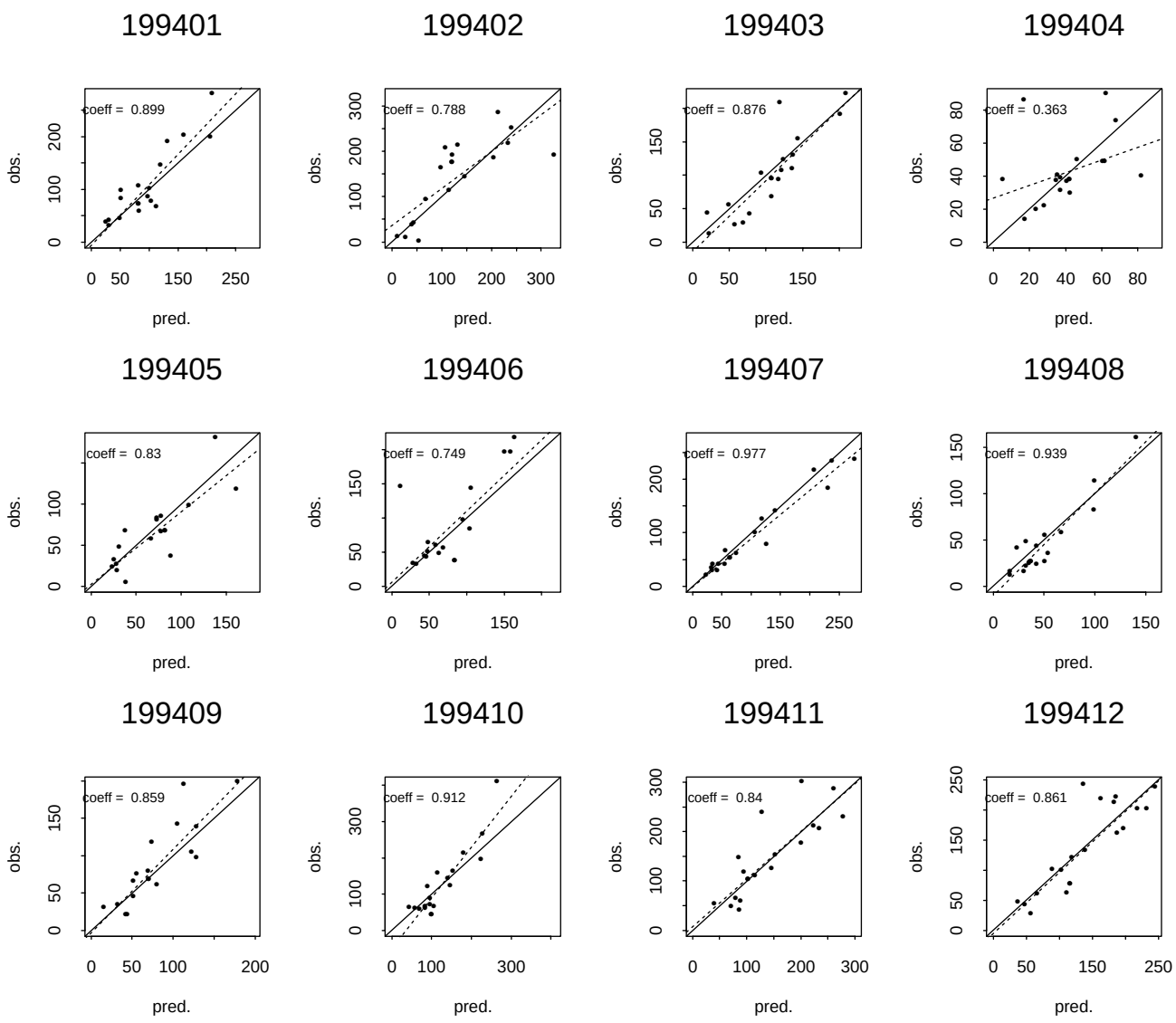
coeff = 0.836
199302
coeff = 0.708
199303
coeff = 0.901
199304
coeff = 0.873
199305
coeff = 0.789
199306
coeff = 0.763
199307
coeff = 0.675
199308
coeff = 0.811
199309
coeff = 0.876
199310
coeff = 0.815
199311
coeff = 0.789
199312
coeff = 0.933
obs.
pred.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coeff = 0.788
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coeff = 0.876
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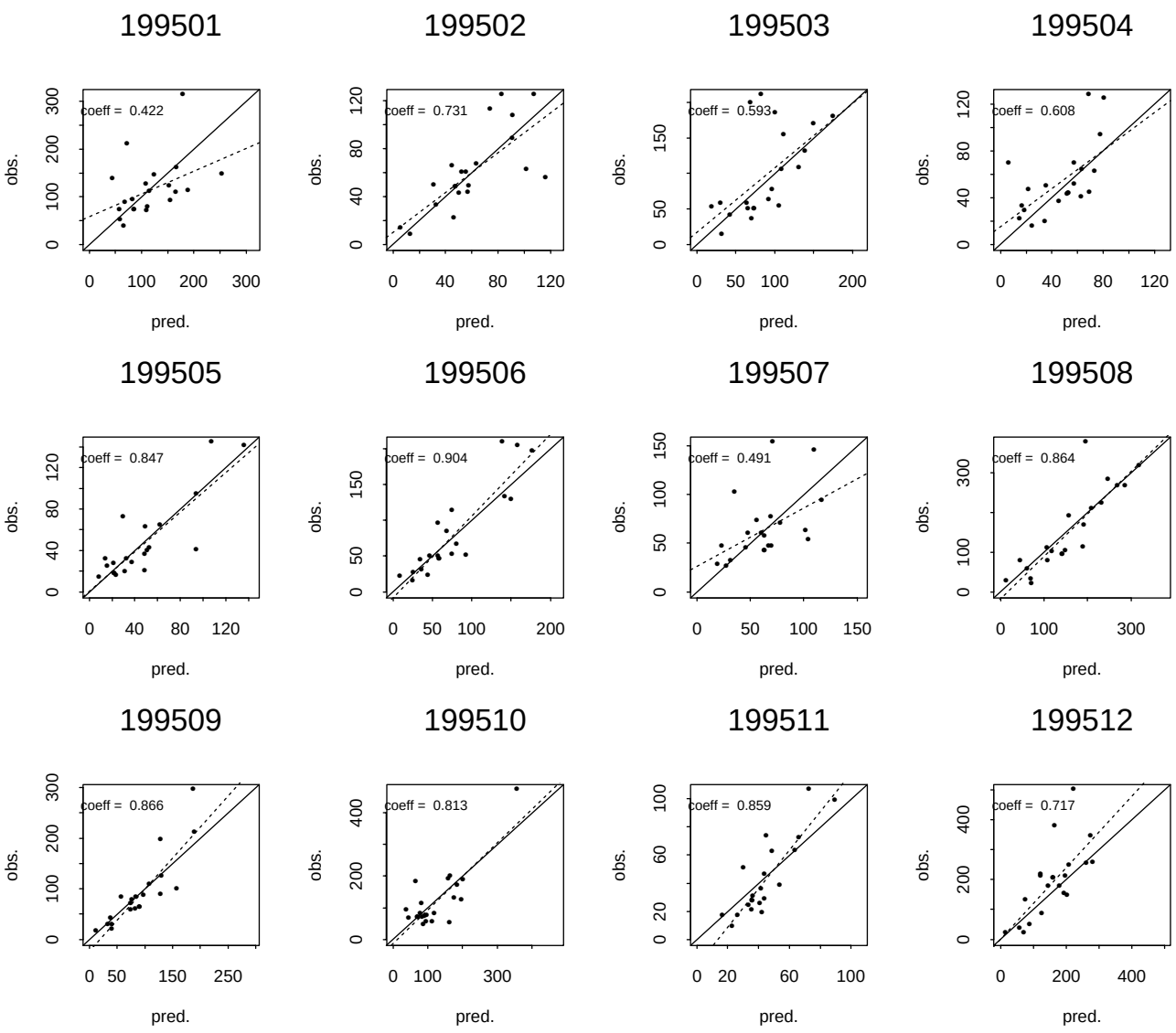
coeff = 0.363
199405
coeff = 0.83
199406
coeff = 0.749
199407
coeff = 0.977
199408
coeff = 0.939
199409
coeff = 0.859
199410
coeff = 0.912
199411
coeff = 0.84
199412
coeff = 0.861
obs.
pred.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coeff = 0.731
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coeff = 0.593
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coeff = 0.608
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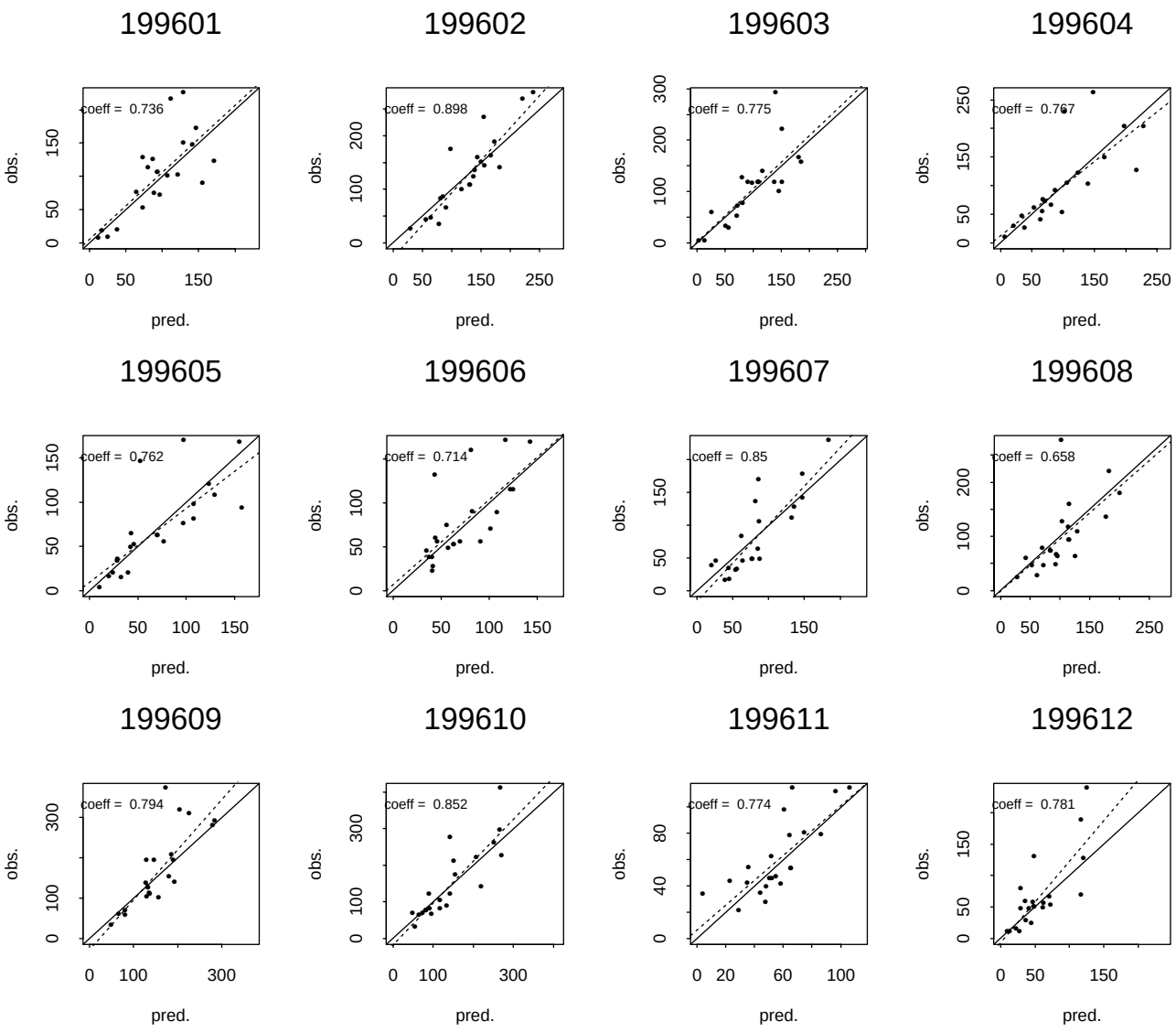
coeff = 0.847
199506
coeff = 0.904
199507
coeff = 0.491
199508
coeff = 0.864
199509
coeff = 0.866
199510
coeff = 0.813
199511
coeff = 0.859
199512
coeff = 0.717
obs.
pred.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coeff = 0.898
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coeff = 0.775
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coeff = 0.767
199605
coeff = 0.762
199606
coeff = 0.714
199607
coeff = 0.85
199608
coeff = 0.658
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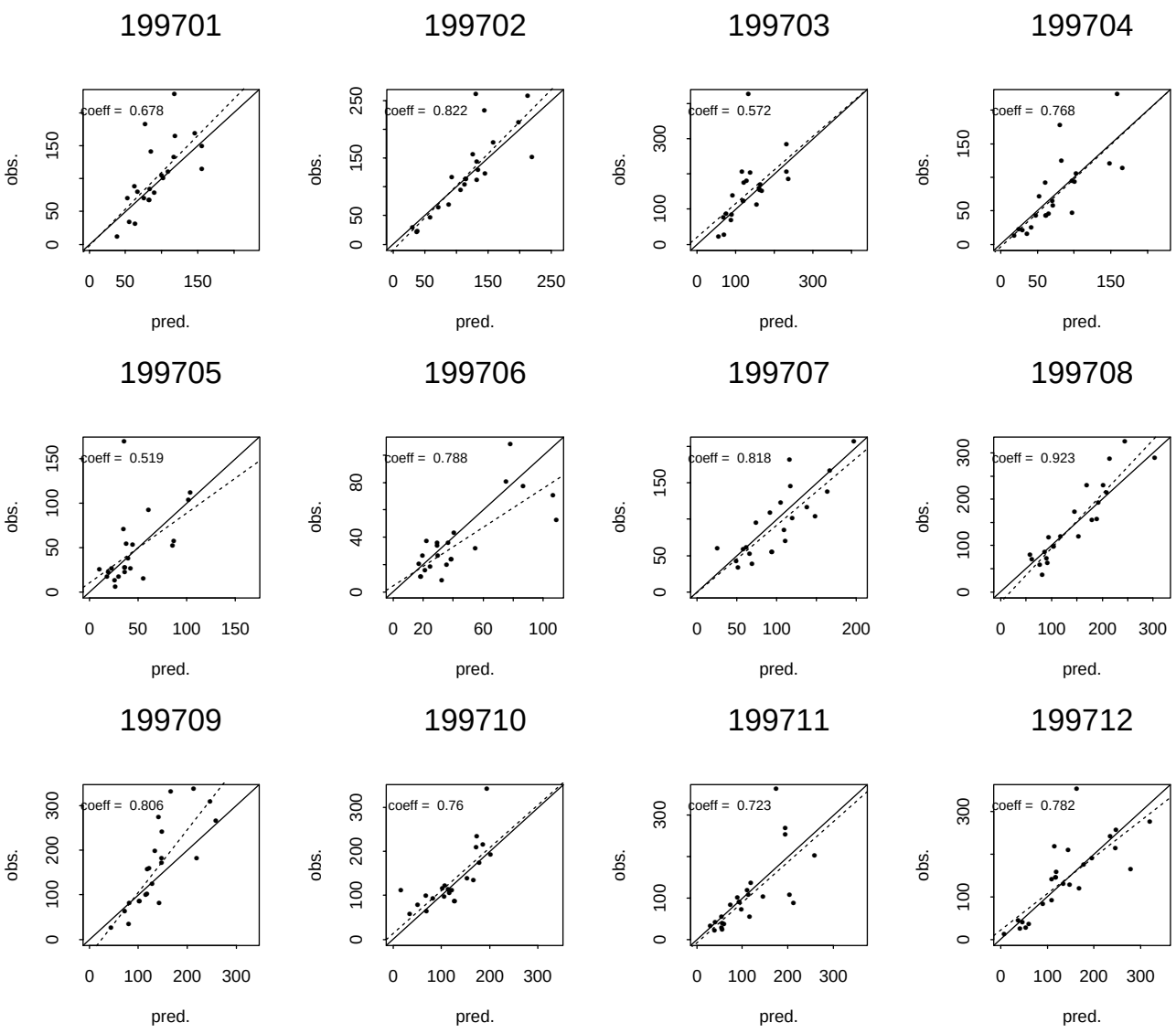
coeff = 0.794
199610
coeff = 0.852
199611
coeff = 0.774
199612
coeff = 0.781
obs.
pred.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coeff = 0.822
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coeff = 0.572
199704
coeff = 0.768
199705
coeff = 0.519
199706
coeff = 0.788
199707
coeff = 0.818
199708
coeff = 0.923
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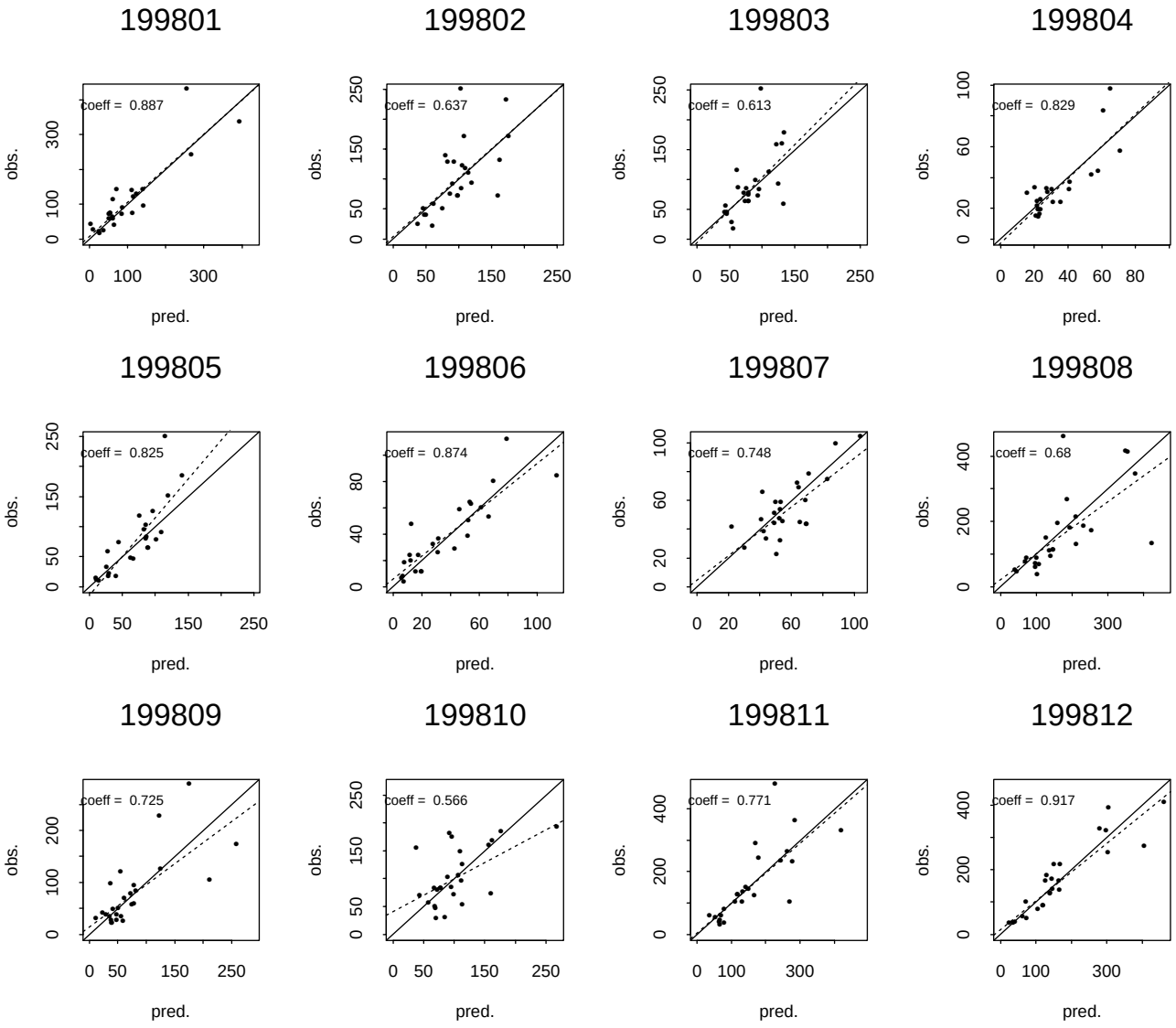
coeff = 0.806
199710
coeff = 0.76
199711
coeff = 0.723
199712
coeff = 0.782
obs.
pred.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coeff = 0.825
199806
coeff = 0.874
199807
coeff = 0.748
199808
coeff = 0.68
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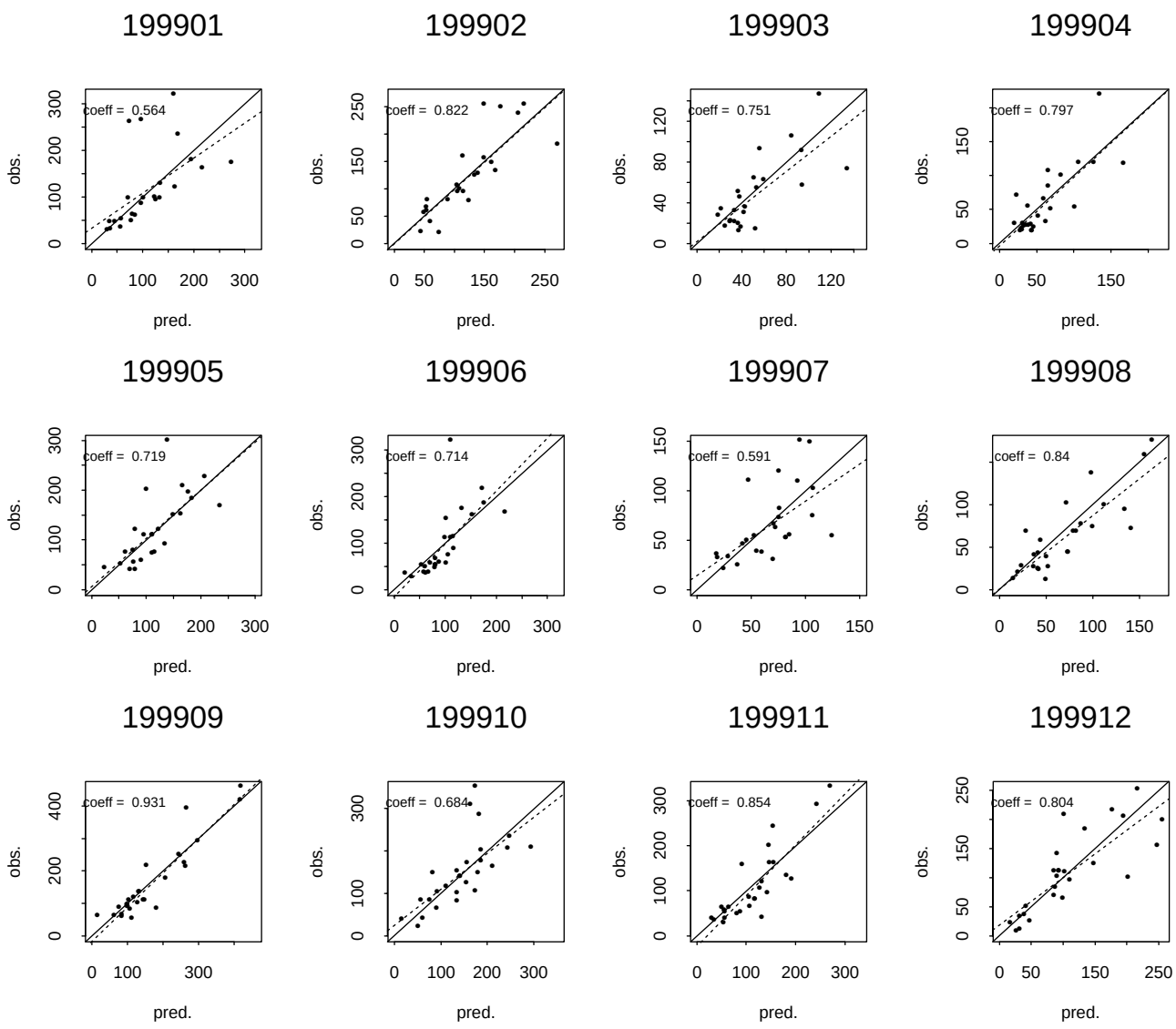
coeff = 0.725
199810
coeff = 0.566
199811
coeff = 0.771
199812
coeff = 0.917
obs.
pred.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coeff = 0.822
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coeff = 0.751
199904
coeff = 0.797
199905
coeff = 0.719
199906
coeff = 0.714
199907
coeff = 0.591
199908
coeff = 0.84
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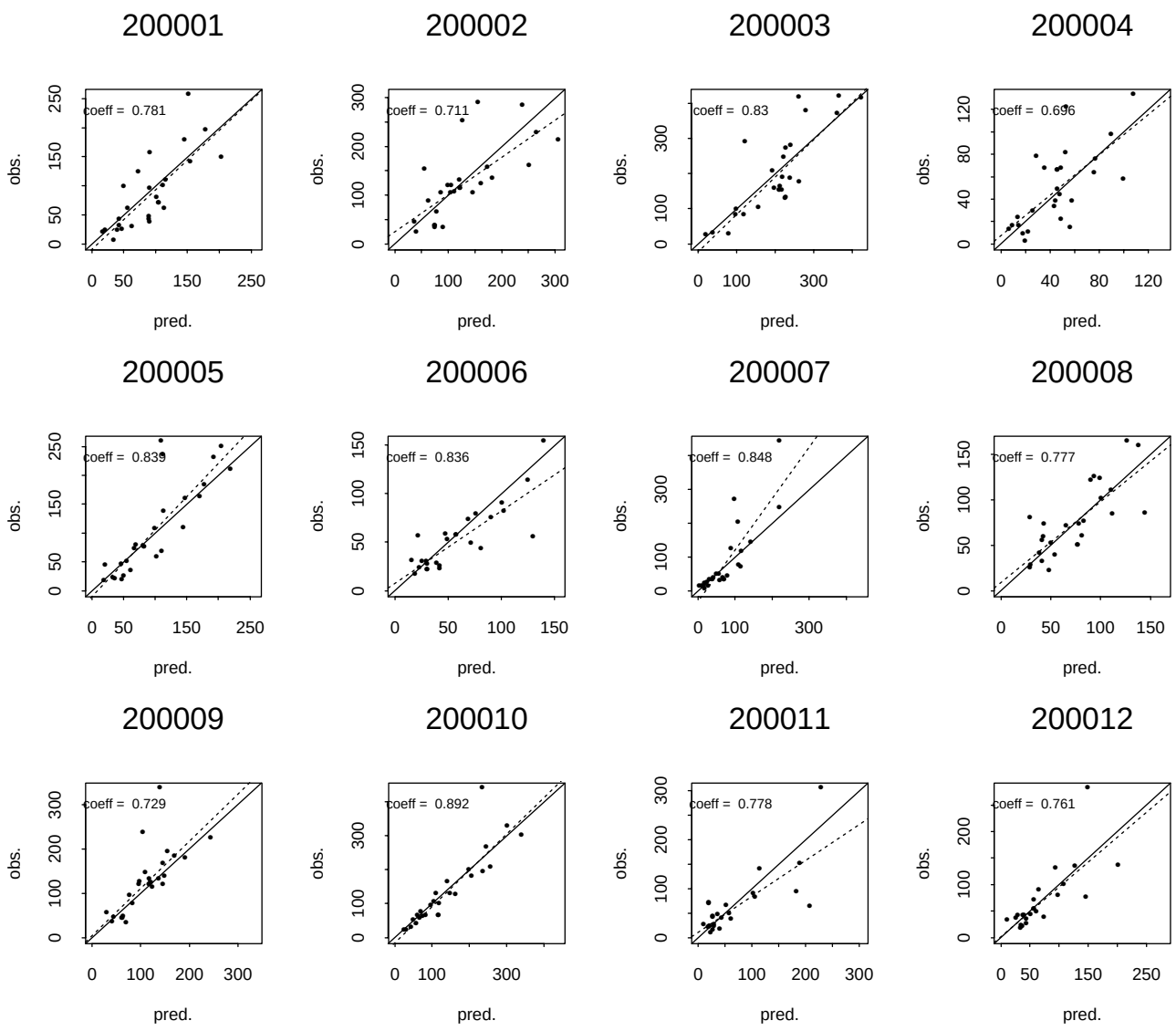
coeff = 0.931
199910
coeff = 0.684
199911
coeff = 0.854
199912
coeff = 0.804
obs.
pred.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coeff = 0.781
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coeff = 0.711
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coeff = 0.83
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coeff = 0.696
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coeff = 0.839
200006
coeff = 0.836
200007
coeff = 0.848
200008
coeff = 0.777
200009
coeff = 0.729
200010
coeff = 0.892
200011
coeff = 0.778
200012
coeff = 0.761
obs.
pred.

Appendix 7

Annual precipitation maps from 1980 to 2000
(4 km resolution)

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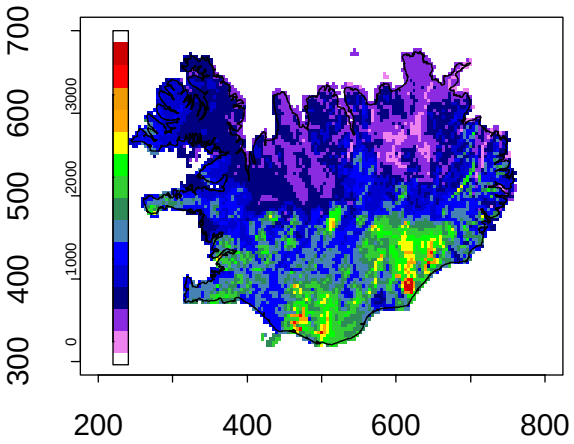

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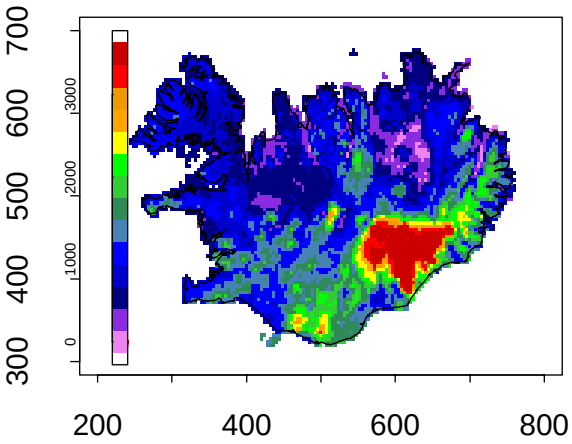

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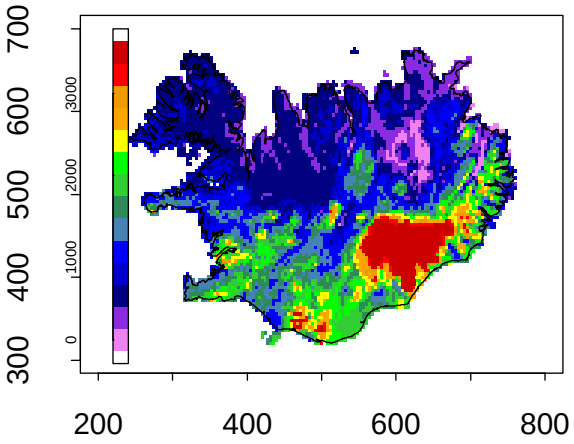

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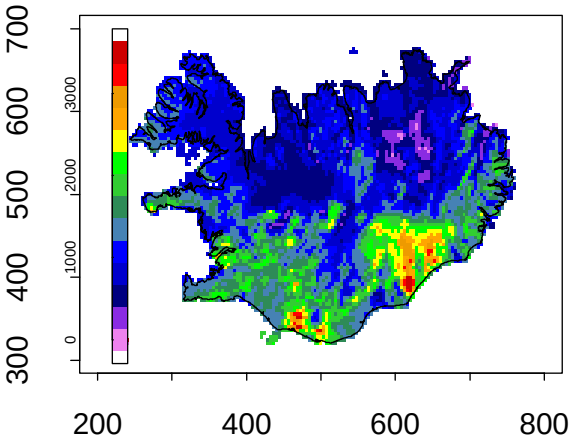

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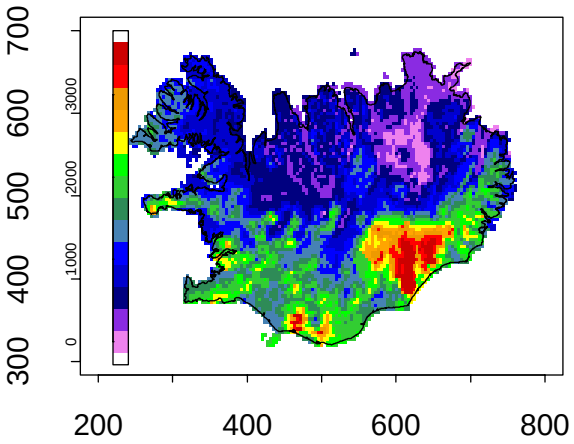

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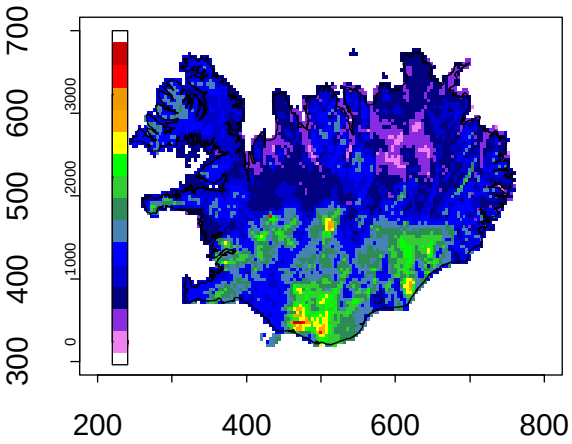

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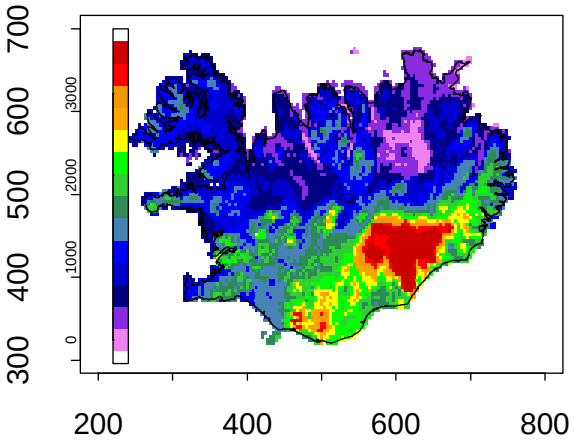

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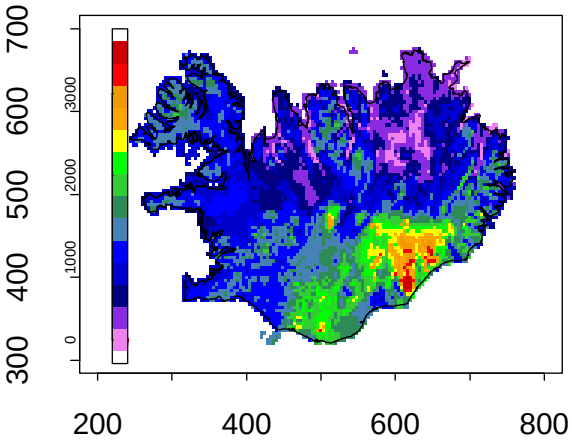

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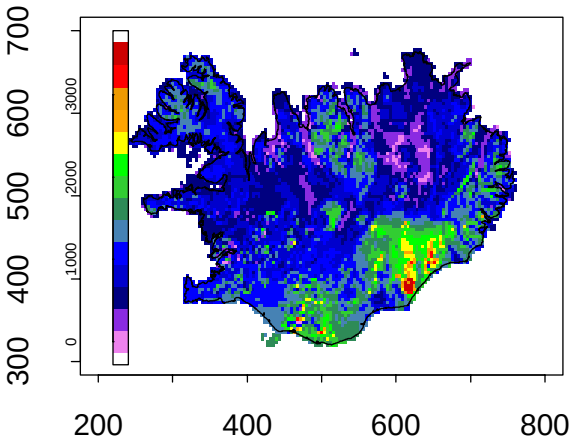

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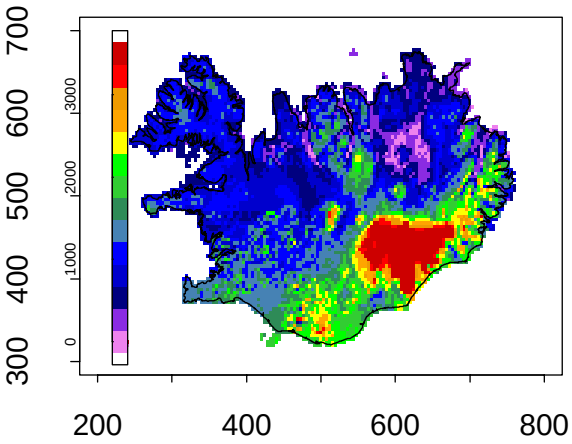

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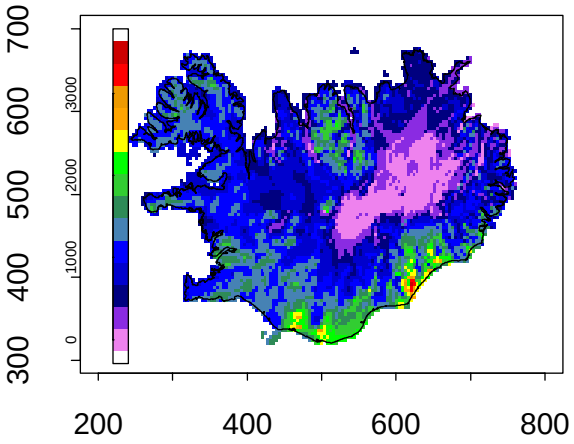

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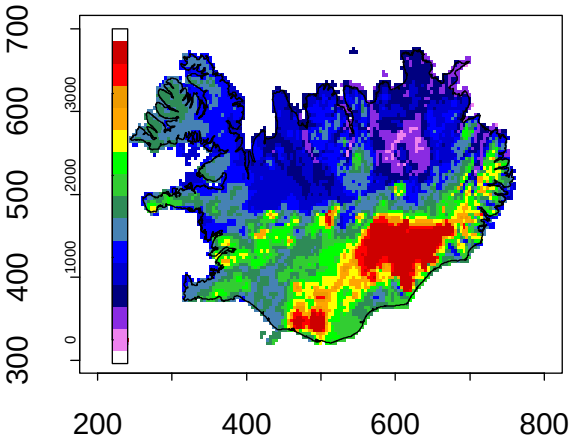

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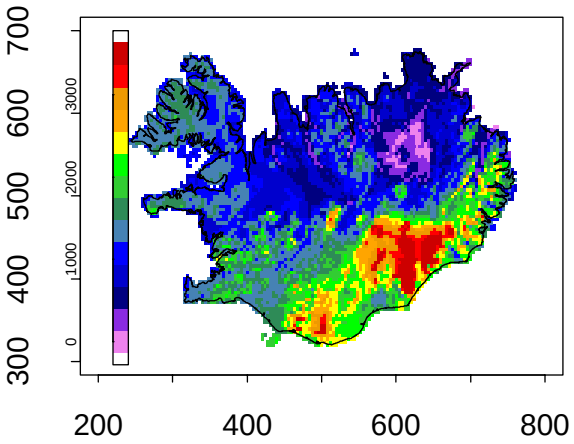

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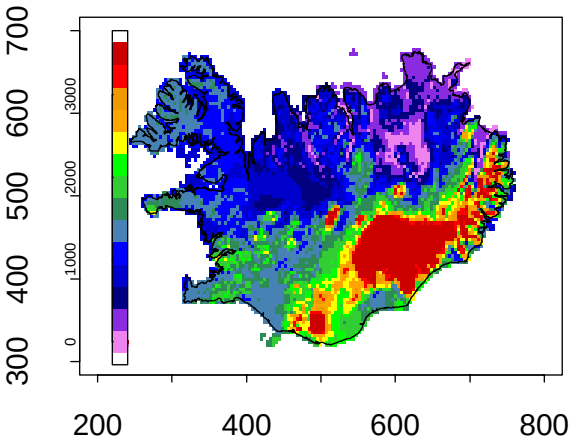

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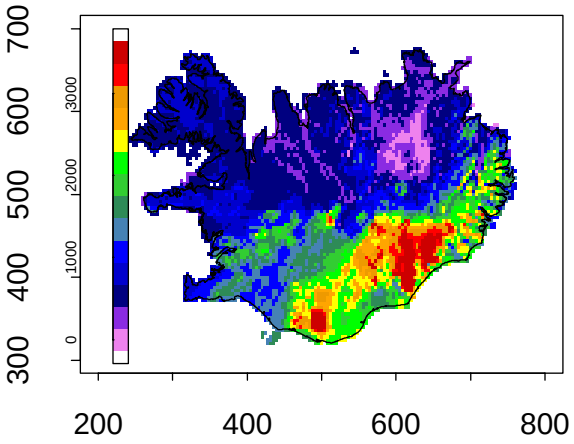

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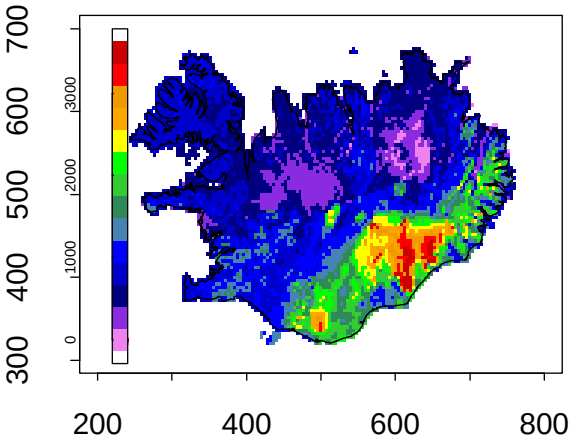

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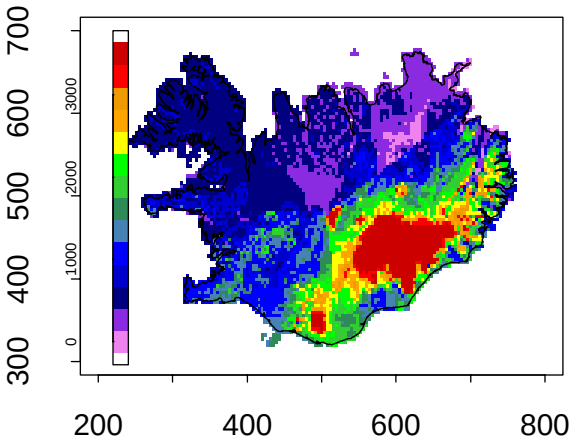

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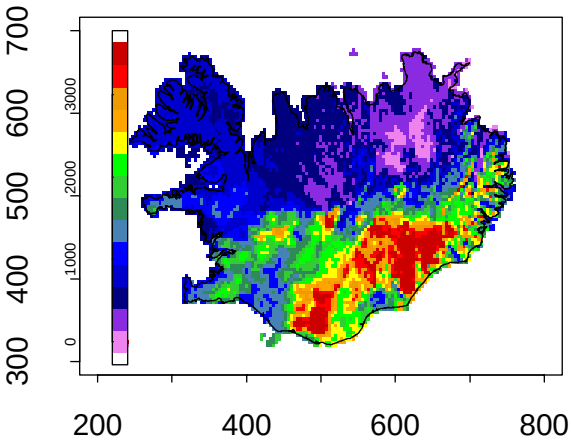

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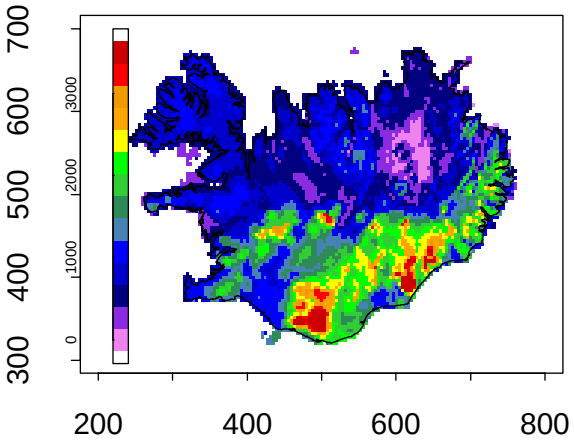

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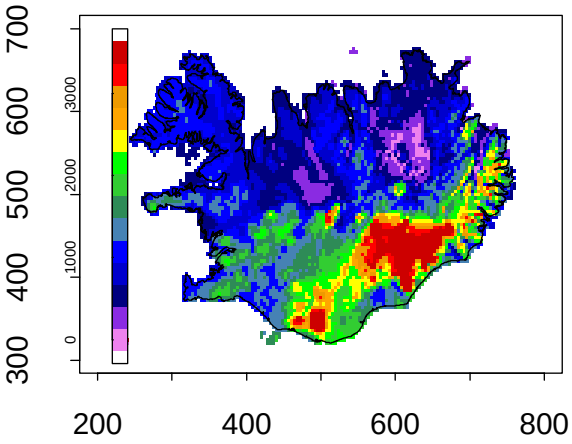

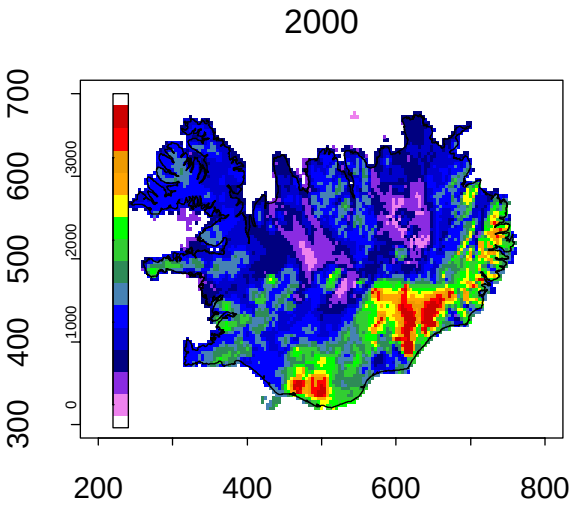
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3000
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200
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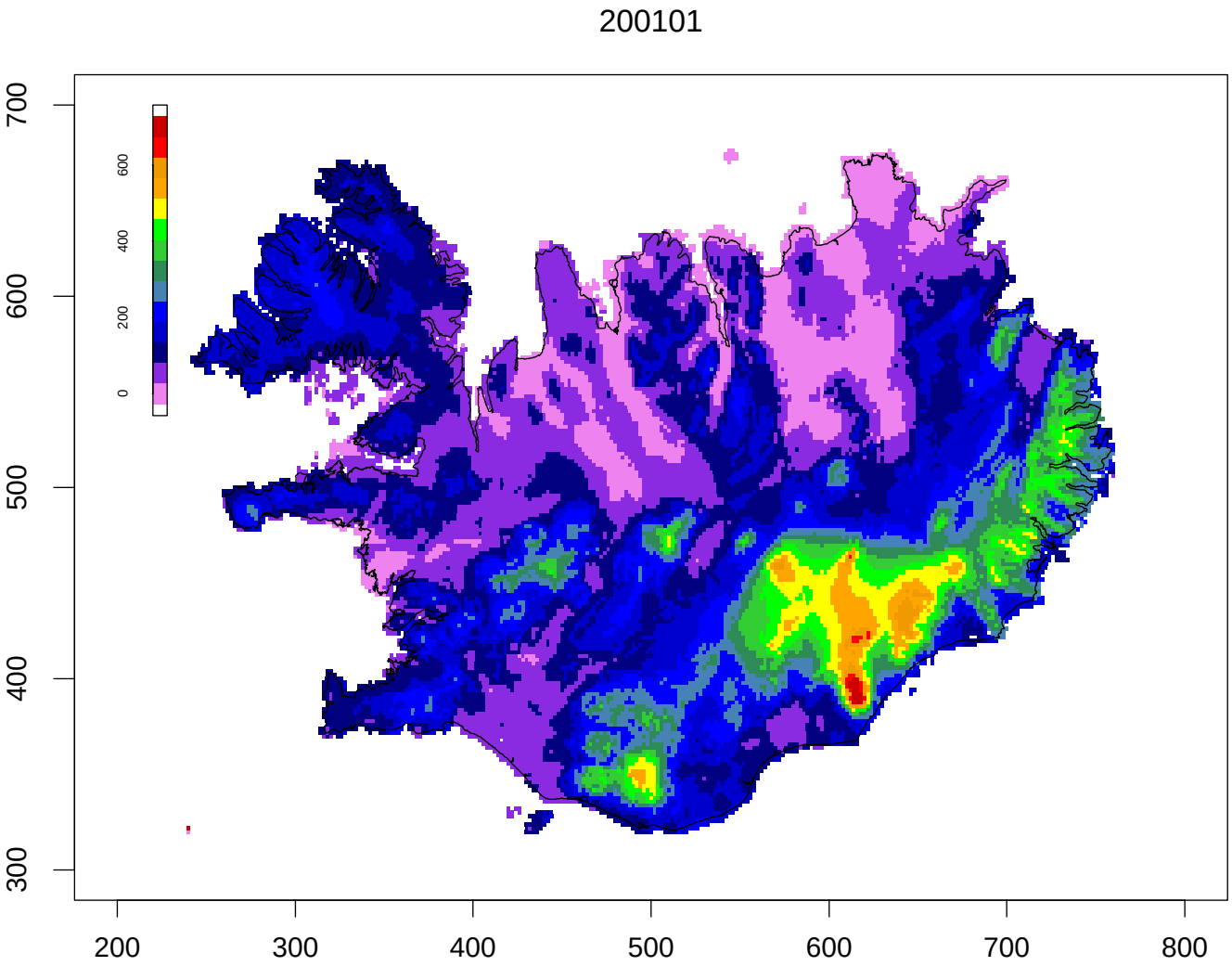
Appendix 8

Monthly precipitation maps in 2001
(2 km resolution)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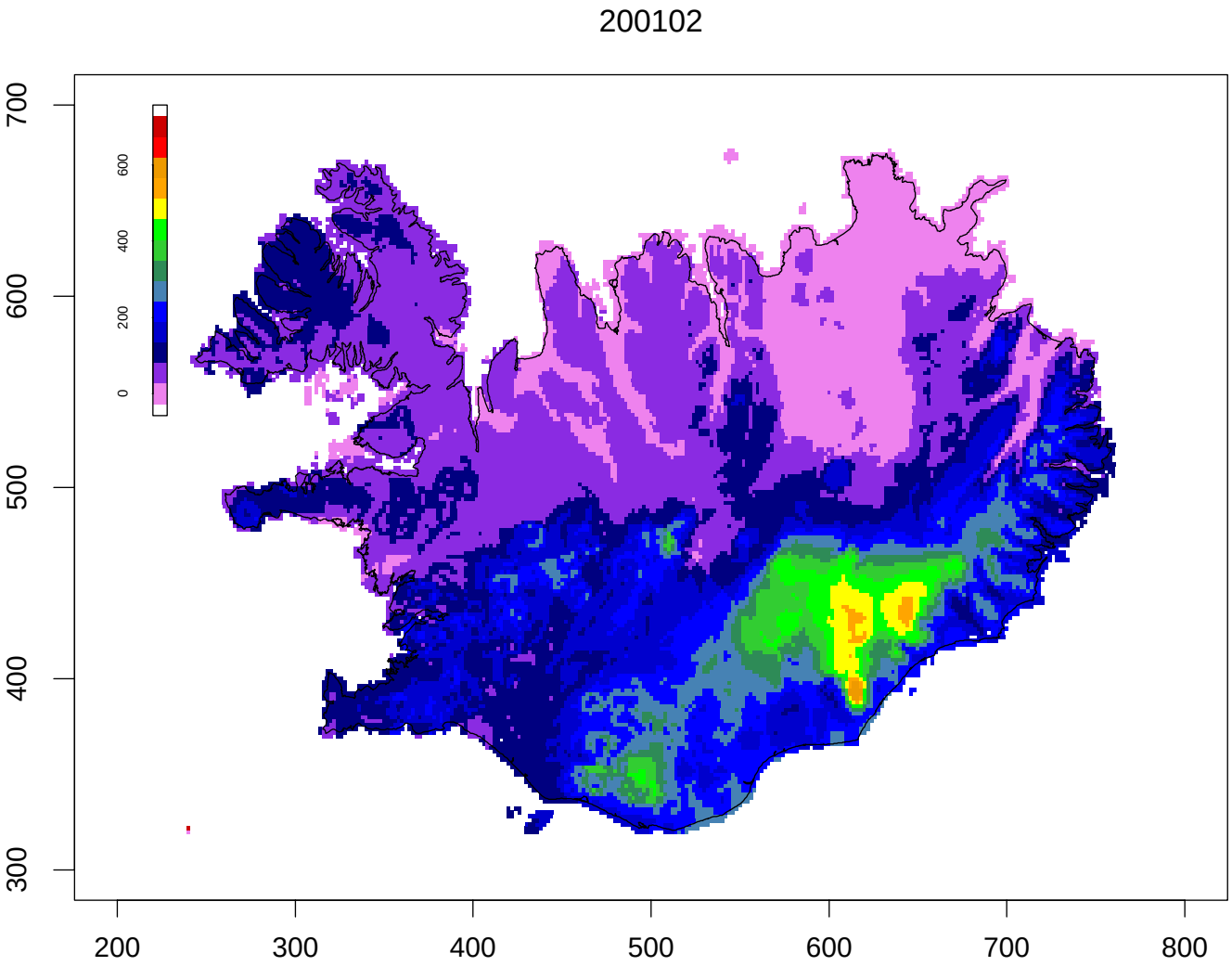
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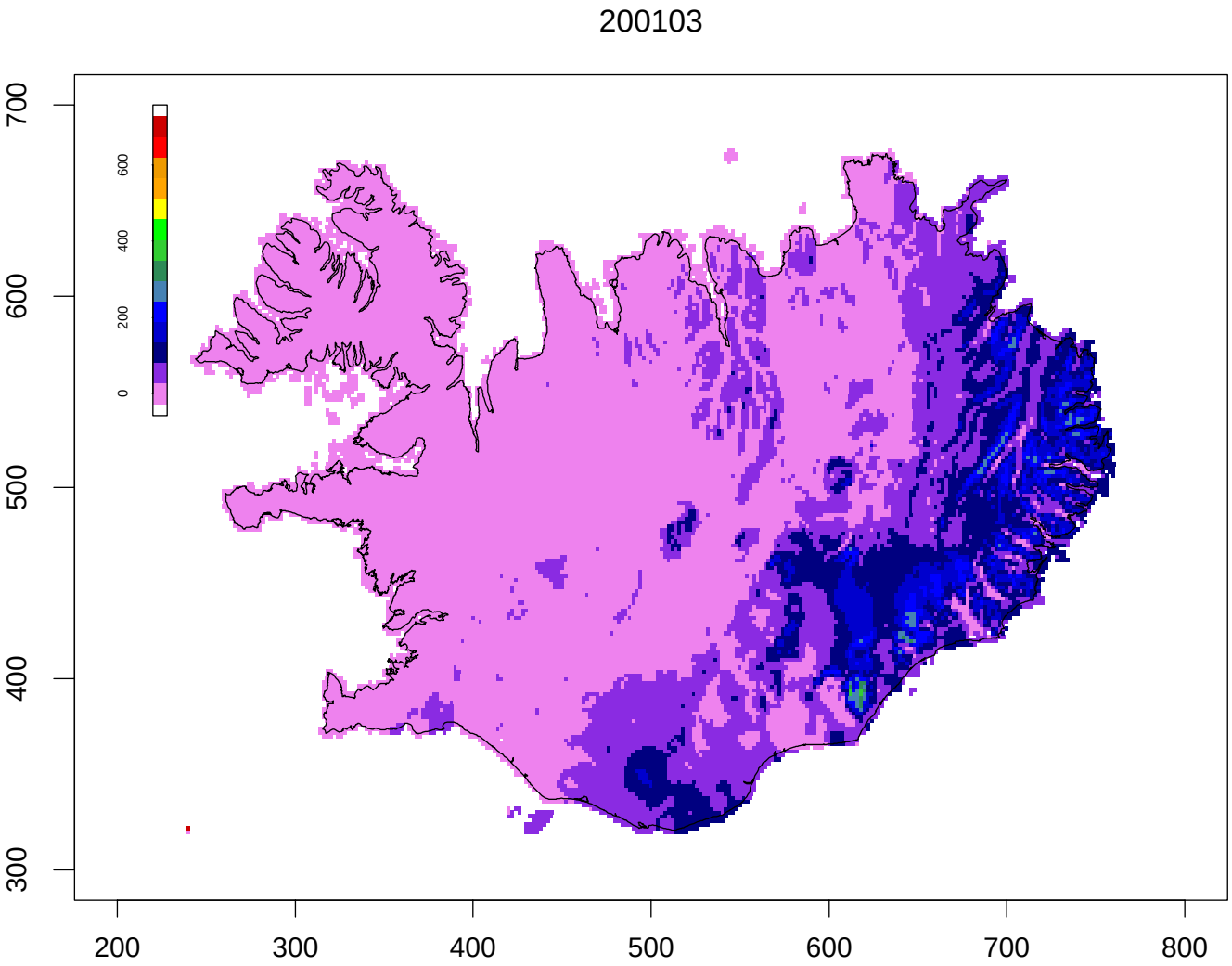
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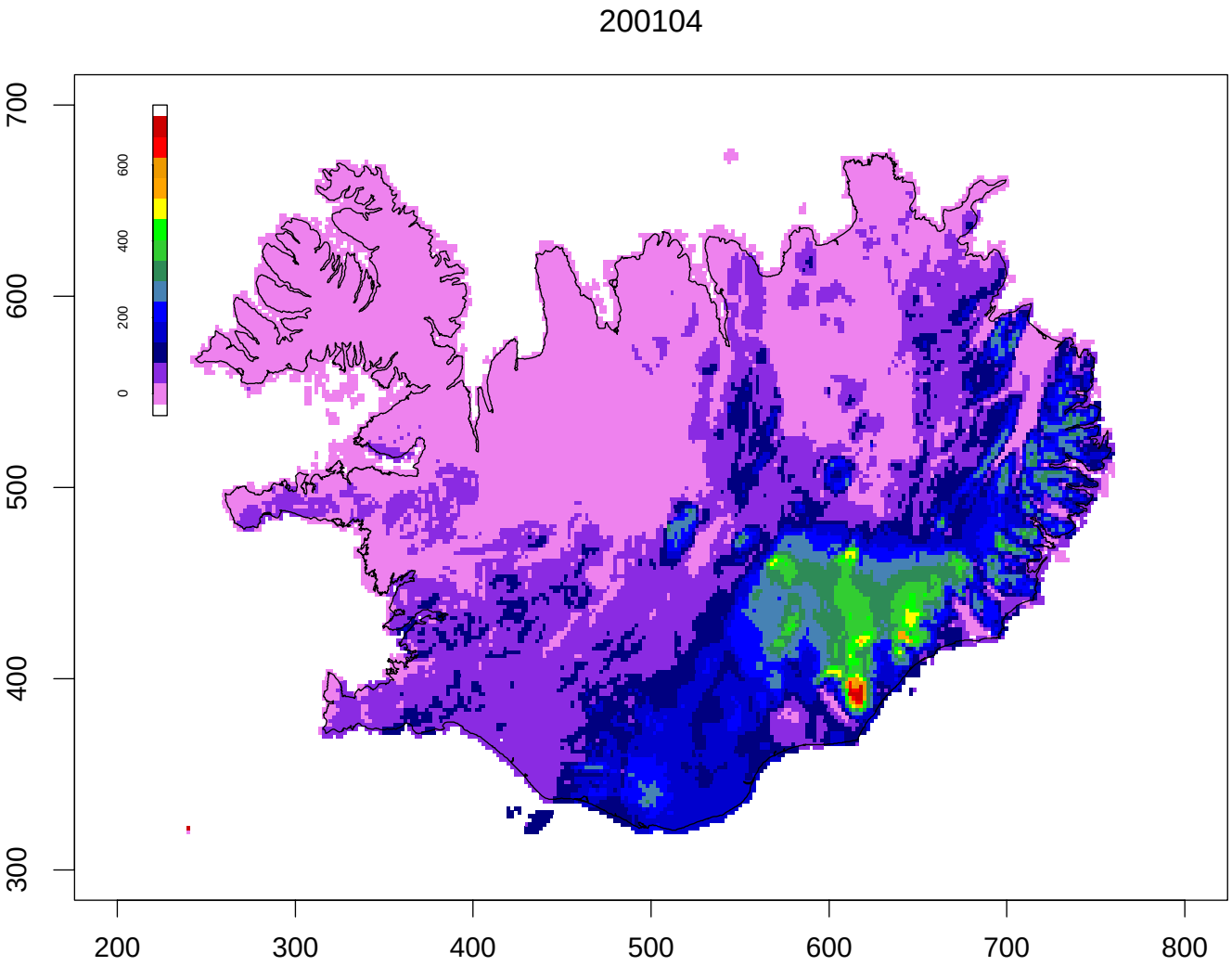
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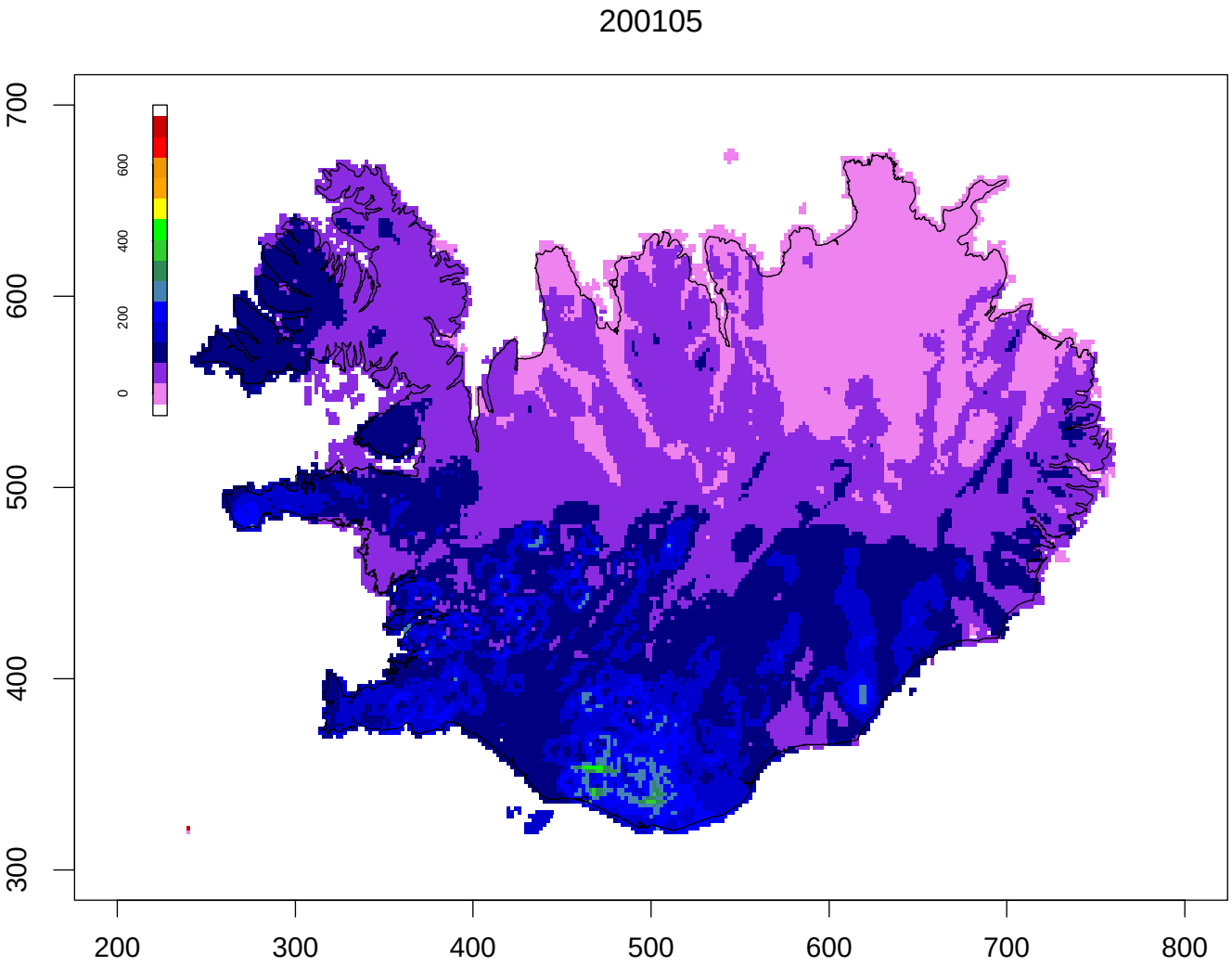
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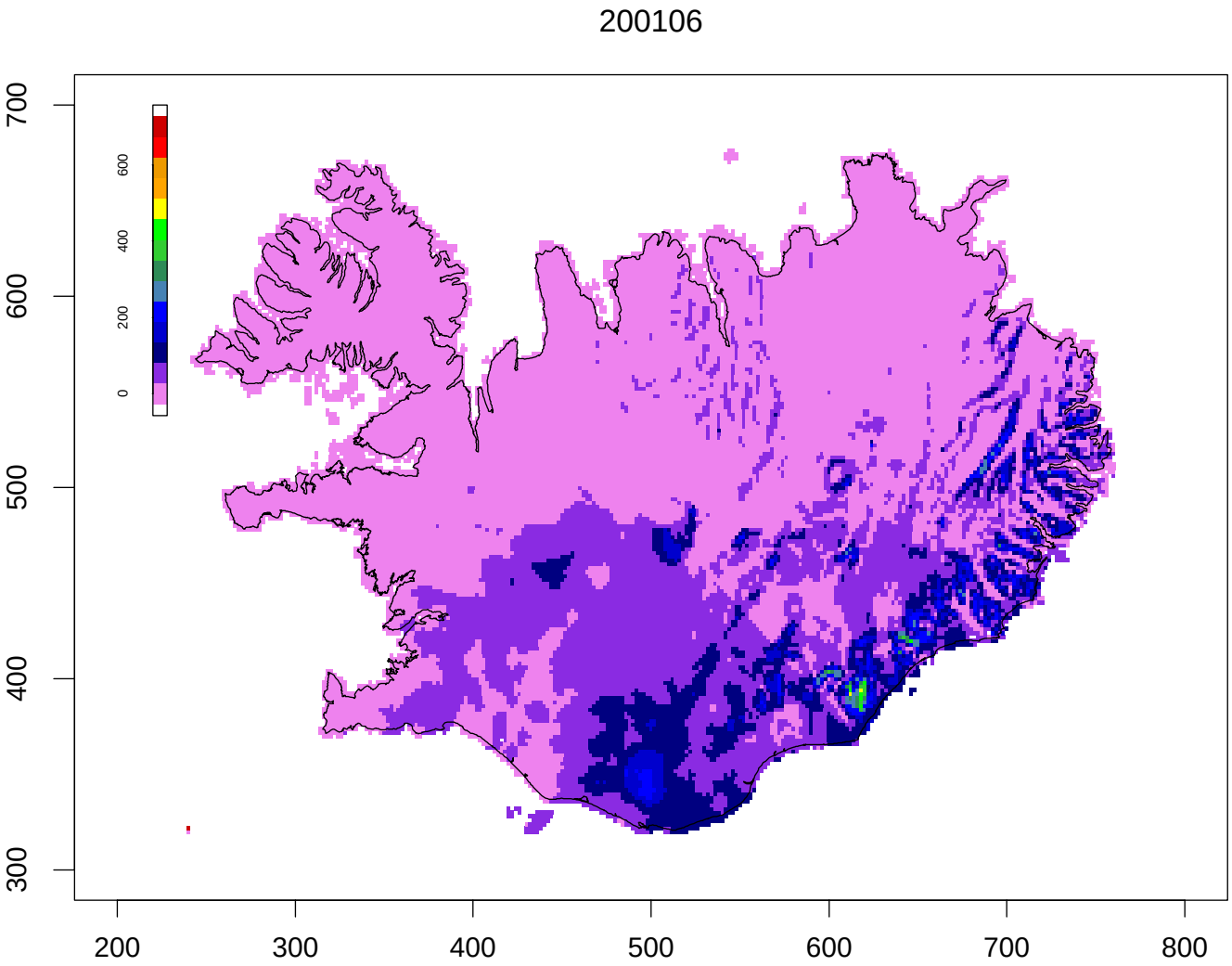
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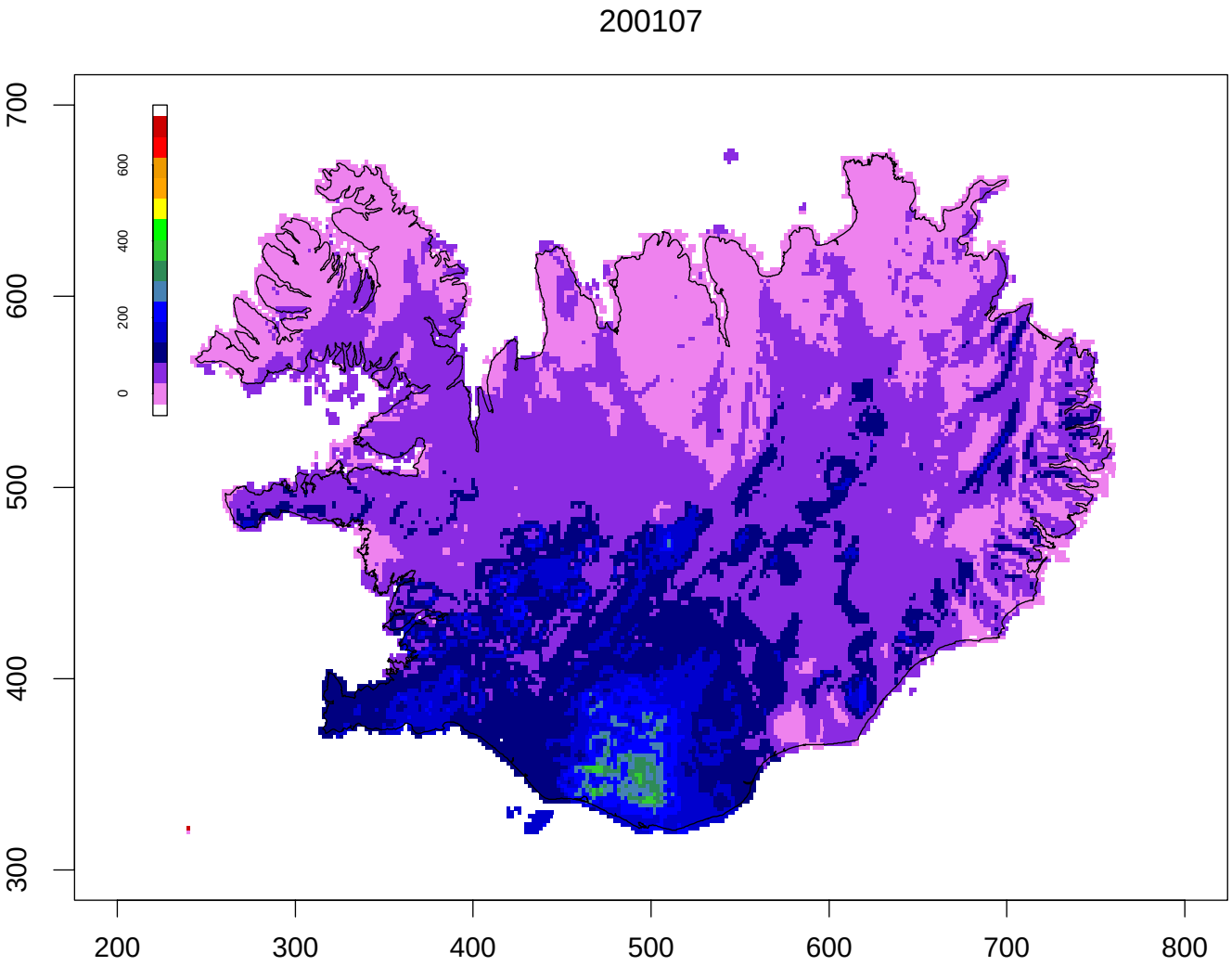
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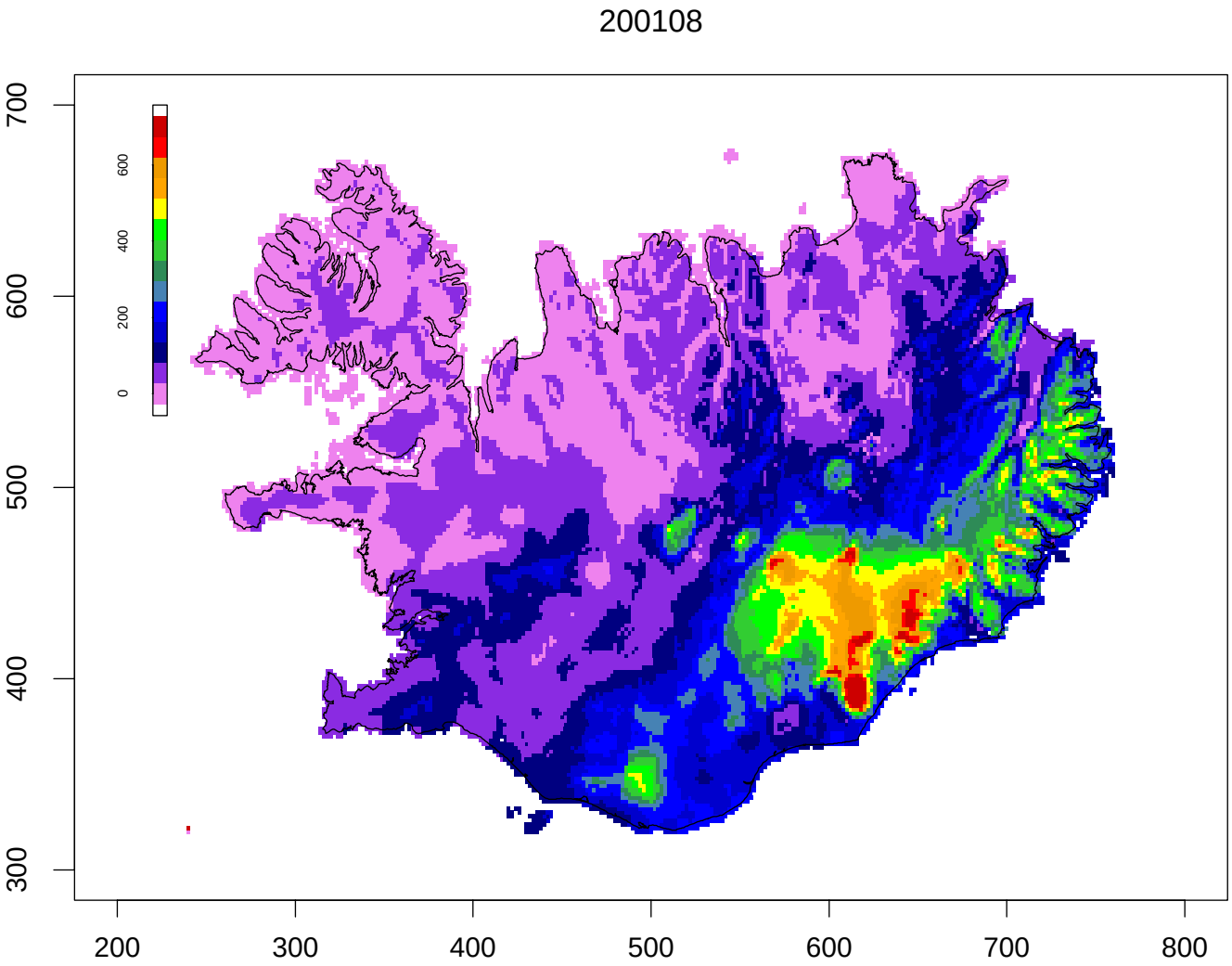
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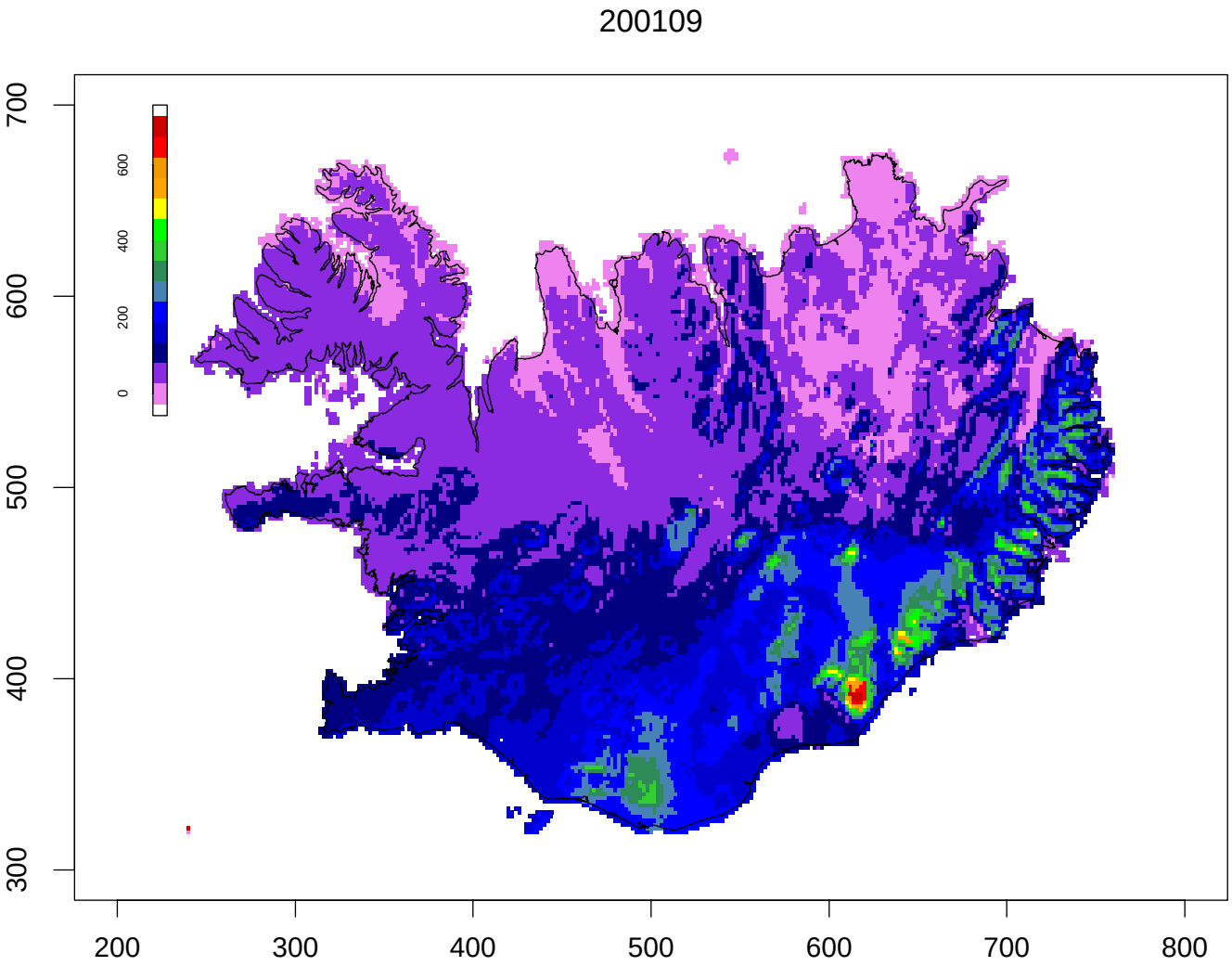
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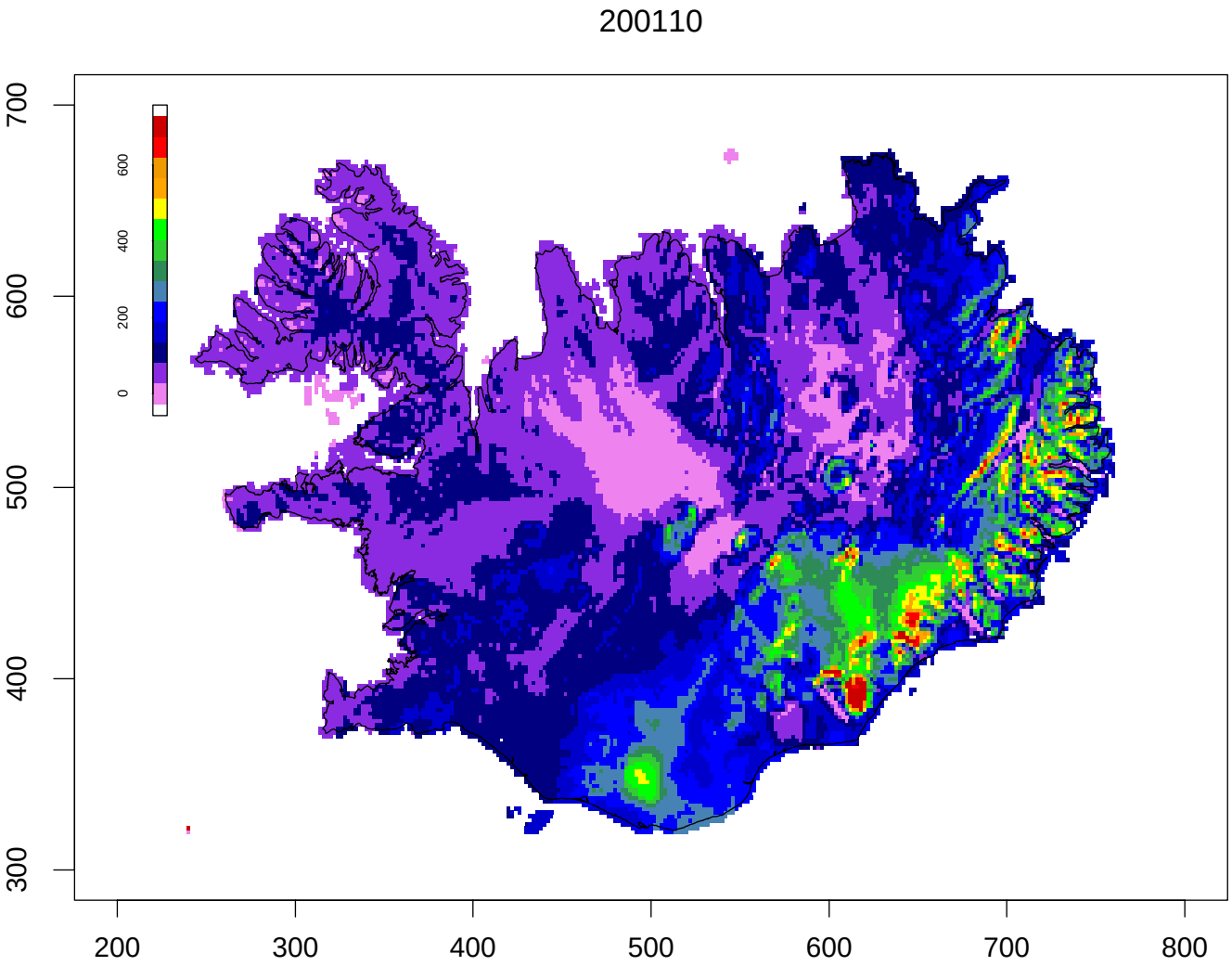
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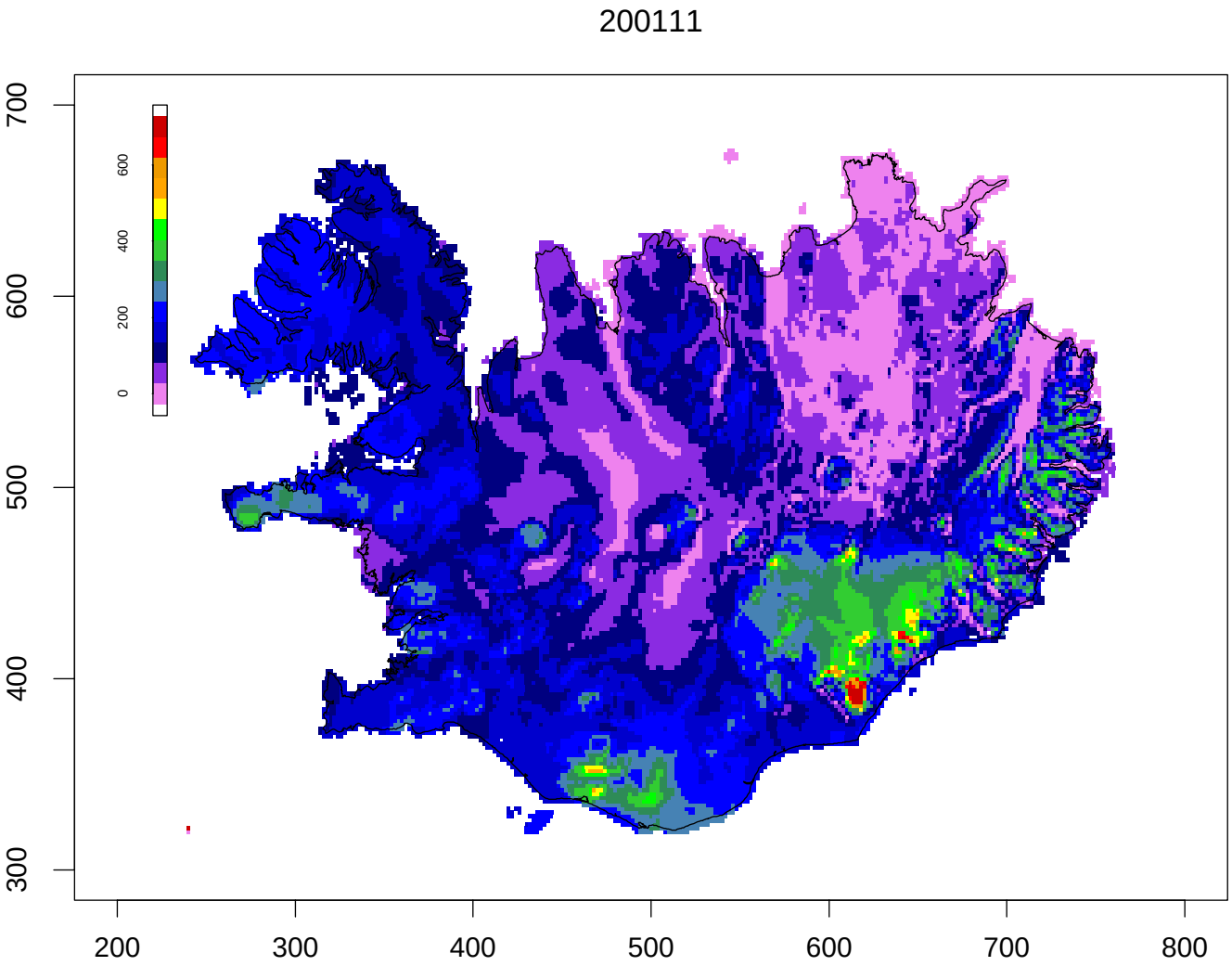
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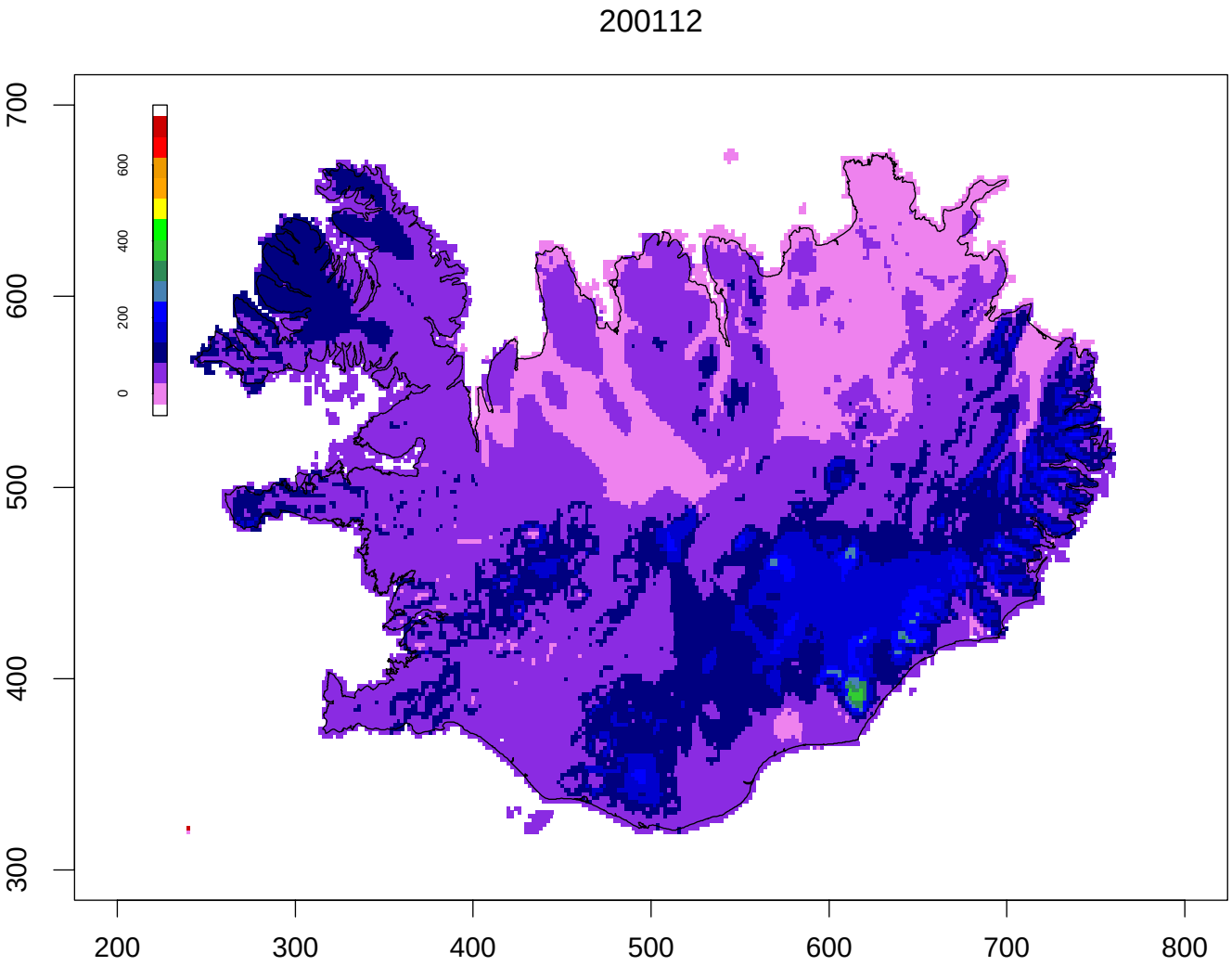
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