



Supplement of

Inconclusive early warning signals for Dansgaard-Oeschger events across Greenland ice cores

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S1 Additional figures

S1.1 Significance testing

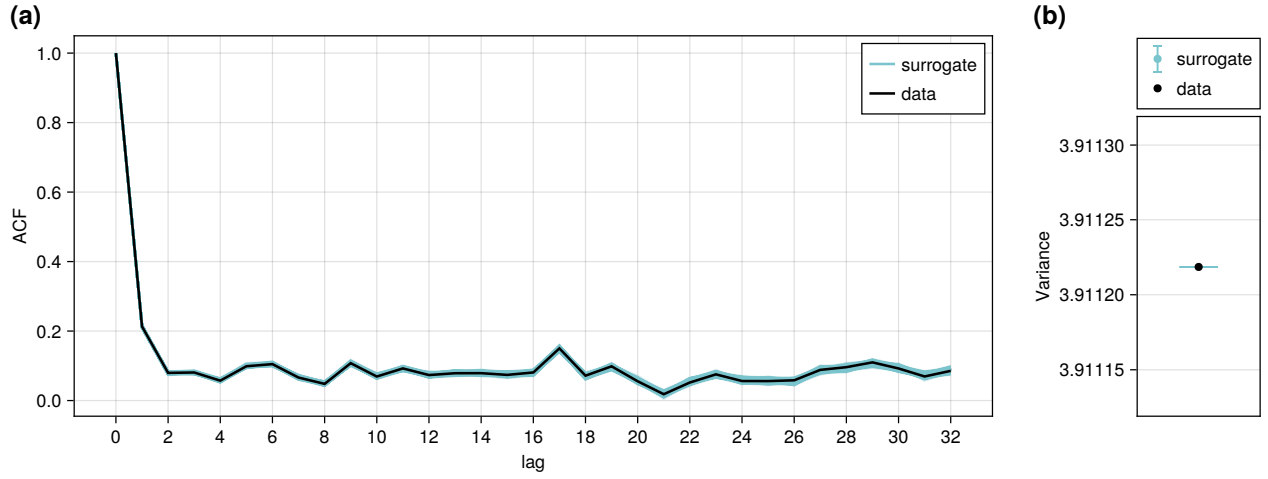


Figure S1. Autocorrelation function (a) and variance (b) of the NGRIP $\delta^{18}\text{O}$ record in 5-year resolution (black) and its TFTS surrogates (blue) during the longest GS considered prior to DO-1.

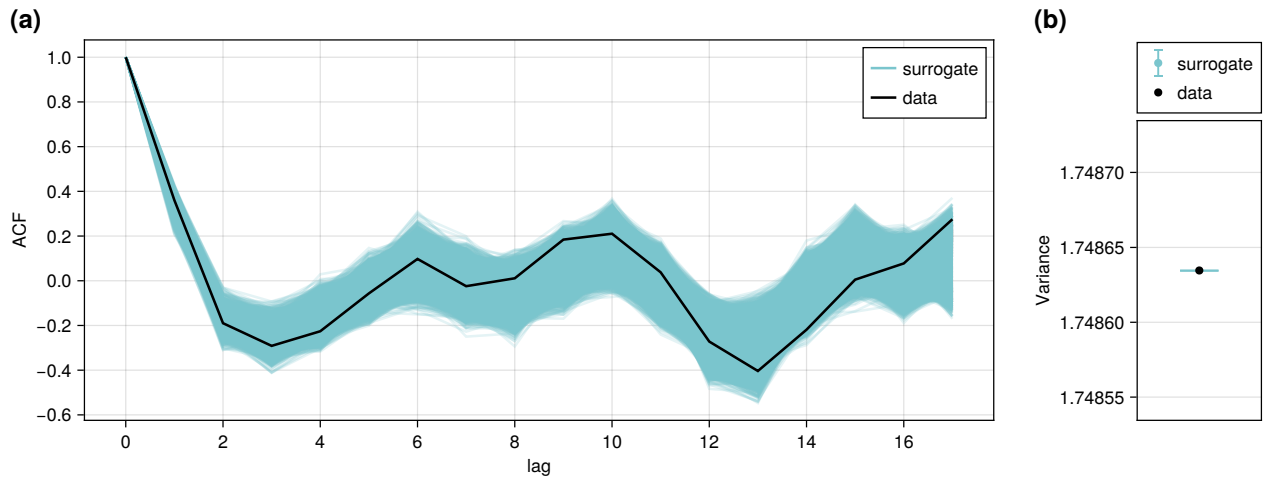
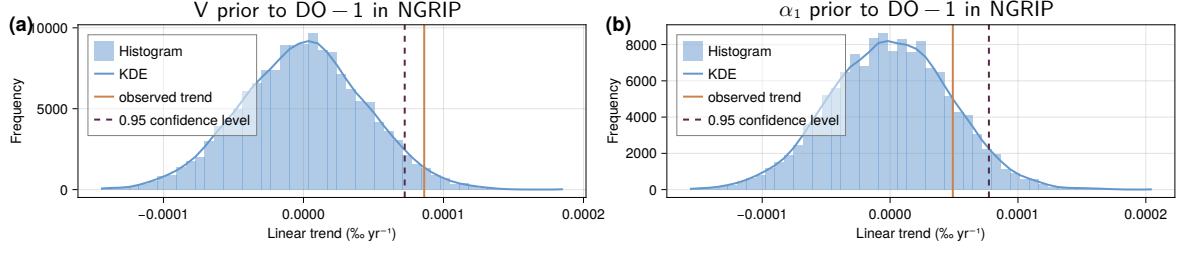
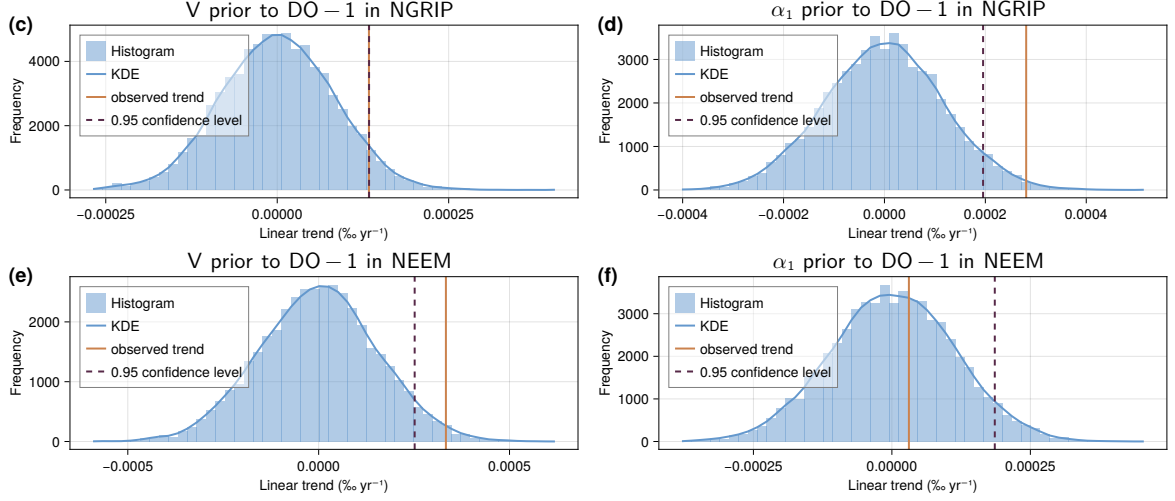


Figure S2. Autocorrelation function (a) and variance (b) of the NGRIP $\delta^{18}\text{O}$ record in 5-year resolution (black) and its TFTS surrogates (blue) during the shortest GS considered prior to DO-16.

Null-model distribution of linear trends in EWS of 100-year high-pass filtered records with 5-year resolution



Null-model distribution of linear trends in EWS of 100-year high-pass filtered records with 10-year resolution



Null-model distribution of linear trends in EWS of 100-year high-pass filtered records with 20-year resolution

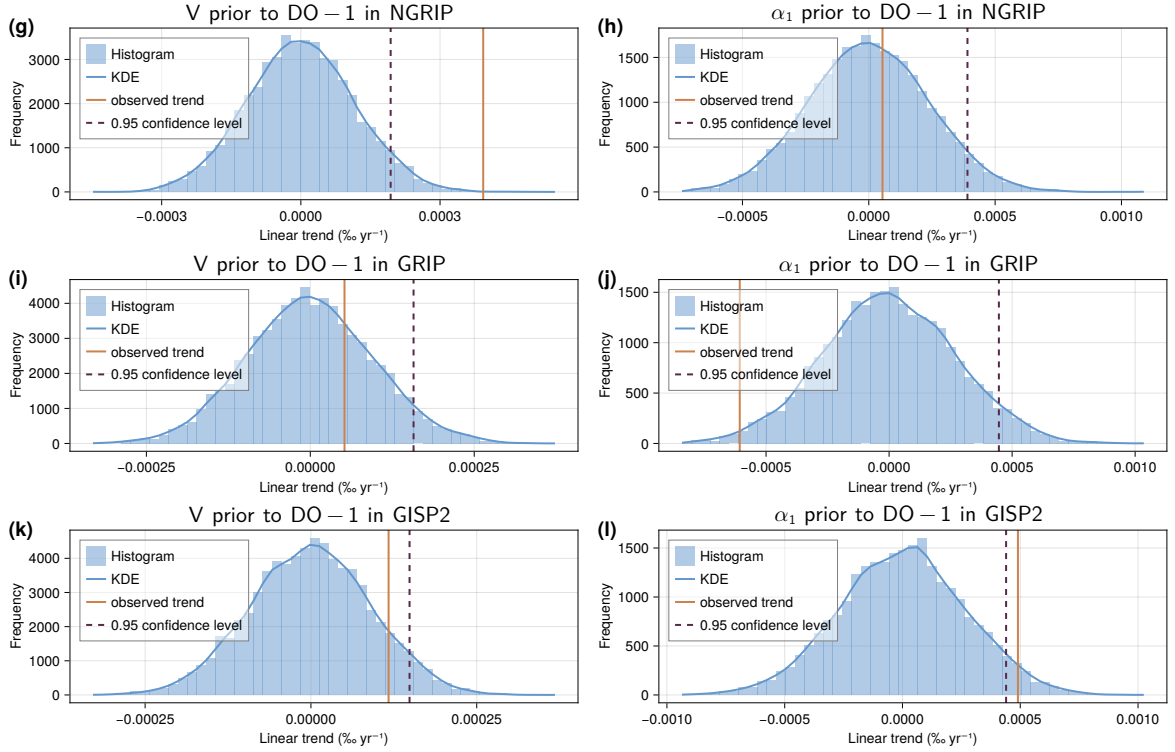
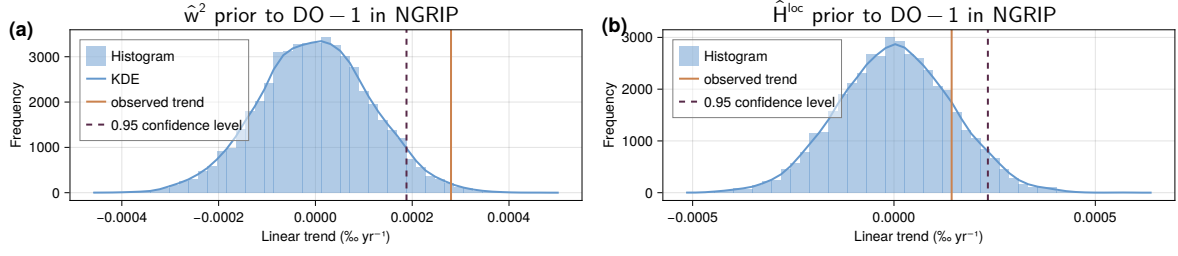
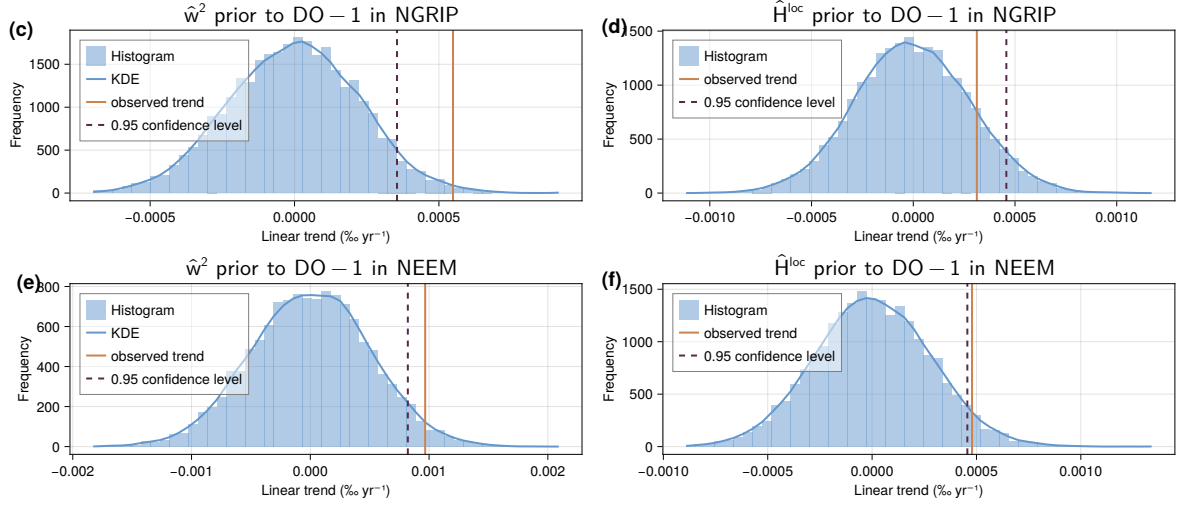


Figure S3. Null-model distribution for linear trends in the CSD-based EWS estimators prior to DO-1 in the NGRIP record in 5- (a,b), 10- (c,d) and 20-year resolution (g,h), NEEM (e,f), GRIP (i,j), and GISP2 (k,l). Those for the variance are shown in the left column (a,c,e,g,i,k), those for the lag-1 autocorrelation coefficient in the right (b,d,f,h,j,l). Histograms, kernel density estimates of the probability density function, and confidence levels of the null-model distributions are obtained from 10 000 surrogates with partially randomised phases of the records in the GS prior to DO-1 (see main text Sect. 2.3).

Null-model distribution of linear trends in EWS of (20-60) year band of records with 5-year resolution



Null-model distribution of linear trends in EWS of (20-60) year band of records with 10-year resolution



Null-model distribution of linear trends in EWS of (20-60) year band of records with 20-year resolution

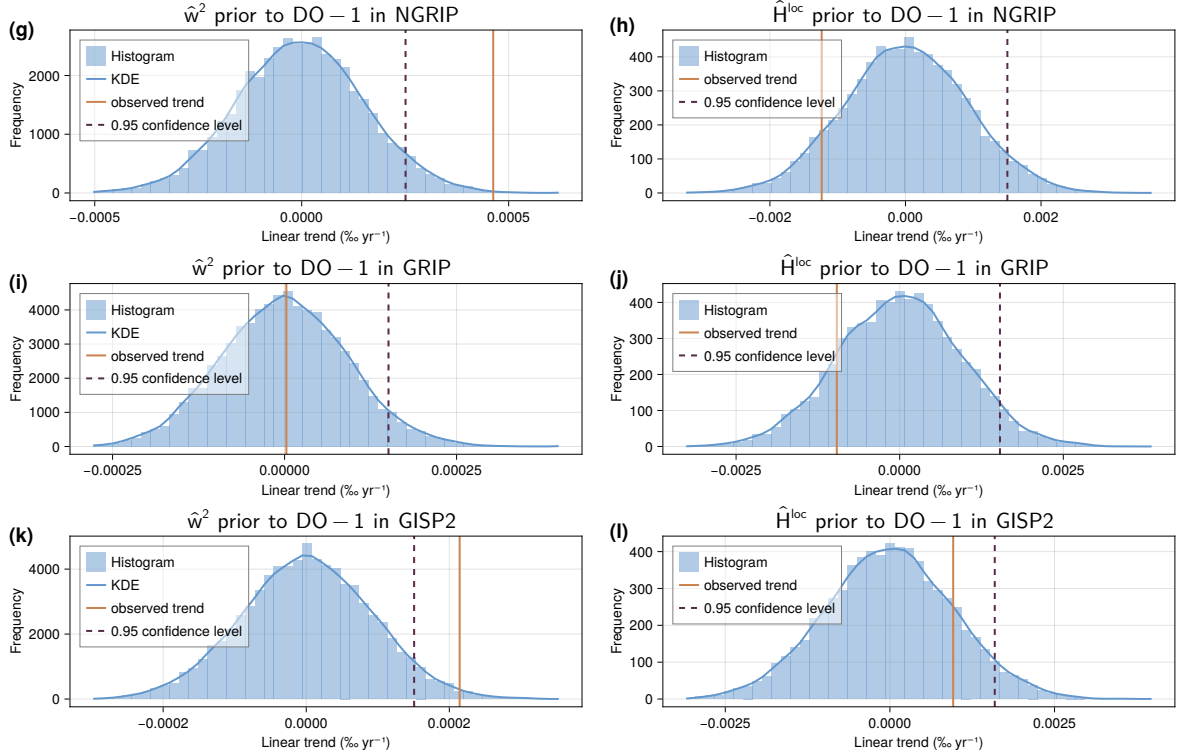


Figure S4. Null-model distribution for linear trends in the wavelet-based EWS estimators prior to DO-1 in the NGRIP record in 5- (a,b), 10- (c,d) and 20-year resolution (g,h), NEEM (e,f), GRIP (i,j), and GISP2 (k,l). Those for the scale-averaged wavelet coefficient are shown in the left column (a,c,e,g,i,k), those for the local Hurst exponent in the right (b,d,f,h,j,l). Histograms, kernel density estimates of the probability density function, and confidence levels of the null-model distributions are obtained from 10 000 surrogates with partially randomised phases of the records in the GS prior to DO-1 (see main text Sect. 2.3).

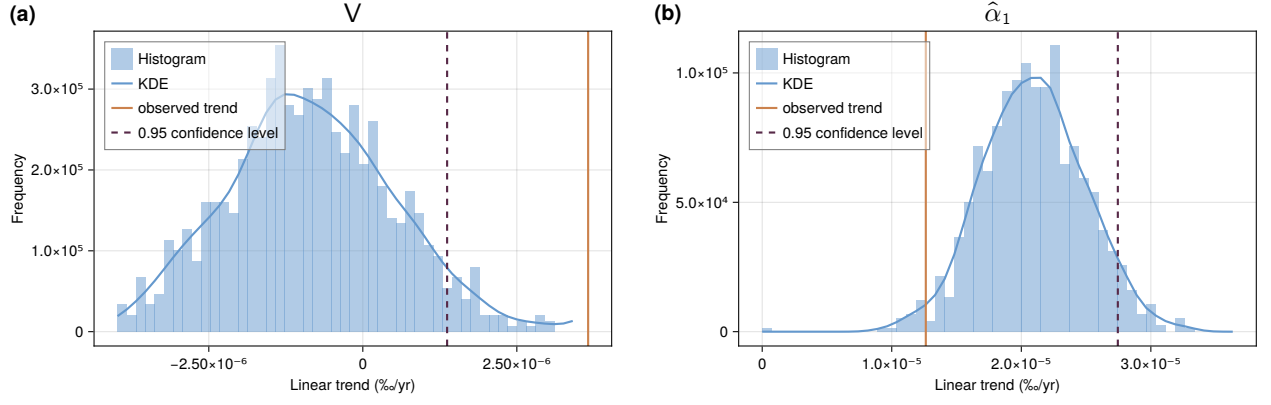


Figure S5. Null-model distribution for linear trends in the CSD-based EWS estimators variance (a) and autocorrelation (b) prior to DO-1 in the raw NGRIP record with irregular time steps. Histograms, kernel density estimates of the probability density function, and confidence levels of the null-model distributions are obtained from 1 000 surrogates with partially randomised phases of the record in the GS prior to DO-1 (see main text Sect. 2.3).

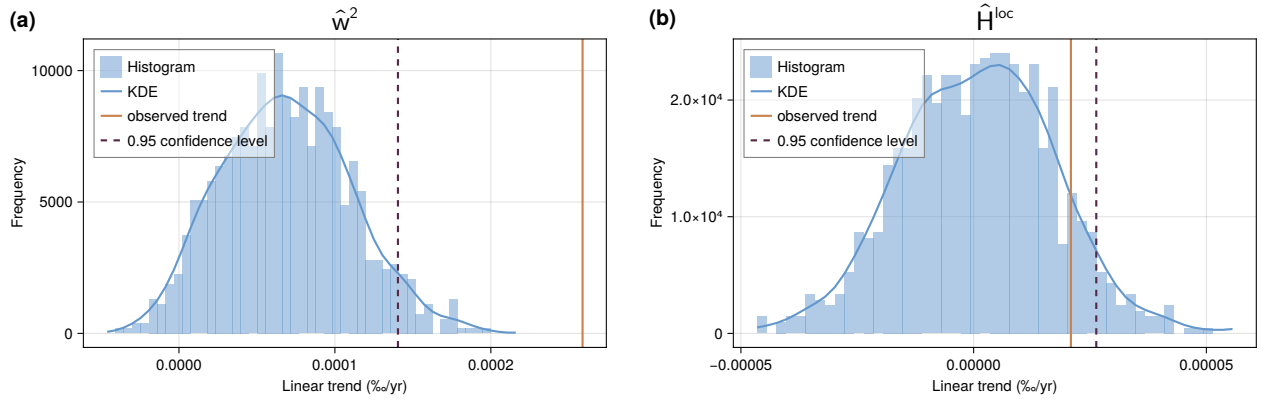


Figure S6. Null-model distribution for linear trends in the wavelet-based EWS estimators scale-averaged wavelet coefficient (a) and local Hurst exponent (b) prior to DO-1 in the raw NGRIP record with irregular time steps. Histograms, kernel density estimates of the probability density function, and confidence levels of the null-model distributions are obtained from 1 000 surrogates with partially randomised phases of the record in the GS prior to DO-1 (see main text Sect. 2.3).

S1.2 Early warning signals in the NGRIP record with 5-year resolution

S1.2.1 Method modifications

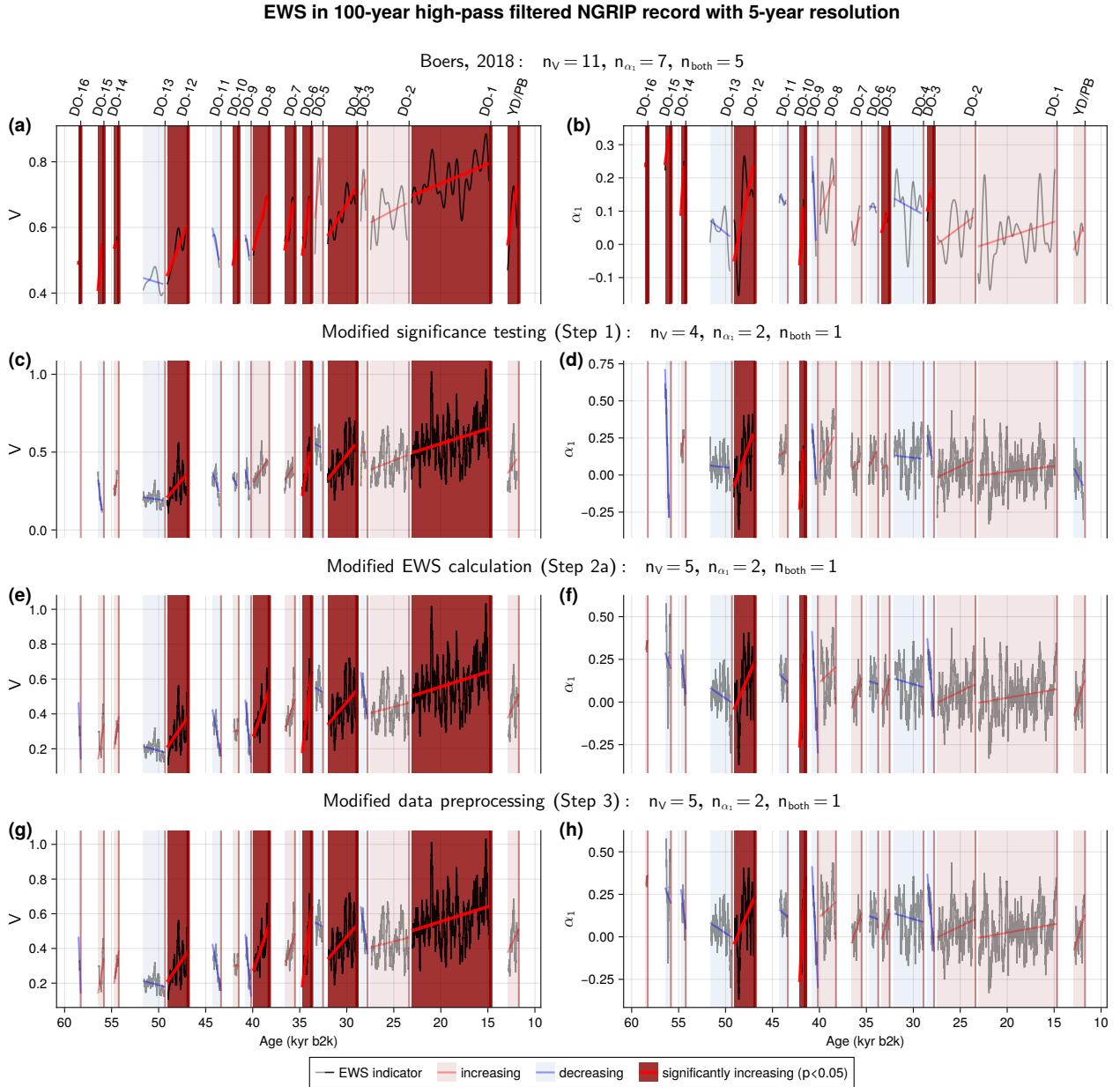


Figure S7. Early warning signals in the variance and autocorrelation of the 5-year interpolated and 100-year high-pass filtered NGRIP $\delta^{18}\text{O}$ record with sequential method modifications. (a) Time series of the variance (black) during GS calculated using the methods described by Boers (2018). (b) Same as (a) but for the lag-1 autocorrelation coefficient. (c-d) Same as (a-b) but with modified significance testing. (e-f) Same as (c-d) but with modified indicator calculation. (g-h) Same as (e-f) but with modified data preprocessing. DO events and the YD/PB transition are marked by the red vertical lines. Linear trends of the indicators are shown by red (blue) lines and the corresponding pale shading of the GS period if the trend is positive (negative). Significant linear increases are indicated by a dark red shading of the GS preceding transitions. The number of significant increases in V , α_1 and both indicators simultaneously are denoted by n_V , n_{α_1} and n_{both} , respectively.

EWS in 100-year high-pass filtered NGRIP record with 5-year resolution

Boers, 2018: $n_V = 11$, $n_{\alpha_1} = 7$, $n_{\text{both}} = 5$

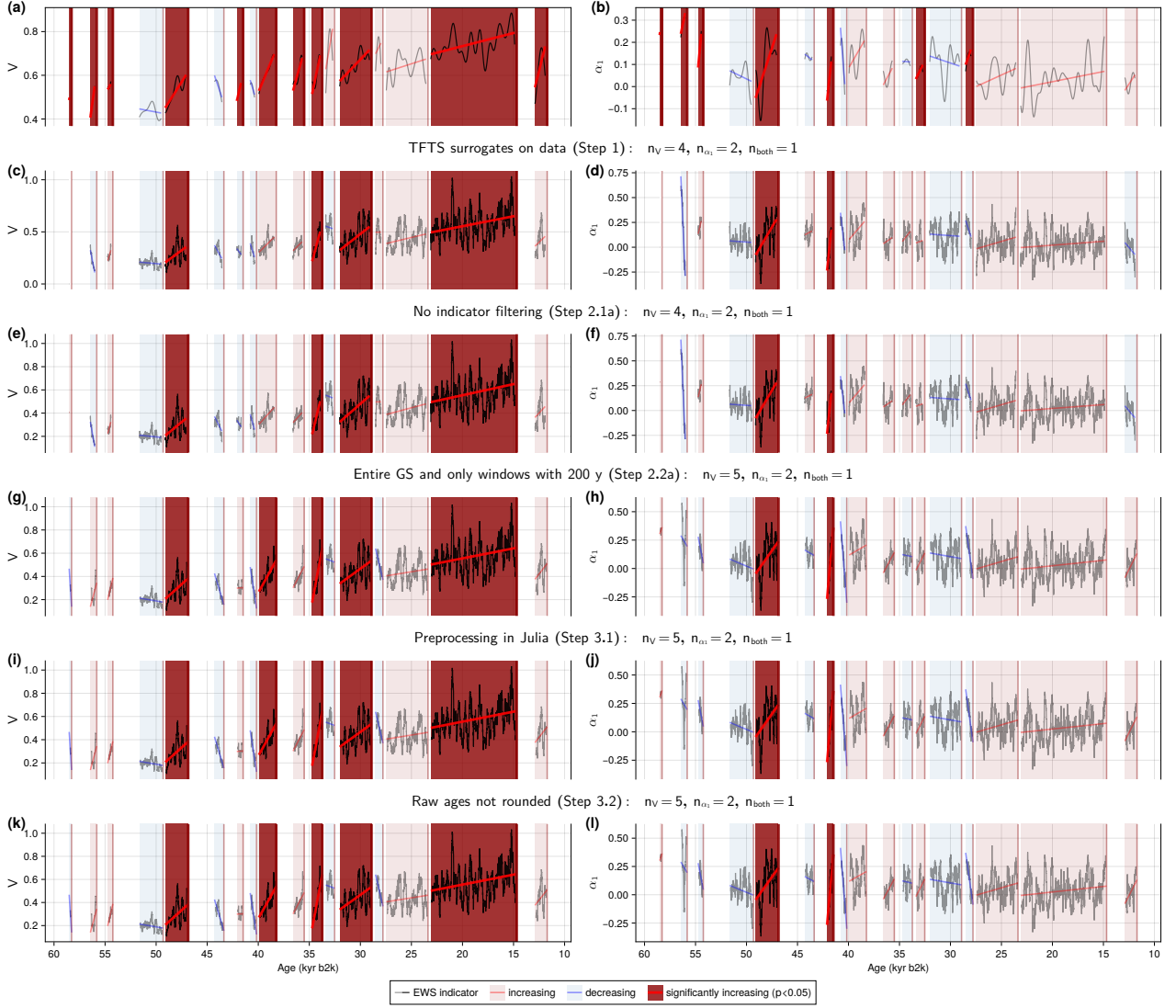


Figure S8. Same as Fig. S7, but including the sub-steps described in Table 2 in the main text for sequential modifications to significance testing (c,d), CSD-based EWS calculation (e-h), and data preprocessing (i-l).

EWS in (10-50) year band of NGRIP record with 5-year resolution

Boers, 2018: $n_{\hat{w}^2} = 12$, $n_{\hat{H}^{loc}} = 8$, $n_{both} = 7$

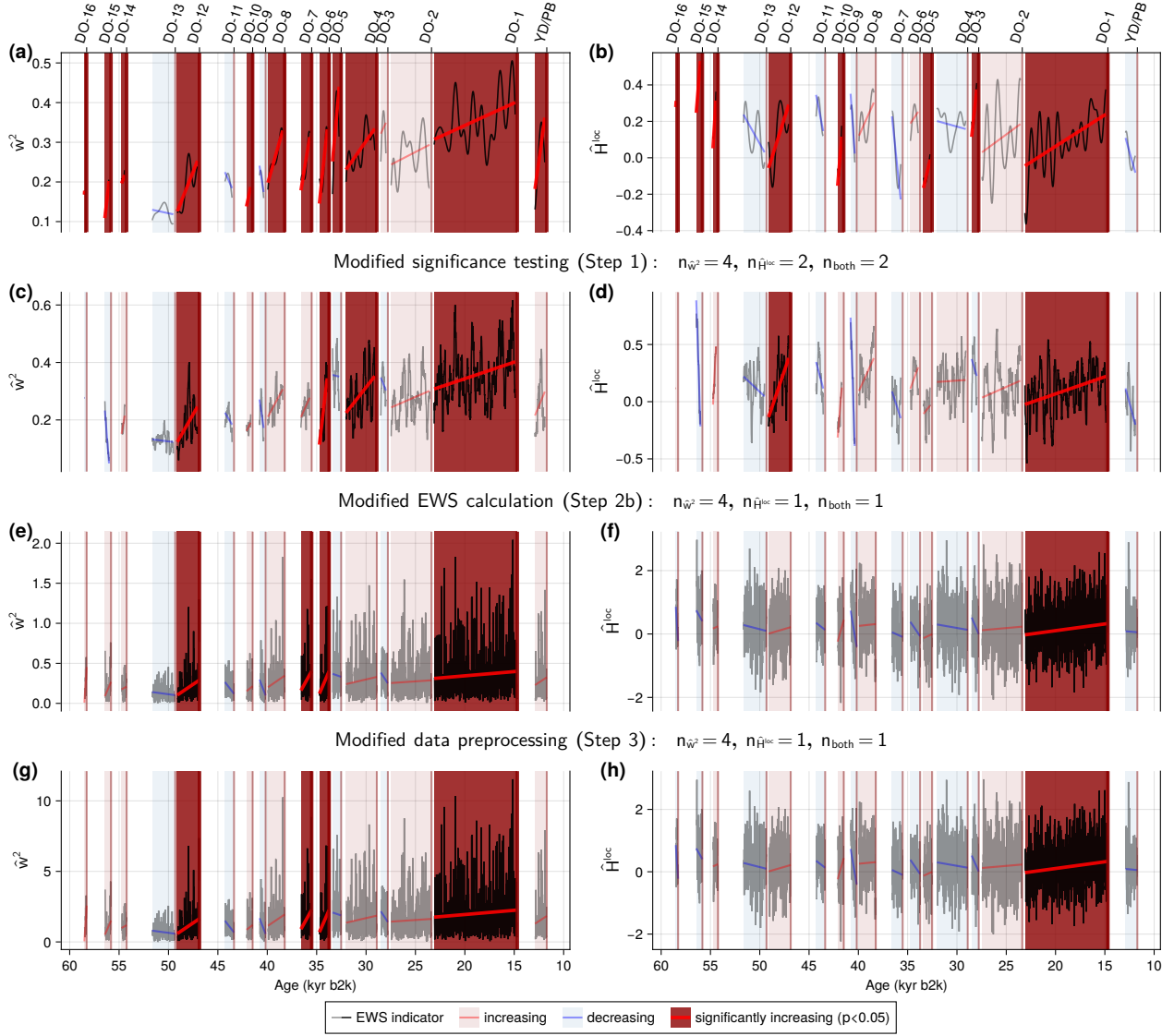


Figure S9. Early warning signals in the wavelet-based indicators confined to the 10–50-year periodicity band of the 5-year interpolated NGRIP $\delta^{18}\text{O}$ record with sequential method modifications. (a) Time series of the scale-averaged wavelet coefficient (black) during GS, calculated using the methods described by Boers (2018). (b) Same as (a) but for the local Hurst exponent. (c-d) Same as (a-b) but with modified significance testing. (e-f) Same as (c-d) but with modified estimator calculation. (g-h) Same as (e-f) but with modified data preprocessing. Line colours and shadings are applied in the same way as in Fig. S7.

EWS in (10-50) year band of NGRIP record with 5-year resolution

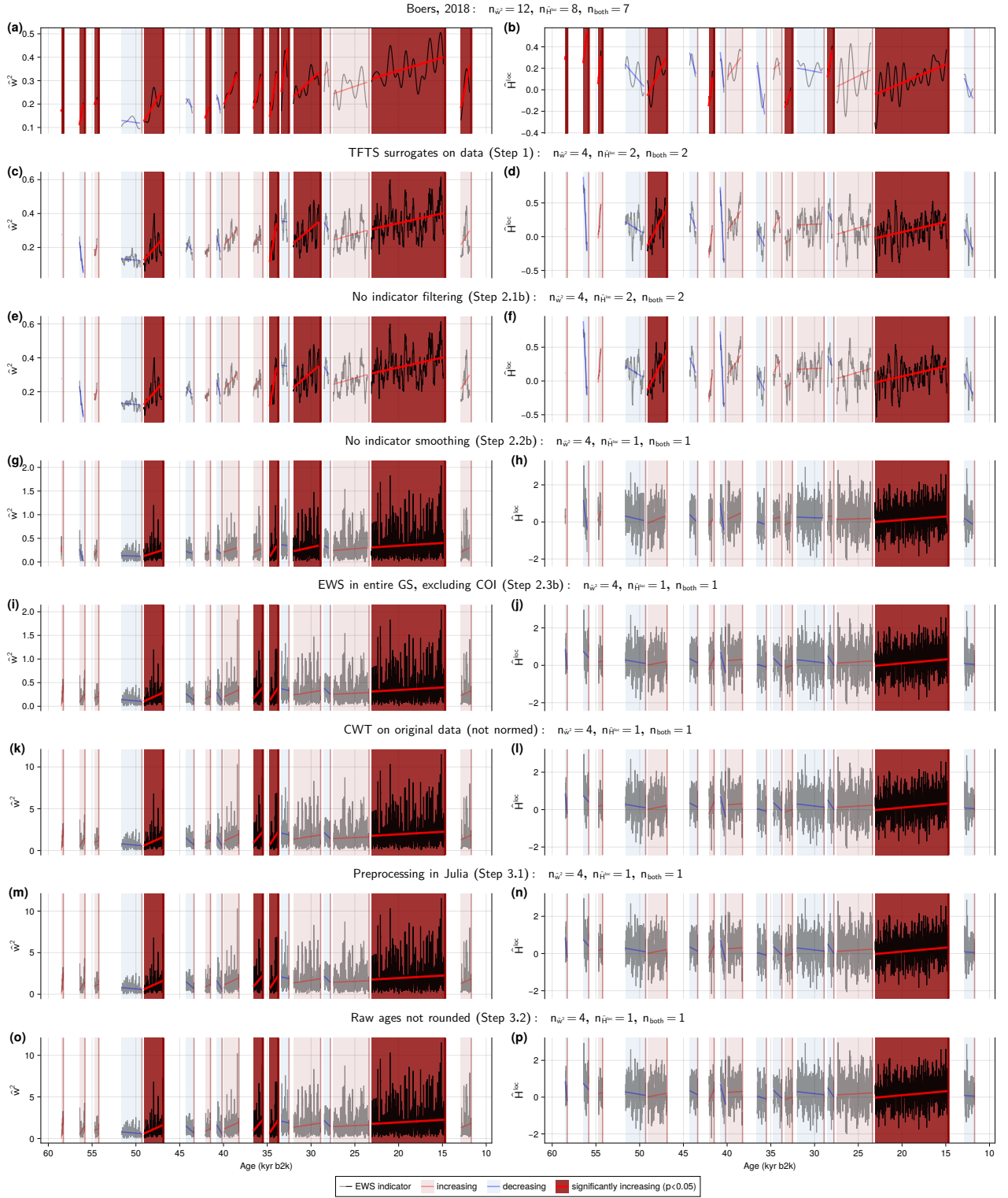


Figure S10. Same as Fig. S9, but including the sub-steps described in Table 2 in the main text for sequential modifications to significance testing (c,d), wavelet-based EWS calculation (e-l), and data preprocessing (m-p).

S1.3 Early warning signals in the NGRIP record with irregular temporal resolution

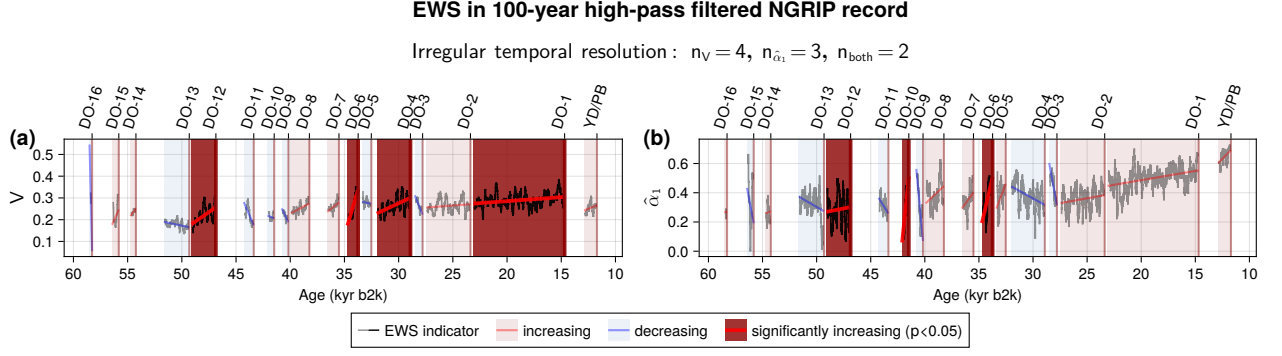


Figure S11. Early warning signals in the variance and autocorrelation of the raw, irregularly sampled, 100-year high-pass filtered NGRIP $\delta^{18}\text{O}$ record. (a) Time series of the variance (black) during GS (b) Same as (a) but for the autocorrelation coefficient. Line colours and shadings are applied in the same way as in Fig. S7.

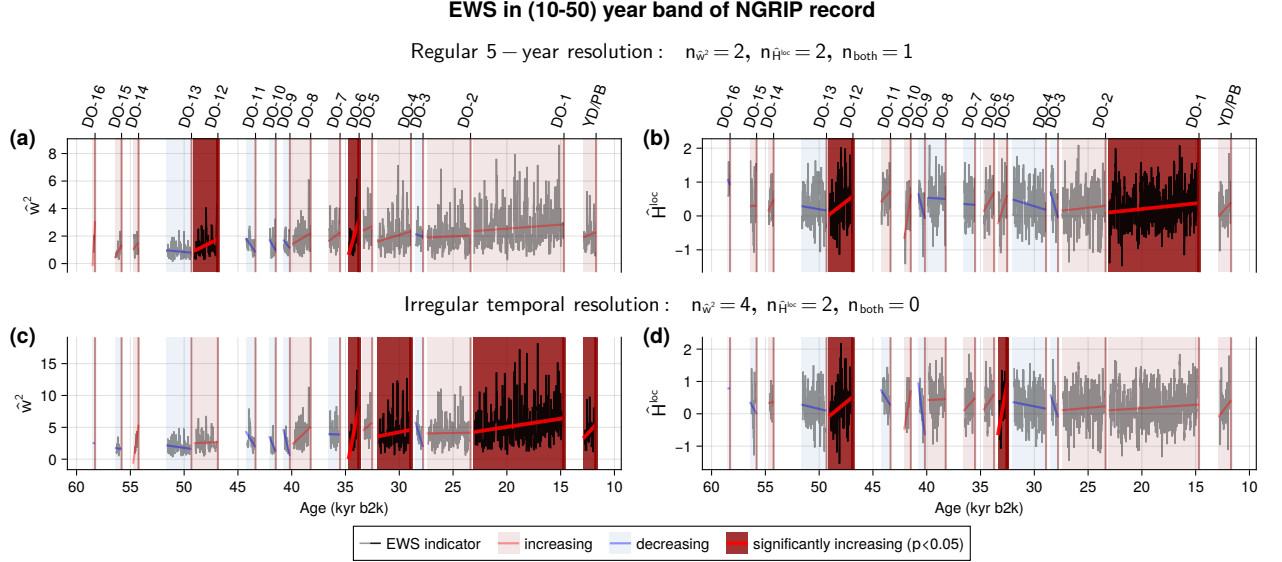


Figure S12. Early warning signals in the wavelet-based indicators confined to the 10–50-year periodicity band of the 5-year interpolated and raw NGRIP $\delta^{18}\text{O}$ records. (a) Time series of the scale-averaged wavelet coefficient (black) during GS of the 5-year interpolated NGRIP record using the Morlet wavelet function. (b) Same as (a) but for the local Hurst exponent. (c-d) Same as (a-b) but for the raw, irregularly sampled NGRIP record. Line colours and shadings are applied in the same way as in Fig. S7.

S1.4 Early warning signals across ice core records

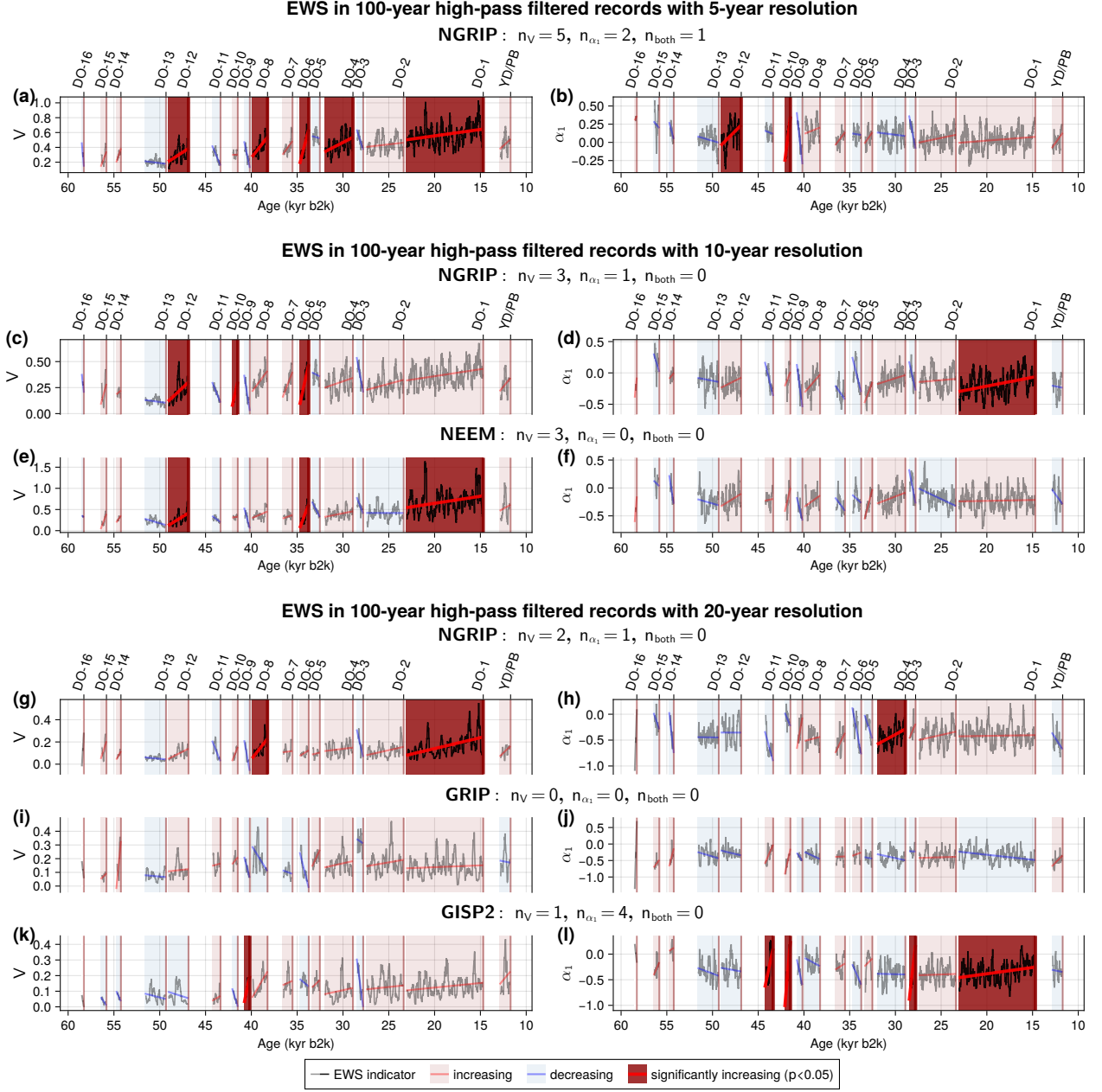


Figure S13. Early warning signals in the variance and autocorrelation of various 100-year high-pass filtered Greenland $\delta^{18}\text{O}$ records. (a) Time series of the variance (black) during GS of the 5-year NGRIP record. (b) Same as (a) but for the lag-1 autocorrelation coefficient. (c-d) Same as (a-b) but for the 10-year NGRIP record. (e-f) Same as (a-b) but for the 10-year NEEM record. (g-h) Same as (a-b) but for the 20-year NGRIP record. (i-j) Same as (a-b) but for the 20-year GRIP record. (k-l) Same as (a-b) but for the 20-year GISP2 record. Line colours and shadings are applied in the same way as in Fig. S7.

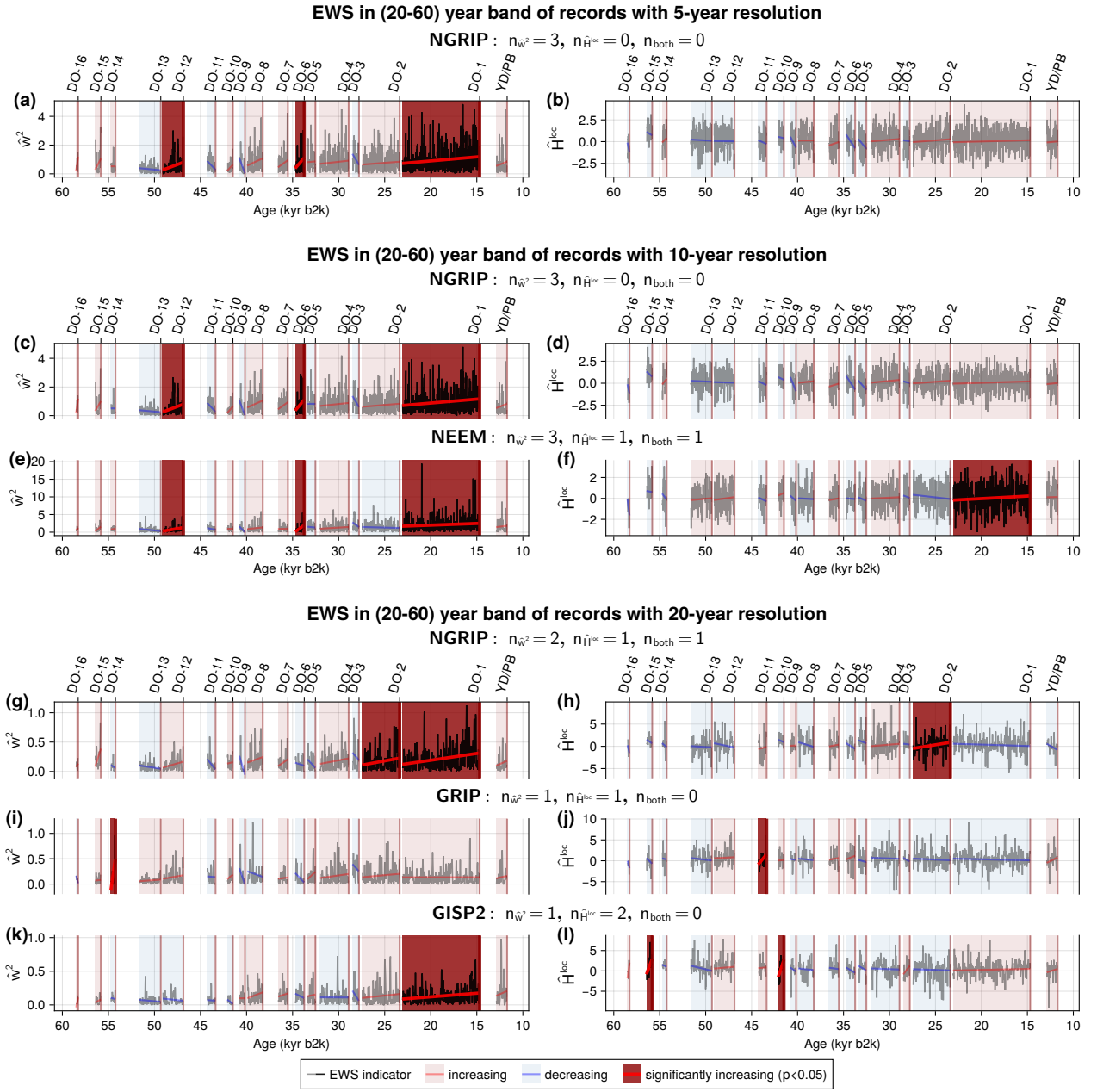


Figure S14. Early warning signals in the wavelet-based indicators confined to the 20–60-year periodicity band of various Greenland $\delta^{18}\text{O}$ records. (a) Time series of the scale-averaged wavelet coefficient (black) during GS. (b) Same as (a) but for the local Hurst exponent. (c-d) Same as (a-b) but for the 10-year NGRIP record. (e-f) Same as (a-b) but for the 10-year NEEM record. (g-h) Same as (a-b) but for the 20-year NGRIP record. (i-j) Same as (a-b) but for the 20-year GRIP record. (k-l) Same as (a-b) but for the 20-year GISP2 record. Line colours and shadings are applied in the same way as in Fig. S7.

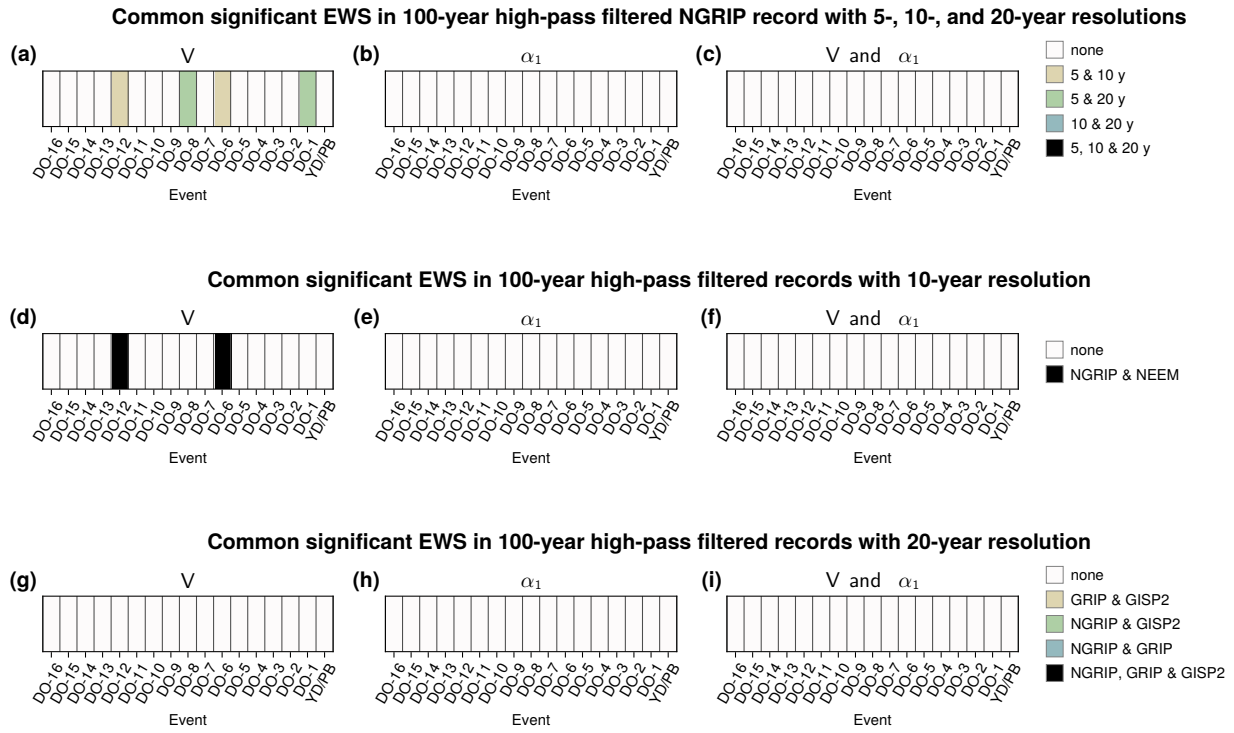


Figure S15. Common significant EWS in the CSD indicators for individual transitions across the $\delta^{18}\text{O}$ NGRIP record with different temporal resolutions (a-c), records with 10- (d-f) and 20-year resolution (g-i). Common significant increases of the variance are shown in the left (a,d,e), those of the lag-1 autocorrelation coefficient in the middle column (b,e,h). The right column shows those simultaneously occurring in both CSD estimators.

Linear trends of indicators in (s_1-s_2) year bands of records with 5-year resolution

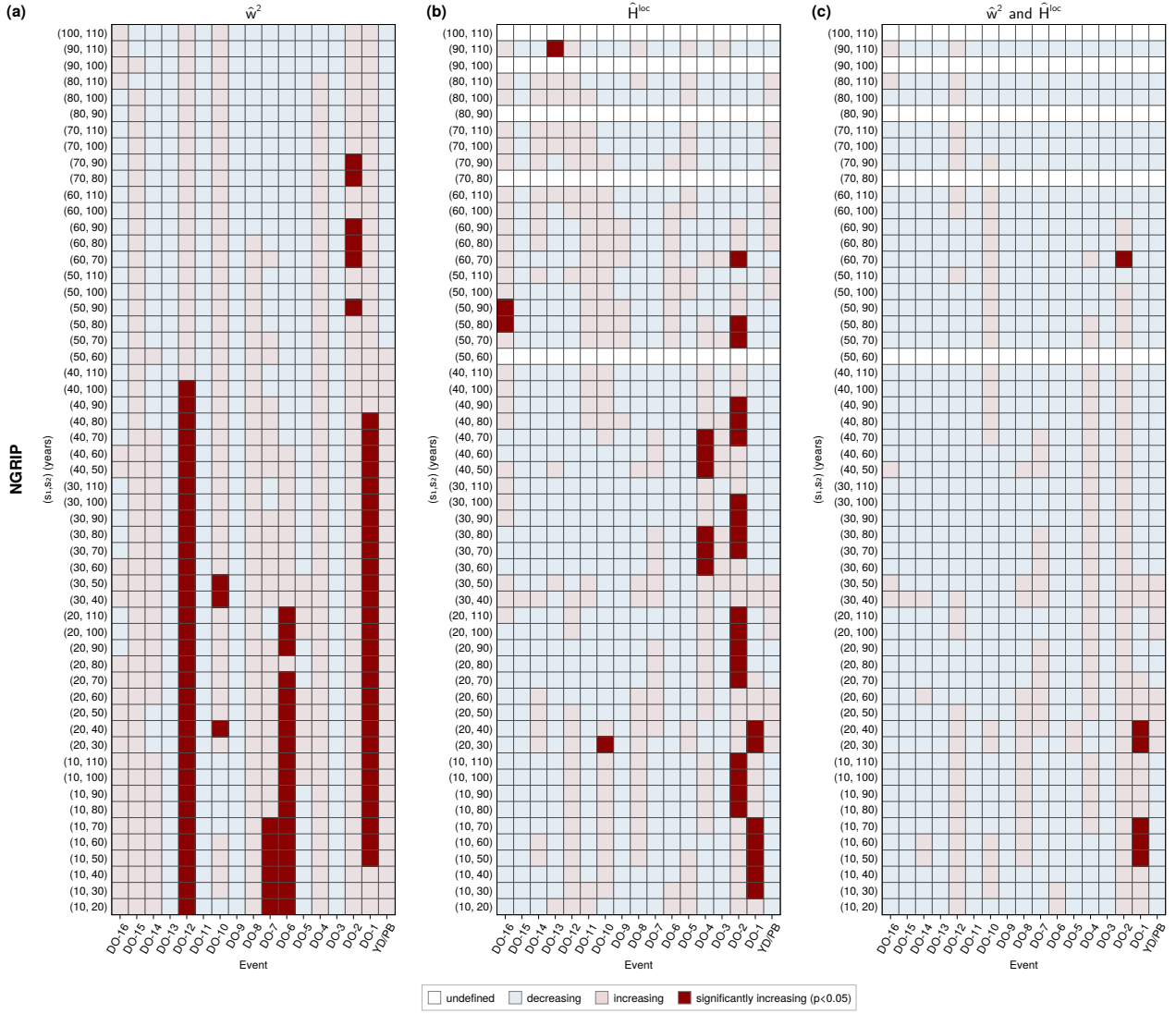


Figure S16. Same as Fig. A4 (a-c) in the main text, but including all scale ranges (s_1, s_2) considered for the NGRIP record with 5-year resolution.

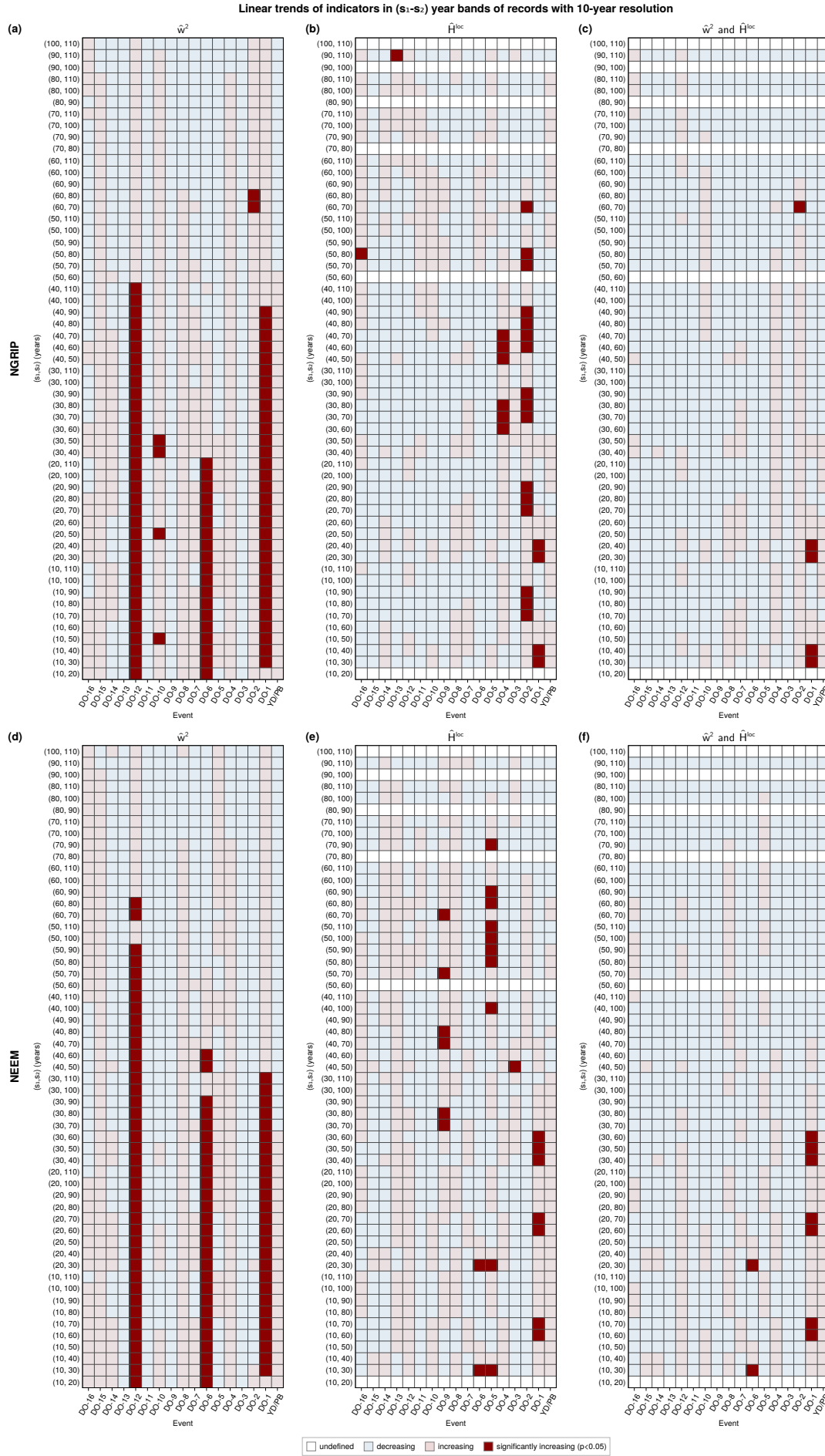


Figure S17. Same as Fig. A4 (d-i) in the main text, but including all scale ranges (s_1, s_2) considered for the NGRIP and NEEM records with 10-year resolution.

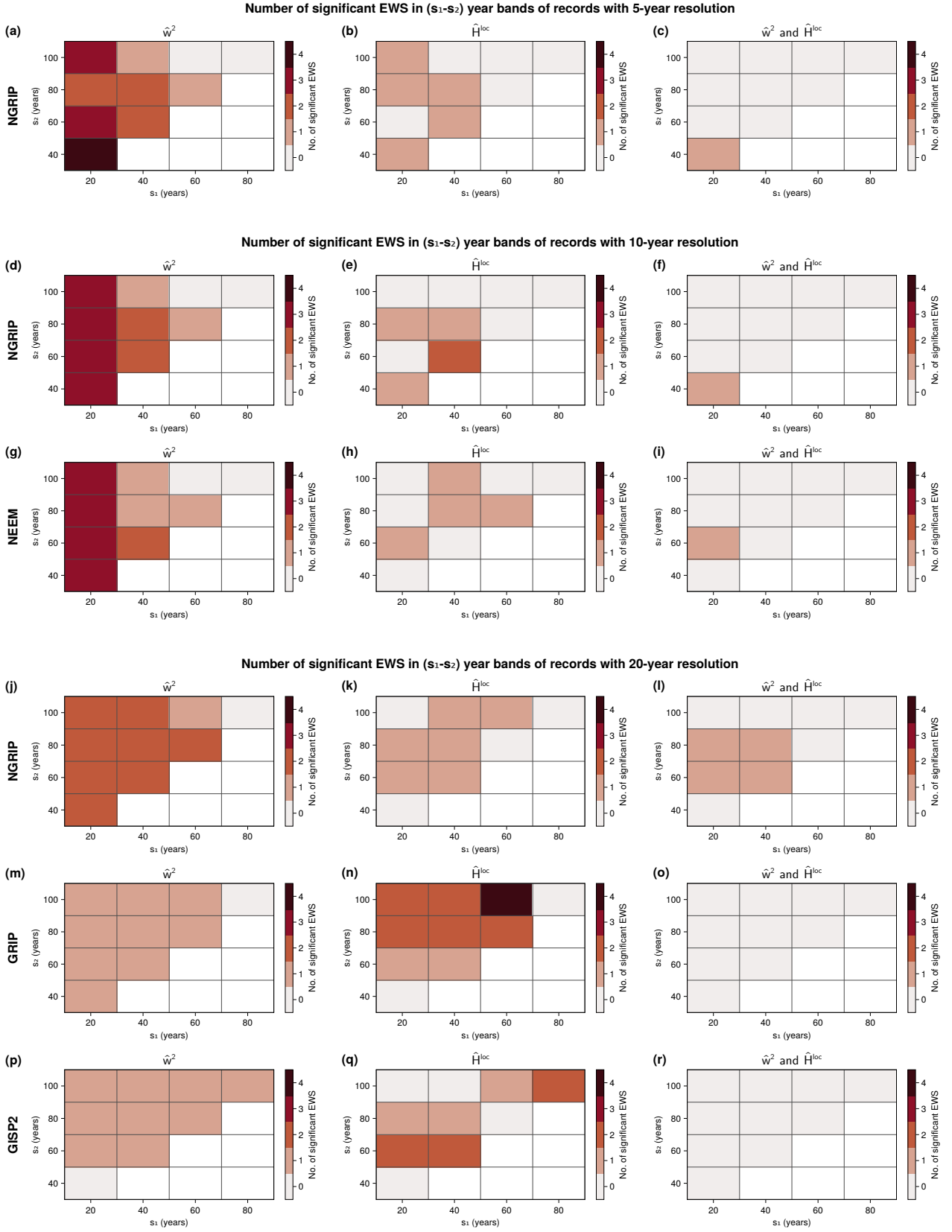


Figure S18. Same as Fig. A5 in the main text, but only including scale ranges (s_1, s_2) applicable to all $\delta^{18}\text{O}$ records with different temporal resolutions.

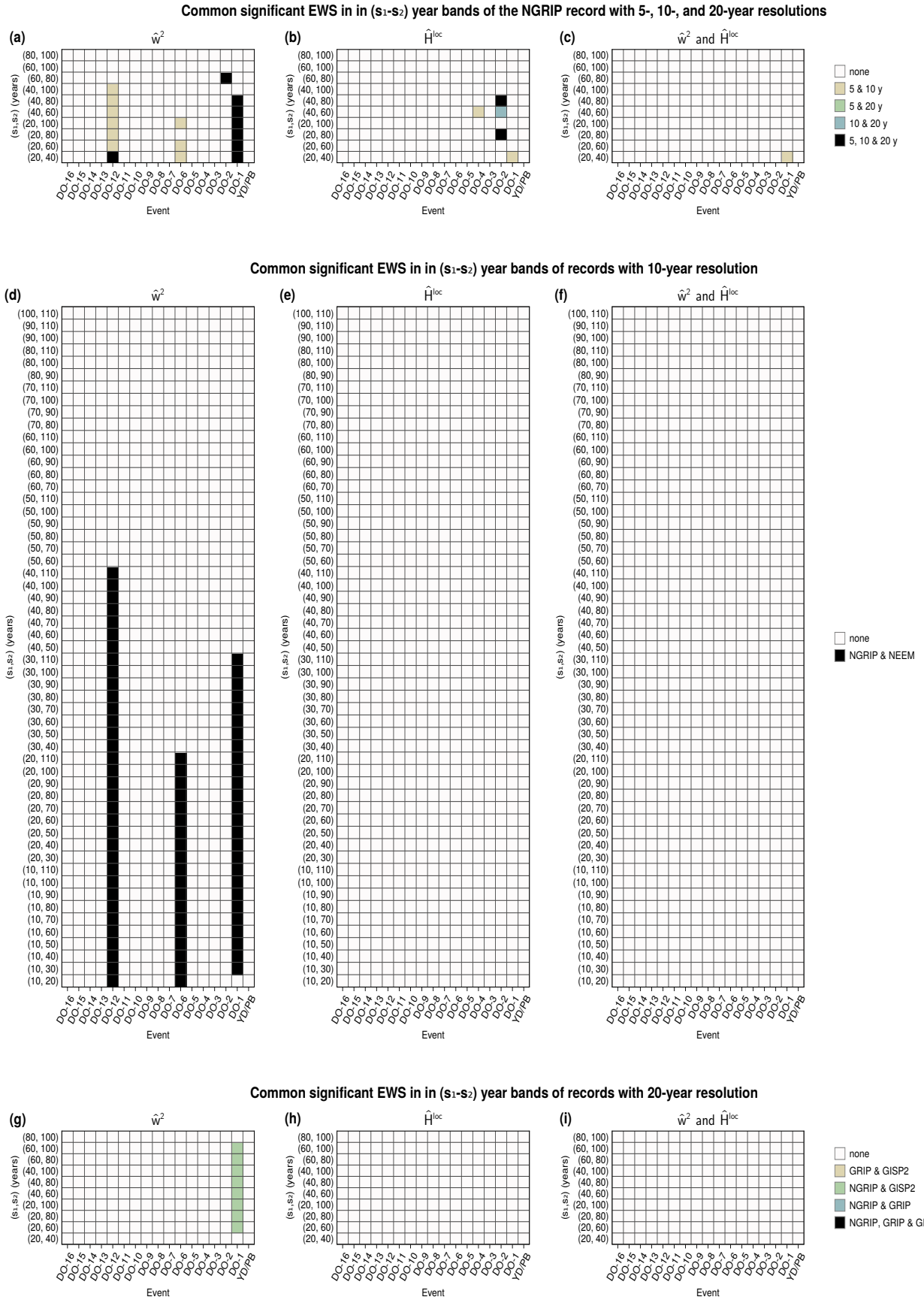


Figure S19. Common significant EWS in the wavelet-based indicators for individual transitions and various scale ranges (s_1, s_2) across the $\delta^{18}\text{O}$ NGRIP record with different temporal resolutions (a-c), records with 10- (d-f) and 20-year resolution (g-i). Common significant increases of the scale-averaged wavelet coefficient are shown in the left (a,d,e), those of the local Hurst exponent in the middle column (b,e,h). The right column shows those simultaneously occurring in both estimators.

S2 Results without low-pass filtering during interpolation

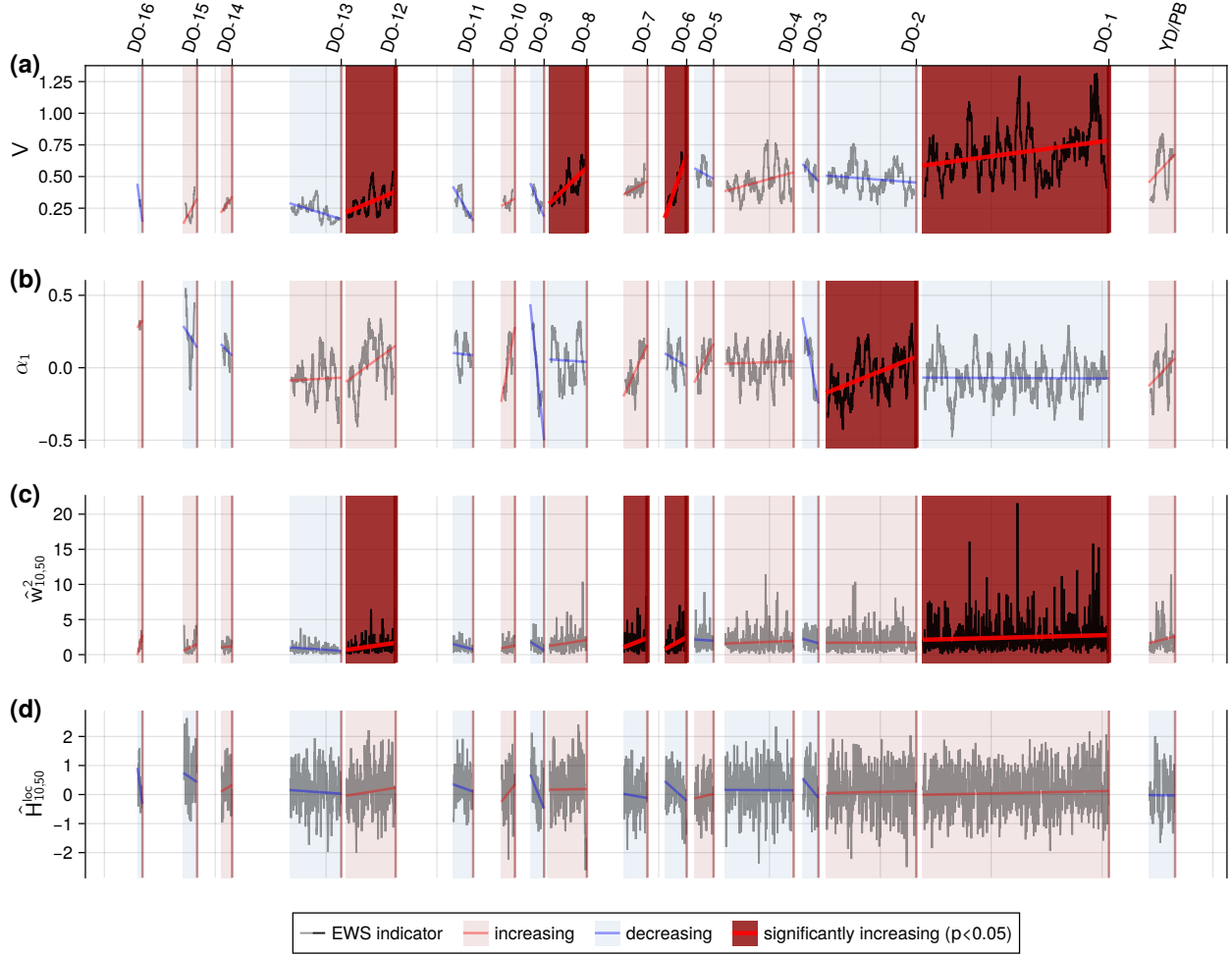


Figure S20. Early warning signals of the 5-year interpolated NGRIP $\delta^{18}\text{O}$ record, where no low-pass filter has been applied between interpolation of the irregularly sampled record and resampling. (a) Time series of the variance (black) of the 100-year high-pass filtered record during GS. (b) Same as (a) but for the lag-1 autocorrelation coefficient. (c-d) Time series of the the scale-averaged wavelet coefficient and local Hurst exponent confined to the 10–50 year periodicity band (black) during GS, respectively. DO events and the YD/PB transition are marked by the red vertical lines. Linear trends of the indicators are shown by red (blue) lines and the corresponding pale shading of the GS period if the trend is positive (negative). Significant linear increases are indicated by a dark red shading of the GS preceding transitions.

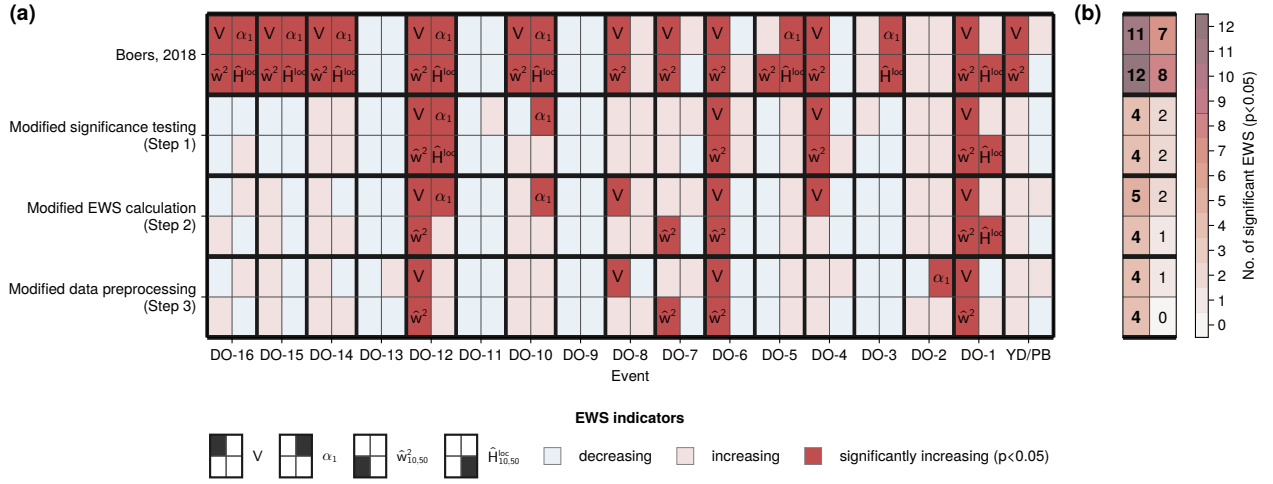


Figure S21. Same as Fig. 6 in the main text, but for the NGRIP record with 5-year temporal resolution, where no low-pass filter has been applied between interpolation of the irregularly sampled record and resampling.

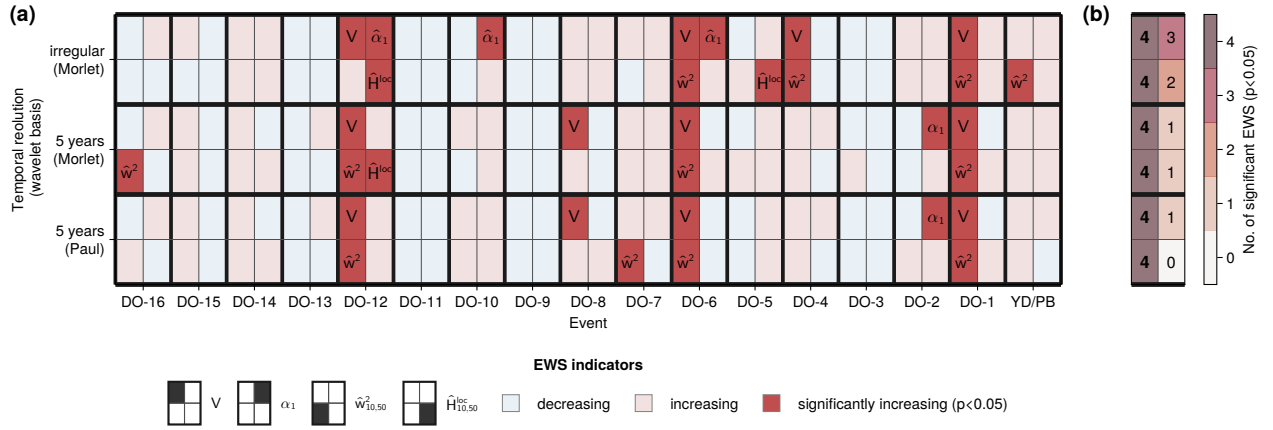


Figure S22. Same as Fig. 7 in the main text, but including the NGRIP record in 5-year resolution, where no low-pass filter has been applied between interpolation of the irregularly sampled record and resampling.

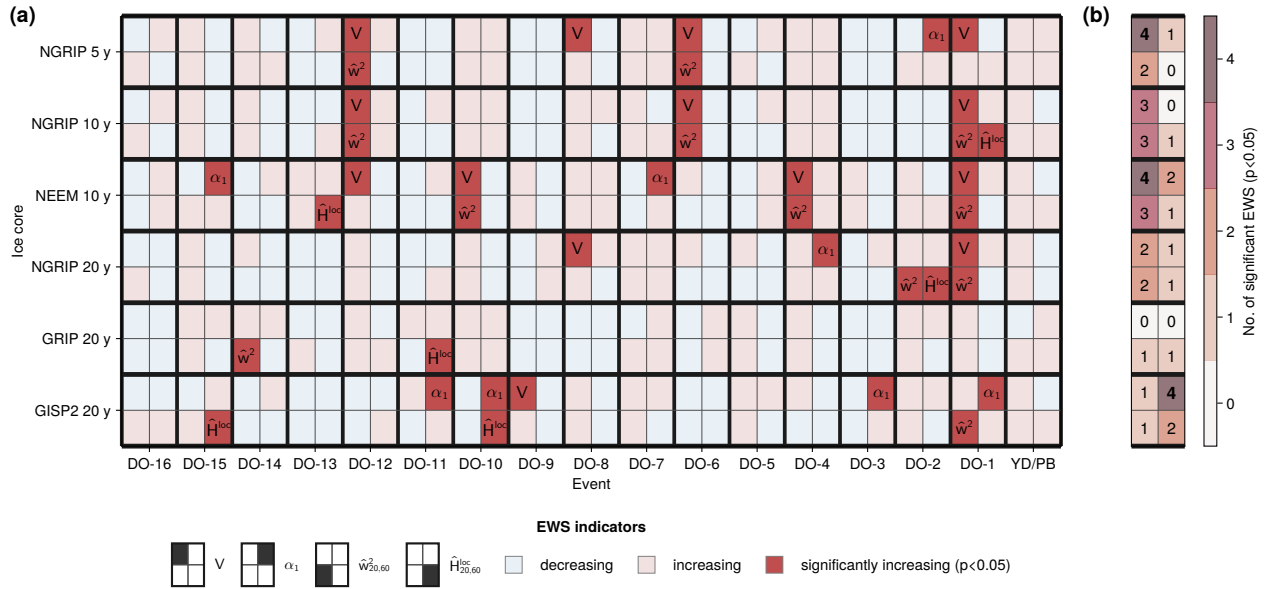


Figure S23. Same as Fig. 8 in the main text, but including the records in 5- and 10-year temporal resolution, where no low-pass filter has been applied between interpolation of the irregularly sampled record and resampling.

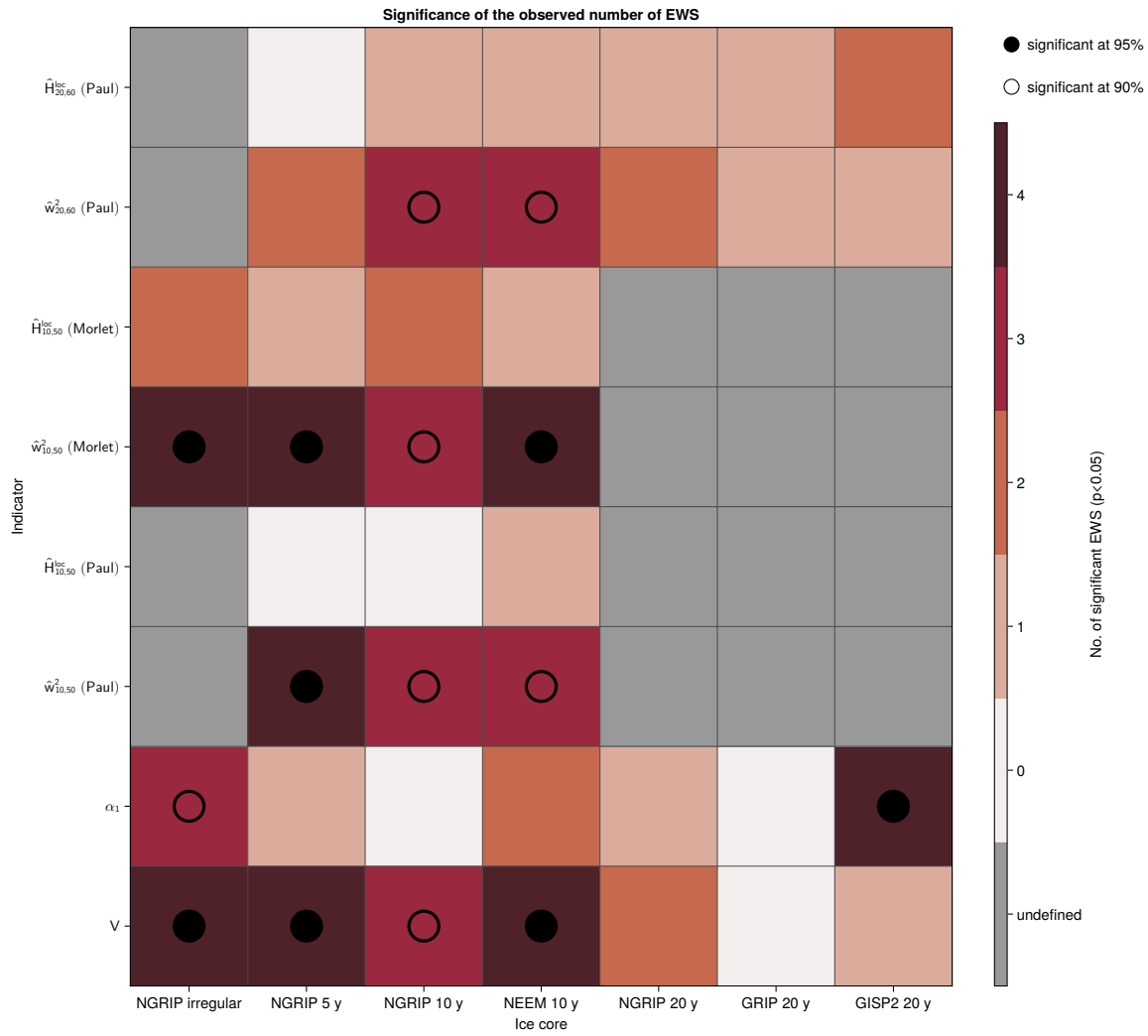


Figure S24. Same as Fig. 9 in the main text, but including the records in 5- and 10-year temporal resolution, where no low-pass filter has been applied between interpolation of the irregularly sampled record and resampling.

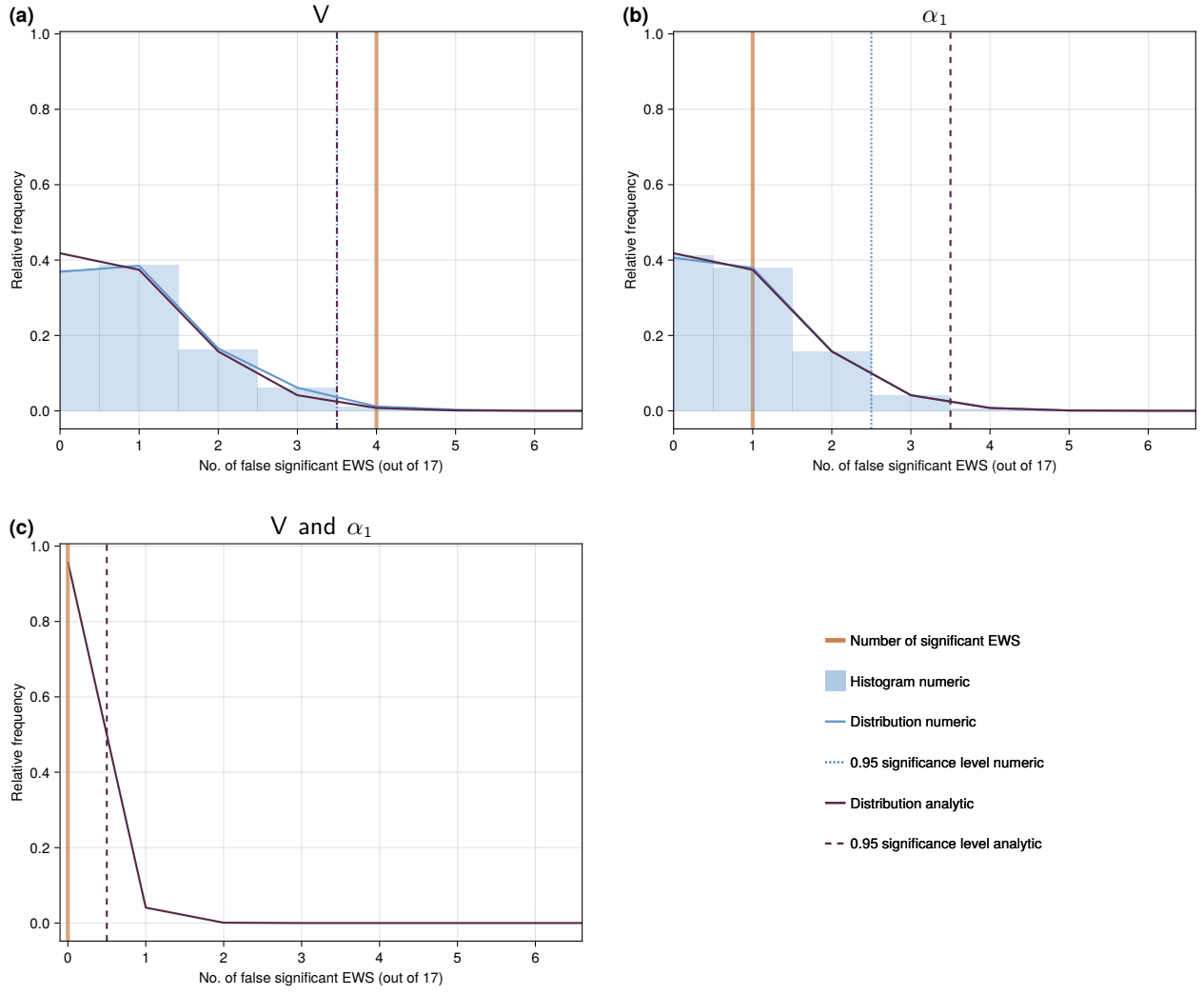


Figure S25. Same as Fig. 3 in the main text, but for the NGRIP record with 5-year temporal resolution, where no low-pass filter has been applied between interpolation of the irregularly sampled record and resampling.

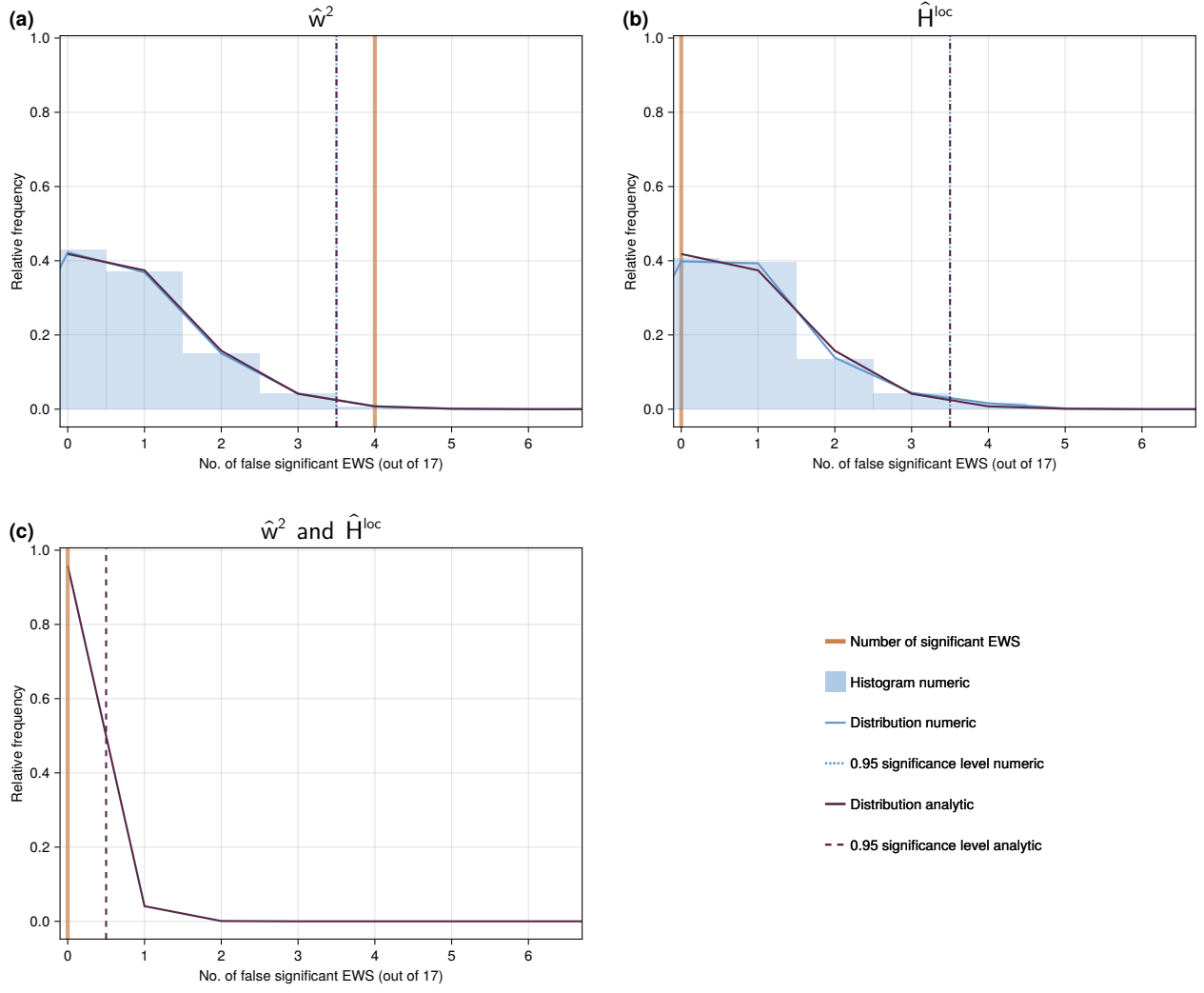


Figure S26. Same as Fig. A3 in the main text, but for the NGRIP record with 5-year temporal resolution, where no low-pass filter has been applied between interpolation of the irregularly sampled record and resampling.

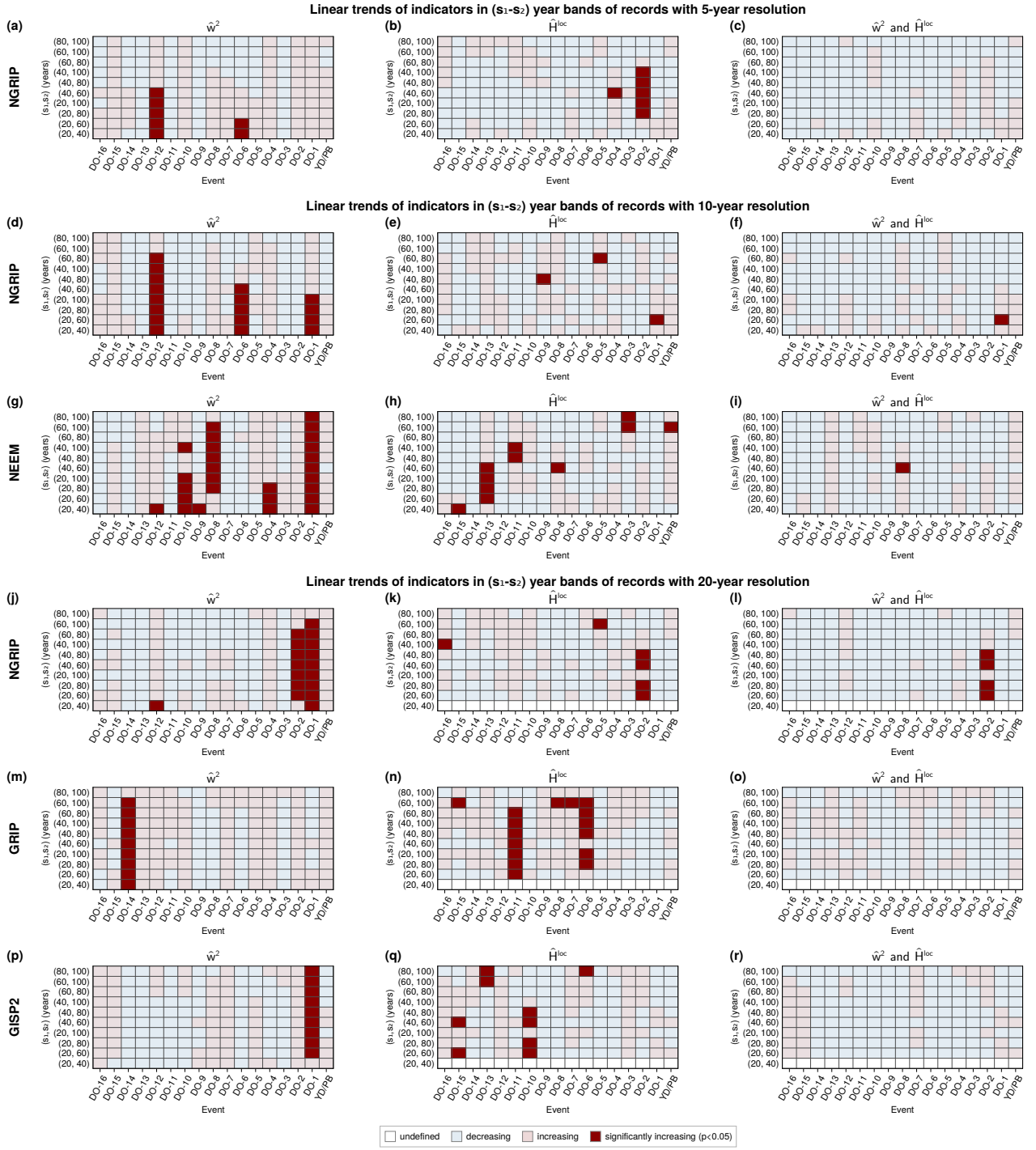


Figure S27. Same as Fig. A4 in the main text, but including the records in 5- (a,c) and 10-year temporal resolution (d-i), where no low-pass filter has been applied between interpolation of the irregularly sampled record and resampling.

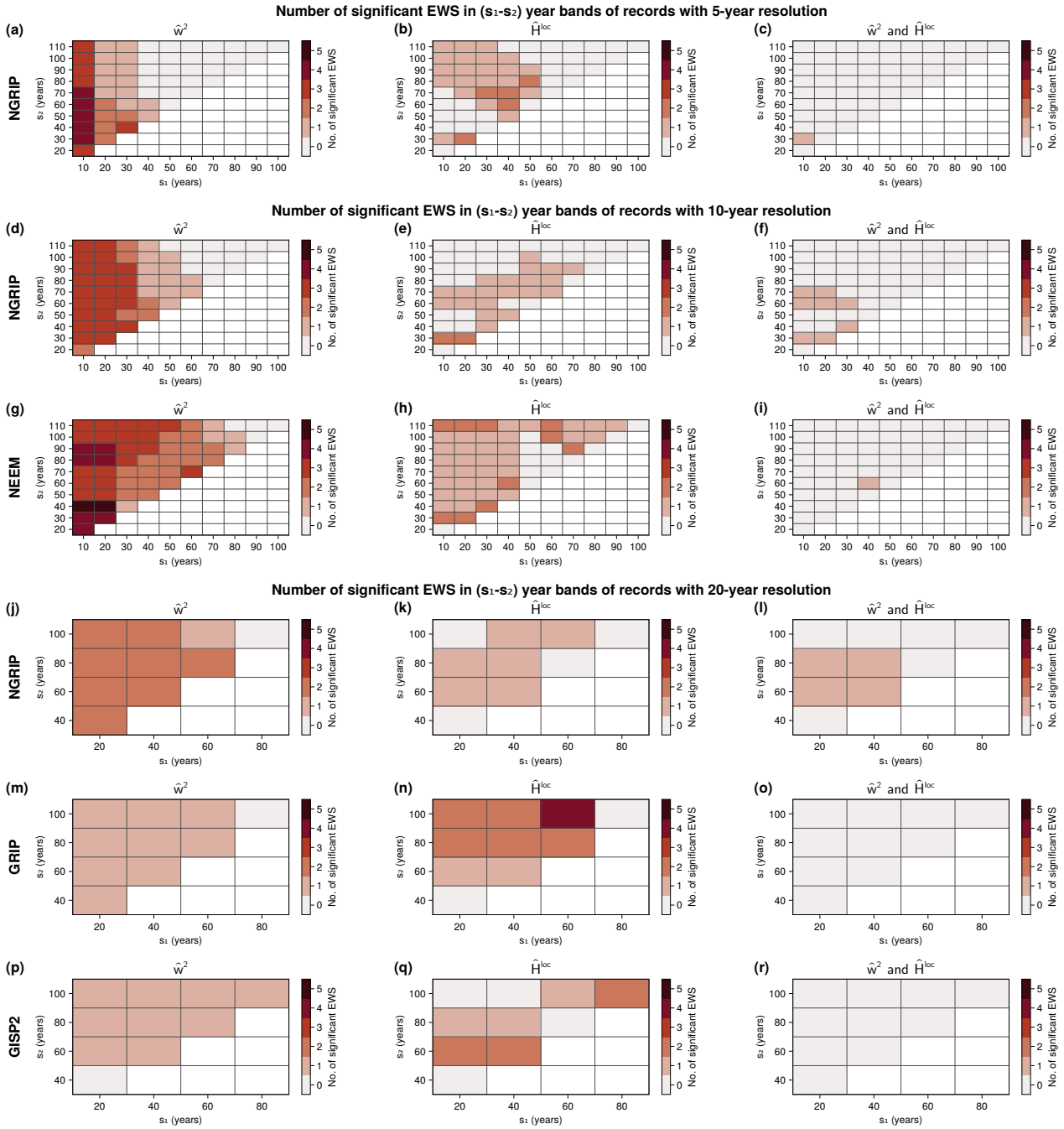


Figure S28. Same as Fig. A5 in the main text, but including the records in 5- (a,c) and 10-year temporal resolution (d-i), where no low-pass filter has been applied between interpolation of the irregularly sampled record and resampling.

References

Boers, N.: Early-warning signals for Dansgaard-Oeschger events in a high-resolution ice core record, *Nature Communications*, 9, 2556, <https://doi.org/10.1038/s41467-018-04881-7>, number: 1 Publisher: Nature Publishing Group, 2018.