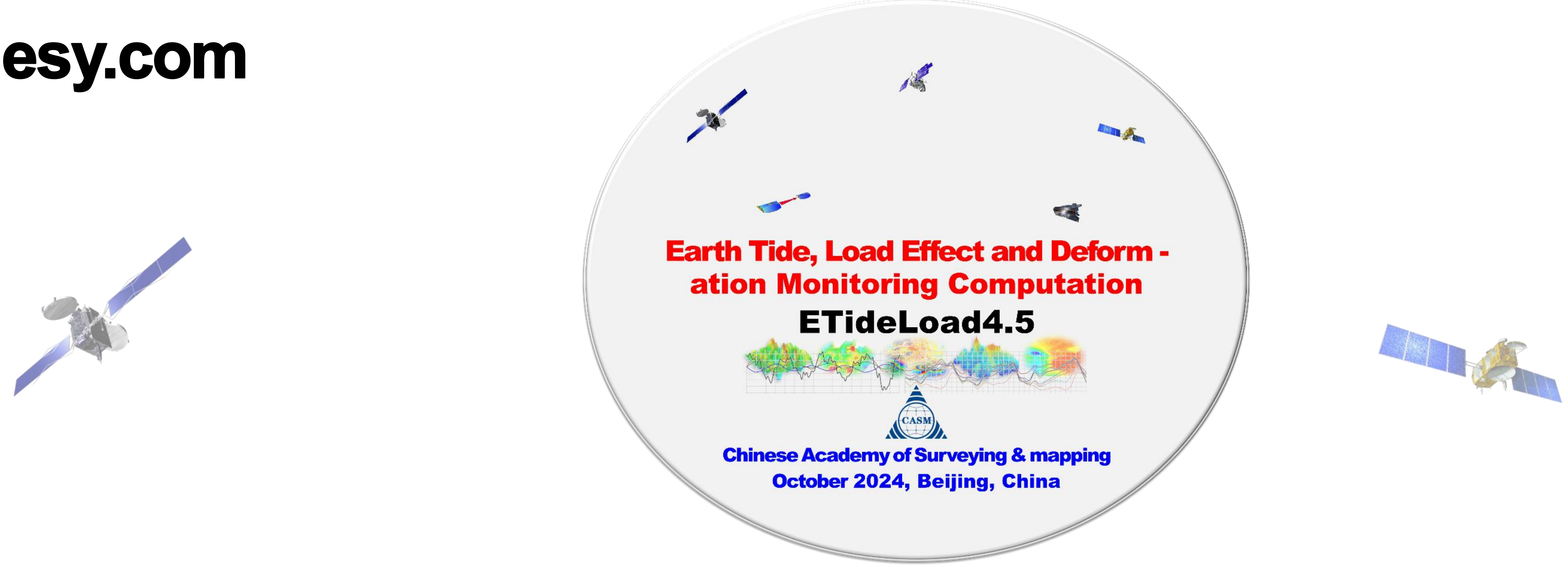
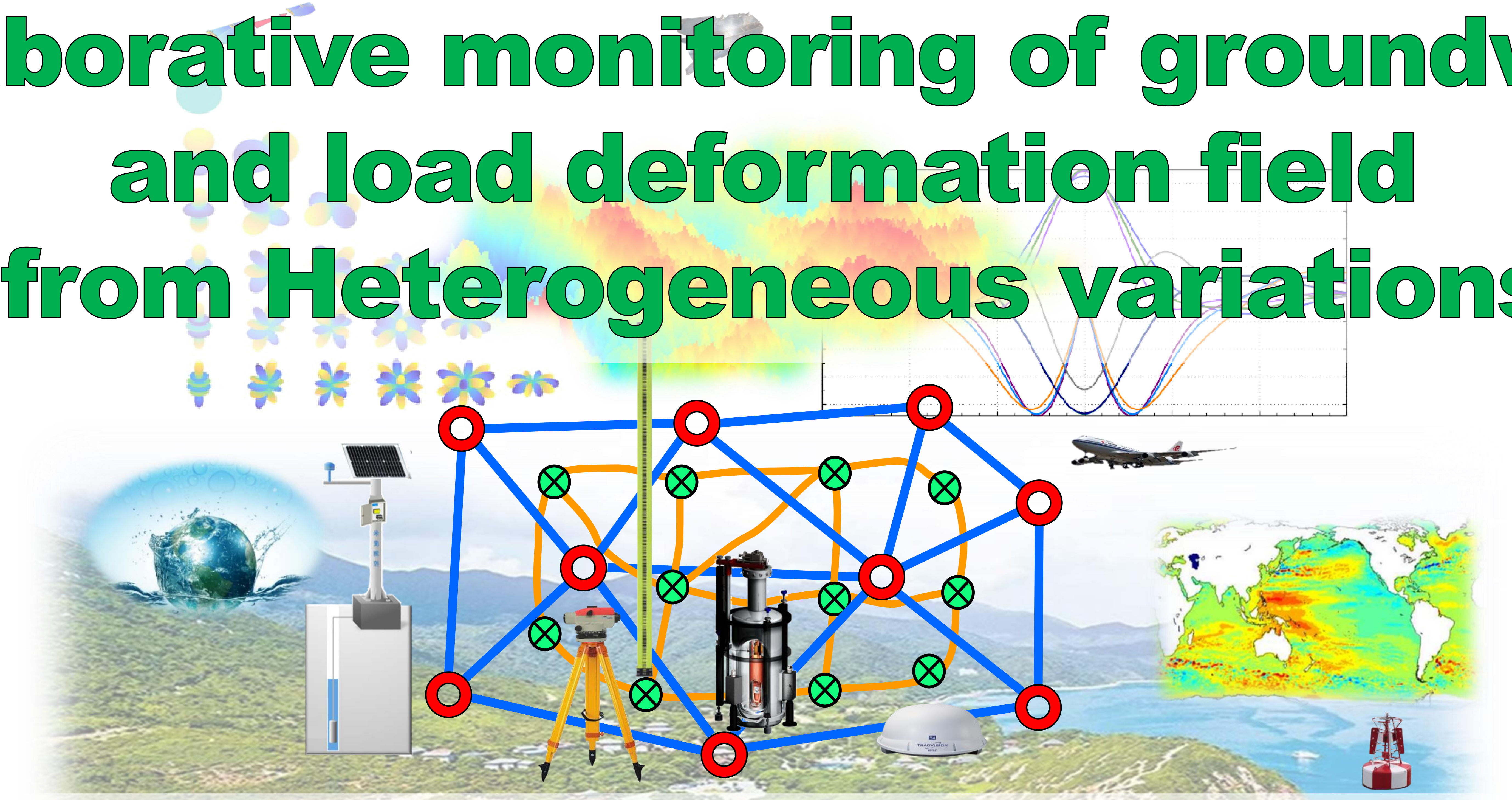
www.zcyphygeodesy.com

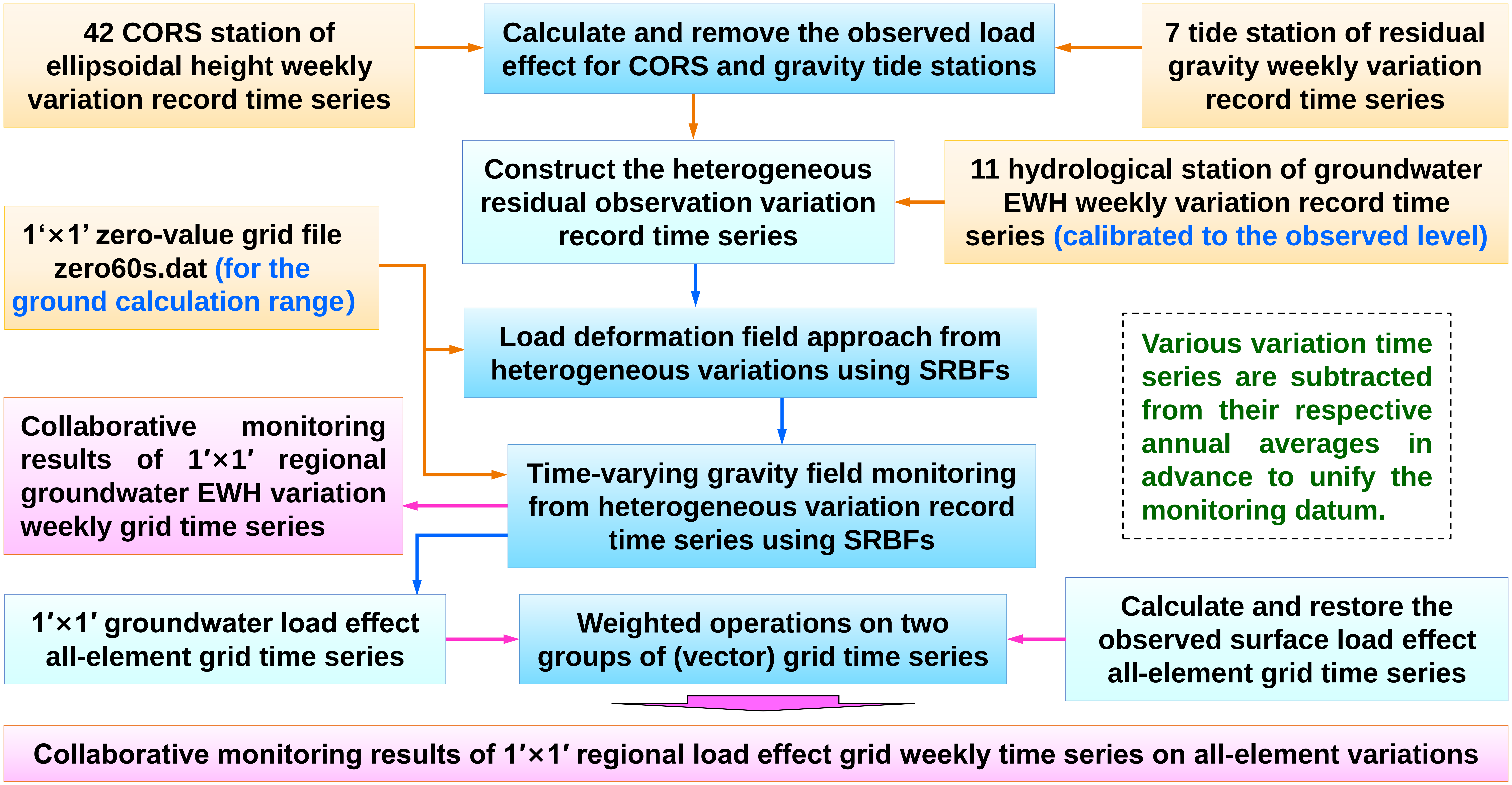


Collaborative monitoring of groundwater and load deformation field from Heterogeneous variations



CORS + gravity tide + groundwater + surface load collaborative monitoring by 5 steps

Step 1: Data preparation and preprocessing of various geodetic and surface load observations (ommited)



42 CORS station of ellipsoidal height weekly variation record time series

Calculate and remove the observed load effect for CORS and gravity tide stations

7 tide station of residual gravity weekly variation record time series

Construct the heterogeneous residual observation variation record time series

11 hydrological station of groundwater EWH weekly variation record time series (calibrated to the observed level)

1‘×1’ zero-value grid file zero60s.dat (for the ground calculation range)

Load deformation field approach from heterogeneous variations using SRBFs

Various variation time series are subtracted from their respective annual averages in advance to unify the monitoring datum.

Collaborative monitoring results of 1′×1′ regional groundwater EWH variation weekly grid time series

Time-varying gravity field monitoring from heterogeneous variation record time series using SRBFs

1′×1′ groundwater load effect all-element grid time series

Weighted operations on two groups of (vector) grid time series

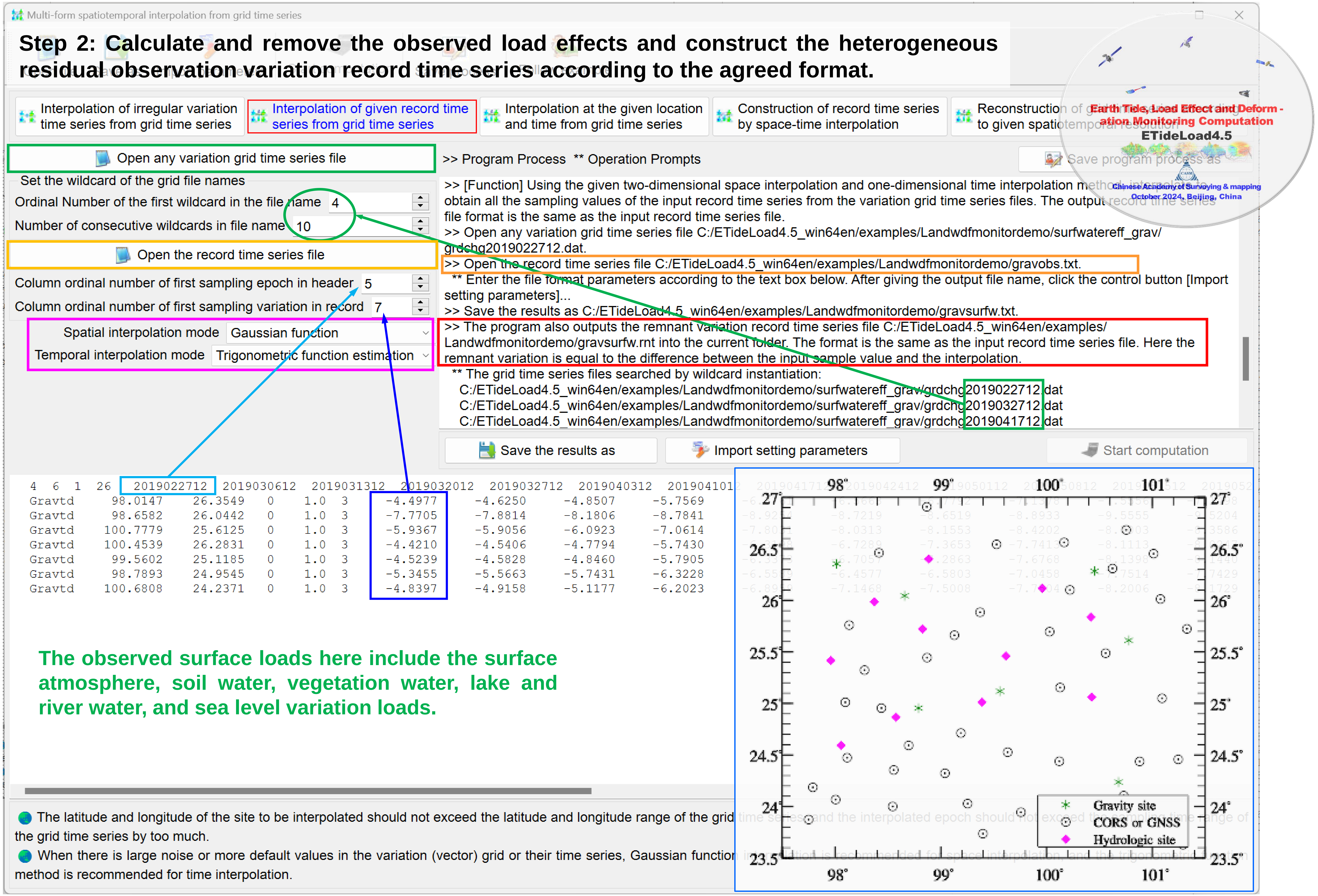
Calculate and restore the observed surface load effect all-element grid time series

Collaborative monitoring results of 1′×1′ regional load effect grid weekly time series on all-element variations

Heterogeneous collaborative monitoring process of groundwater variations and load deformation field

Chuanyin Zhang, Beijing, China October 2024 www.zcyphygeodesy.com

Step 2: Calculate and remove the observed load effects and construct the heterogeneous residual observation variation record time series according to the agreed format.



Set the wildcard of the grid file names

Ordinal Number of the first wildcard in the file name: 4

Number of consecutive wildcards in file name: 10

Column ordinal number of first sampling epoch in header: 5

Column ordinal number of first sampling variation in record: 7

Spatial interpolation mode: Gaussian function

Temporal interpolation mode: Trigonometric function estimation

>> Program Process ** Operation Prompts

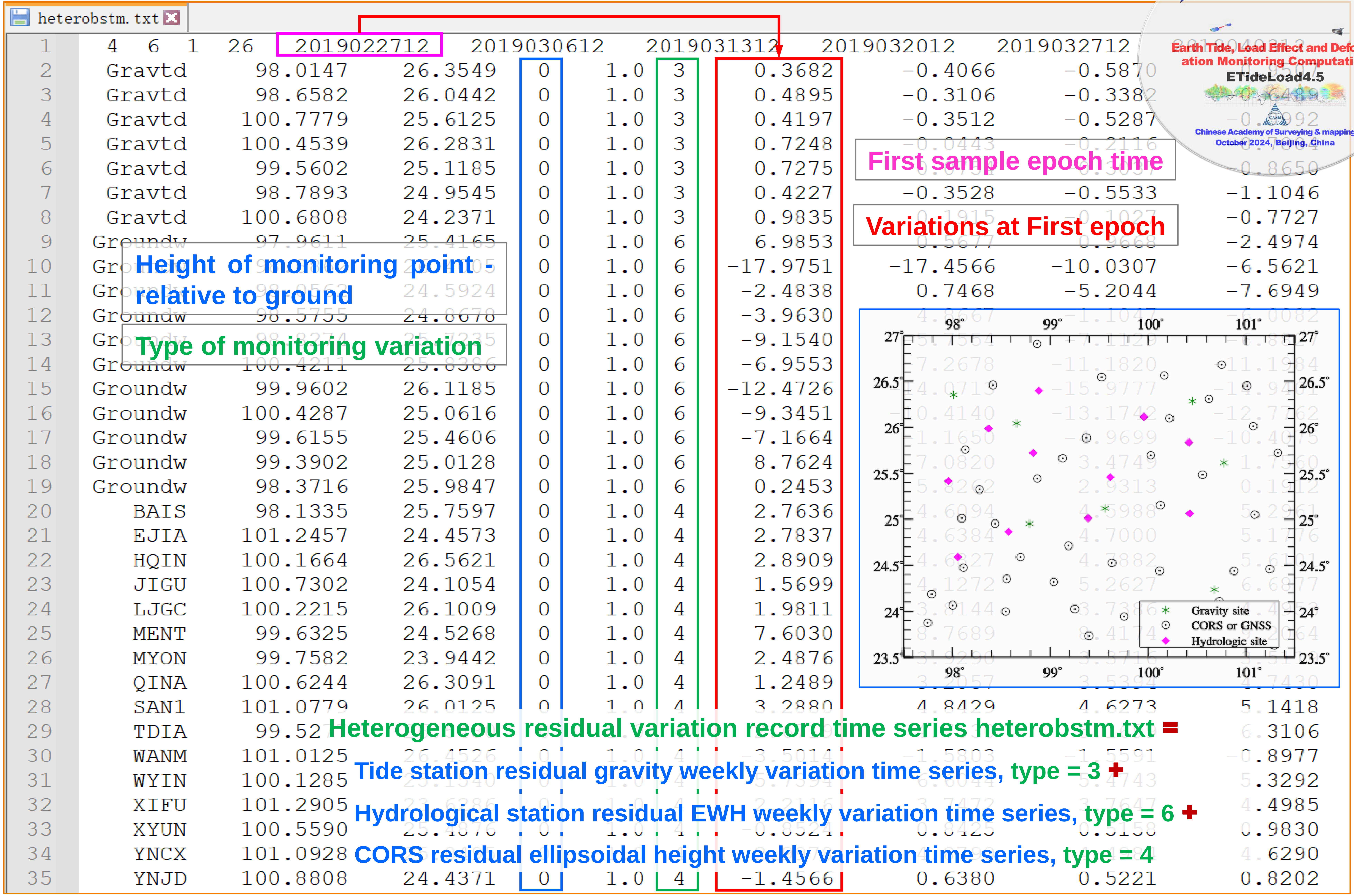
```
>> [Function] Using the given two-dimensional space interpolation and one-dimensional time interpolation method, interpolate to obtain all the sampling values of the input record time series from the variation grid time series files. The output record time series file format is the same as the input record time series file.
>> Open any variation grid time series file C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfwatereff_grav/grdchg2019022712.dat.
>> Open the record time series file C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/gravobs.txt.
 ** Enter the file format parameters according to the text box below. After giving the output file name, click the control button [Import setting parameters]...
>> Save the results as C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/gravsurfw.txt.
>> The program also outputs the remnant variation record time series file C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/gravsurfw.rnt into the current folder. The format is the same as the input record time series file. Here the remnant variation is equal to the difference between the input sample value and the interpolation.
 ** The grid time series files searched by wildcard instantiation:
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfwatereff_grav/grdchg2019022712.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfwatereff_grav/grdchg2019032712.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfwatereff_grav/grdchg2019041712.dat
```

```
 4   6   1   26   2019022712  2019030612  2019031312  2019032012  2019032712  2019040312  201904101
 Gravtd     98.0147     26.3549    0     1.0   3     -4.4977     -4.6250     -4.8507     -5.7569
 Gravtd     98.6582     26.0442    0     1.0   3     -7.7705     -7.8814     -8.1806     -8.7841
 Gravtd    100.7779     25.6125    0     1.0   3     -5.9367     -5.9056     -6.0923     -7.0614
 Gravtd    100.4539     26.2831    0     1.0   3     -4.4210     -4.5406     -4.7794     -5.7430
 Gravtd     99.5602     25.1185    0     1.0   3     -4.5239     -4.5828     -4.8460     -5.7905
 Gravtd     98.7893     24.9545    0     1.0   3     -5.3455     -5.5663     -5.7431     -6.3228
 Gravtd    100.6808     24.2371    0     1.0   3     -4.8397     -4.9158     -5.1177     -6.2023
```

The observed surface loads here include the surface atmosphere, soil water, vegetation water, lake and river water, and sea level variation loads.

- The latitude and longitude of the site to be interpolated should not exceed the latitude and longitude range of the grid time series and the interpolated epoch should not exceed the sampling time range of the grid time series by too much.
- When there is large noise or more default values in the variation (vector) grid or their time series, Gaussian function interpolation is recommended for space interpolation, and the trigonometric function method is recommended for time interpolation.

Construct the heterogeneous residual observation variation record time series.



```
   4   6   1   26   2019022712     2019030612      2019031312     2019032012     2019032712
  Gravtd      98.0147    26.3549    0     1.0   3     0.3682     -0.4066     -0.5870
  Gravtd      98.6582    26.0442    0     1.0   3     0.4895     -0.3106     -0.3382
  Gravtd     100.7779    25.6125    0     1.0   3     0.4197     -0.3512     -0.5287
  Gravtd     100.4539    26.2831    0     1.0   3     0.7248     -0.0443     -0.2116
  Gravtd      99.5602    25.1185    0     1.0   3     0.7275                              -0.8650
  Gravtd      98.7893    24.9545    0     1.0   3     0.4227     -0.3528     -0.5533     -1.1046
  Gravtd     100.6808    24.2371    0     1.0   3     0.9835                              -0.7727
 Groundw      97.9611    25.4165    0     1.0   6     6.9853      0.5677      0.9668     -2.4974
 Gr                                   0     1.0   6   -17.9751    -17.4566    -10.0307     -6.5621
 Gr                      24.5924    0     1.0   6    -2.4838      0.7468     -5.2044     -7.6949
 Groundw      98.5755    24.8678    0     1.0   6    -3.9630      4.8667     -1.1047     -6.0082
 Gr                                   0     1.0   6    -9.1540
 Groundw     100.4211    25.8386    0     1.0   6    -6.9553
 Groundw      99.9602    26.1185    0     1.0   6   -12.4726
 Groundw     100.4287    25.0616    0     1.0   6    -9.3451
 Groundw      99.6155    25.4606    0     1.0   6    -7.1664
 Groundw      99.3902    25.0128    0     1.0   6     8.7624
 Groundw      98.3716    25.9847    0     1.0   6     0.2453
    BAIS      98.1335    25.7597    0     1.0   4     2.7636
    EJIA     101.2457    24.4573    0     1.0   4     2.7837
    HQIN     100.1664    26.5621    0     1.0   4     2.8909
    JIGU     100.7302    24.1054    0     1.0   4     1.5699
    LJGC     100.2215    26.1009    0     1.0   4     1.9811
    MENT      99.6325    24.5268    0     1.0   4     7.6030
    MYON      99.7582    23.9442    0     1.0   4     2.4876
    QINA     100.6244    26.3091    0     1.0   4     1.2489
    SAN1     101.0779    26.0125    0     1.0   4     3.2880      4.8429      4.6273      5.1418
    TDIA      99.52                                                                     6.3106
    WANM     101.0125    26.4526    0     1.0   4    -3.5014     -1.5803     -1.5591     -0.8977
    WYIN     100.1285                                                                   5.3292
    XIFU     101.2905                                                                   4.4985
    XYUN     100.5590    25.4876    0     1.0   4    -0.8524      0.8425      0.5158      0.9830
    YNCX     101.0928                                                                   4.6290
    YNJD     100.8808    24.4371    0     1.0   4    -1.4566      0.6380      0.5221      0.8202
```

First sample epoch time

Variations at First epoch

Height of monitoring point - relative to ground

Type of monitoring variation

Heterogeneous residual variation record time series heterobstm.txt =

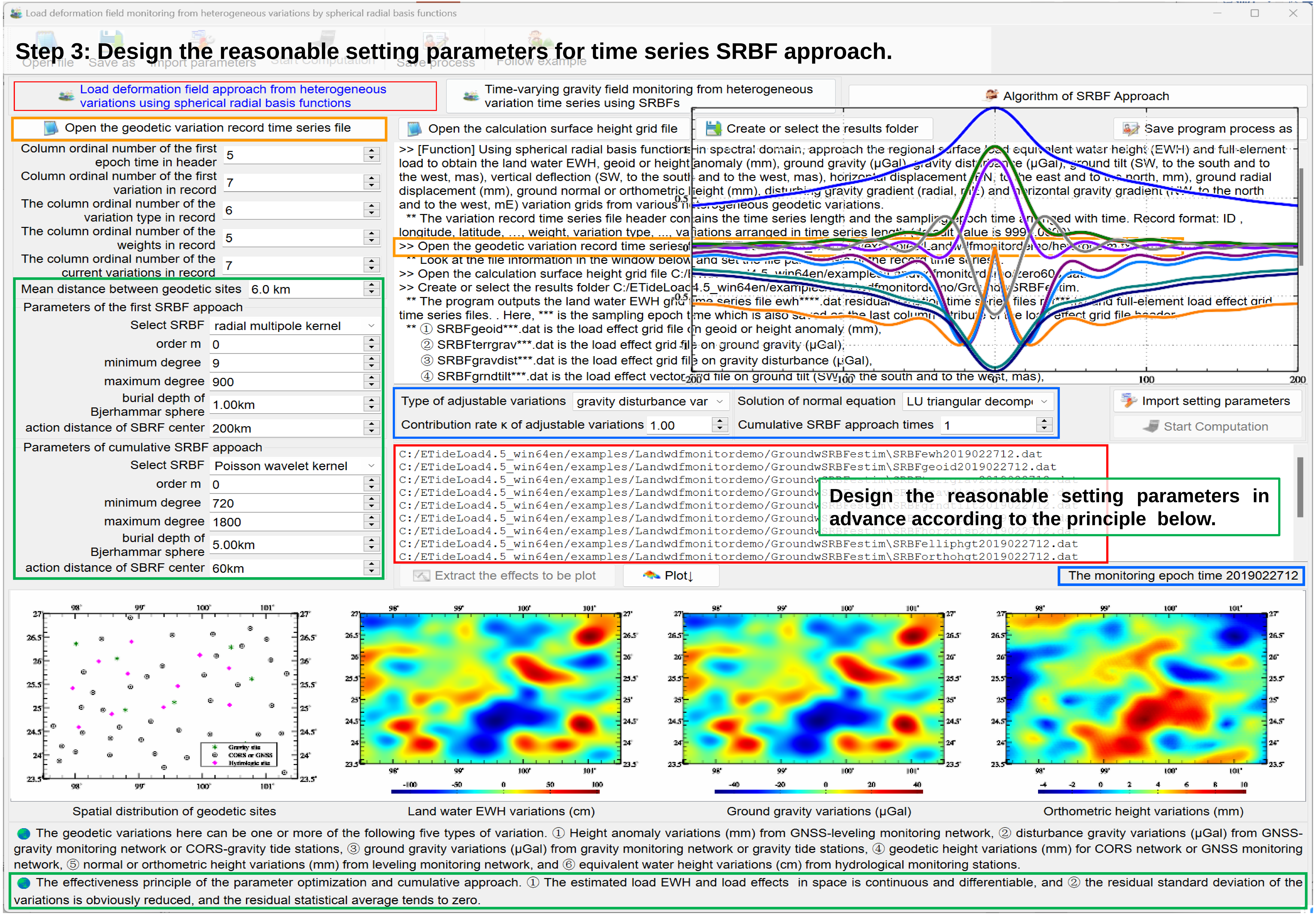
Tide station residual gravity weekly variation time series, type = 3 +

Hydrological station residual EWH weekly variation time series, type = 6 +

CORS residual ellipsoidal height weekly variation time series, type = 4

Earth Tide, Load Effect and Deformation Monitoring Computation
ETideLoad4.5
Chinese Academy of Surveying & mapping
October 2024, Beijing, China

Step 3: Design the reasonable setting parameters for time series SRBF approach.



Column ordinal number of the first epoch time in header: 5

Column ordinal number of the first variation in record: 7

The column ordinal number of the variation type in record: 6

The column ordinal number of the weights in record: 5

The column ordinal number of the current variations in record: 7

Mean distance between geodetic sites: 6.0 km

Parameters of the first SRBF appoach

Select SRBF: radial multipole kernel

order m: 0

minimum degree: 9

maximum degree: 900

burial depth of Bjerhammar sphere: 1.00km

action distance of SBRF center: 200km

Parameters of cumulative SRBF appoach

Select SRBF: Poisson wavelet kernel

order m: 0

minimum degree: 720

maximum degree: 1800

burial depth of Bjerhammar sphere: 5.00km

action distance of SBRF center: 60km

\>> [Function] Using spherical radial basis functions in spectral domain, approach the regional surface load equivalent water height (EWH) and full-element load to obtain the land water EWH, geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, mE) and horizontal gravity gradient (NW, to the north and to the west, mE) variation grids from various heterogeneous geodetic variations.

** The variation record time series file header contains the time series length and the sampling epoch time arranged with time. Record format: ID , longitude, latitude, ..., weight, variation type, ..., variations arranged in time series length (default value is 9999.0000).

\>> Open the geodetic variation record time series file [illegible] examples/Landwdfmonitordemo/he[illegible]

** Look at the file information in the window below and set the file pa[illegible] the record time series.

\>> Open the calculation surface height grid file C:/[illegible]4.5_win64en/examples/[illegible]monitordemo/zero60[illegible].dat.

\>> Create or select the results folder C:/ETideLoad4.5_win64en/examples/[illegible]monitordemo/Gro[illegible]SRBFestim.

** The program outputs the land water EWH grid time series file ewh****.dat residual [illegible] time series files r[illegible]*** [illegible] and full-element load effect grid time series files. . Here, *** is the sampling epoch time which is also saved as the last column attribute of the load effect grid file header.

** ① SRBFgeoid***.dat is the load effect grid file on geoid or height anomaly (mm),

② SRBFterrgrav***.dat is the load effect grid file on ground gravity (μGal),

③ SRBFgravdist***.dat is the load effect grid file on gravity disturbance (μGal),

④ SRBFgrndtilt***.dat is the load effect vector grid file on ground tilt (SW, to the south and to the west, mas),

Type of adjustable variations: gravity disturbance var

Solution of normal equation: LU triangular decomp

Contribution rate κ of adjustable variations: 1.00

Cumulative SRBF approach times: 1

```
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBFewh2019022712.dat
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBFgeoid2019022712.dat
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBFterrgrav2019022712.dat
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBFgravdist2019022712.dat
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBFgrndtilt2019022712.dat
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/Groundw[illegible]
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBFhorzdisp2019022712.dat
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBFelliphgt2019022712.dat
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBForthohgt2019022712.dat
```

Design the reasonable setting parameters in advance according to the principle below.

The monitoring epoch time 2019022712

Spatial distribution of geodetic sites

Land water EWH variations (cm)

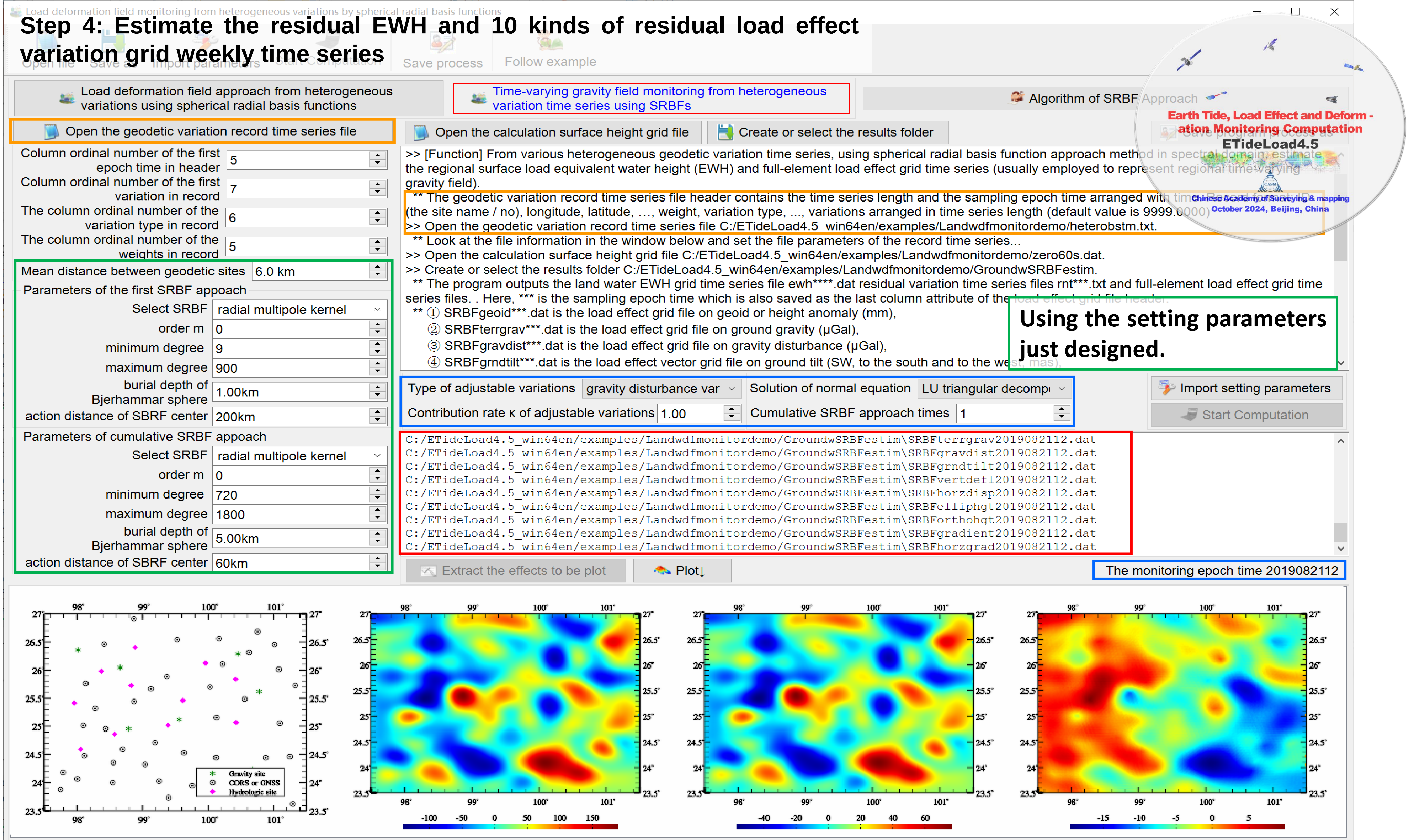
Ground gravity variations (μGal)

Orthometric height variations (mm)

The geodetic variations here can be one or more of the following five types of variation. ① Height anomaly variations (mm) from GNSS-leveling monitoring network, ② disturbance gravity variations (μGal) from GNSS-gravity monitoring network or CORS-gravity tide stations, ③ ground gravity variations (μGal) from gravity monitoring network or gravity tide stations, ④ geodetic height variations (mm) for CORS network or GNSS monitoring network, ⑤ normal or orthometric height variations (mm) from leveling monitoring network, and ⑥ equivalent water height variations (cm) from hydrological monitoring stations.

The effectiveness principle of the parameter optimization and cumulative approach. ① The estimated load EWH and load effects in space is continuous and differentiable, and ② the residual standard deviation of the variations is obviously reduced, and the residual statistical average tends to zero.

Step 4: Estimate the residual EWH and 10 kinds of residual load effect variation grid weekly time series



Column ordinal number of the first epoch time in header: 5
Column ordinal number of the first variation in record: 7
The column ordinal number of the variation type in record: 6
The column ordinal number of the weights in record: 5

Mean distance between geodetic sites: 6.0 km

Parameters of the first SRBF appoach
Select SRBF: radial multipole kernel
order m: 0
minimum degree: 9
maximum degree: 900
burial depth of Bjerhammar sphere: 1.00km
action distance of SBRF center: 200km

Parameters of cumulative SRBF appoach
Select SRBF: radial multipole kernel
order m: 0
minimum degree: 720
maximum degree: 1800
burial depth of Bjerhammar sphere: 5.00km
action distance of SBRF center: 60km

Type of adjustable variations: gravity disturbance var
Solution of normal equation: LU triangular decomp
Contribution rate κ of adjustable variations: 1.00
Cumulative SRBF approach times: 1

```
>> [Function] From various heterogeneous geodetic variation time series, using spherical radial basis function approach method in spectral domain, estimate the regional surface load equivalent water height (EWH) and full-element load effect grid time series (usually employed to represent regional time-varying gravity field).
  ** The geodetic variation record time series file header contains the time series length and the sampling epoch time arranged with time... (the site name / no), longitude, latitude, ..., weight, variation type, ..., variations arranged in time series length (default value is 9999.0000)
>> Open the geodetic variation record time series file C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/heterobstm.txt.
  ** Look at the file information in the window below and set the file parameters of the record time series...
>> Open the calculation surface height grid file C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/zero60s.dat.
>> Create or select the results folder C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim.
  ** The program outputs the land water EWH grid time series file ewh****.dat residual variation time series files rnt***.txt and full-element load effect grid time series files. . Here, *** is the sampling epoch time which is also saved as the last column attribute of the load effect grid file header.
  ** ① SRBFgeoid***.dat is the load effect grid file on geoid or height anomaly (mm),
     ② SRBFterrgrav***.dat is the load effect grid file on ground gravity (μGal),
     ③ SRBFgravdist***.dat is the load effect grid file on gravity disturbance (μGal),
     ④ SRBFgrndtilt***.dat is the load effect vector grid file on ground tilt (SW, to the south and to the west, mas),
```

Using the setting parameters just designed.

```
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBFterrgrav2019082112.dat
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBFgravdist2019082112.dat
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBFgrndtilt2019082112.dat
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBFvertdefl2019082112.dat
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBFhorzdisp2019082112.dat
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBFelliphgt2019082112.dat
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBForthohgt2019082112.dat
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBFgradient2019082112.dat
C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/GroundwSRBFestim\SRBFhorzgrad2019082112.dat
```

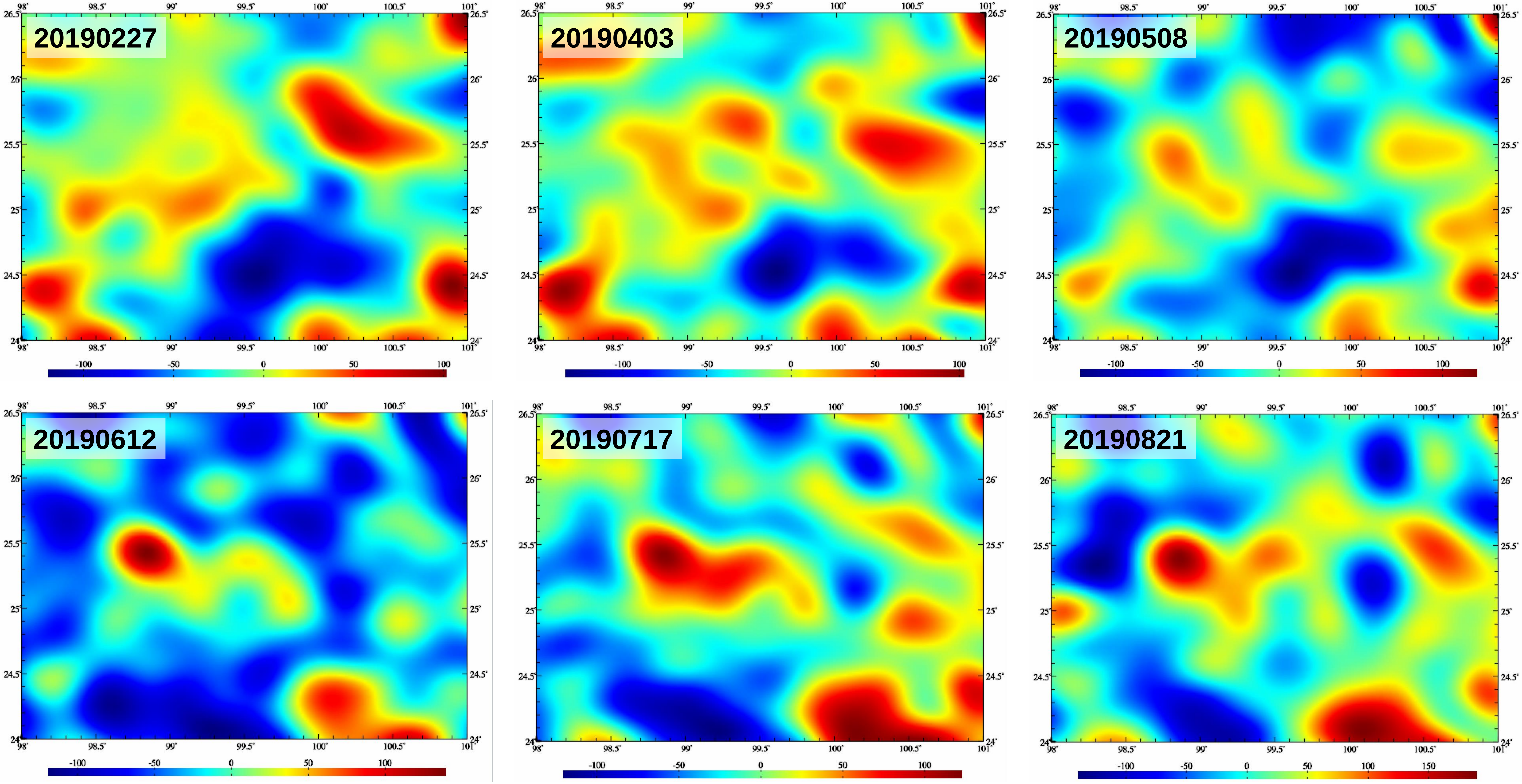
The monitoring epoch time 2019082112

Spatial distribution of geodetic sites | Land water EWH variations (cm) | Ground gravity variations (μGal) | Orthometric height variations (mm)

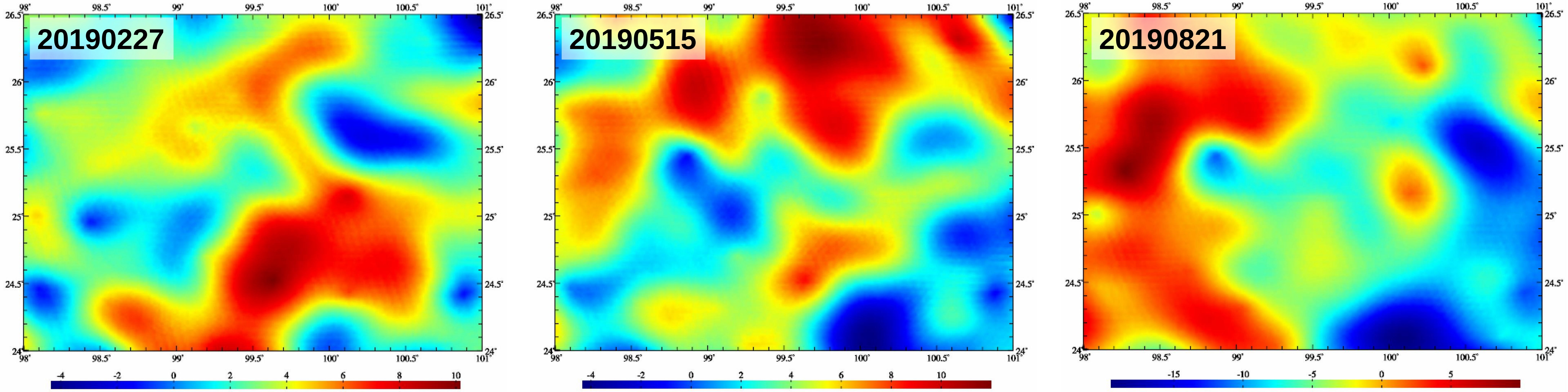
🌐 The geodetic variations here can be one or more of the following five types of variation. ① Height anomaly variations (mm) from GNSS-leveling monitoring network, ② disturbance gravity variations (μGal) from GNSS-gravity monitoring network or CORS-gravity tide stations, ③ ground gravity variations (μGal) from gravity monitoring network or gravity tide stations, ④ geodetic height variations (mm) for CORS network or GNSS monitoring network, ⑤ normal or orthometric height variations (mm) from leveling monitoring network, and ⑥ equivalent water height variations (cm) from hydrological monitoring stations.

🌐 The effectiveness principle of the parameter optimization and cumulative approach. ① The estimated load EWH and load effects in space is continuous and differentiable, and ② the residual standard deviation of the variations is obviously reduced, and the residual statistical average tends to zero.

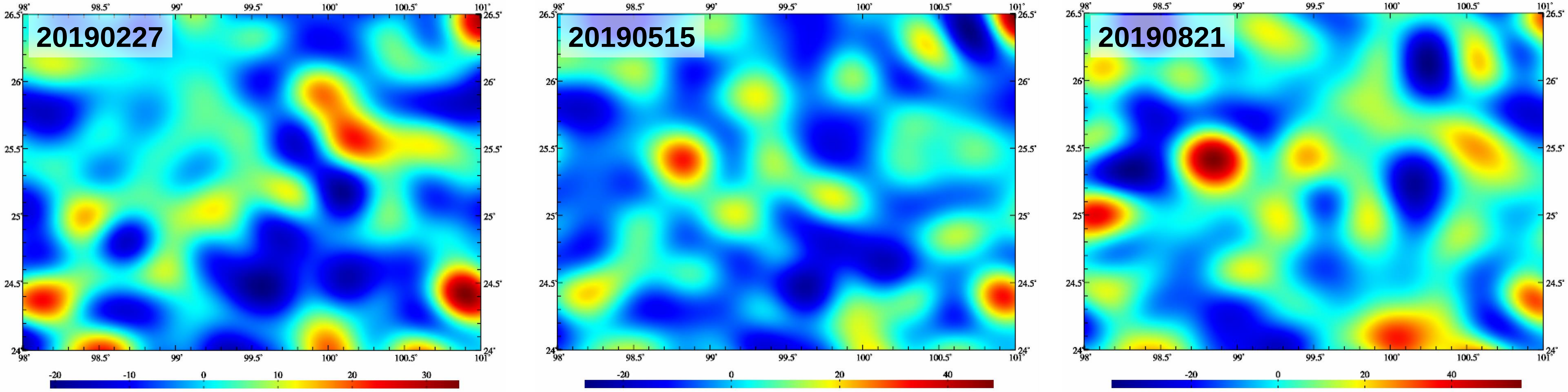
Heterogeneous collaborative monitoring: 42 CORS stations, 7 gravity tide stations and 11 hydrological stations



Collaborative monitoring results of 1′×1′ regional groundwater EWH variation grid weekly time series



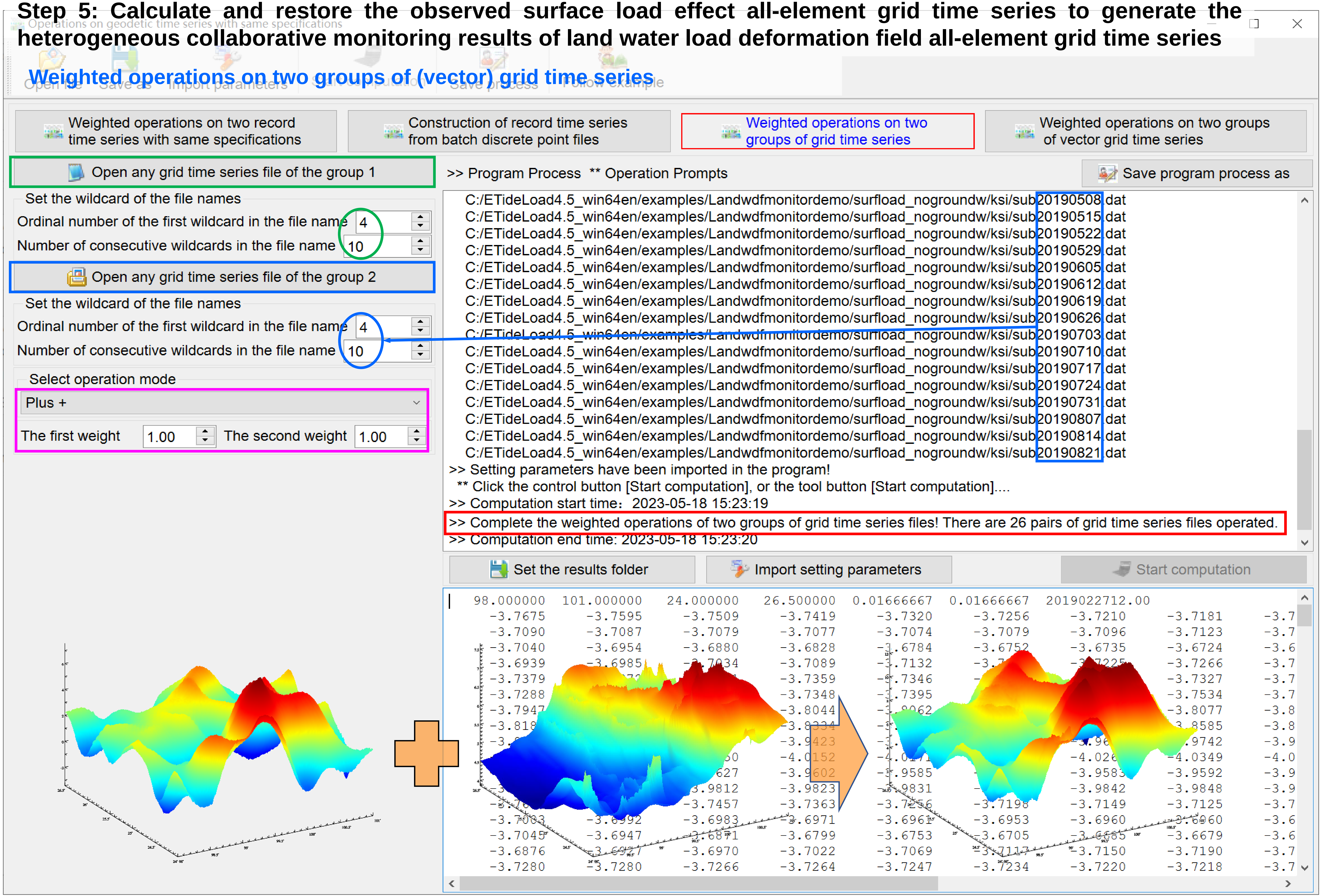
1′×1′ regional groundwater load effect variation (mm) grid weekly time series on ground orthometric height



1′×1′ regional groundwater load effect variation (mE) grid weekly time series on gravity gradient

Step 5: Calculate and restore the observed surface load effect all-element grid time series to generate the heterogeneous collaborative monitoring results of land water load deformation field all-element grid time series

Weighted operations on two groups of (vector) grid time series



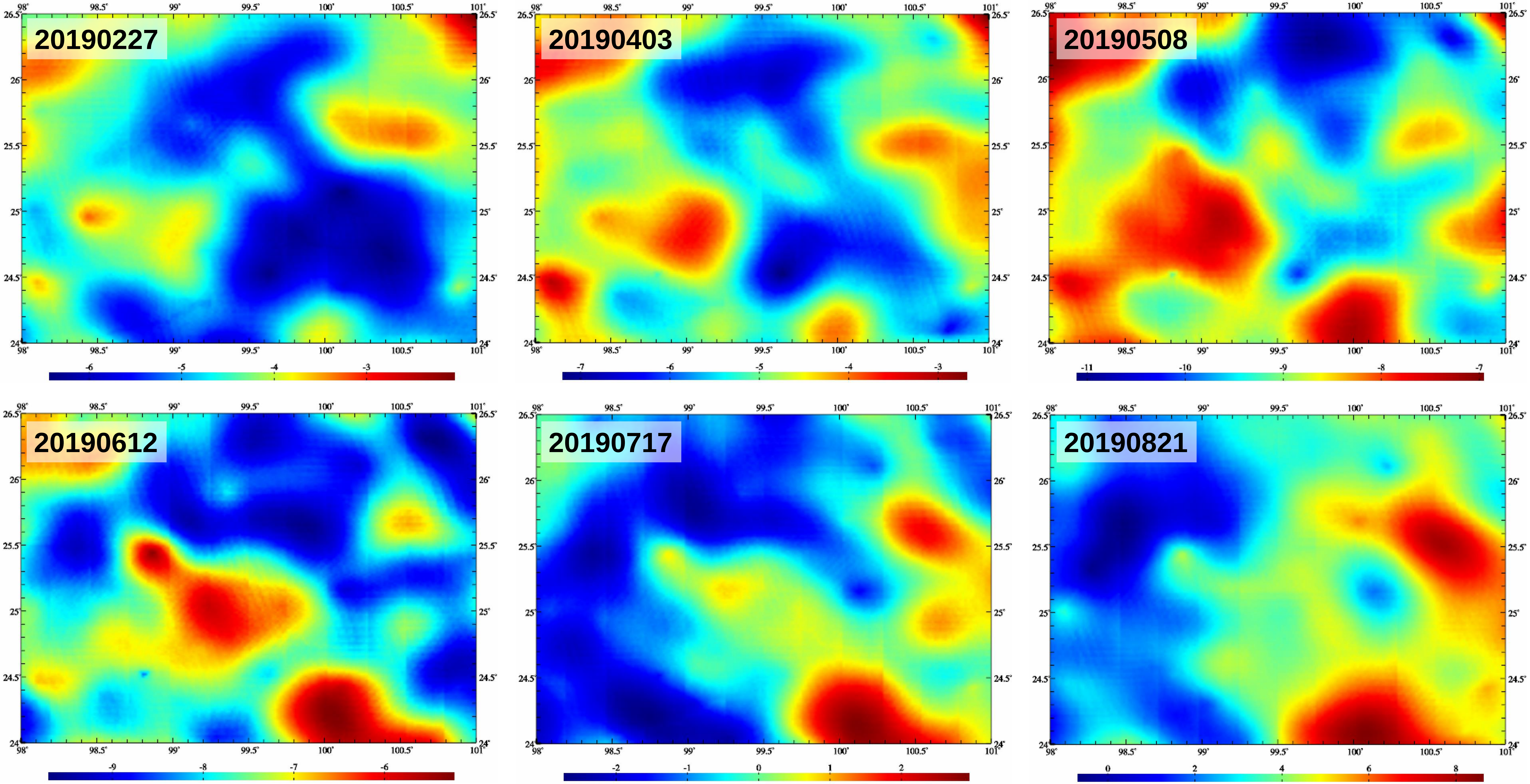
Set the wildcard of the file names
Ordinal number of the first wildcard in the file name 4
Number of consecutive wildcards in the file name 10

Set the wildcard of the file names
Ordinal number of the first wildcard in the file name 4
Number of consecutive wildcards in the file name 10

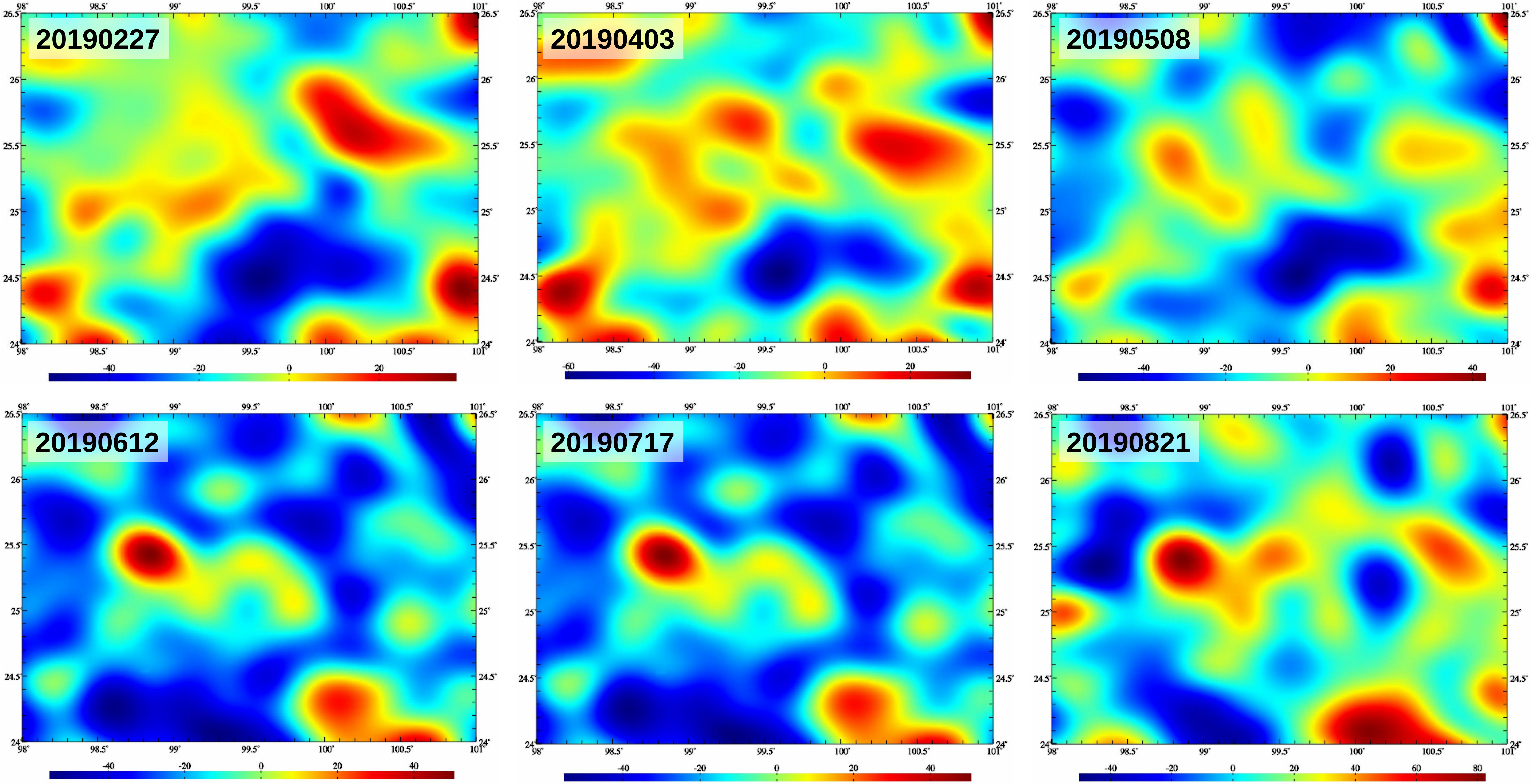
Select operation mode
Plus +
The first weight 1.00 The second weight 1.00

```
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfload_nogroundw/ksi/sub20190508.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfload_nogroundw/ksi/sub20190515.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfload_nogroundw/ksi/sub20190522.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfload_nogroundw/ksi/sub20190529.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfload_nogroundw/ksi/sub20190605.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfload_nogroundw/ksi/sub20190612.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfload_nogroundw/ksi/sub20190619.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfload_nogroundw/ksi/sub20190626.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfload_nogroundw/ksi/sub20190703.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfload_nogroundw/ksi/sub20190710.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfload_nogroundw/ksi/sub20190717.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfload_nogroundw/ksi/sub20190724.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfload_nogroundw/ksi/sub20190731.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfload_nogroundw/ksi/sub20190807.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfload_nogroundw/ksi/sub20190814.dat
  C:/ETideLoad4.5_win64en/examples/Landwdfmonitordemo/surfload_nogroundw/ksi/sub20190821.dat
>> Setting parameters have been imported in the program!
 ** Click the control button [Start computation], or the tool button [Start computation]....
>> Computation start time: 2023-05-18 15:23:19
>> Complete the weighted operations of two groups of grid time series files! There are 26 pairs of grid time series files operated.
>> Computation end time: 2023-05-18 15:23:20
```

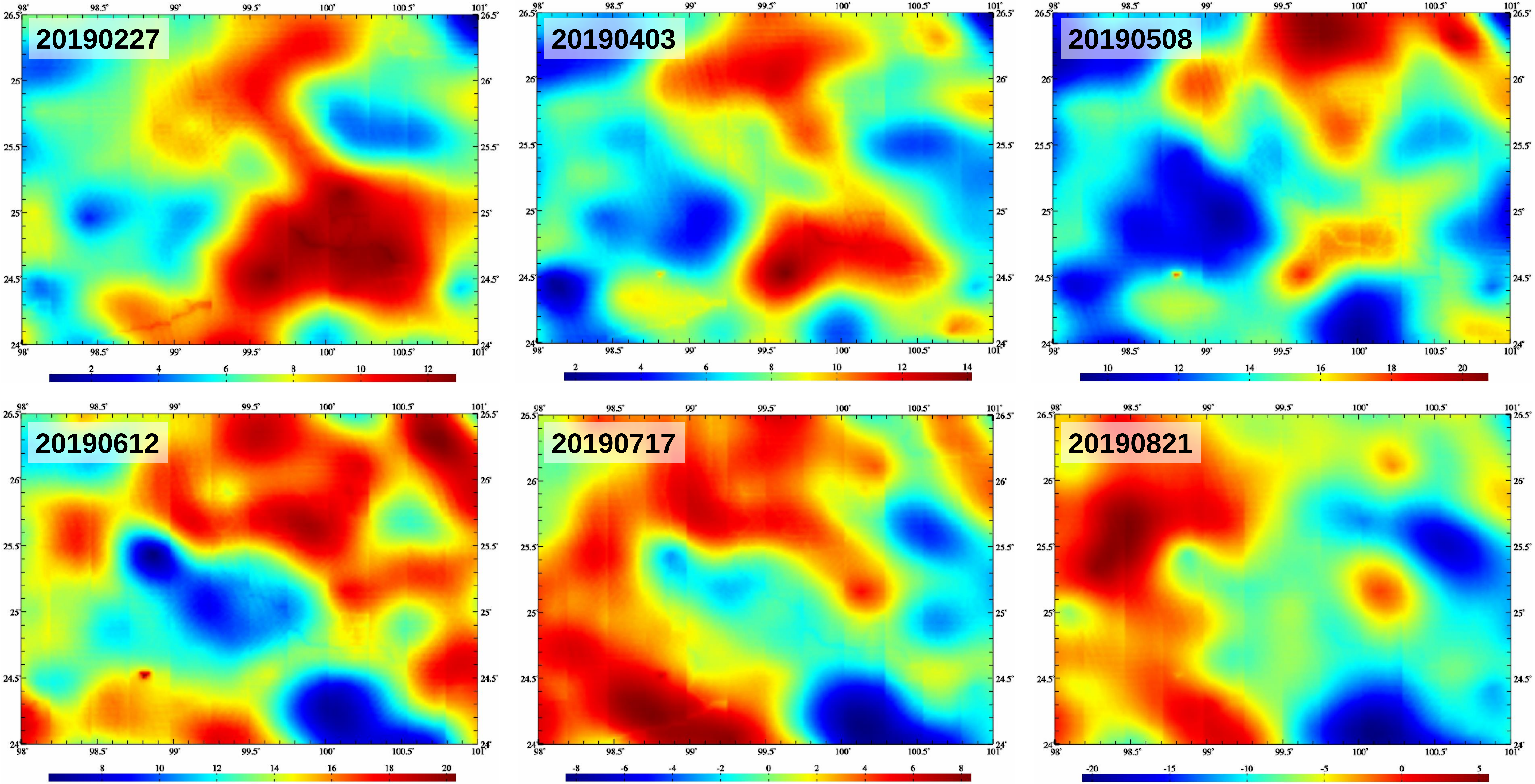
```
 98.000000  101.000000  24.000000  26.500000  0.01666667  0.01666667  2019022712.00
   -3.7675     -3.7595    -3.7509    -3.7419     -3.7320     -3.7256      -3.7210    -3.7181    -3.7
   -3.7090     -3.7087    -3.7079    -3.7077     -3.7074     -3.7079      -3.7096    -3.7123    -3.7
   -3.7040     -3.6954    -3.6880    -3.6828     -3.6784     -3.6752      -3.6735    -3.6724    -3.6
```



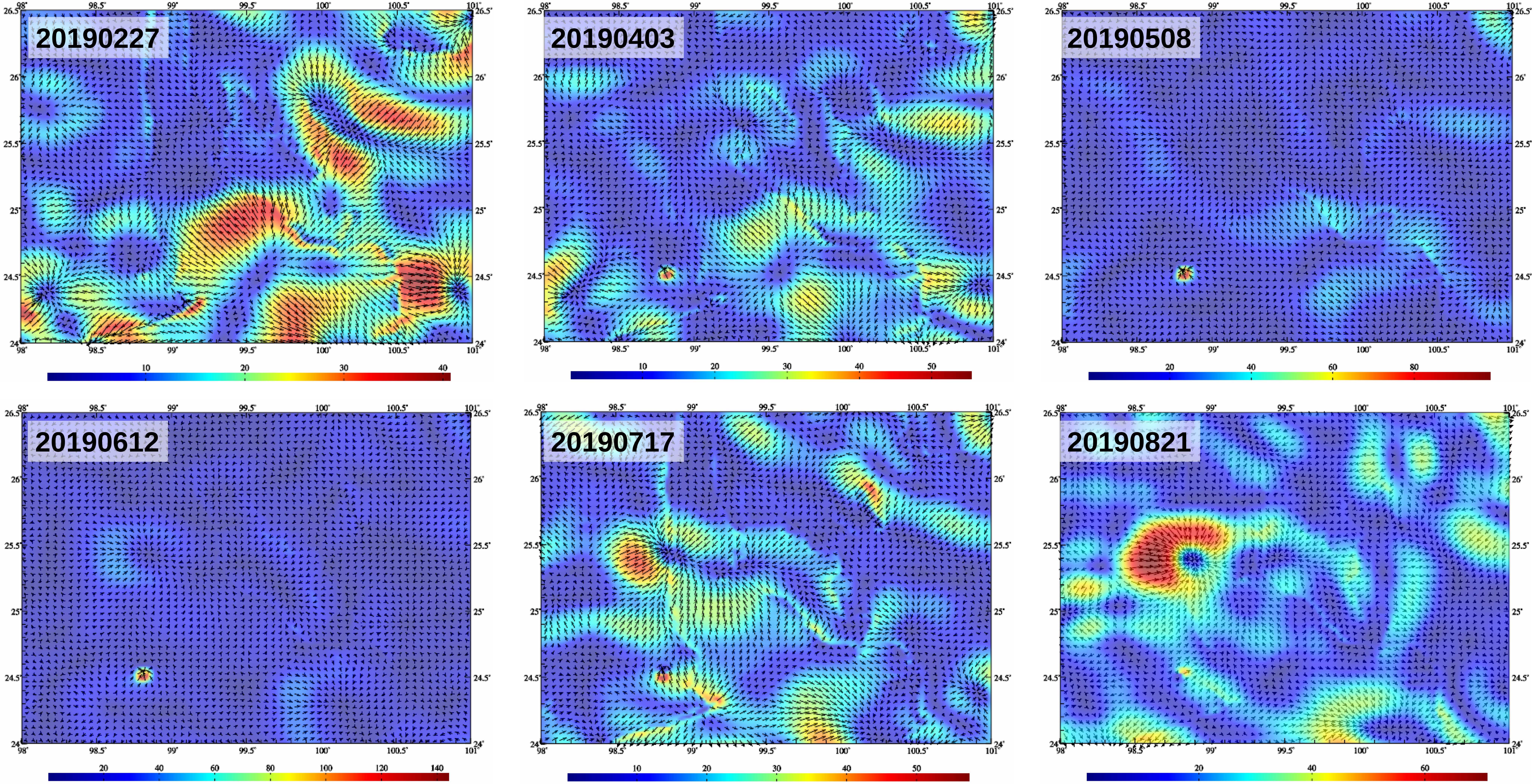
Collaborative monitoring results of 1′×1′ surface load effect variation (mm) grid weekly time series on geoid



Collaborative monitoring results of 1′×1′ load effect variation (μGal) grid weekly time series on ground gravity



Collaborative monitoring results of 1′×1′ load effect variation (mm) grid weekly time series on ground ellipsoidal height



Collaborative monitoring results of 1′×1′ load effect variation (mas) vector grid weekly time series on ground tilt

🌏 Heterogeneous collaborative monitoring process of groundwater variations and load deformation field

Step 1: Data preparation and preprocessing of various geodetic and surface load observations.

Step 2: Calculate and remove the observed load effects and construct the heterogeneous residual observation variation record time series according to the agreed format.

Step 3: Design the reasonable setting parameters for time series SRBF approach, and then estimate the residual EWH and 10 kinds of residual load effect variation grid weekly time series.

Step 4: Calculate and restore the observed surface load effect all-element grid weekly time series to generate the heterogeneous collaborative monitoring results of land water load deformation field all-element grid time series.

Main features of ETideLoad4.5's algorithm of heterogeneous collaborative monitoring

- The algorithm can effectively solve the troubles of high-degree oscillation, poor convergence, spectrum leakage and singularity of load Green′s integral around the calculation point, and then realize the collaborative monitoring of GNSS, gravity, leveling, ground tilt and groundwater strictly according to solid geophysical analytical constraints.
- There are rigorous analytical relationships between observation equations, and various heterogeneous geodetic monitoring systems can be deeply collaborated by normalization of their normal equations to avoid the collaborative algorithms affected by the observation errors. The algorithm has high stability and universality, which is suitable for massive computation of multiple geodetic collaborative monitoring..
- The algorithm has the functions of the spatial and spectrum domain separation of geophysical signals and measurement equipment parameter calibration, which can improve the medium and long-term monitoring ability for the gravity tide station and make the EWH monitoring ability for groundwater monitoring station, so as to enhance the level of collaborative monitoring from space, terrestrial and marine geodesy.

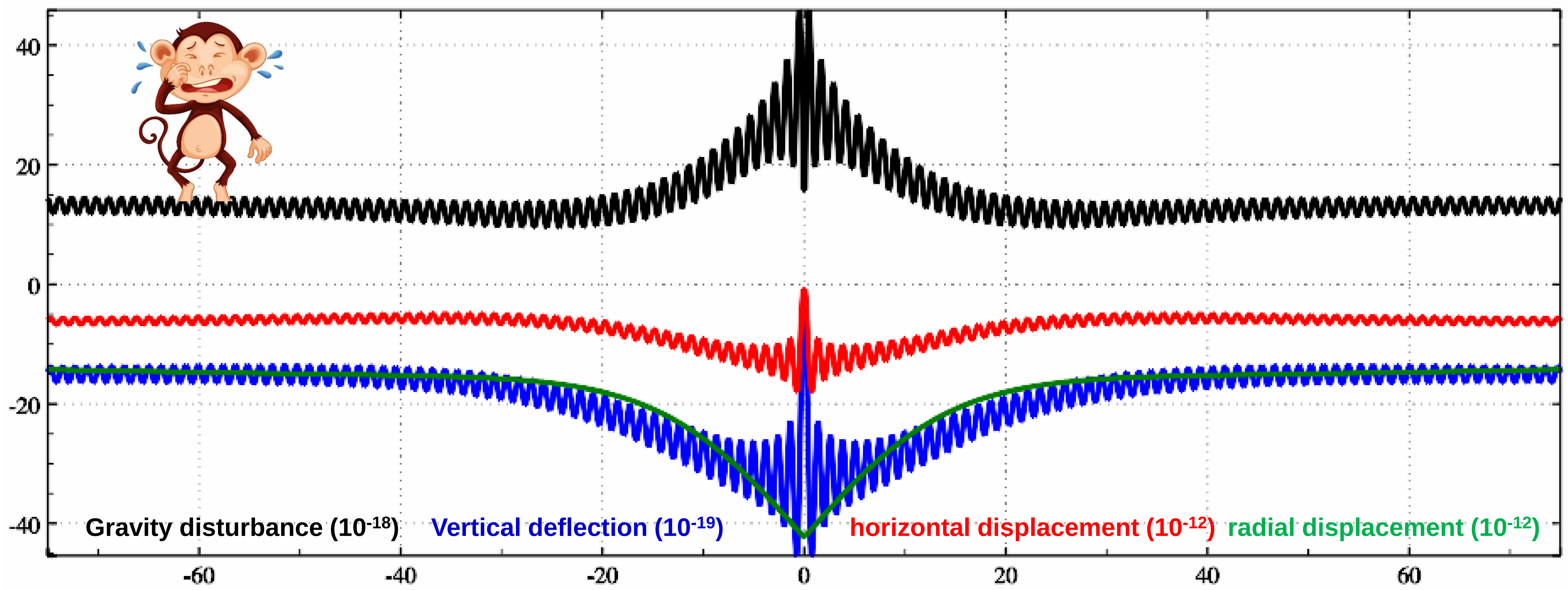


Fig.1 Near-region properties of load Green's function on geopotential differential variable

High-degree oscillation

Non-convergence

Integral singularity

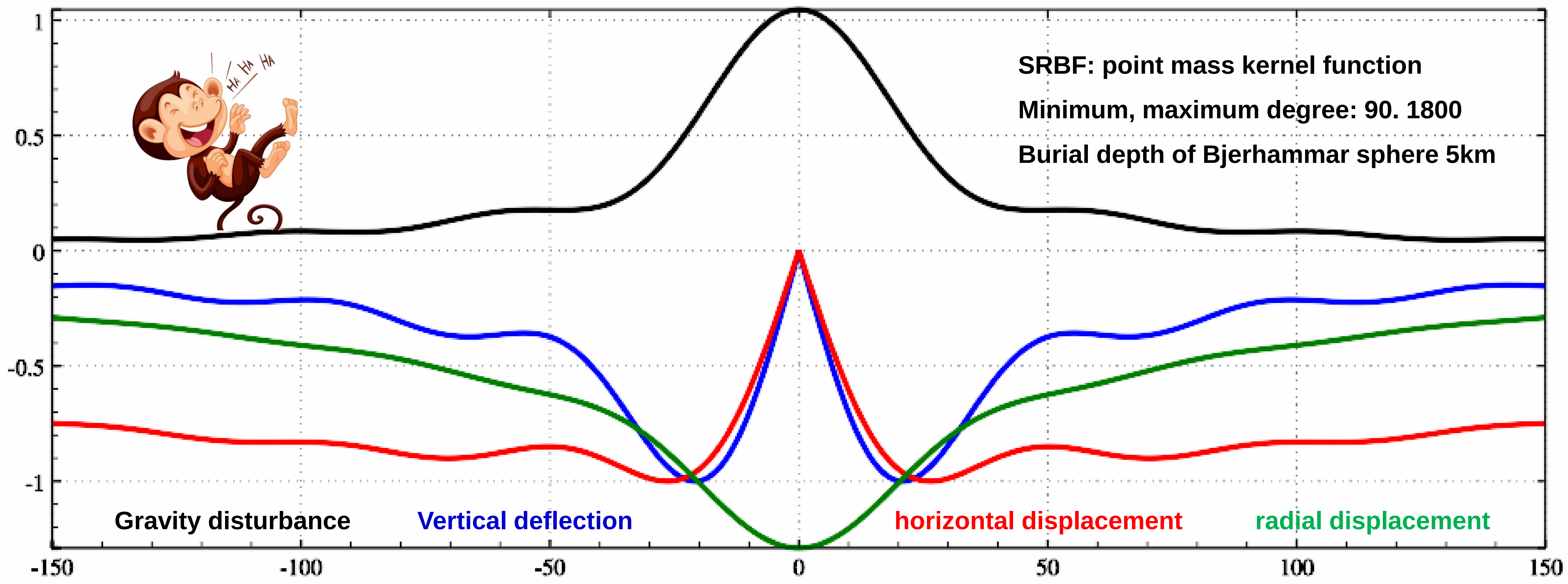


Fig.2 Near-region properties of SRBF spatial curve on geopotential differential variable

Stable

Convergence

Monotonic