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Small-scale clustering of the Russian part of Arctic by periodicity type of the topographic patterns

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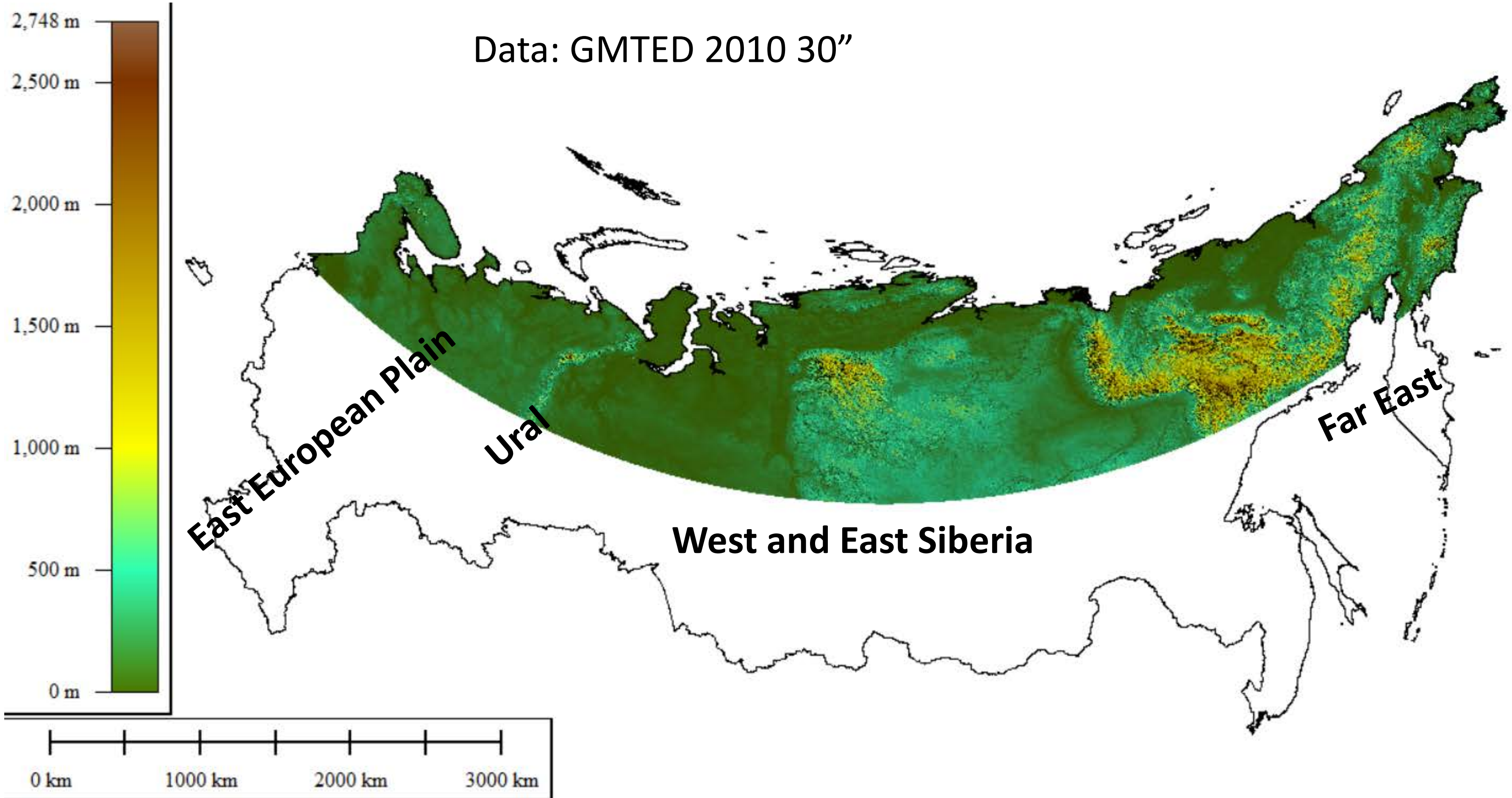
Introduction. Landform’s mapping automation – is old, but actual challenge

- Problems:
  - Gomogenous (similar) morphology of the terrain created by different exogenous and endogenous processes;
  - Complex origin of the some landforms;
  - Transfer from morphological to genetic or age characteristics.
- Possible solutions:
  - Development of the special geomorphometric variables;
  - Using powerful statistical and pattern recognition techniques;
  - More and more numerical data.

Study area

- Russian part of the Arctic (without islands and Chukotka Peninsula) – territory north of 60° N.
- Elevation's range – 0-3003 m (highest point – the Peak Pobeda, Chersky Range)
- Geological features – from Archean and Proterozoic rocks on the Scandinavian and Anabar Shields to wide quaternary sea sediment plains
- Climate: polar and subpolar very cold (subarctic or boreal and tundra climates in Koppen scheme)
- Landscapes: tundra and taiga
- Landforms (according to study's small scale): middle and high mountains (mostly on the Far East, Middle Siberia and Ural), low mountains (Khibiny and others), flat or high dissected plateaus, uplands and wide lowlands.



Methods

RES
- Preparation of the data, DEM resampling and reprojection into equal-area projection (for correctness of results).

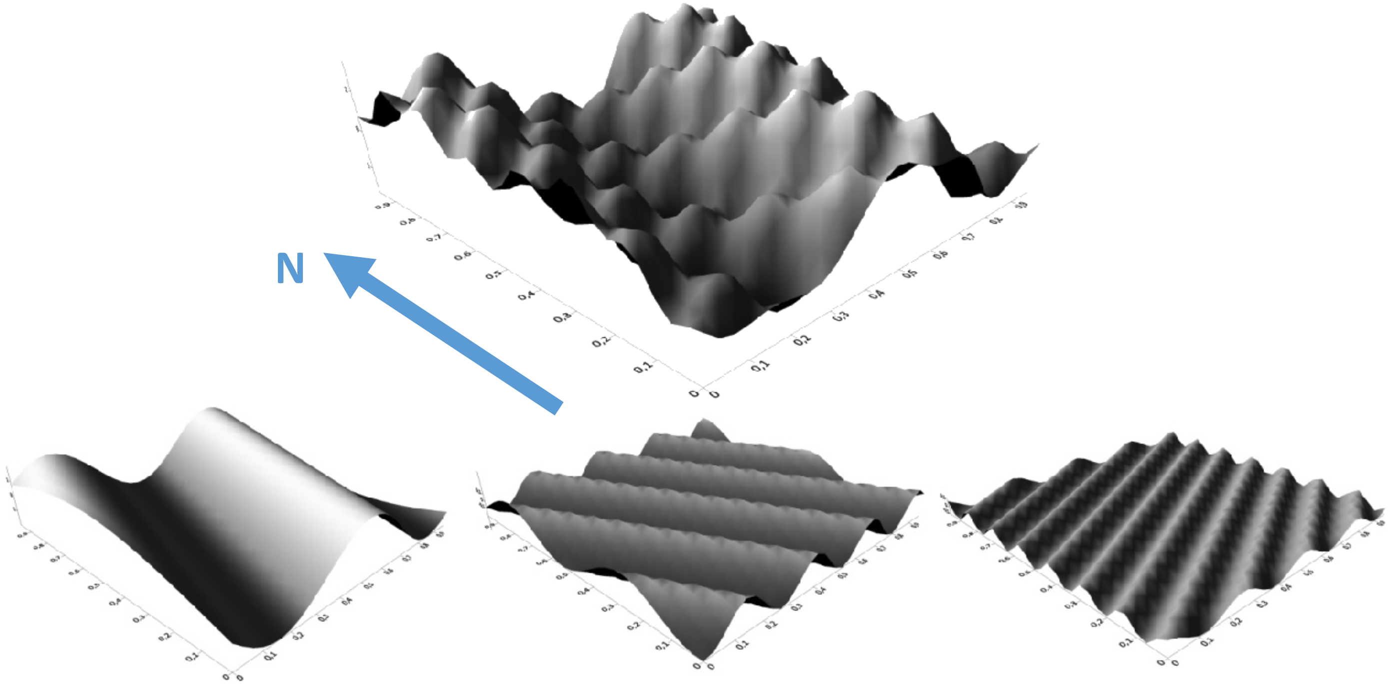
COM
- Computing the spectral geomorphometric variables (2D fast Fourier transform with moving window and selection of topographical dissection indicators from Fourier-image)

PREP
- Preprocessing of resulting data for clustering (uniformation of model's resolution computed with different scales / window sizes, Box-Cox transform for data normalization)

CLUS
- Clustering with unsupervised Kohonen neural network, mapping and interpretation

What are spectral geomorphometric variables (SGV)?

- A small number of geomorphometric variables describe the spatial context (“pattern”) of the elevation's distribution.
- To automation of the topographic patterns recognition we need pattern-based variables.
- Spectral geomorphometric variables – example of such variables, based on the Fourier decomposition of DEM.



No. of the Wave	Direction, °	Spatial frequency, waves / window	Magnitude, units
1	108	≈2	4
2	63	≈5,5	2
3	152	≈10,5	1

Example. Topographic surface decomposed into 3 waves

SGV list

1. Magnitude of the main harmonic wave (maximum magnitude value in the Fourier-image);
2. Wavelength of the main harmonic wave (wavelength related the wave with biggest magnitude);
3. Variance of elevation given by 5% of the most important waves in relation to the general elevation variance (ratio of elevation variance related to biggest waves and overall elevation variance);
4. General direction of the elevation field oscillations (the circular mean direction of biggest waves weighted by magnitude);
5. Uniformity of the general direction (Rayleigh test);

6-8. Conformance testing of magnitudes/frequency distribution to exponential distribution. Coefficients (A0, L, RD) of the approximation function relates with general shapes of the terrain. Fractal terrain will have ideal accordance, any non-fractal terrain will different.

Elementary sample (Vilyuy Plateau). Start of decomposition

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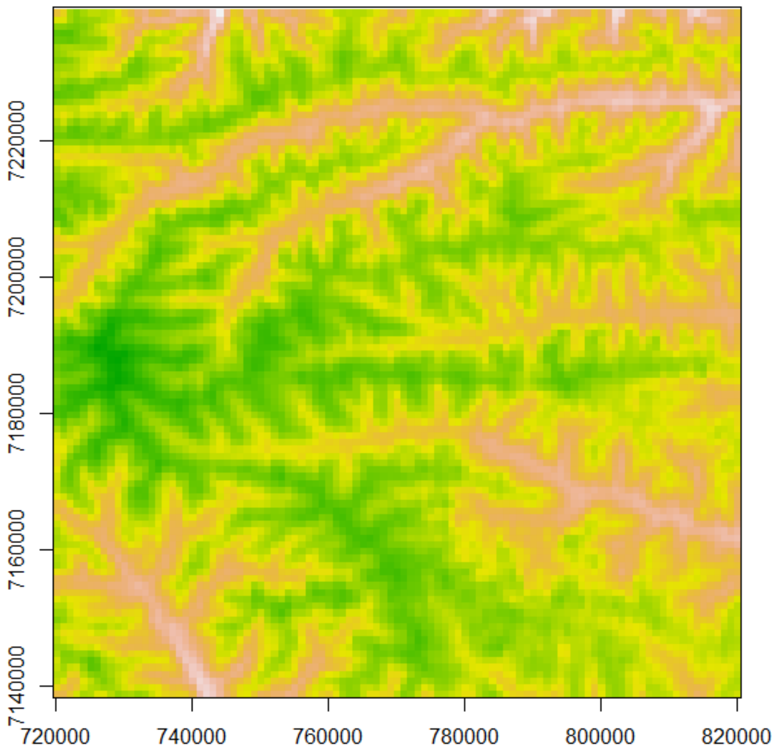
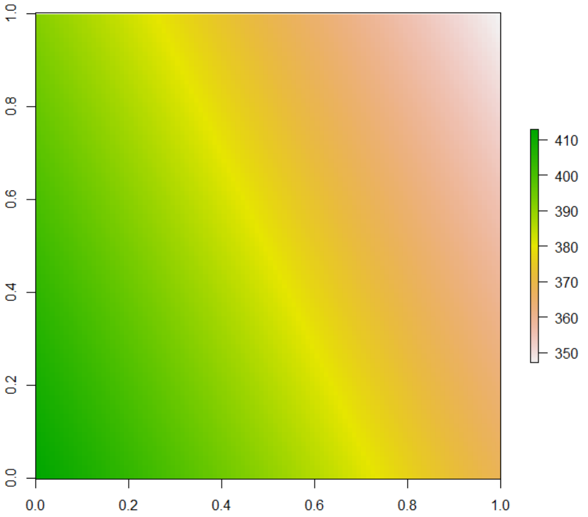
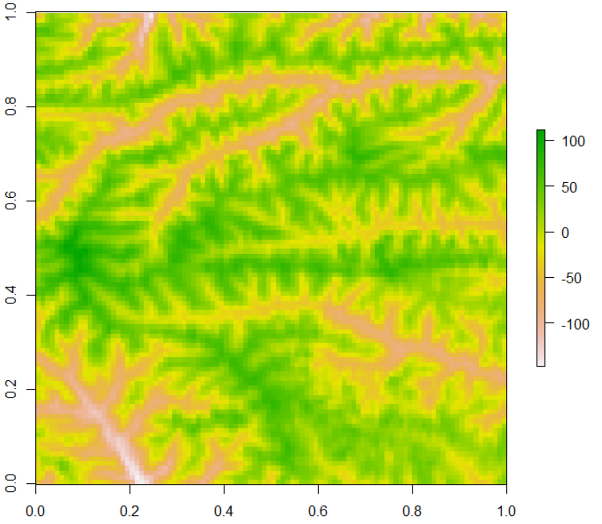
1) Fitting the surface by 2D linear trend 2) DEM detrending

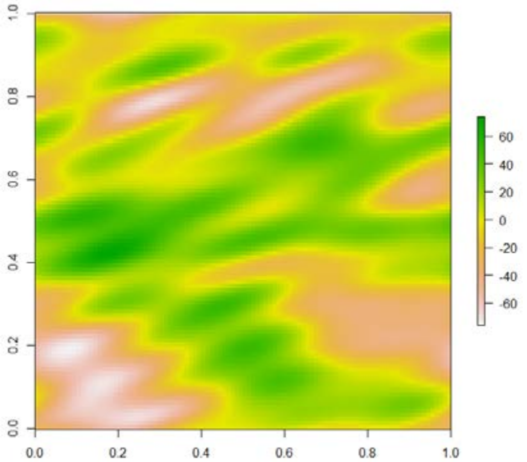
Source DEM (100*100 km)

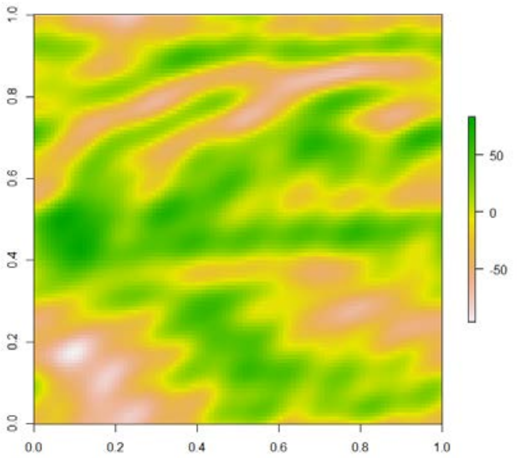


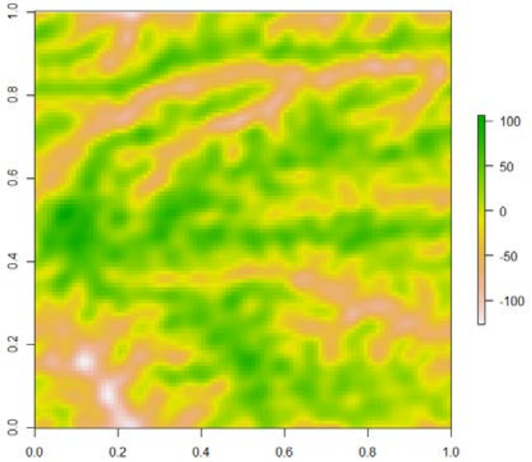




3) Demonstration of reconstructed DEMs on the 2%, 5%, 20% shares of all waves

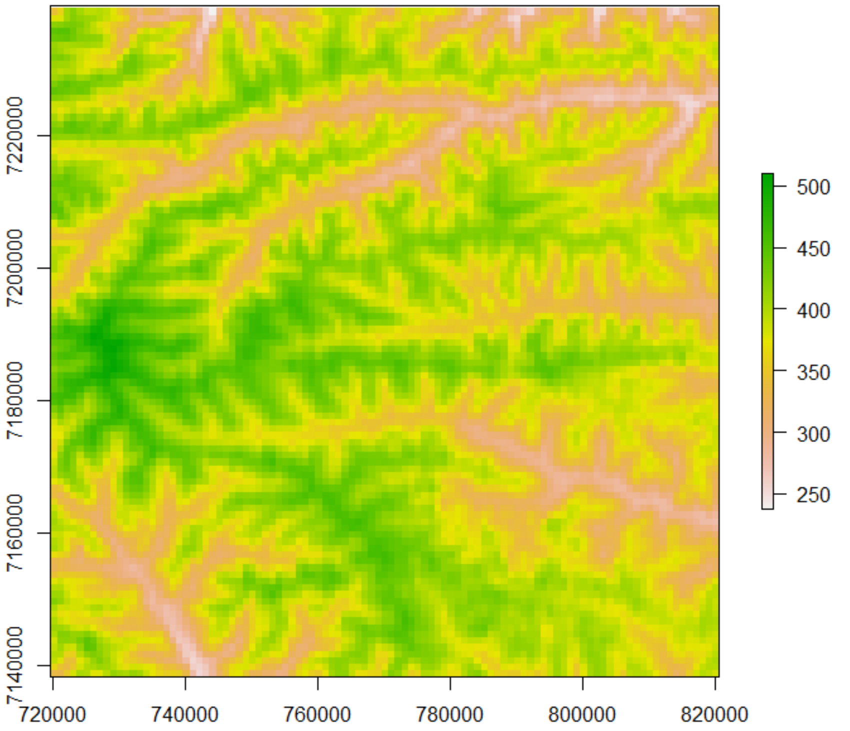




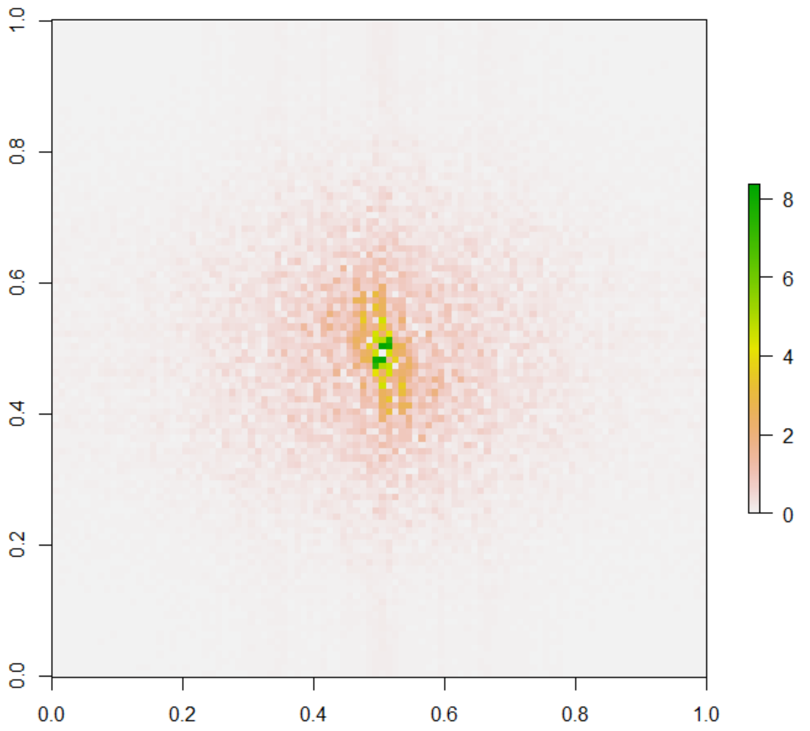


Elementary sample (Vilyuy Plateau). Wave separation from Fourier-image

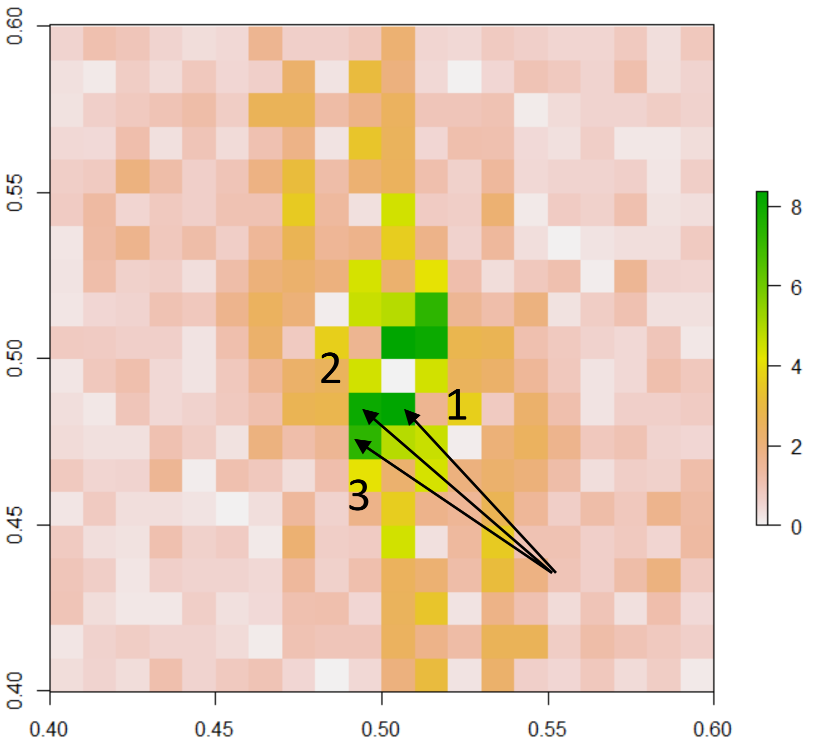
Source DEM



Fourier-image…



… and its center



Three main cells / waves (and its central symmetrical “twins”) marks with black arrows. Their positions relative to the image's center displays spatial frequency and wavelength.

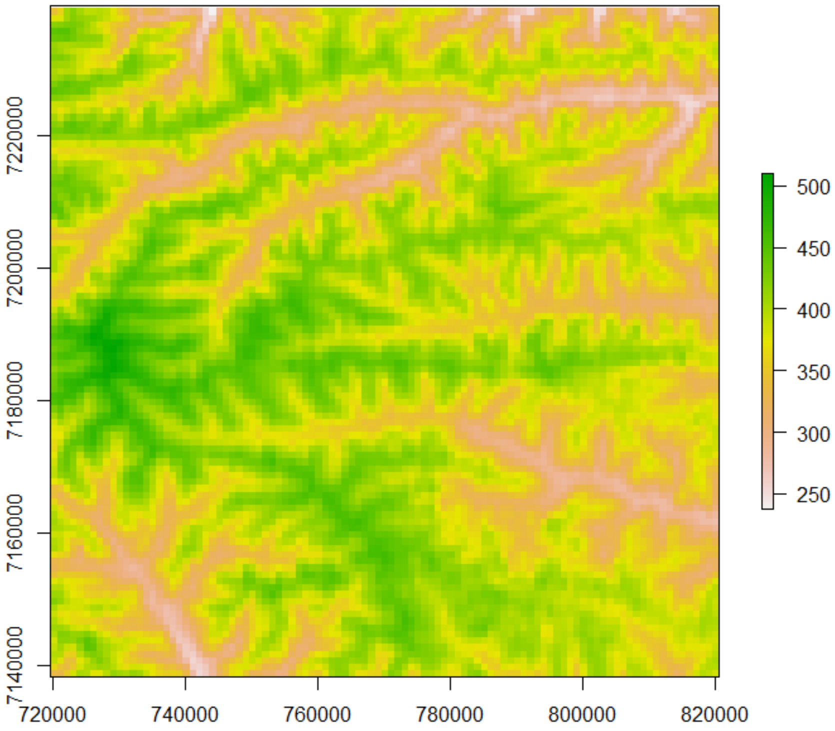
Biggest wave located under center-cell, and so its wavelength is window size (100 km) divided to distance to the center (1 cell in the North-South direction and 0 cell in the West-East direction) – 100 km.

Second order wave located 1 cell left (or right symmetrically) and 1 cell down (or top). This elevation field’s wave directed SW-NE and wavelength is 100 km / $(1^2 + 1^2)^{0.5} \approx 70$ km.

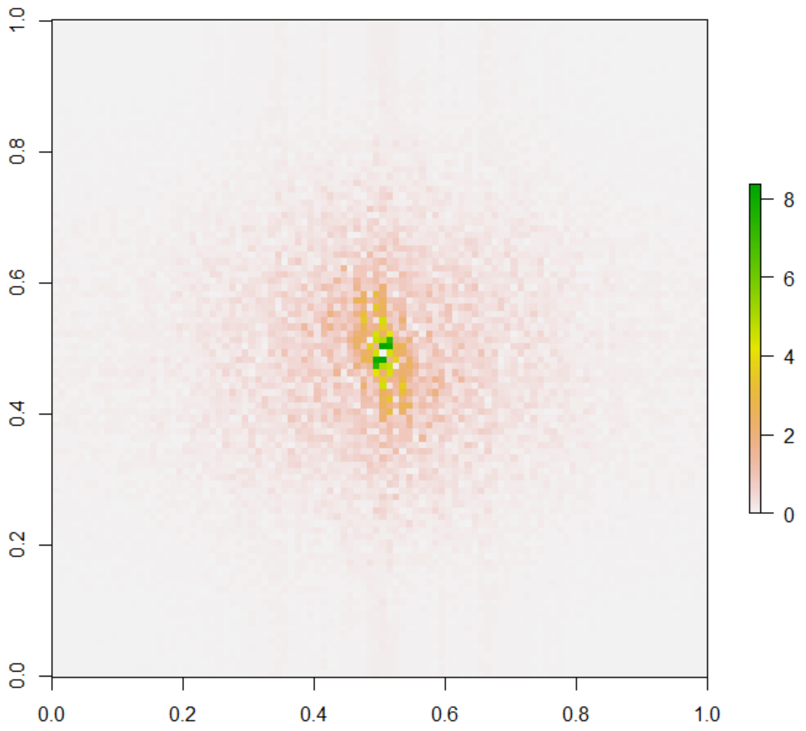
And the **third wave** have shift from the center – 1 cell to left and 2 cells to down. Direction of this wave: SSW-NNE. Wavelength is 100 km / $(1^2 + 2^2)^{0.5} \approx 45$ km.

Elementary sample (Vilyuy Plateau). Wave separation from Fourier-image

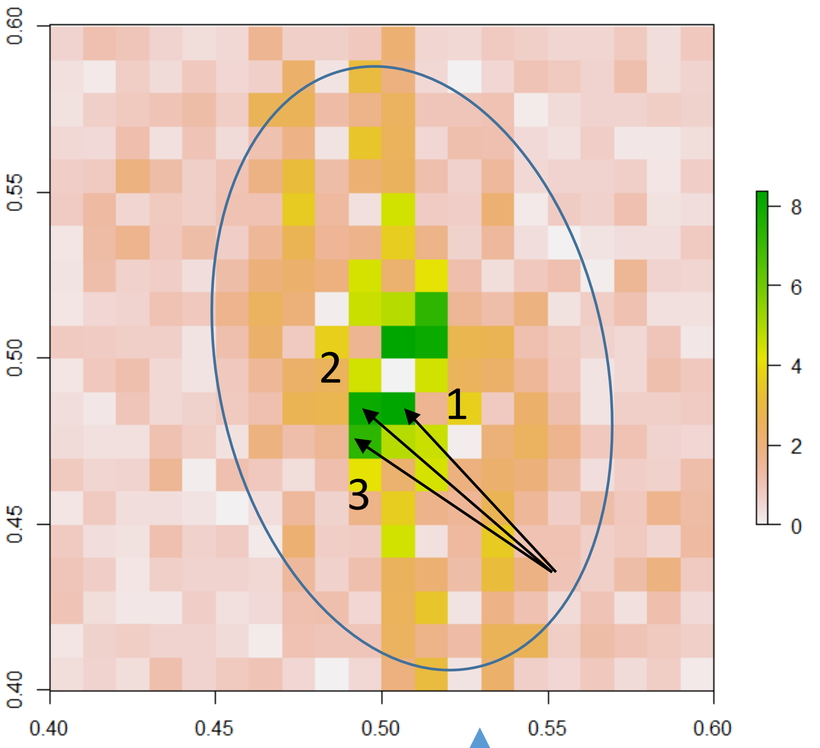
Source DEM



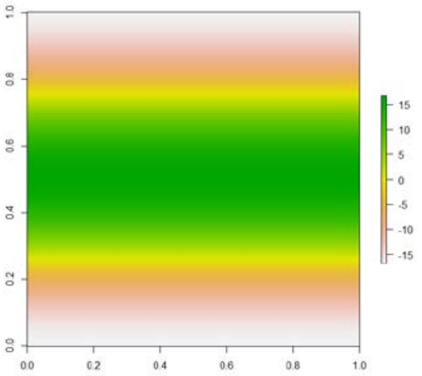
Fourier-image…

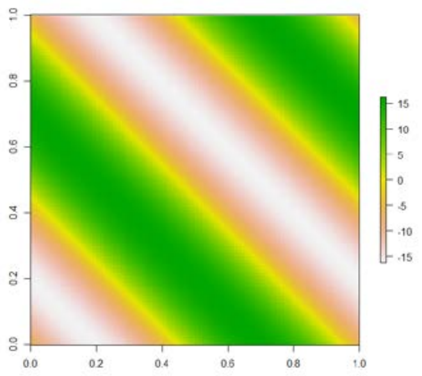


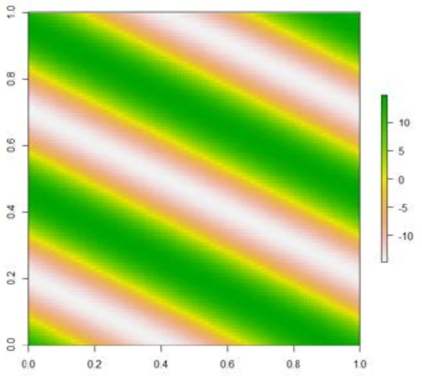
… and its center



Three biggest waves in the terrain structure:



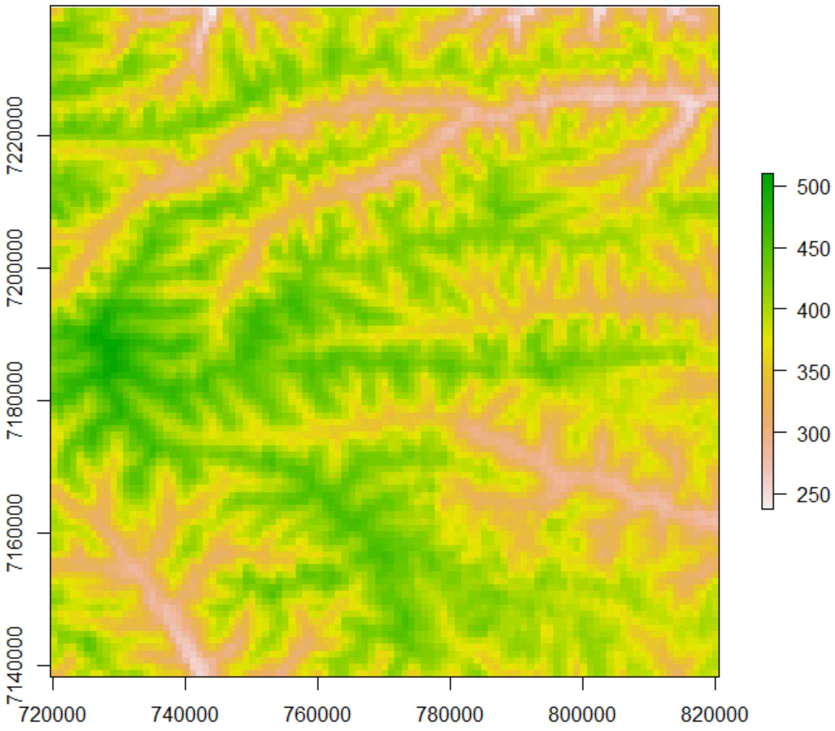




Three waves aren’t describe geomorphological diversity. The accounting of high frequency waves is needed.

Elementary sample (Vilyuy Plateau). Computing variables

Source DEM



1) Magnitude of the main harmonic wave

Formula:

4 * max(MAG),

where MAG – matrix of magnitudes from Fourier-image,

4 – coefficient for accounting symmetry of the Fourier-image (x2) and symmetry of sinusoidal function (x2)

2) Wavelength of the main harmonic wave

Formula:

WINDOW.SIZE / (SΔX^2 + SΔY^2)$^{0.5}$,

where WINDOW.SIZE – length of window edge, km,

SΔX – shift the biggest wave's position relative Fourier-image center (west – east)

SΔY – shift the biggest wave's position relative Fourier-image center (north - south)

3) Importance of 5% biggest waves.

Formula:

1 - (sd(ELEV – ELEV.REC) / sd(ELEV)),

where ELEV – elevations without linear trend,

ELEV.REC – recovered elevations based on the 5% biggest waves

Elementary sample (Vilyuy Plateau). Computing variables

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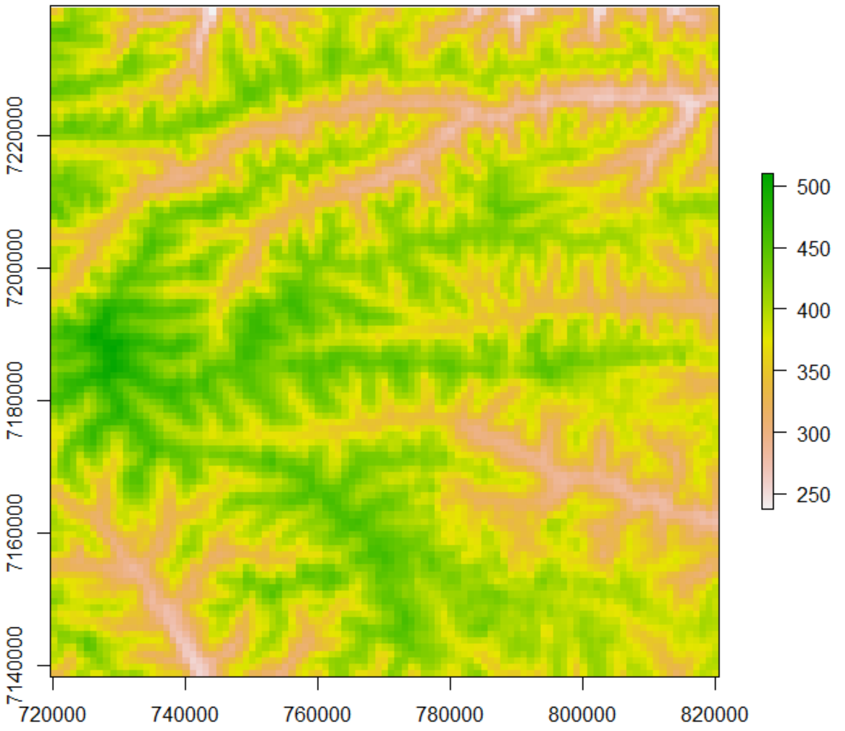
Source DEM



4) General direction of the elevation field oscillations

Formula:

$$\tan^{-1}(\mathrm{mean}(MAG_i * S\Delta X_i / S\Delta Y_i)),$$

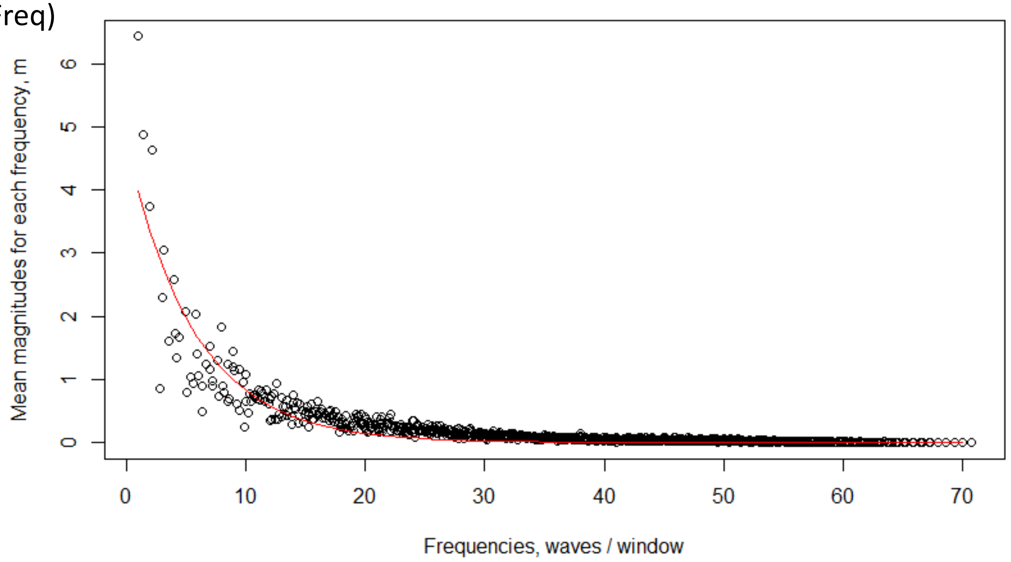
where MAG_i – magnitude of the i^{st} wave,

$S\Delta X_i$ – shift the i^{st} wave's position relative Fourier-image center (west – east),

$S\Delta Y_i$ – shift the i^{st} wave's position relative Fourier-image center (north - south)

5) Uniformity of the general direction (Rayleigh test)

6-8) Coefficients (A0, L, sum of squares for residuals deviance RD) of the fitting function $A = A0 * \exp(1)^{(-L*Freq)}$



Variable	1) Max. mag., m	2) Wavelength, km	3) Importance, %	4) Direction, °	5) Unif., %	6) A0, m	7) L, coeff.	8) RD, m²
Value	33.5	100	43	66.6	0.46	4.75	0.174	31.6

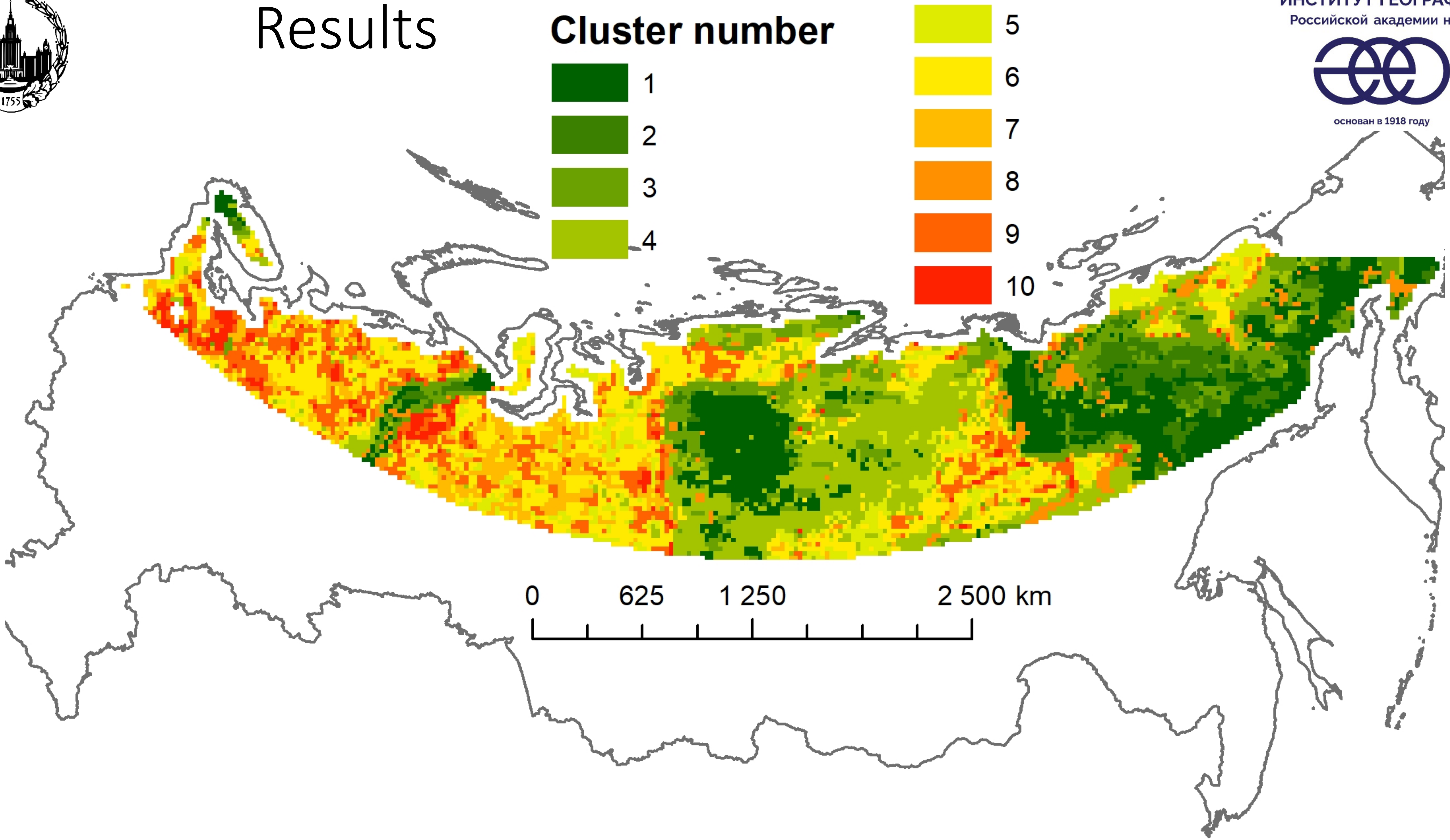
Overlay the moving window and the DEM 42160 times in the seven scales (40, 50, 60, 70, 80, 90, 100 km window size) gives data-matrix for clustering

Head of the matrix

	100_a_exp.tif	100_dev_exp.tif	100_l_exp.tif	100_max.imp.tif	100_max.mag.tif	100_pr.deg.tif	100_pr.dir.tif	100_wavelen.tif	40_a_exp.tif	40_dev_exp.t
1	8.77	20.35	0.42	0.38	29.50	0.01	81.77	70710.68	2.84	7.03
2	7.03	10.92	0.40	0.35	23.44	0.00	132.64	70710.68	5.13	3.15
3	7.84	9.35	0.51	0.41	27.26	0.04	14.42	100000.00	3.54	7.31
4	7.76	9.26	0.51	0.41	27.36	0.04	20.47	100000.00	2.16	1.75
5	5.59	6.87	0.46	0.44	29.82	0.01	173.17	99983.02	2.80	2.01
6	7.13	5.65	0.57	0.50	32.08	0.01	5.15	98909.26	4.09	2.34
7	8.03	16.59	0.53	0.49	36.38	0.00	4.74	98261.84	2.57	0.61
8	8.64	13.67	0.54	0.41	39.04	0.04	6.97	100000.00	4.55	3.50
9	8.52	13.48	0.53	0.41	38.52	0.04	13.16	100000.00	1.61	0.99
10	5.57	8.64	0.38	0.34	25.38	0.01	169.83	99547.14	1.29	1.01
11	4.48	15.07	0.32	0.36	24.91	0.02	22.10	70902.90	3.05	4.78
12	4.37	11.90	0.31	0.35	26.59	0.09	19.51	70710.68	3.79	5.43
13	5.16	7.04	0.32	0.31	23.00	0.03	24.88	98087.67	5.35	2.38

1) Box-Cox transform **> 2)** creation of the Kohonen self-organized map **>**
3) clustering of the Kohonen neurons (nodes of the net) by hierarchical clustering

Results



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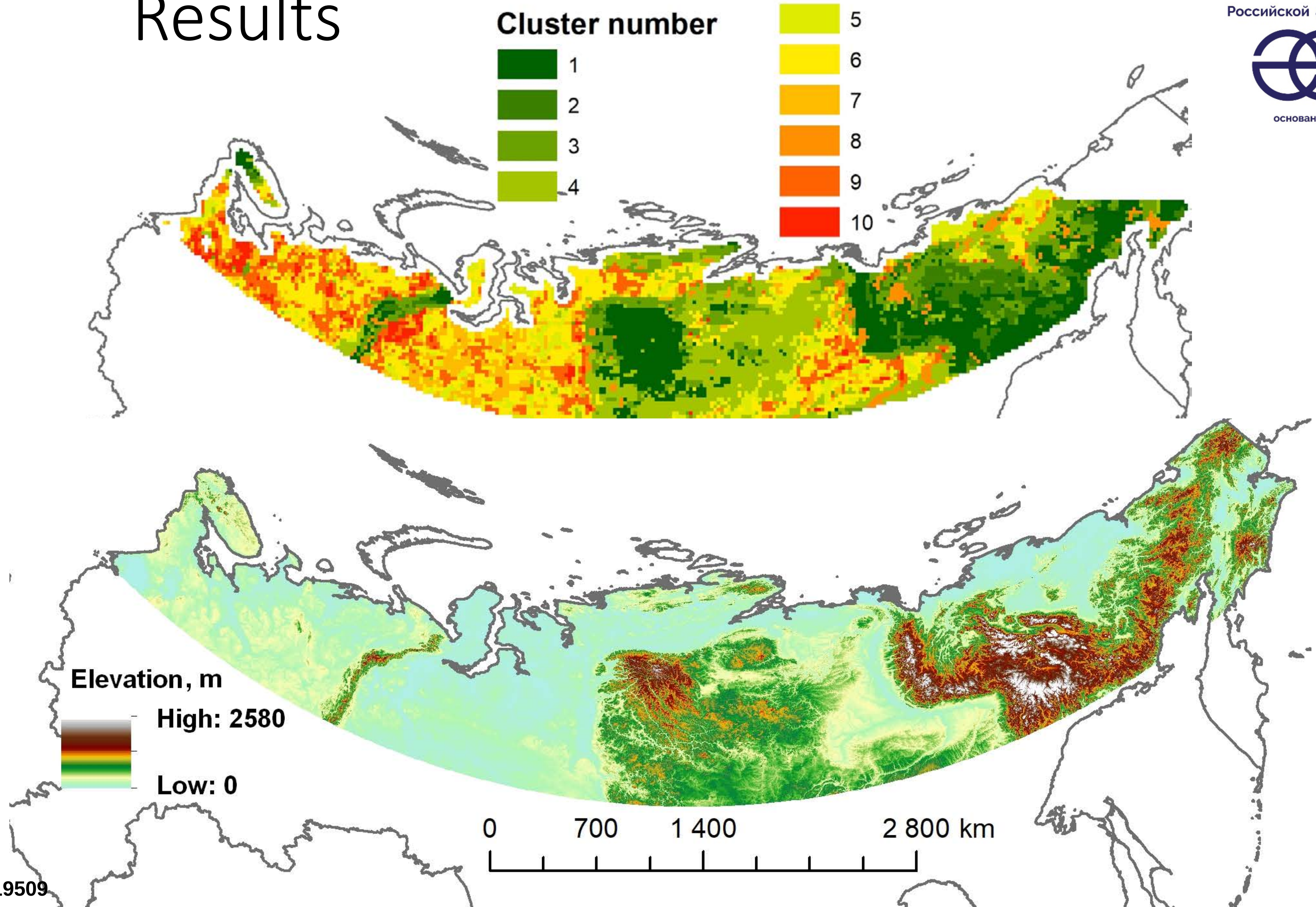
Results


Cluster number
1
2
3
4
5
6
7
8
9
10
Elevation, m
High: 2580
Low: 0
0
700
1 400
2 800 km

Cluster's interpretation

Standardized relative scores for each cluster and all variables (if standard score more – initial variable more too). The median values are used.

Cluster no.	Max Mag.	Wavelength	Importance	Direction	Unif.	A0	L	RD
1	1,06	-0,47	-0,8	-0,15	0,31	0,81	-0,81	1,17
2	1,69	0	0,42	-0,13	-0,26	1,66	0,33	1,65
3	0,91	0,61	0,58	0,12	-0,47	1	0,49	0,88
4	0,05	-0,22	-0,64	0,09	-0,16	-0,11	-0,59	0,1
5	-1,32	-0,13	-0,93	0,13	-0,13	-1,48	-0,91	-1,25
6	-0,87	-0,14	0,06	-0,17	-0,11	-0,87	0,13	-0,84
7	-0,88	0,87	0,73	-0,06	-0,74	-0,67	0,9	-0,88
8	0,52	-0,4	0,49	1,17	1,2	0,38	0,06	0,43
9	-0,46	0,16	1,18	-0,54	0,22	-0,27	1,07	-0,6
10	-0,15	0,91	1,67	0,06	-0,62	0,44	1,67	-0,39

Geomorphological interpretation of recognized clusters

Cluster no.	Area, tous. sq. km	Max elev., m	Mean elev., m	SD elev., m	Landforms
1	1110,8	2543	727	355	High mountains and large dissected highlands (Khibiny, Sub-Polar and Polar Ural mountains, Putorana Plateau, Verkhoyanskiy Range, Kolyma Highland). Density of dissection is very high. Orthogonal topographic pattern. The great impact of the gully's dissection.
2	334,9	2749	831	461	Highest mountains on the area (Cherskiy and Momskiy Ranges, highest part of Ural Mountains). Tops of the mountains. Density of dissection is moderate. The great impact on the elevation variance has the large landforms only.
3	735,7	2213	359	275	Low mountains (Byrranga) and piedmonts
4	1203,1	1357	307	155	Hilly erosional uplands and plateaus (Syverma Plateau, Vilyuy Plateau). A landforms of various sizes affect topographic dissection.
5	429,8	587	149	132	Mostly criogenic and thermokarst lowlands (Central Yakutian Lowland, Yana and Indigirka Lowland, West Siberian Plain, North Siberian Plain). There are many ouval lake depressions and flat interfluve spaces.
6	1168,1	617	132	99	Similar to cluster no. 5. With more importance of erosional network. Erosional and thermokarst plains. The most "fractal" terrain type.
7	537,5	530	102	75	Large flat areas without dense dissection. Big values of prevailing wavelengths and importance of biggest waves. Low values of uniformity of the wave direction. Soft and smooth lowland terrain.
8	197,8	1910	299	213	Very regular orthogonal dissected terrain of structural plains with relatively large depth of dissection and relatively small density of erosional network. Uplands between mountains of the NE Russia and coastal plains.
9	609,8	583	113	72	Mostly lowlands (less commonly plateaus) around big post-glacial lakes and upper parts of biggest rivers. As a rule, the one big wave according to linear depression
10	156,8	586	114	75	Very regular erosional terrain without small-scale erosional dissection. Small values of the depth of dissection. Post-glacial plains in the valleys of the big rivers of Russian North: Severnaya Dvina, Pechora, Ob'. Difference with cluster no.9 is in more depth of dissection and missing of one main wave.

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Conclusions

- Using of the spectral geomorphometric variables (SGV) and clustering techniques allows make fully-automatic multiscale landform classification based on the types of terrain dissection pattern.
- The 8 SGV has been created. Each of these describes topographical pattern from one side or another.
- SGV can be used together with another variables, but even by SGV are sufficient to classify the terrain by the type of topographical dissection.
- For the territory of Russian Arctic the map of landform types was created fully-automatically (the user define some input variables only). The ten clusters were recognized – 2 (no. 1 and 2) for middle and high mountains, 1 for low mountains and piedmonts (no. 3, but partially no. 8), 2 for structural and layered high plains (no. 4 and 8) and 5 mostly for lowlands with landforms of criogenic, termokarst, glacial, limnoglacial and erosional origin.

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