Broadband assessment of polar motion excitation determined from recent gravity field solutions

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GRACE/GRACE-FO Science Team Meeting 2024, 8-10 October 2024, Potsdam, Germany

Introduction

- Variations in Earth's rotation, including polar motion (PM) and changes in the length of the day (LOD), are primarily caused by the varying distribution and movement of mass within the atmosphere, oceans, and hydrosphere. Identifying the different sources of these rotational changes is crucial for understanding processes occurring within the Earth system.
- Large-scale mass variations are reflected in changes of spherical harmonic coefficients of geopotential. In the study of variations in Earth's rotation, coefficients of degree two and order one (ΔC_{21}, ΔS_{21}) are particularly important, as they are linearly related to the equatorial components (χ_1, χ_2) of PM excitation.
- ΔC_{21}, ΔS_{21} coefficients can be measured using various techniques, with satellite gravimetry and Satellite Laser Ranging (SLR) being most popular in recent years. Various data centres produce temporal gravity solutions based on data from Gravity Recovery and Climate Experiment (GRACE) and its successor GRACE Follow-On (GRACE-FO). There are currently many solutions available determined from either GRACE/GRACE-FO data alone or their combinations with various techniques such as SLR or satellite-to-satellite tracking.
- In this study, we reassess **the mass-related excitation of PM computed from various ΔC_{21} and ΔS_{21} solutions based on GRACE/GRACE-FO, SLR, and combinations of these techniques**.
- All series are analysed for various oscillations, including seasonal and non-seasonal variations. They are then evaluated by comparison with hydrological signal in geodetic angular momentum obtained from precise geodetic measurements of Earth's rotation.

ΔC_{21} ΔS_{21} data

Here, we use ΔC_{21}, ΔS_{21} series from the following temporal gravity solutions:

GRACE/GRACE-FO only solutions

- Six single solutions provided by:
  - Center for Space Research (CSR), called **G CSR**
  - Jet Propulsion Laboratory (JPL), called **G JPL**
  - GeoForschungsZentrum (GFZ), called **G GFZ**
  - Institute of Geodesy at Graz University of Technology (ITSG), called **G ITSG**
  - Astronomical Institute University Bern (AIUB), called **G AIUB**
  - Huazhong University of Science and Technology, Wuhan, China (HUST), called **G HUST**
- One combined GRACE/GRACE-FO solution provided by International Combination Service for Time-variable Gravity Field (COST-G), called **G COST**
- One spherical harmonic representation of the mascon solution from Center for Space Research (CSR), called **G MAS CSR**

All datasets were obtained from International Centre for Global Earth Models (ICGEM) website (https://icgem.gfz-potsdam.de/home)

ΔC_{21} ΔS_{21} data

Here, we use ΔC_{21}, ΔS_{21} series from the following temporal gravity solutions:

Hybrid SLR + GRACE/GRACE-FO solutions

- Hybrid SLR + GRACE/GRACE-FO solution provided by Centre National d'Etudes Spatiales (CNES), called **H CNES**
- Five gravity field solutions and their ensemble mean provided by Institut für Geodäsie und Geoinformation (IGG), Universität Bonn (Löcher and Kusche 2021). The data are determined from SLR using a hybrid parametrization including SH coefficients and empirical orthogonal functions (EOF) from GRACE (number after “S” shows maximum degree of SH estimated, number before “E” shows number of EOFs applied):
    - IGG-SLR-HYBRID_S0+6E, called **H IGG S0 6E**
    - IGG-SLR-HYBRID_S2+6E, called **H IGG S2 6E**
    - IGG-SLR-HYBRID_S3+6E, called **H IGG S3 6E**
    - IGG-SLR-HYBRID_S4+6E, called **H IGG S4 6E**
    - IGG-SLR-HYBRID_S5+4E, called **H IGG S5 4E**
    - IGG-SLR-HYBRID_EnsMean, called **H IGG M**

All datasets were obtained from International Centre for Global Earth Models (ICGEM) website (https://icgem.gfz-potsdam.de/home)

Löcher, A., Kusche, J. (2021). A hybrid approach for recovering high-resolution temporal gravity fields from satellite laser ranging. https://doi.org/10.1007/s00190-020-01460-x

ΔC_{21} ΔS_{21} data

Here, we use ΔC_{21}, ΔS_{21} series from the following temporal gravity solutions:

SLR solutions

- Monthly 5x5 gravity harmonics provided by University of Texas (UT) and CSR, called **S CSR**
- IGG_UPWr_SLR – SLR gravity solution provided by Wrocław University of Environmental and Life Science, called **S UPWr**

Hybrid HL-SST + SLR solutions

- Gravity field solutions based on high-low satellite-to-satellite tracking (HL-SST) and SLR provided by Leibniz University Hannover (without and with filtering of solutions using Kalman filter):
  - QuantumFrontiers/HLSST_SLR_COMB2023s_Kalman, called **QF k**
  - QuantumFrontiers/HLSST_SLR_COMB2023s_unfiltered, called **QF nk**

IGG_UPWr_SLR and QuantumFrontiers solutions were obtained from the ICGEM website (https://icgem.gfz-potsdam.de/home)
UT/CSR solution was taken from UT/CSR website (https://filedrop.csr.utexas.edu/pub/slr/degree_5/CSR_Monthly_5x5_Gravity_Harmonics.txt)

HAM computation from ΔC_{21} ΔS_{21}

The equatorial components (χ_1 and χ_2) of PM excitation, associated with the terrestrial hydrosphere and referred to as Hydrological Angular Momentum (HAM), were calculated using equations that describe the linear relationship between (χ_1, χ_2) and changes in the degree-2 order-1 coefficients of the geopotential (Gross, 2015):

$$\chi_1 = -\sqrt{\frac{5}{3}} \cdot \frac{1.608 \cdot R_e^2 \cdot M}{C - A'} \Delta C_{21}, \qquad \chi_2 = -\sqrt{\frac{5}{3}} \cdot \frac{1.608 \cdot R_e^2 \cdot M}{C - A'} \Delta S_{21}$$

- where R is the Earth's mean radius; M is the Earth's mass; A, B, and C are the principal moments of inertia for Earth (A = 8.0101×10^{37} kg·m^2, B = 8.0103×10^{37} kg·m^2, and C = 8.0365×10^{37} kg·m^2), A' = (A + B)/2 is an average of the equatorial principal moments of inertia, and ΔC_{21} and ΔS_{21} are the normalized SH coefficients of geopotential.
- Factor 1.608 includes the modification of the Love load number due to the mantle and elasticity.

GAO computation

To evaluate HAM series computed from temporal gravity field solutions, **we use hydrological signal in PM excitation as a reference**.

Hydrological signal in PM excitation – GAO is computed as a difference between geodetic angular momentum (GAM) and a sum of atmospheric angular momentum (AAM) and oceanic angular momentum (OAM):

$$\mathrm{GAO} = \mathrm{GAM} - \mathrm{AAM} - \mathrm{OAM}$$

To compute GAO, we use the following datasets:

- χ_1 and χ_2 components of GAM based on time series of Earth Orientation Parameters from the IERS EOP 20 C04 solution
- χ_1 and χ_2 components of AAM (mass + motion terms) based on ECMWF (European Center for Medium–Range Weather Forecasts) model and provided by GeoForschungsZentrum (GFZ)
- χ_1 and χ_2 components of OAM (mass + motion terms) based on MPIOM (Max Planck Institute Ocean Model) model and provided by GFZ

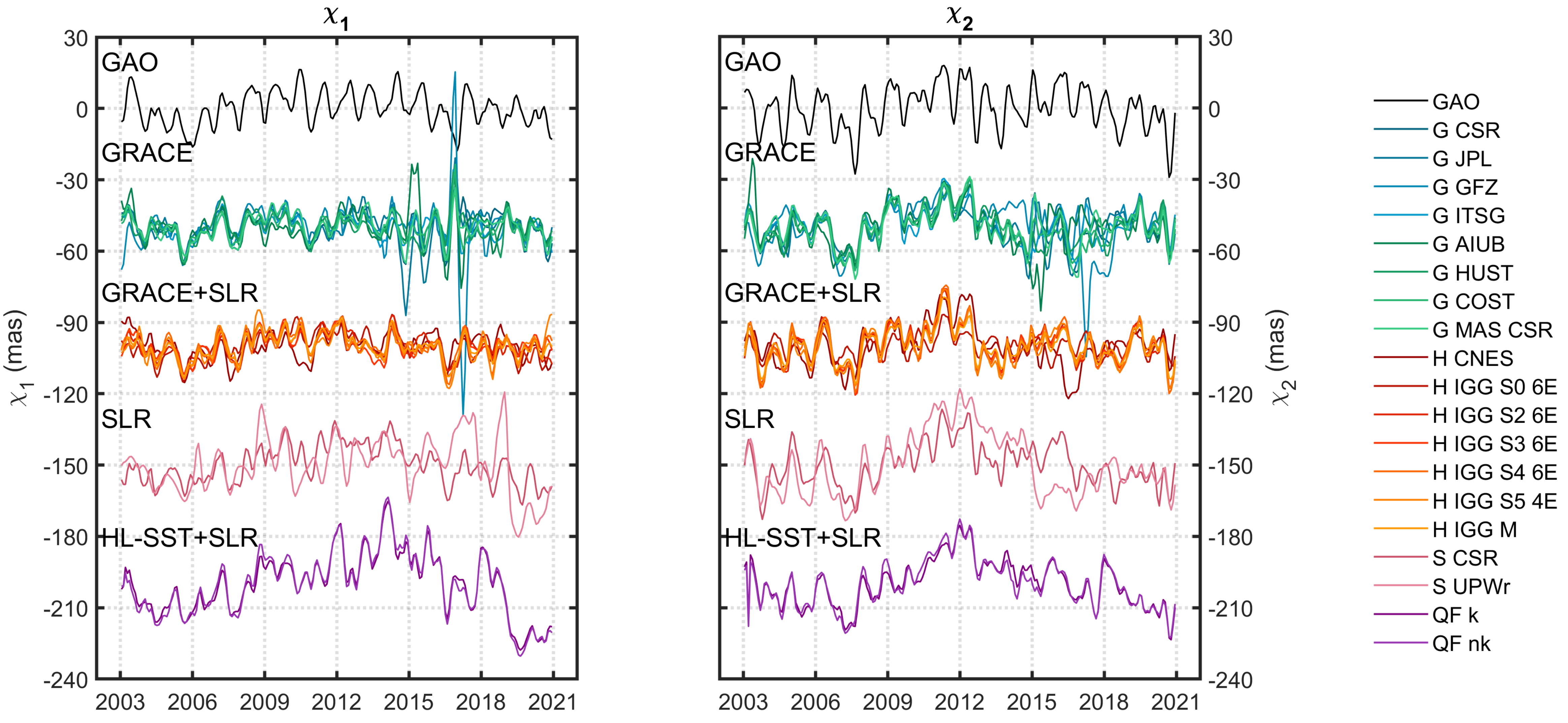
Data processing

Before analysing the series, we filled a 1-year data gap in the GRACE/GRACE-FO-based series using autoregressive integrated moving average (ARIMA).

We analyse **overall detrended, seasonal and non-seasonal variations** in the PM excitation series:

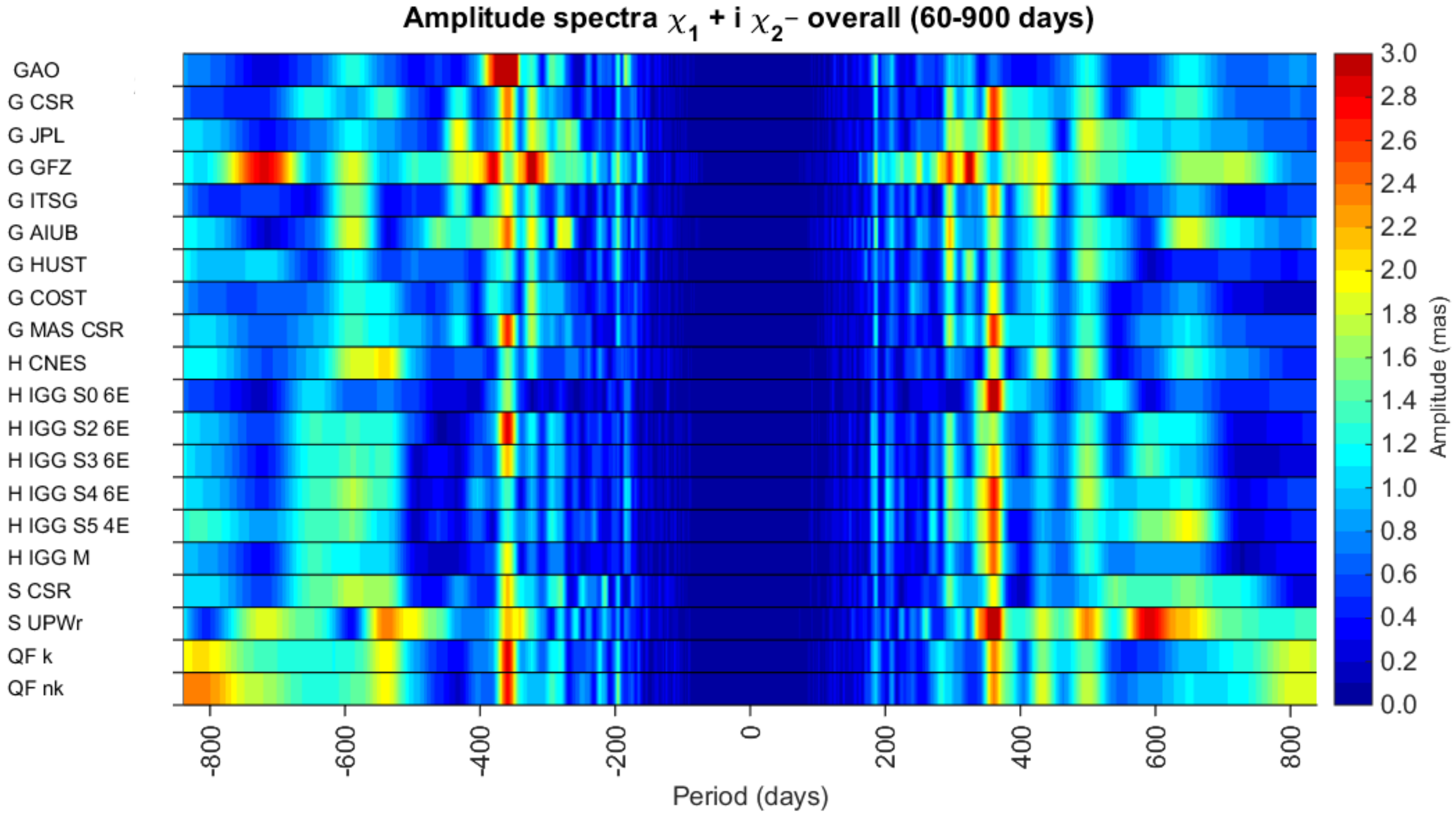
- **Overall detrended series** – obtained after filtering with Gaussian filter (FWHM = 60 days), interpolating into the same moments between January 2003 and December 2020 and removing linear trends
- **Seasonal oscillations** – obtained by fitting the sum of annual, semi-annual, and terannual oscillation to the overall detrended series using the least squares method
- **Non-seasonal variations** – obtained after removing seasonal oscillations from overall detrended series

Overall detrended series



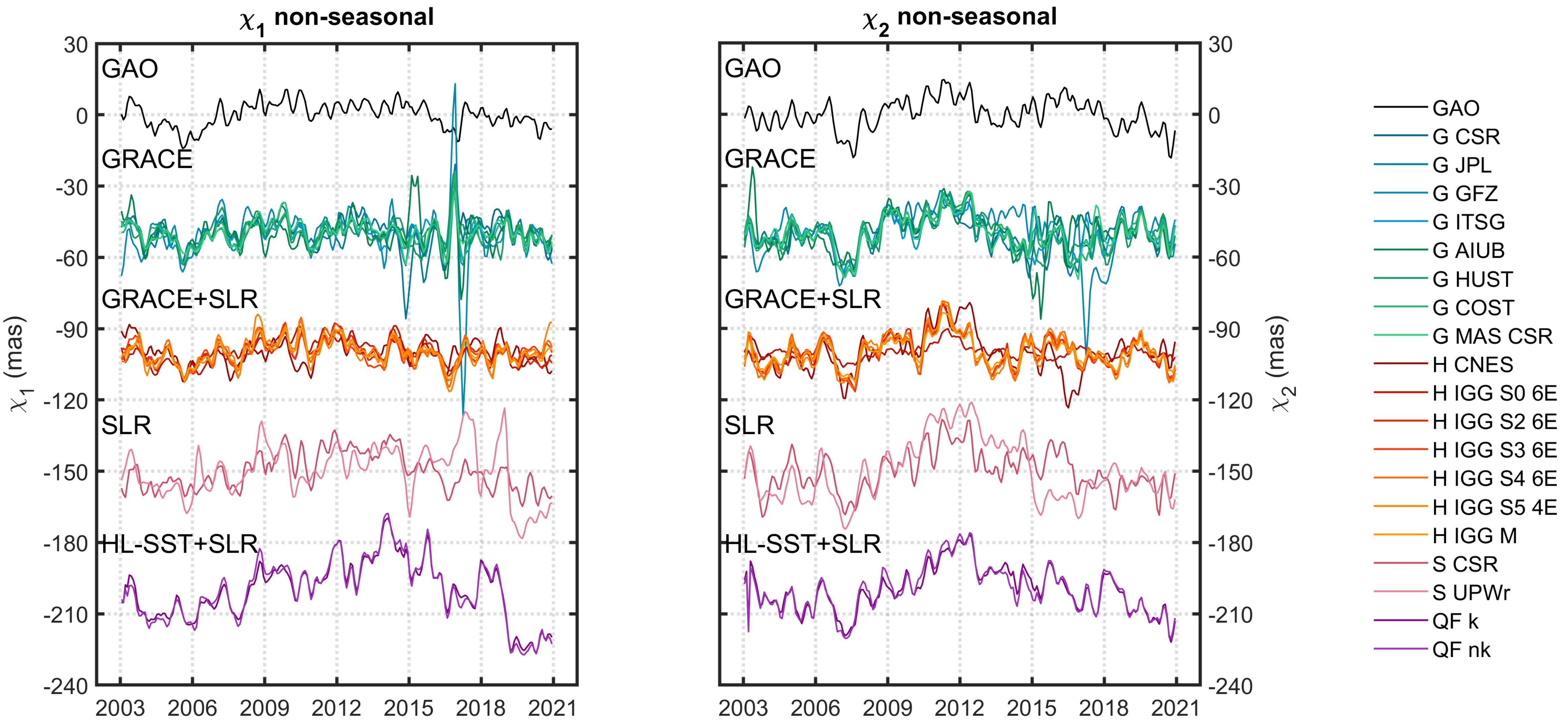
χ_1 and χ_2 components of overall detrend series of GAO and HAM computed from different gravity solutions

Amplitude spectra



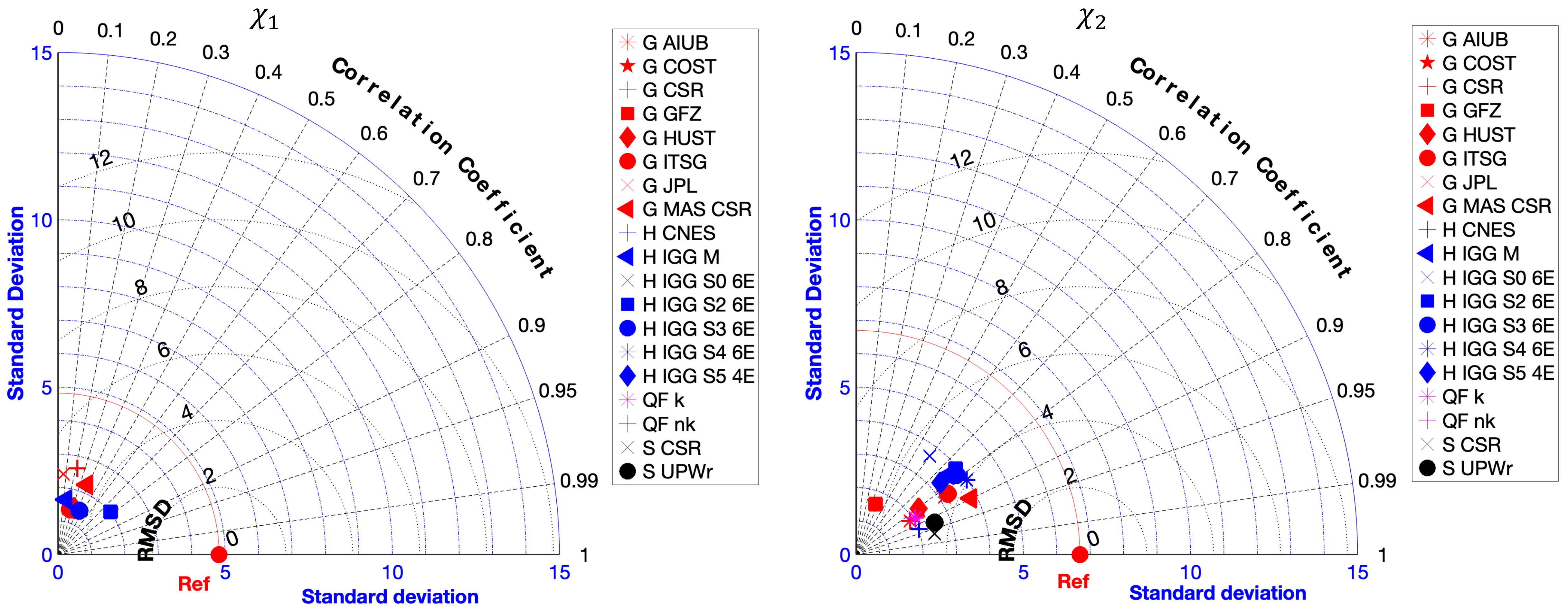
Spectra of complex-valued components of GAO and HAM computed from different gravity solutions

Non-seasonal variations



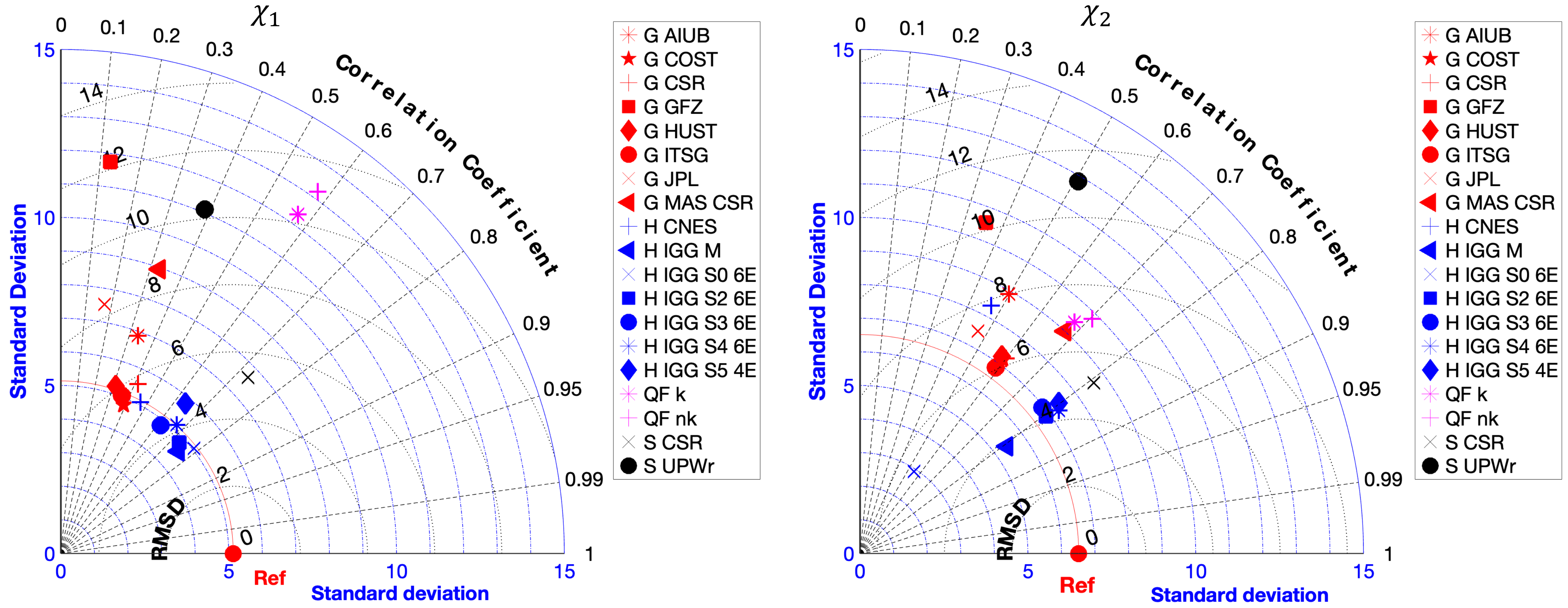
χ_1 and χ_2 components of non-seasonal variations in GAO and HAM computed from different gravity solutions

Taylor diagrams for seasonal oscillations



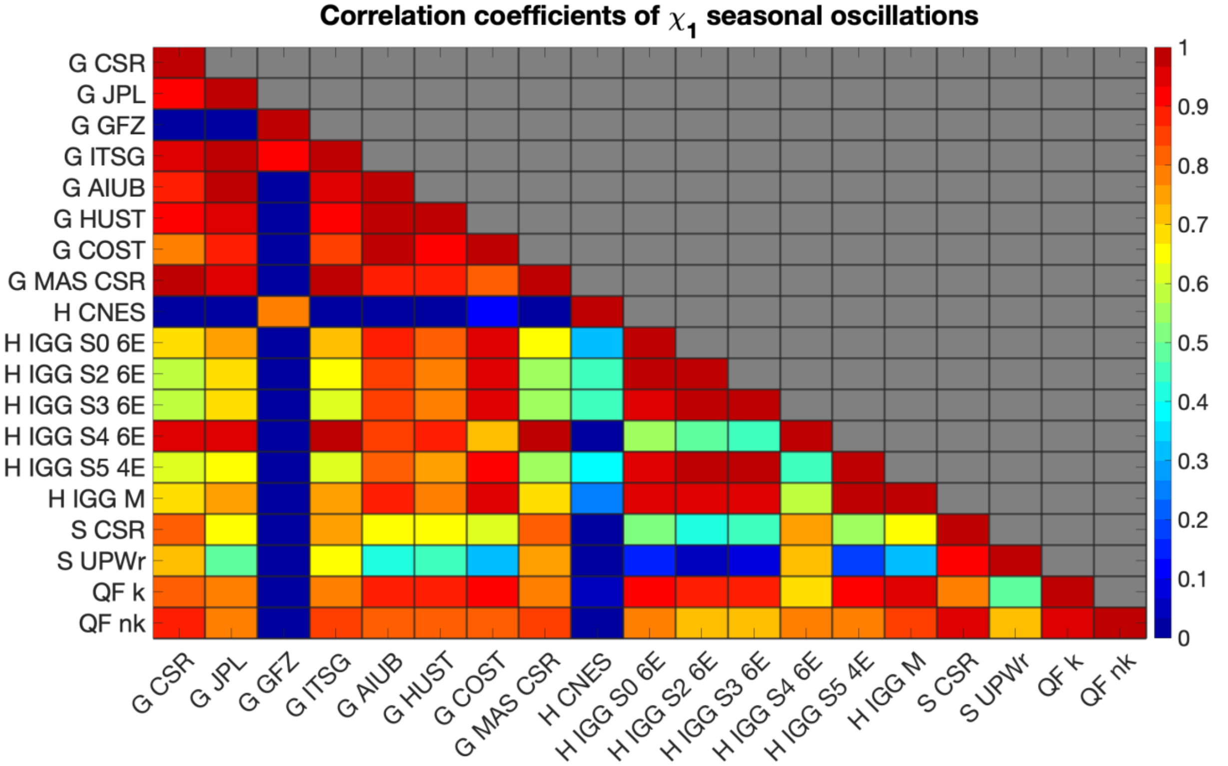
Taylor diagrams showing the agreement (correlation, root mean square deviation RMSD and standard deviation) between GAO (reference series) and HAM computed from different gravity solutions (evaluated series) – seasonal oscillations

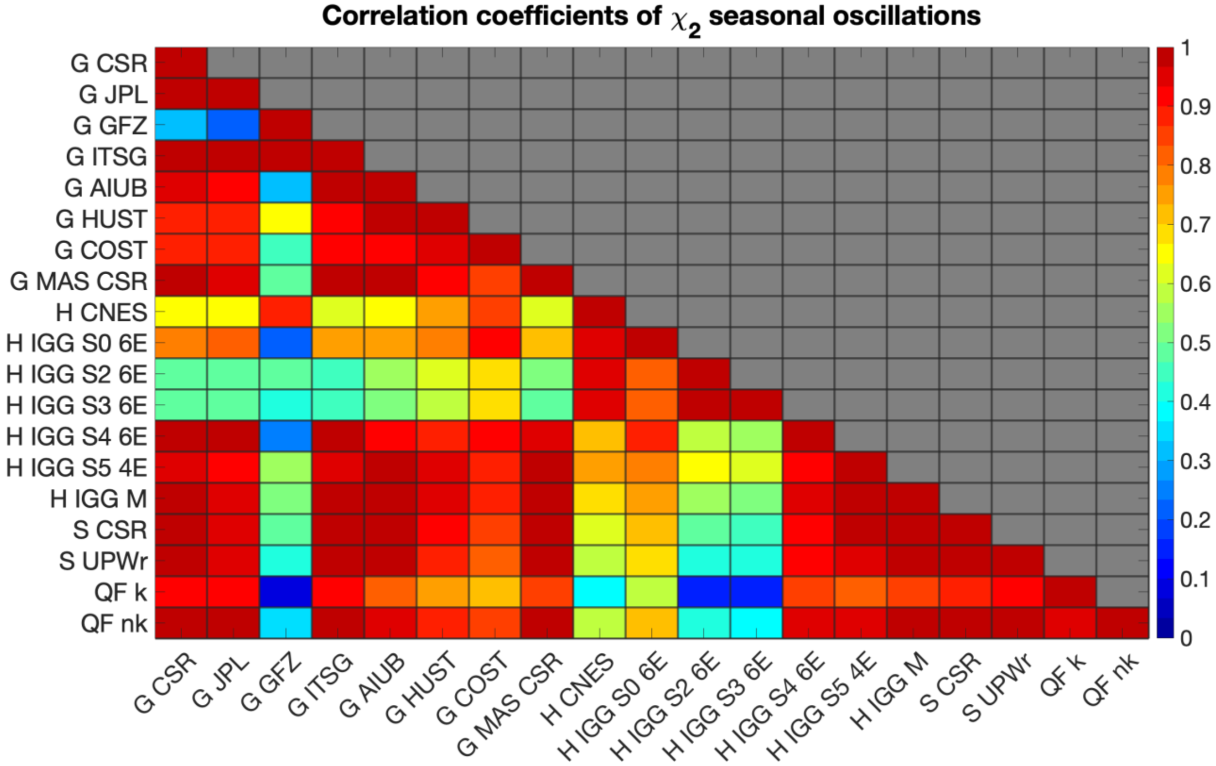
Taylor diagrams for non-seasonal variations



Taylor diagrams showing the agreement (correlation, root mean square deviation RMSD and standard deviation) between GAO (reference series) and HAM computed from different gravity solutions (evaluated series) – non-seasonal variations

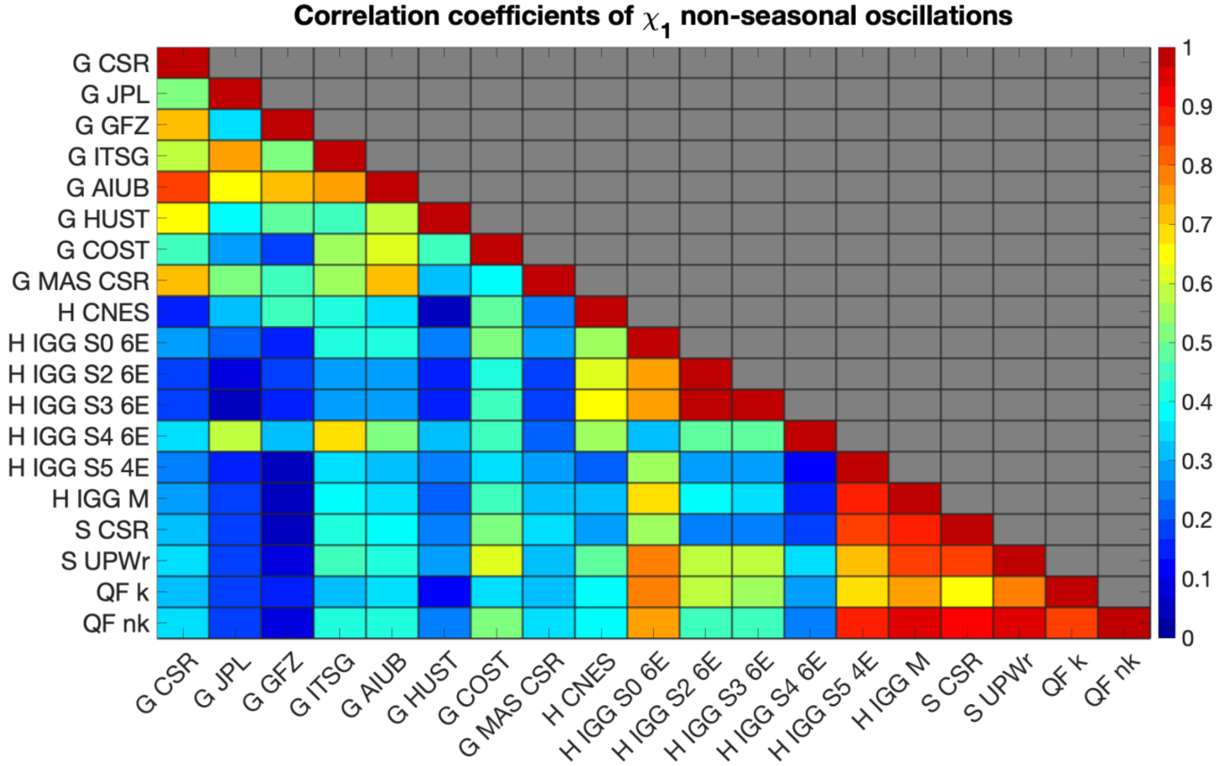
Correlations between HAM estimates – seasonal oscillations

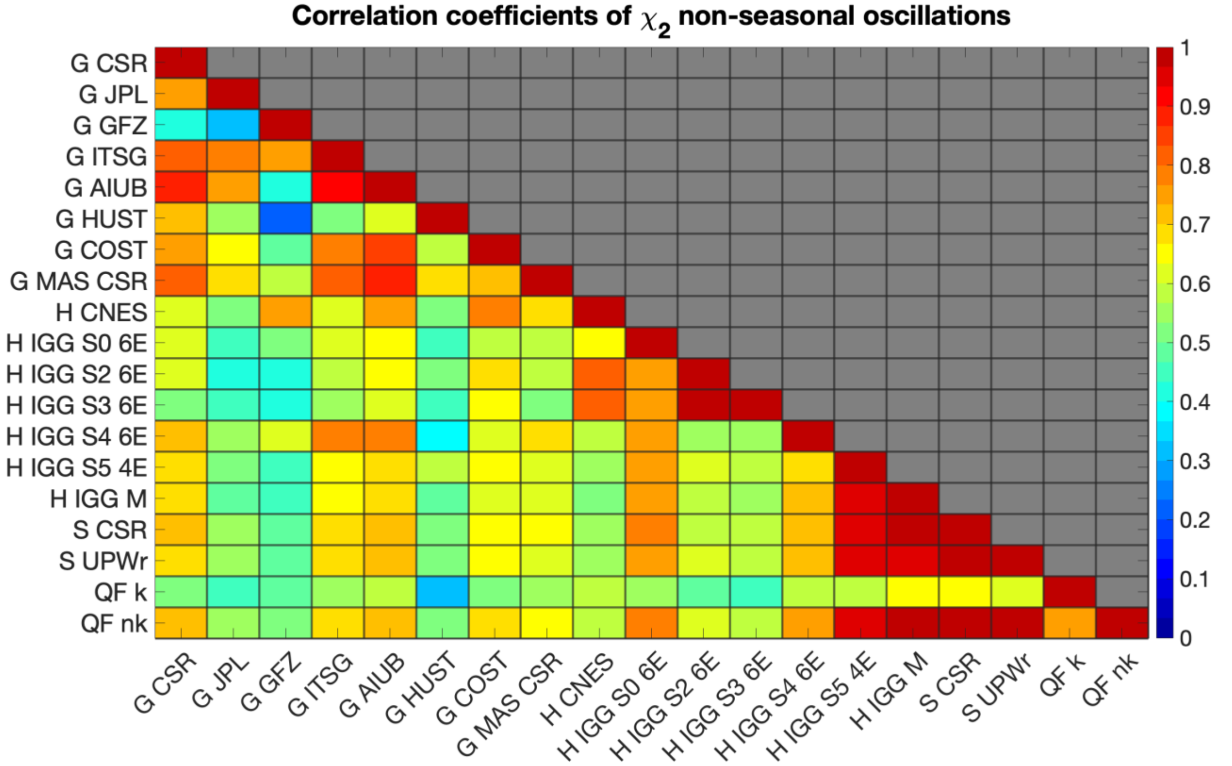




Correlation coefficients between various HAM series computed from different gravity solutions – seasonal oscillations

Correlations between HAM estimates – non-seasonal variations





Correlation coefficients between various HAM series computed from different gravity solutions – non-seasonal variations

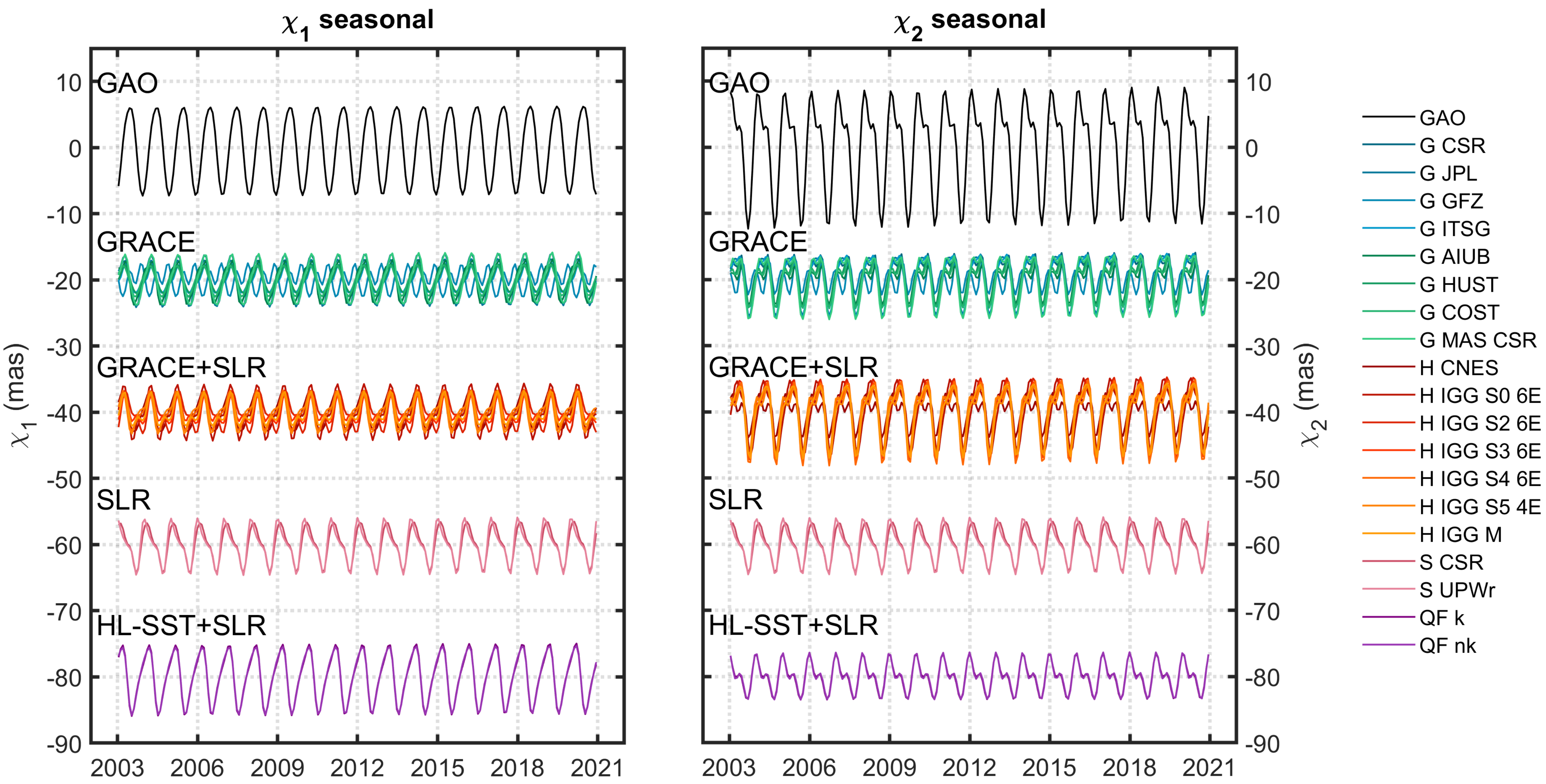
Conclusions

- We presented estimates of hydrological angular momentum (HAM) series computed using GRACE/GRACE-FO, SLR and hybrid (GRACE/GRACE-FO+SLR, HL-SST+SLR) solutions.
- HAM series were evaluated using hydrological signal in geodetically observed excitation (GAO) for overall detrended, seasonal and non-seasonal series.
- Our findings demonstrate that the HAM derived from the hybrid SLR+GRACE/GRACE-FO solution closely aligns with the GAO. They perform similarly or even better than the series derived from GRACE/GRACE-FO data.
- For seasonal oscillations, both single GRACE/GRACE-FO and hybrid solutions (GRACE/GRACE-FO+SLR) provide similar level of agreement with GAO. The highest consistency with GAO for seasonal oscillations was obtained for H IGG S2 6E (for χ_1) and G MAS CSR (for χ_2) series.
- In the case of non-seasonal changes, the superiority of hybrid GRACE/GRACE-FO+SLR solutions over the GRACE/GRACE-FO is noticeable as all series based on data from IGG exhibit visibly higher correlations with GAO and lower RMSD.
- Regarding the internal correlation between HAM time series, our study shows that higher correlation occurs for the χ_2 components than for χ_1.

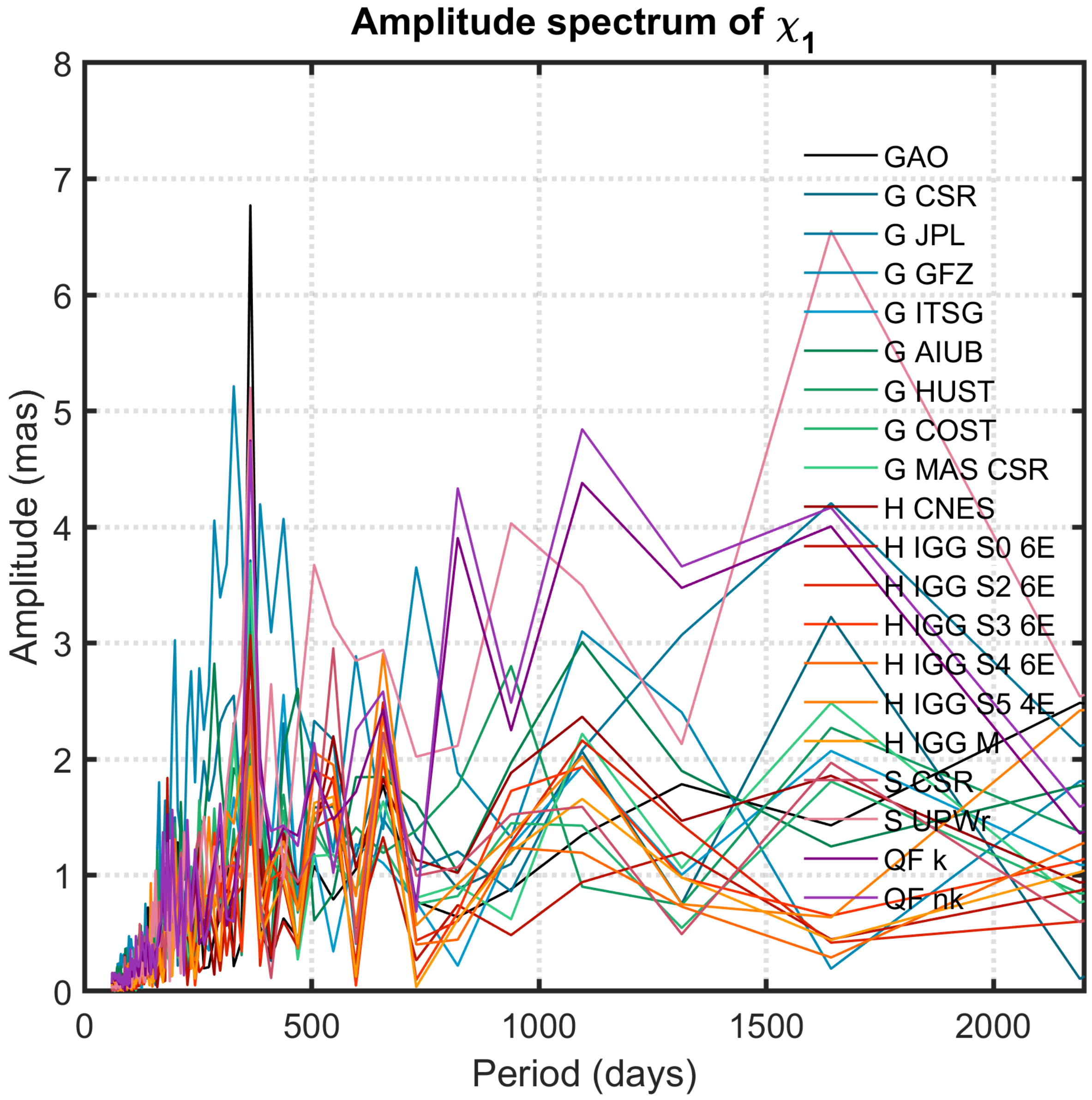
Thank you

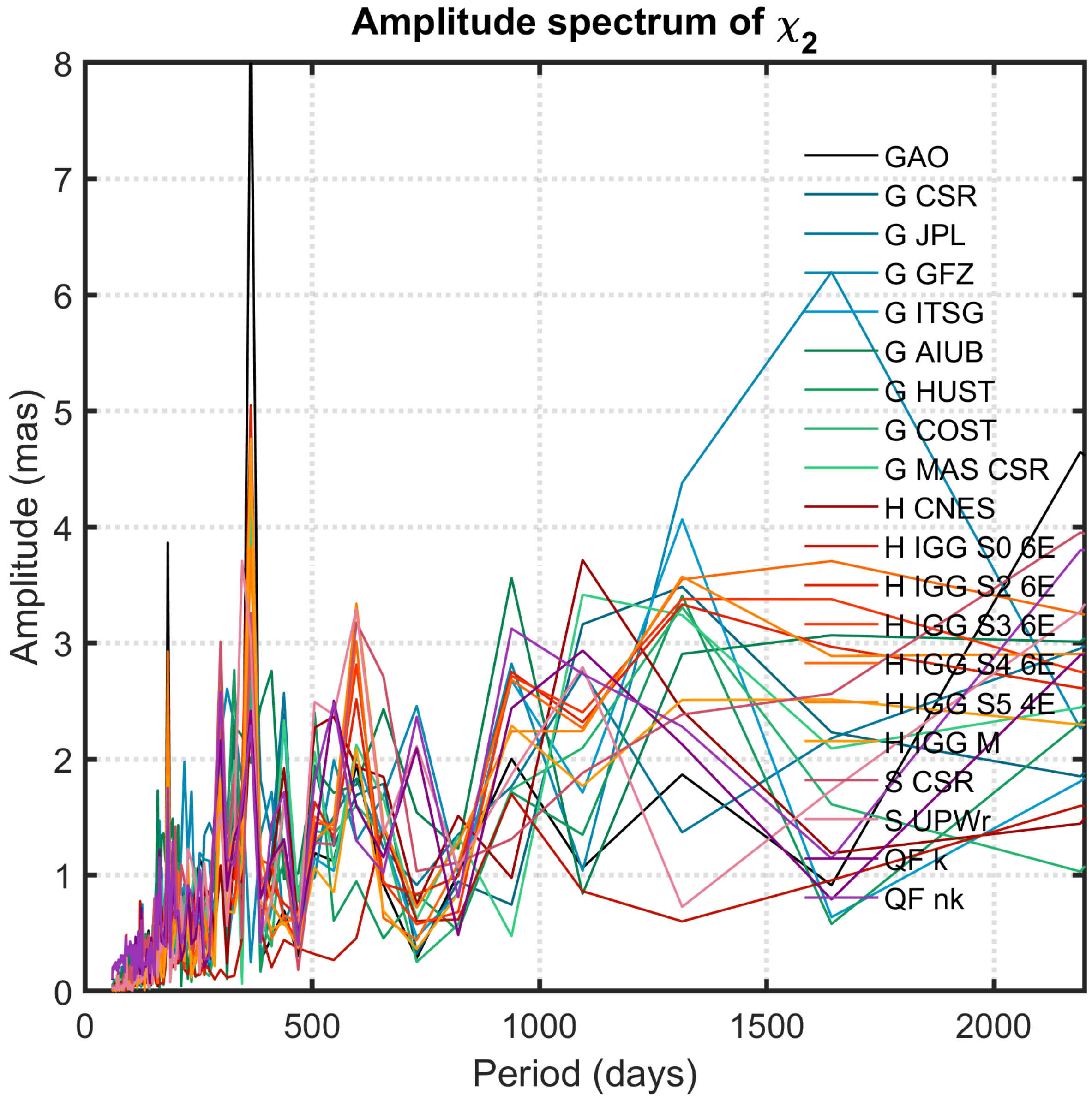
Appendix

Seasonal series

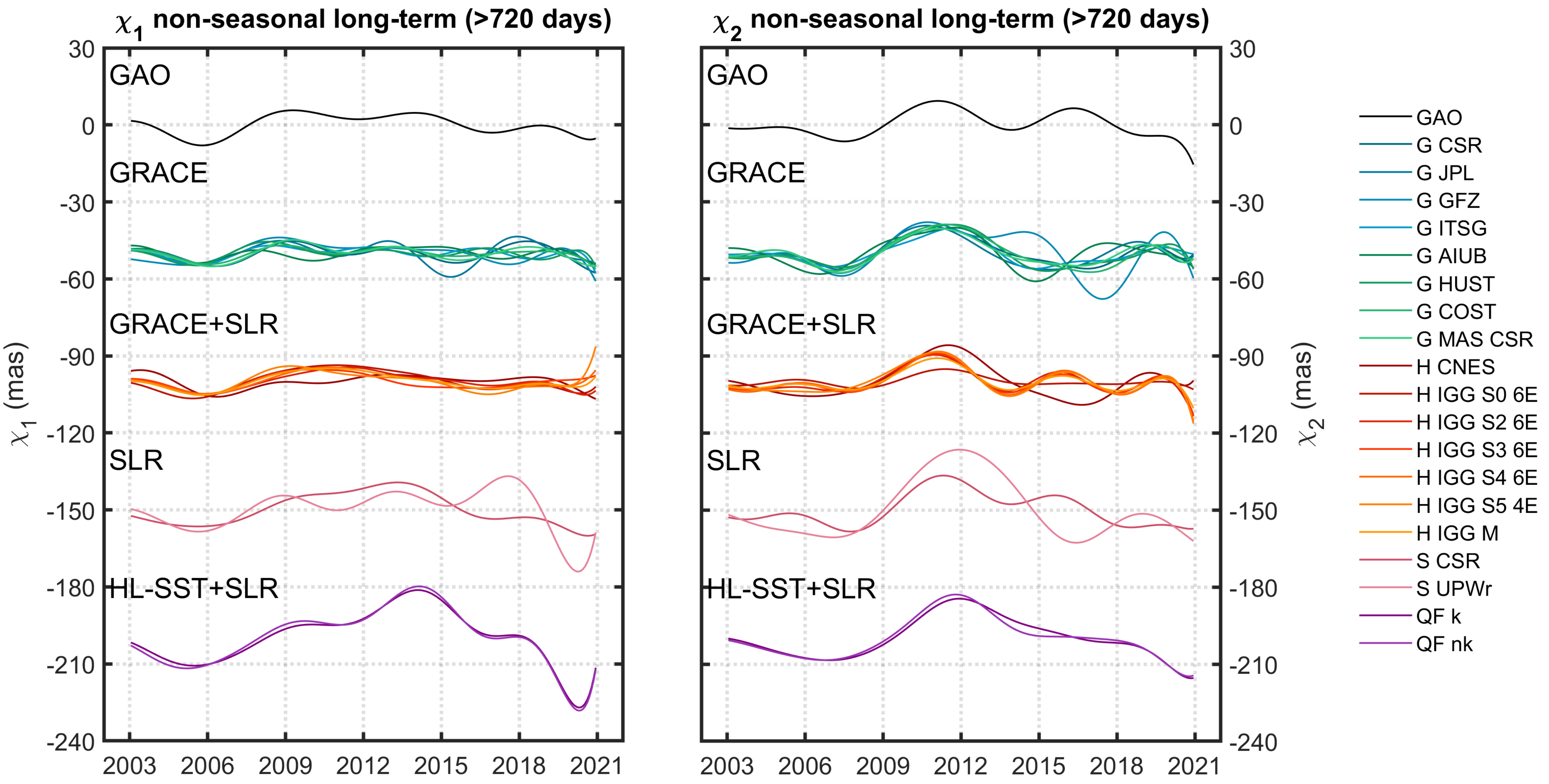


Amplitude spectra

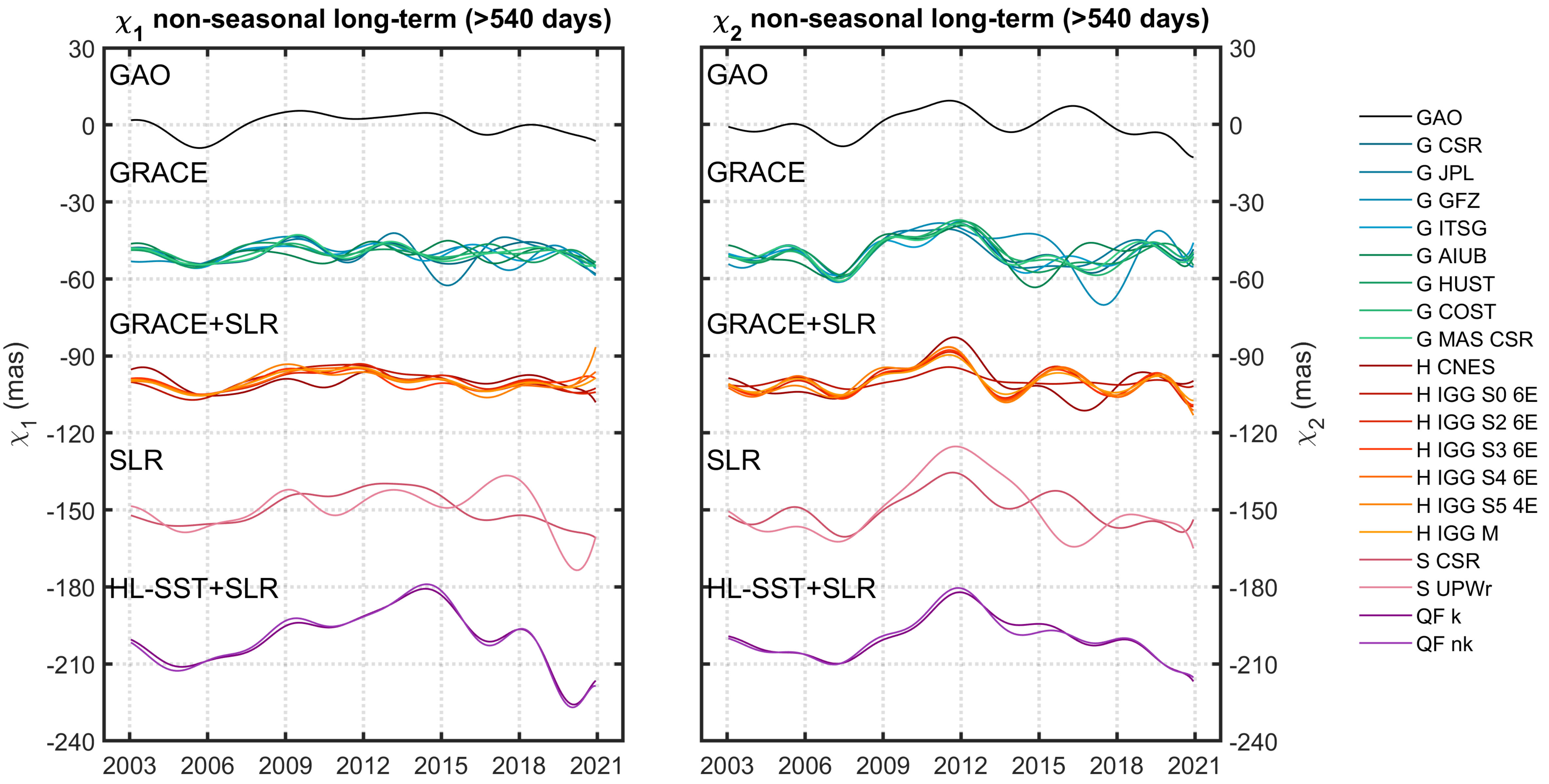




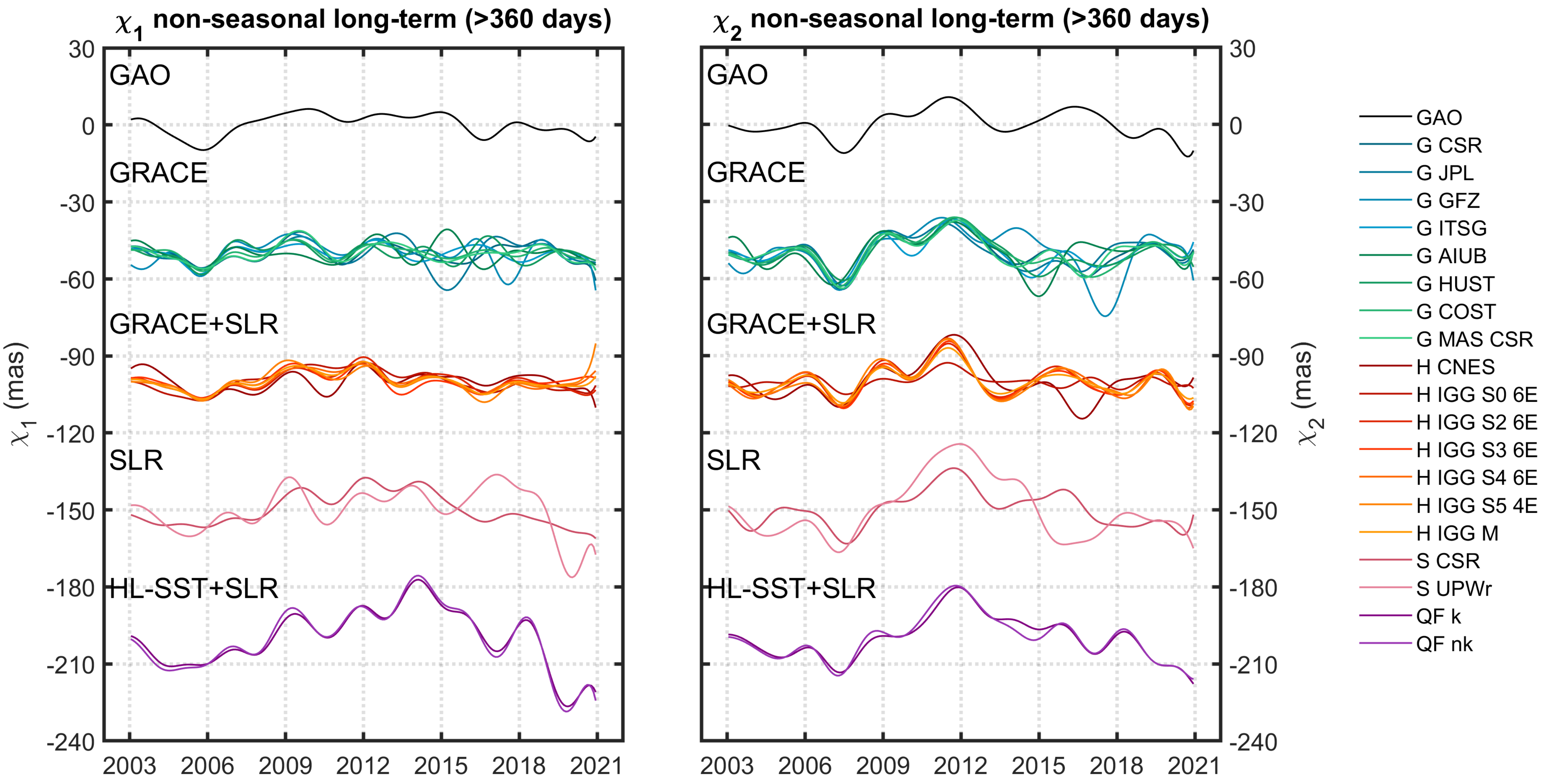
Non-seasonal long-term (>720 days)



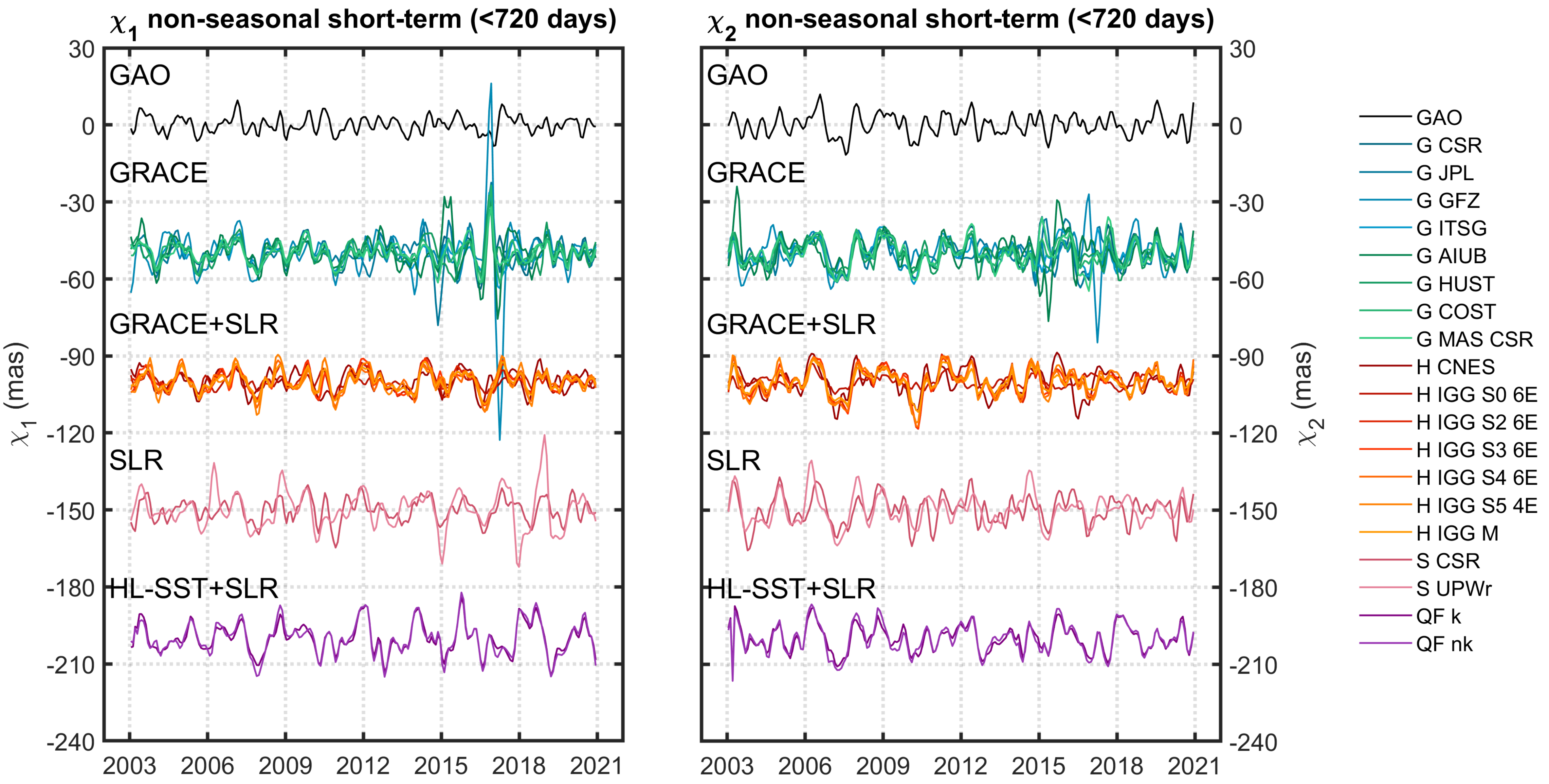
Non-seasonal long-term (>540 days)



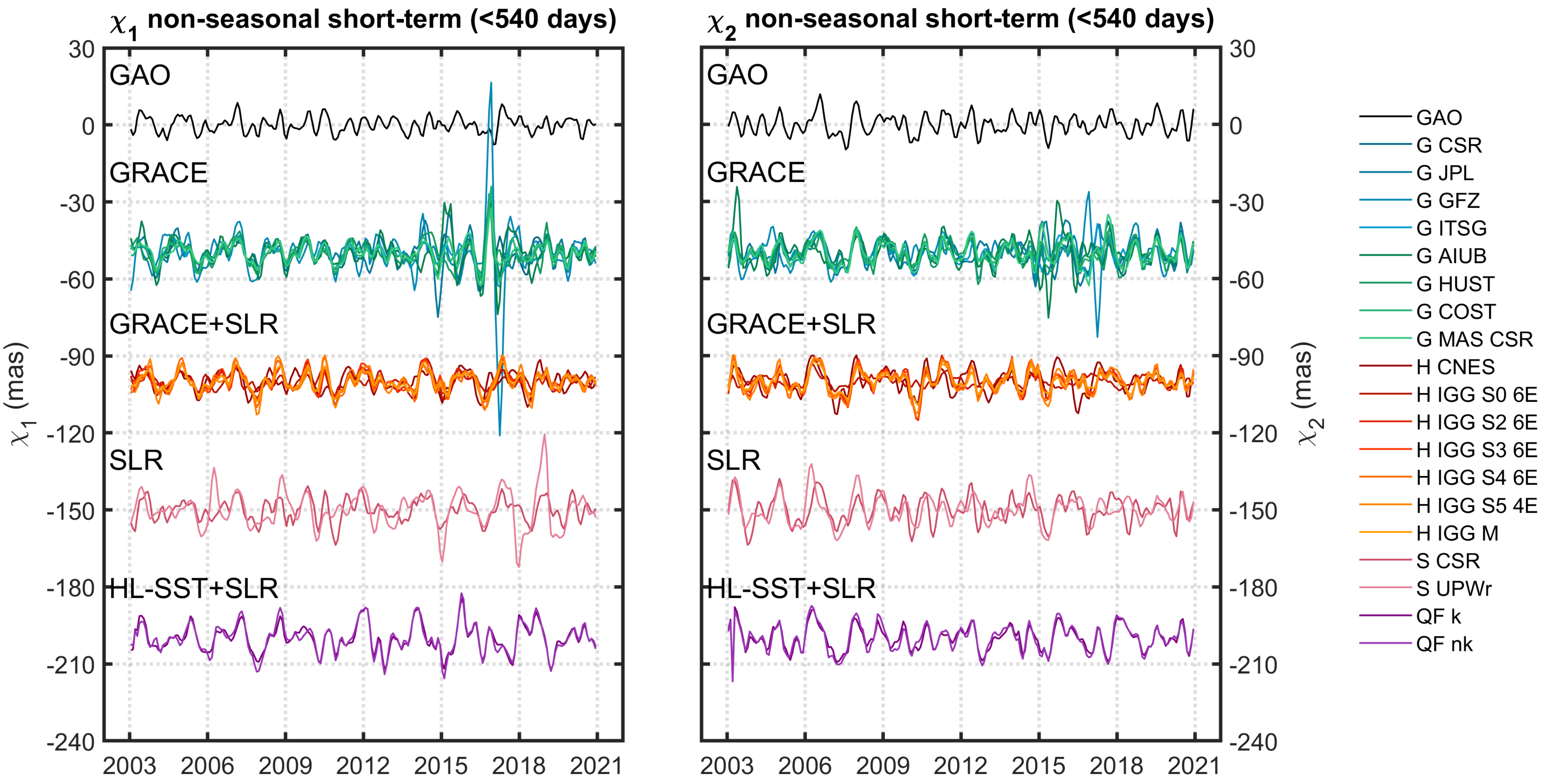
Non-seasonal long-term (>360 days)



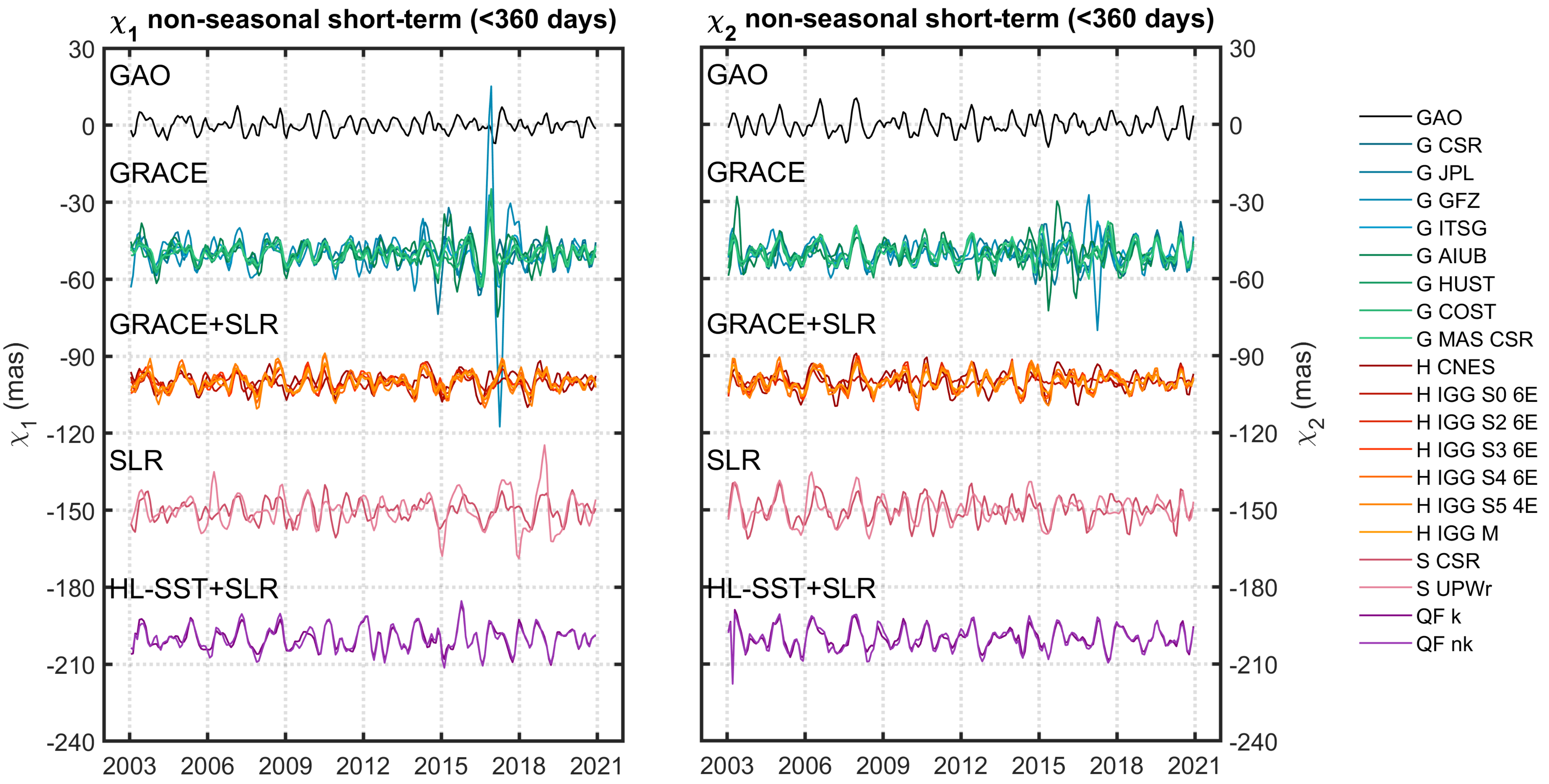
Non-seasonal short-term (<720 days)



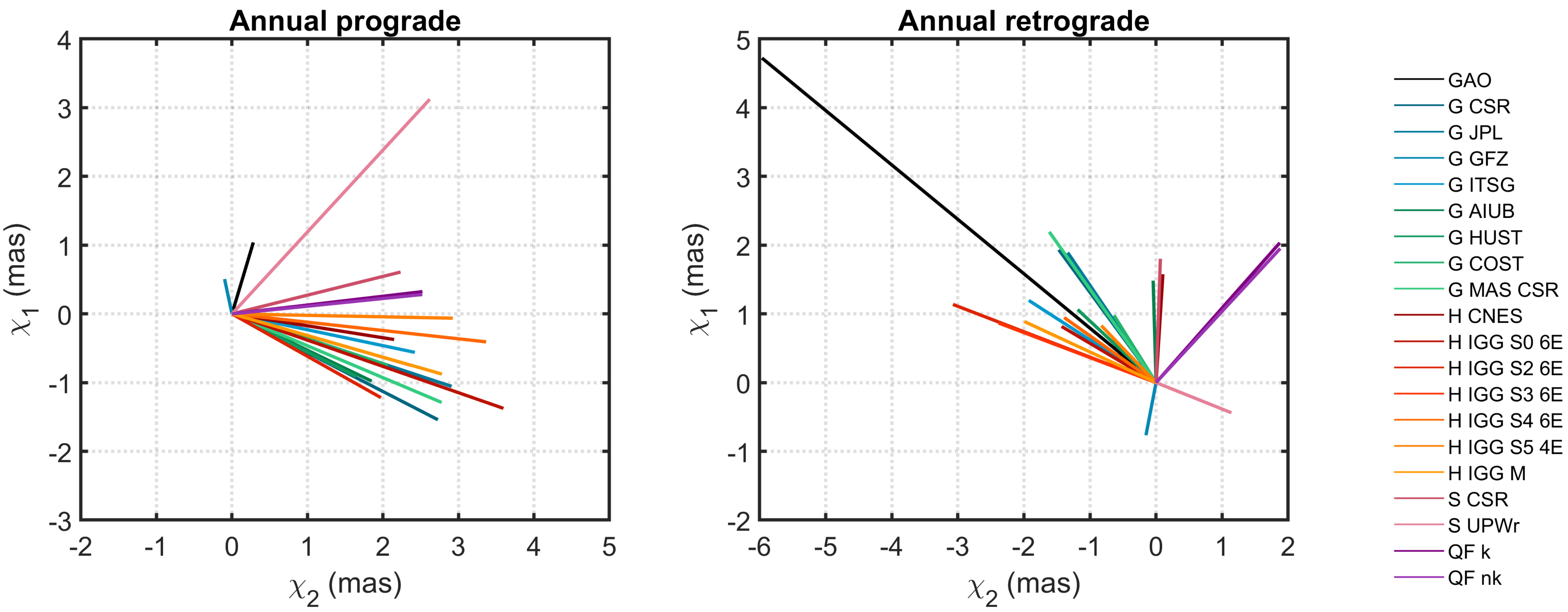
Non-seasonal short-term (<540 days)



Non-seasonal short-term (<360 days)

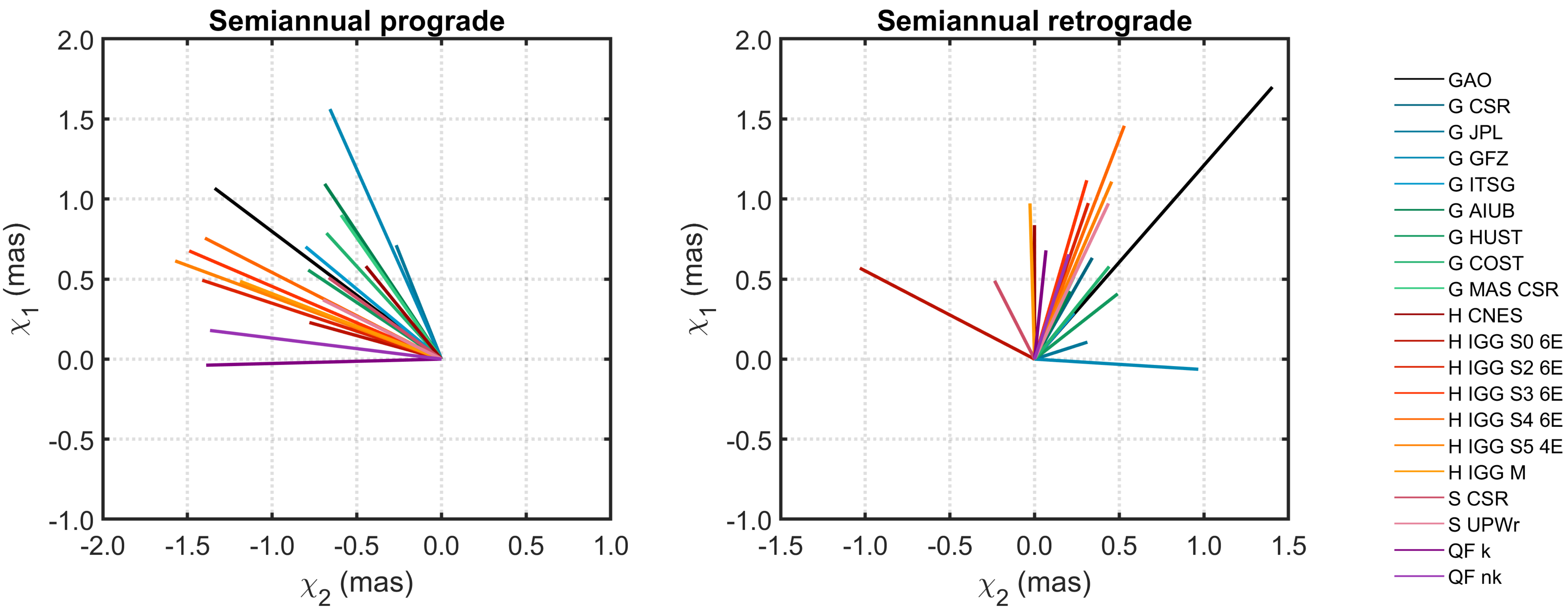


Phasor diagrams for annual oscillations



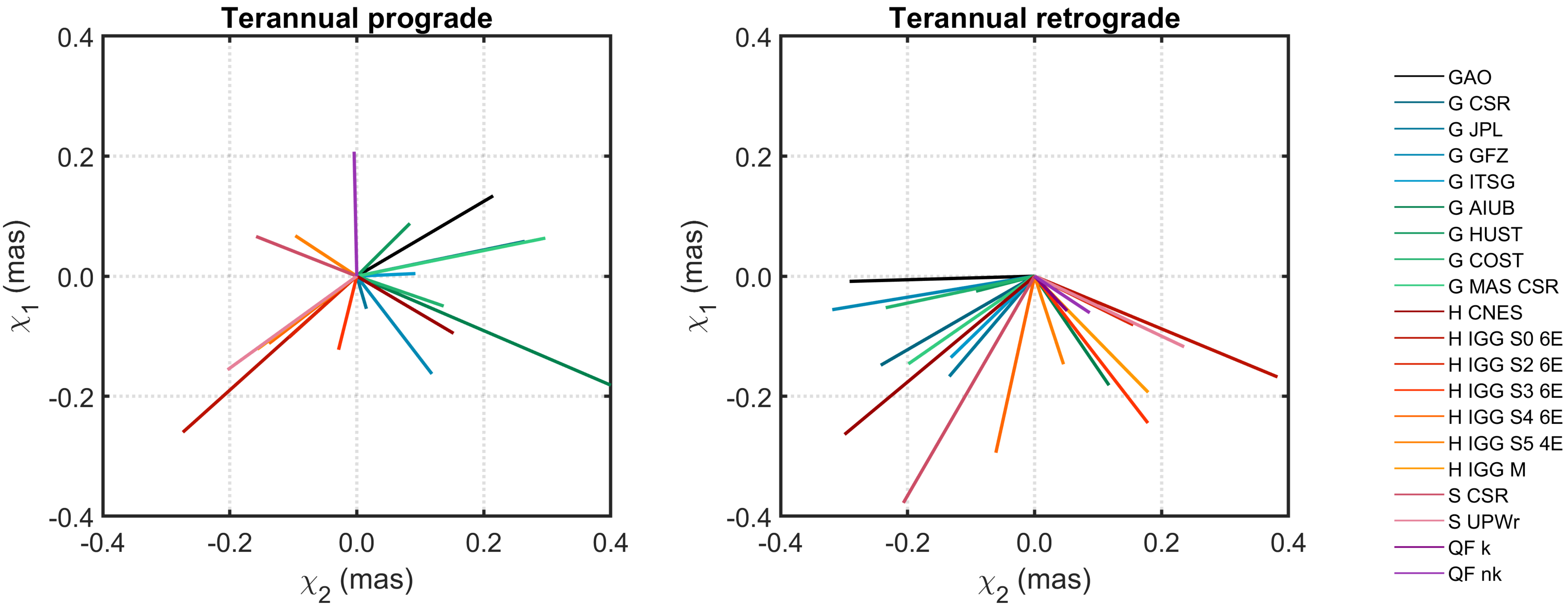
Phasor diagrams of annual variations of the complex-valued components of GAO and HAM computed from different gravity solutions

Semiannual



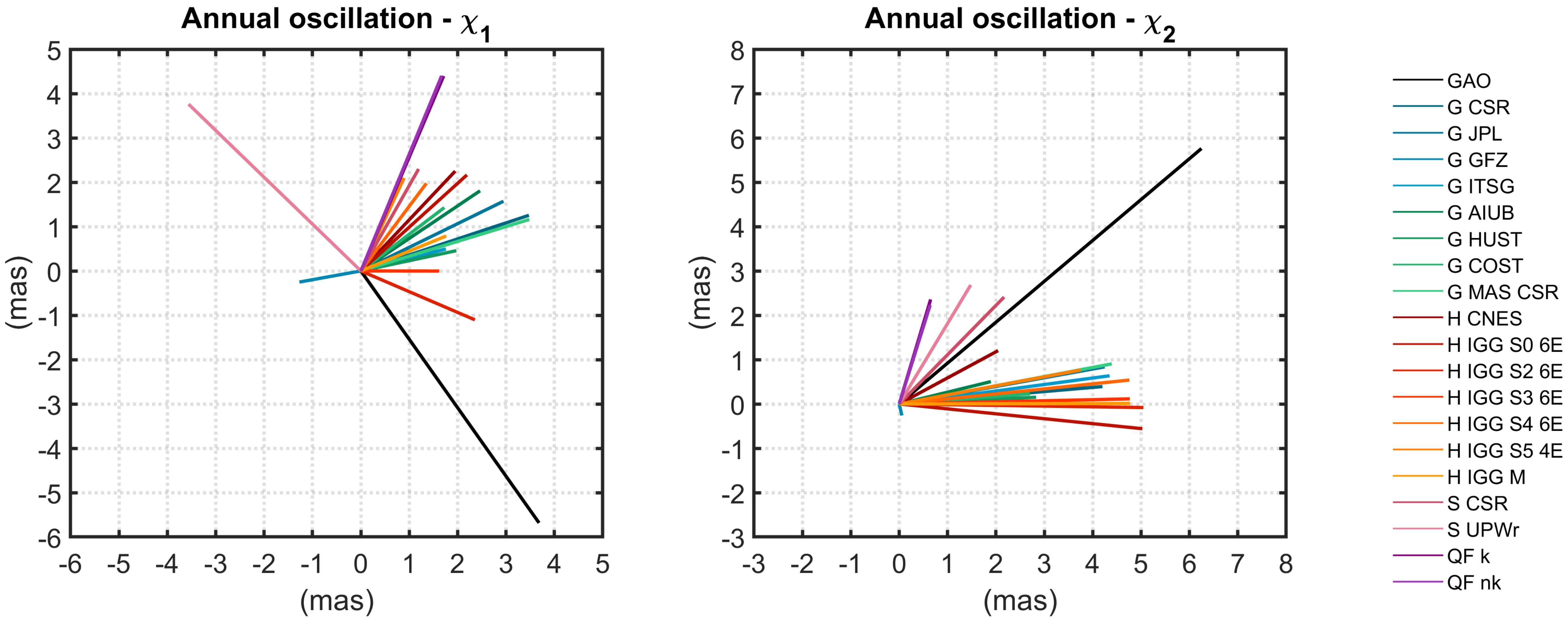
Semiannual prograde
Semiannual retrograde
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
χ_1 (mas)
χ_2 (mas)
GAO
G CSR
G JPL
G GFZ
G ITSG
G AIUB
G HUST
G COST
G MAS CSR
H CNES
H IGG S0 6E
H IGG S2 6E
H IGG S3 6E
H IGG S4 6E
H IGG S5 4E
H IGG M
S CSR
S UPWr
QF k
QF nk

Terannual

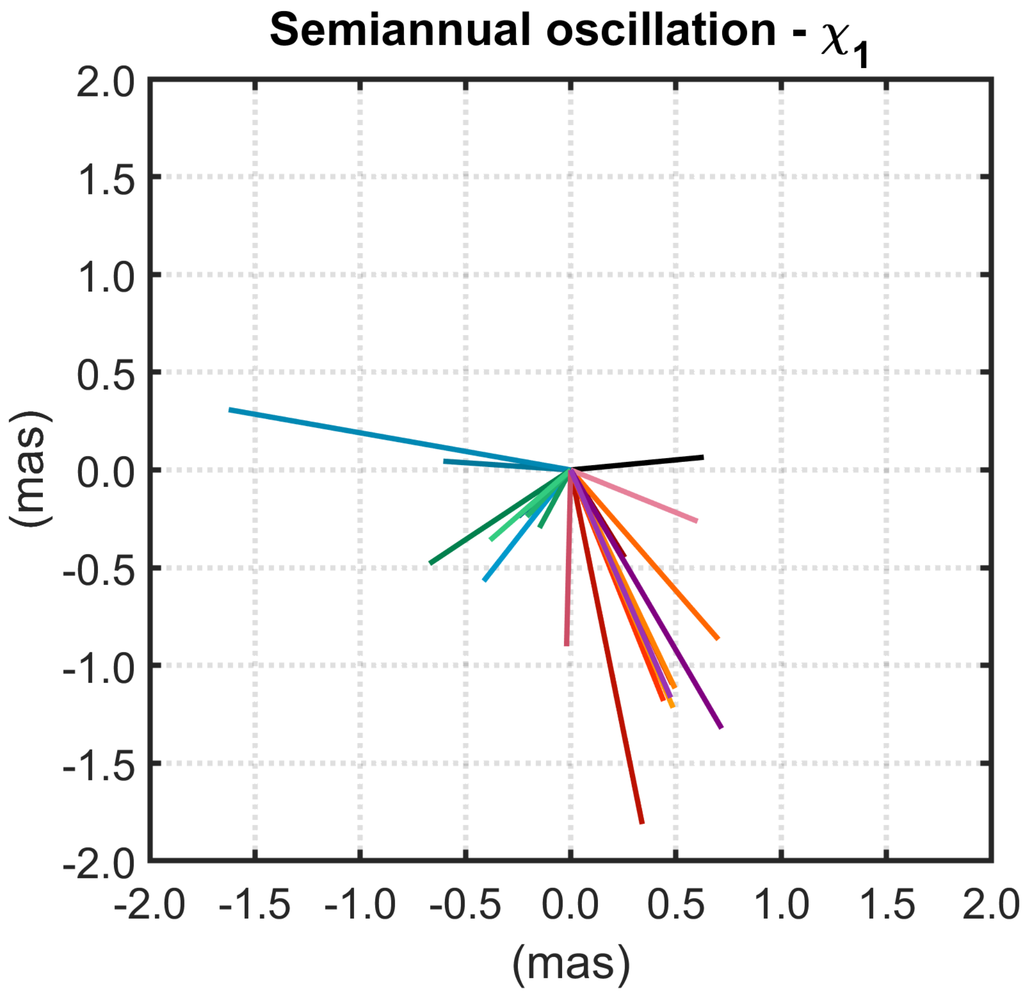


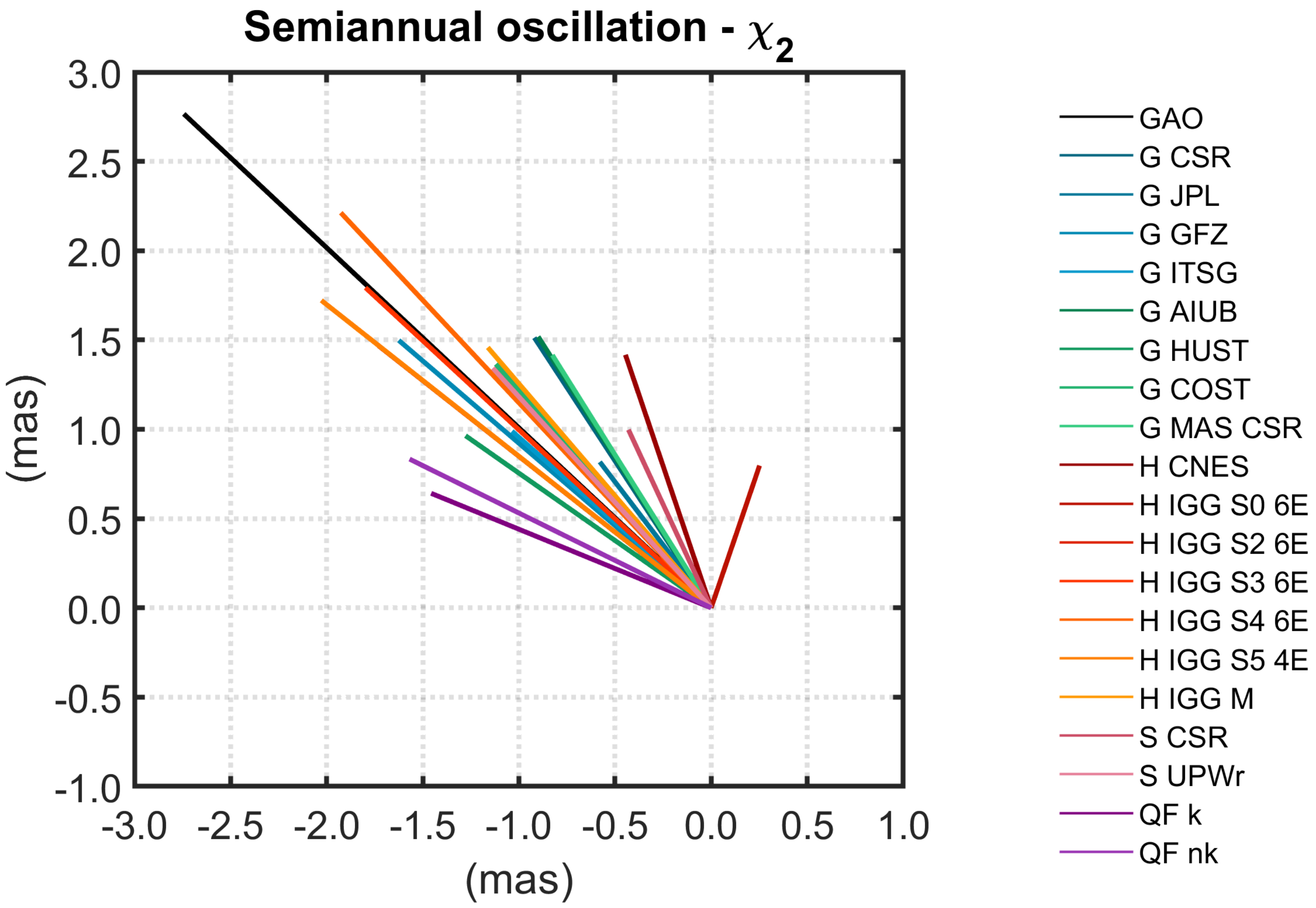
Terannual prograde
Terannual retrograde
0.4
0.2
0.0
-0.2
-0.4
χ_1 (mas)
χ_2 (mas)
GAO
G CSR
G JPL
G GFZ
G ITSG
G AIUB
G HUST
G COST
G MAS CSR
H CNES
H IGG S0 6E
H IGG S2 6E
H IGG S3 6E
H IGG S4 6E
H IGG S5 4E
H IGG M
S CSR
S UPWr
QF k
QF nk

Annual χ_1, χ_2



Semiannual χ_1, χ_2





Terannual χ_1, χ_2