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A timescale analysis of the NH temperature response to volcanic and solar forcing in the past millenium

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Abstract

The Northern Hemisphere temperature response to volcanic and solar forcing is studied using first a set of simulations with an intermediate-complexity climate model, driven by reconstructed forcings. Results are than compared with those obtained from the seven high-resolution reconstructed temperature records for the last millenium that are at present available. Focus of the analysis is on the timescale dependence of the response. Results between the model and the proxy-based reconstructions are remarkably consistent. The response to solar forcing is found to equilibrate at interdecadal timescales, reaching an equilibrium value for the regression of 0.2–0.3°C per W/m^2. The time interval between volcanic eruptions is typically shorter than the dissipation timescale of the climate system, so that the response to volcanic forcing never equilibrates. As a result, the regression on the volcanic forcing is always lower than the equilibrium value and goes to zero for the longest temporal scales. The trends over the pre-anthropogenic period are found to be relatively large in all reconstructed temperature records compared to their interdecadal-centennial variability. This is at variance with a recent claim that reconstructed temperature records underestimate climatic variations at multi-centennial scales.

1. Introduction

External forcings, like volcanic eruptions or solar irradiance variations, have been shown to play an important role in generating Northern Hemisphere (NH) temperature variations during the past millenium (Mann et al., 1998; Crowley, 2000). The response to volcanic forcing is reliably detected in temperature reconstructions for the past millenium, but the response to solar forcing is claimed to be weakly present in some periods only (Hegerl et al., 2003). However, it seems likely that the relative importance of each forcing factor depends on the timescale. Volcanic eruptions result in a strong, but short-lived reduction of the large-scale radiative forcing, so that this forcing is probably most relevant for annual-decadal timescales. The solar irradiance spectrum, on the other hand, has increasing power at longer timescales. Numerous studies have found evidence of solar forcing at long temporal scales (e.g. Crowley and Kim, 1996). Therefore, this forcing might be important primarily for temperature variations at multidecadal and longer timescales.

The present paper examines how the large-scale temperature response depends on the timescale. This is first done by using a set of model simulations with the ECBilt climate model, driven by reconstructed forcing factors. The simulated NH temperature response is analysed as a function of timescale by computing the regression and correlation with the forcing for a range of low-pass filter periods. The model results are than compared with results from seven high-resolution temperature reconstructions that go back at least to 1000 AD. Four of these are based on (partly overlapping) multi-proxy datasets (Jo98: Jones et al., 1998; Ma99: Mann et al., 1999; Cr00: Crowley and Lowery; 2000; Ma03: Mann and Jones, 2003), while two are based on tree-ring data only (Br00: Briffa, 2000; Es02: Esper et al., 2002). One reconstruction combines annual tree-ring data with low-resolution records to obtain the longer temporal scales (Mo05: Moberg et al., 2005). All reconstructions are available at the World Data Center for Paleoclimatology (http://www.ngdc.noaa.gov/paleo). It will be examined whether these reconstructions contain a plausible forced signal, given the response characteristics of the climate system. This can be considered as an evaluation of the quality of these records, as the proxy data underlying the reconstructed forcings are independent of the datasets used for the temperature reconstructions. In the present paper focus will be on the timescale dependence of the solar and volcanic forced signals in both the model runs and the proxy-based reconstructions.

2. Climate model and experimental design

ECBilt is an intermediate-complexity climate model containing a dynamic atmosphere, a global 3-D ocean model and a thermodynamic sea-ice model. The atmospheric component (T21, L3) incorparates simplified representations of the diabatic-heating processes and the hydrological cycle. There is a land surface parameterisation, based on a bucket model for soil moisture and a thermodynamic snow model. Cloud cover is prescribed from seasonal climatology. The atmospheric component is synchronously coupled to a flat-bottom ocean component with comparable horizontal resolution and 12 vertical levels. More details on the model are given by Weber et al. (2004).

Four 1000-yr experiments were carried out: two use both volcanic and solar forcing, but start from a different initial state. Two other experiments are driven by either volcanic or solar forcing alone. The forcing factors are taken from Crowley (2000). The solar forcing results in a 0.20% decrease in total solar irradiance (TSI) for the deepest part of the Maunder Minimum (at ca. 1690 AD) with respect to the mean value of 1366 W/m^2. In the following the radiative forcing is defined as the prescribed anomalies in TSI divided by four to account for the Earth's geometry.

The analysis period is taken to be 1000–1850 AD. This minimizes anthropogenic effects in the reconstructed temperatures. The model analysis is carried out over the same period, in order to have identical forcing records and record lengths in the analysis. Reconstructed temperatures are representative of the Northern Hemisphere or emphasize temperatures in the extra-tropics. Although some records are calibrated against annual-mean temperature, all reconstructions rely mainly on proxy data that reflect warm-season temperatures. For this reason simulated June–July–August (JJA) data are used in the analysis, taken over latitudes north of 20° N.

3. Climatic signals due to volcanic and solar forcing

The radiative forcing due to reconstructed variations in solar irradiance and volcanic eruptions is shown in Fig. 1. The solar forcing mainly consists of a low-frequency signal. The present reconstruction does not resolve annual-decadal timescales, as is evident from Fig. 1 where low-pass filtered data (for filter periods of 20, 40, 150 and 400 yr) are shown as well. The filter periods are chosen such that low-pass filtering of the record results in visually different signals, reflecting decadal (20 yr), interdacadal (40 yr), centennial (150 yr) and longer timescales (400 yr).

The volcanic forcing consists of a sequence of strong pulses, which occur at irregular time intervals. In the analysis period 56 eruptions occurred with an amplitude larger than $-0.5\,\mathrm{W/m^2}$. The largest eruption had an amplitude of $-11.8\,\mathrm{W/m^2}$ (in 1259 AD), while the next-largest eruptions fall in the range -5 to $-7\,\mathrm{W/m^2}$ (6 cases). The amplitude of the volcanic forcing rapidly decreases for longer timescales, with clearly different signals at 20, 40 and 150 low-pass filter periods. The trend component (400-yr low-pass filtered) is very small.

Figure 1 also shows the simulated NH temperature from one of the volcanic-solar forced ECBilt runs. A visual inspection of the record already suggests that the temperatures primarily reflect the volcanic forcing at short timescales. Temperatures show a pronounced decline in the year of an eruption. The mean anomaly (not shown) is -0.3°C, taking the composite over all 56 eruptions. Reconstructed temperatures show a much weaker response to volcanic eruptions (0.05–0.1°C; compare Hegerl et al., 2003). Smoothing the model data with a 10-yr low-pass filter results in a mean response that is lower by a factor of two. The temperature reconstructions, however, show a very similar mean response for the smoothed data. This sugggests that the proxy data do not register the strong response to volcanic eruptions at annual timescales, although most records do show pronounced variability at annual timescales. This issue will be examined further below when comparing the regression on the volcanic forcing in the model and as derived from the data. Multi-centennial temperature variations are simulated in the volcanic-solar and solar forced runs, but are very weak in the run with volcanic forcing only.

4. The temperature response as a function of timescale: the model experiments

The temperature regression on the solar and volcanic forcing, R_{sol} and R_{volc}, is shown in Fig. 2a for different low-pass filter periods. As the reconstructed solar forcing does not resolve annual-decadal timescales, results for R_{sol} are only shown for interdecadal and longer timescales. In all model runs the regression on the solar forcing does not depend on the filter period in this timescale range, while it is somewhat higher in the runs which include volcanic forcing than in the run with solar forcing alone. In the volcanic-solar forced runs the mean NH temperature is lower and the temperature variations are larger than in the run with solar forcing only. For this reason, R_{sol} appears to be larger. This spurious effect disappears when the regression is computed from the reduced records, that is, the temperature record minus the response to each volcanic eruption (the mean response scaled by the amplitude of that eruption).

The solar forcing can be thought of as a superposition of periodic components. The linear response to such is forcing is again periodic and the temperature regression can be shown to increase for increasing forcing periods, reaching an equilibrium level for periods considerably longer than the dissipation timescale of the system (White et al., 1998). At shorter timescales the response is damped due to the thermal inertia of the ocean. The dissipation timescale is set by the depth of the oceanic mixed layer and the efficiency of long-wave radiation to space. It is estimated to be a few years (White et al., 1998). In the present experiments R_{sol} seems to have equilibrated at interdecadal timescales, consistent with earlier results from a 10 000 yr solar-forced experiment (Weber et al., 2004).

The volcanic-solar forced and volcanic forced runs give consistent results for R_{volc}. The simulated R_{volc}=0.12°C per W/m^2 for filter periods of 0–20 yr, while it continuously decreases for longer periods. The response to volcanic forcing is seen to remain below the equilibrium value for all filter periods. After a volcanic eruption temperatures relax back to normal values within 3–5 yr, while the time between two eruptions is more than 10 yr in 73% of the cases. Therefore, it is reasonable to assume that the response to each eruption is independent of that to the previous or the next eruption. As a result, the response never equilibrates but instead goes to zero for centennial timescales. For later comparison with the reconstructed temperatures, R_{volc} is also computed for the 10-yr smoothed temperature records. This reduces the value for the "unfiltered" data considerably.

Temperature regressions increase, when the spatial sampling is restricted to more northern latitudes. There is also a weak dependence on the season, with somewhat smaller regressions for summer data than for annual-mean (or winter) data. The functional dependence on the filter period does not depend on the geographical coverage or seasonality.

Correlations show that the volcanic forcing indeed explains most variance at annual-decadal timescales, while the solar forcing dominates at interdacadal and longer timescales (Fig. 2b). Correlations between the two forcing factors are low at all timescales. Therefore, the noise levels are higher and correlations between the temperature and each forcing are lower in the volcanic-solar forced runs than in the runs with one forcing only. Correlations (and regressions) are computed for a range of lags. The lag at which the optimum correlation occurs increases for the longer filter periods, with values of 0–5 yr (volcanic forcing) and 5–10 yr (solar forcing).

The equilibrium temperature regression on the solar forcing of 0.2°C per W/m^2 is a factor of two lower than figures given for comparable solar-forced experiments with more comprehensive GCMs (Weber et al., 2004). The low sensitivity is associated with the lack of cloud and moisture radiative feedbacks, which are assumed to affect all timescales in a similar manner. The correlation coefficient (signal-to-noise ratio) in ECBilt is found to be similar to that in GCMs, as ECBilt also underestimates internal climatic variability due to its coarse atmospheric resolution.

5. The temperature response as a function of timescale: proxy-based reconstructions

The regression on the solar forcing is found to be consistent among five of the reconstructed temperature records. For these records R_{sol} has very similar values for low-pass filter periods of 40 and 150 yr, but has a higher value for the 400 yr low-pass filtered data. The results for four of these records, which also have similar amplitudes, are shown in Fig. 3a. The Mo05 record has a similar timescale dependence, but its regression is higher by a factor of two. Two other records show small negative R_{sol} for all filter periods. No attempt was done to correct the regression on the solar forcing for the effect of volcanic forcing on the reconstructed temperatures, as there is some ambiguity in determining the reduced record without a clear response to volcanic eruptions at annual timescales. The model results indicate that the timescale dependence of R_{sol} is not affected by this, although its amplitude may be somewhat overestimated.

In order to examine the response to the solar forcing in more detail, the regression is considered separately over several timescale bands. In the timescale range 40–120 yr, which can be assumed to be reasonably well resolved in a 850-yr record, the regression is consistent among all seven records. Values (in °C per W/m^2) range between 0.17 and 0.34, with an outlier of 0.57 for the Mo05 record, see Table 1. Also in the centennial range (100–300 yr) regressions are fairly consistent. They diverge most in the multi-centennial range, which is certainly not well resolved because of the limited record length. The two tree-ring based records exhibit correlations that are close to zero in this range. The other records, that all have a positive correlation at multi-centennial timescales, have a (much) higher regression at these timescales than at the 40–120 yr timescale range. The ratio between R_{400+yr} and $R_{40-120yr}$ is given in Table 1 as well. It varies between 1.1 and 2.3.

It is already evident that R_{sol} is anomously high at the longest temporal scales by comparing the linear trend in the reconstructed temperature records with those in the forcing factors. The linear trends (over the 1000-1850 AD period) in the solar and volcanic forcing are −0.15 and −0.19 10^{-3} W/m^2, respectively. Assuming that R_{sol} has equilibrated at the interdecadal-centennial range, this implies a temperature decline of 0.03–0.09°C (per 1000 yr). Assuming that R_{volc} is 0.05 at most at multi-centennial timescales, the volcanic forcing adds a negative trend of 0.01°C to this. This is in all cases lower than the linear trend in the reconstructed temperature records. Assuming, on the other hand, that R_{sol} only equilibrates at multi-centennial timescales implies values of 1.1 to 3.8°C per W/m^2 (dividing the linear trend in the temperatures by that in

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the solar forcing). This is difficult to reconcile with the values found for the 40–120 yr range.

The regression on the volcanic forcing is consistent among all seven records, both in its timescale dependence and its amplitude. The maximum R_{volc} occurs for the 20-yr low-pass filtered data, with a continuously decreasing R_{volc} for increasing filter periods. As in the model, temperatures relax back to normal values within 3–5 yr after an eruption so that the system never equilibrates. Very low regressions are found for the unfiltered data. Clearly the reconstructed temperatures do not capture the strong response to volcanic eruptions at annual timescales, which is also evident from the composite response to all individual eruptions. Taking this into account, the timescale dependence of R_{volc} is very similar in the data and in the model simulations.

It is clear from Fig. 3 and Table 1 that the amplitudes of R_{volc} and R_{sol} vary among the seven different records. This may be related to differences in geographical coverage and seasonality of the underlying proxy dataset or differences in calibration methods (Esper et al., 2005). However, the timescale dependence is very similar for all records in the case of R_{volc}. Tentatively, we conclude that this is also true for R_{sol}, considering the interdecadal-centennial timescale range and the trend component separately. As in the model runs, R_{volc} is lower than R_{sol} for all timescales.

The correlations for the reconstructed records are shown in Fig. 3b. Basically there is a similar timescale dependence as in the model, although overall values are lower. This is not surprising, as the reconstructed forcings are used to drive the model runs. Consequently, they optimally fit the simulated temperatures. In the case of the proxy data, both the forcings and the temperatures are only an estimate of the true historical records (Jones and Mann, 2004). The timescale separation between the influence of volcanic and solar forcing is more rigorous in the model than in the data. This is partly due to the lack of a strong volcanic signal at annual timescales in the proxy data. The lag at which the optimum correlation occurs increases for increasing filter periods. Lags are somewhat longer in the data than in the model, ranging over 0–20 yr (volcanic forcing) and 10–20 yr (solar forcing).

6. Discussion and conclusions

The present analysis shows a remarkable agreement between the timescale dependence of the response of simulated and reconstructed temperature records to the external forcing factors. The regression on the volcanic forcing is maximum at decadal timescales, while it goes to zero at the longest temporal scales. The response to the volcanic forcing never equilibrates, as the time interval between two eruptions is typically larger than the dissipation timescale of the system. This implies that R_{volc} is much lower than R_{sol} for all timescales. Although there are some ambiguities, the regression on the solar forcing seems to equilibrate at interdecadal timescales both in the simulated and in the reconstructed data. The reconstructions have a relatively large R_{sol} at multi-centennial timescales, which may indicate that equilibrium is only reached at these timescales. However, this is hard to reconcile with the typical equilibration timescale of the climate system. Therefore, it is assumed that the system indeed equilibrates at interdecadal timescales and other factors play a role at the longest temporal scales.

It is difficult to establish the statistical significance of the present results, as the number of samples is low. Correlations found in the model are high enough to pass a significance test, but correlations are lower in the data. However, the similarity between model-based and data-derived results is a strong indication of their validity. In addition, the seven temperature reconstructions show a reasonable agreement among each other. The main ambiguity is in the timescale dependence and amplitude of the regression on the solar forcing. The best agreement is seen between those reconstructions that have some overlap between the underlying datasets (Cr00, Ma99, Jo98 and Ma03). A similar timescale dependence, but a larger amplitude of R_{sol}, is found in Mo05. The high-frequency component of this record is based on long tree-ring series only. The calibration is done by variance scaling rather than regression on the instrumental record. The timescale separation (between the high-frequency and the low-frequency components) lies at 80 yr (Moberg et al., 2005), a timescale which is well below that at which R_{sol} is found to rise in the present analysis. Finally, the two other tree-ring based reconstructions (Br00 and Es02) deviate at multi-centennial timescales, showing no correlation with the solar forcing. For the interdecadal-centennial range they give consistent results. The estimated equilibrium regression is 0.2–0.35°C per W/m^2, according to all records that are calibrated by regression methods.

The present analysis indicates that trends over the pre-anthropogenic period are relatively large in all reconstructed temperature records, compared to their interdecadal-centennial variability. These trends cannot be explained from the volcanic and solar forcing (Crowley, 2000), as R_{volc}<0.1 and R_{sol}<0.35°C per W/m^2 at the longest temporal scales. The implied combined trend is −0.05 to −0.1°C (per millenium) over the pre-anthropogenic period, which is much lower than the trends of −0.1 to −0.3 °C which are found in the reconstructions (Table 1). Also, the trend of −0.7 °C in Mo05 is larger than that implied by the combined solar and volcanic forcing. Deforestation prior to 1850 AD (Bauer et al., 2003) and orbital forcing (Mann et al., 1999) have been put forward as alternative explanations for these trends.

Orbital forcing arises due to a shift of the longitude of perihelion relative to the moving Vernal Equinox, corresponding to a shift of ca. 17 days over the past millenium. Its amplitude varies with latitude and season (Berger, 1978). The regression was found to be R_{orb}=0.05°C per W/m^2 in the ECBilt model, at a lag of ca. 1 month (Weber and Oerlemans, 2003). This is consistent with a linear response that is far from equilibrium (R much lower than its equilibrium value), as appropriate for this slow modification of the seasonal cycle (forcing period of 1 yr). Orbital forcing implies a quasi-linear trend in the mean temperature over latitudes north of 20° N of 0.2°C (May) to zero (July) to −0.25°C (September), while values are larger for more northern latitudes. As NH temperature reconstructions are biased toward the warm season and high northern latitudes, it is possible that orbital forcing plays a role. The amplitude of the orbital-forced trend is however difficult to establish, as it would depend on the mixture of seasonality and latitudinal location of the records in the underlying proxy network.

Recent work has claimed that temperature reconstructions based on regression

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methods underestimate low-frequency variability (Von Storch et al., 2005). The present results indicate, however, that low-frequency variations in reconstructed records are higher than expected from the reconstructed forcing factors. A better assessment of the true shape of the temperature spectrum is needed to resolve this issue, possibly using low-resolution data to assess the longest timescales (Moberg et al., 2005). The present paper has analysed the forced component of climatic variability, assuming a linear response model. It is possble that internal feedbacks, which are not represented in the ECBilt climate model, strongly modify the response at multi-centennial timescales. This would imply that the relatively high reconstructed trend component is realistic, arising from volcanic and solar forcing alone. Alternatively, orbital forcing or land-use changes may explain this component. Finally, there may be a random coincidence between long-term trends in NH temperatures and the external forcings over the past millenium.

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Table 1. The regression *R* of the reconstructed NH temperatures on the solar forcing for the 40-120 yr band-pass filtered data, the 400-yr low-pass filtered data and the ratio between these two. The bottom line shows for each record the linear trend computed over the pre-anthropogenic period.

	Cr00	Ma99	Jo98	Br00	Es02	Ma03	Mo05
$R_{40-120yr}$ (°C per W/m^2)	0.21	0.33	0.34	0.27	0.17	0.22	0.57
R_{400+yr} (°C per W/m^2)	0.45	0.35	0.51	0.05	−0.03	0.38	1.29
ratio	2.15	1.06	1.49	0.20	−0.18	1.71	2.28
linear trend (°C per 1000 yr)	−0.30	−0.20	−0.33	−0.17	−0.07	−19	−0.71

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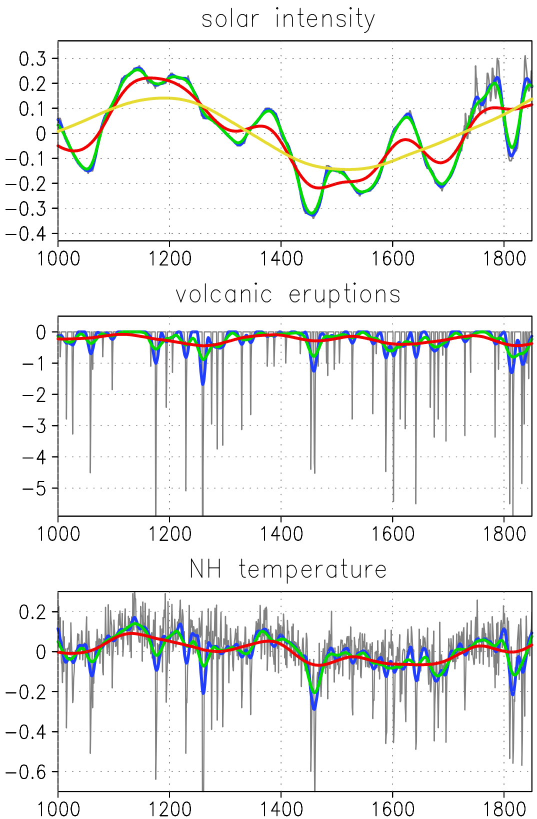

Fig. 1. The radiative forcing due to variations in solar intensity (upper panel), volcanic eruptions (middle panel; both in W/m^2) and the simulated anomalies in NH temperature (in °C) from one of the volcanic-solar forced runs with the ECBilt climate model for the pre-anthropogenic period (time in years AD). Also shown are the smoothed records, using low-pass filter periods of 20 yr (blue), 40 yr (green), 150 yr (red) and 400 yr (yellow; solar forcing only).

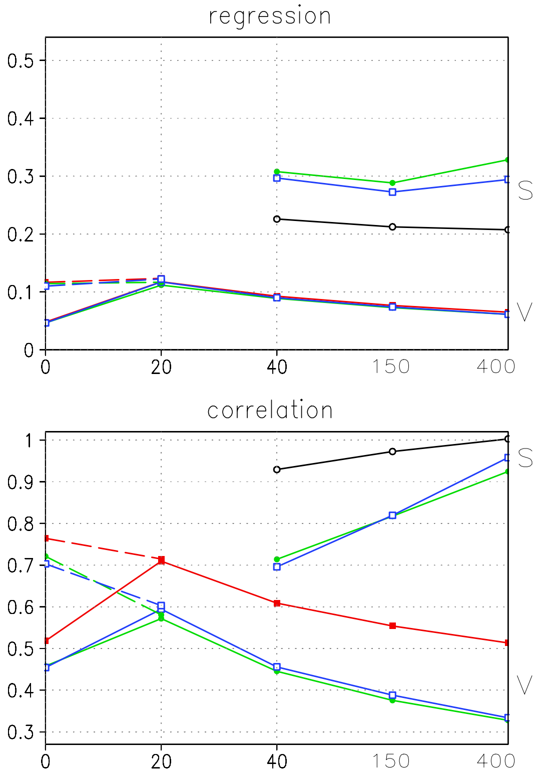

Fig. 2. **(a)** The regression (in °C per W/m^2) for different low-pass filter periods (in yr) of the NH temperatures on the volcanic and solar forcing, indicated by V and S, in the ECBilt experiments driven by solar-volcanic forcing (blue and green lines), solar forcing alone (black line) and volcanic forcing alone (red line), and **(b)** same for the correlation. The temperature data are smoothed with a 10-yr low-pass filter prior to the analysis (dotted lines give results for the unsmoothed data) for later comparison with the proxy-based estimates.

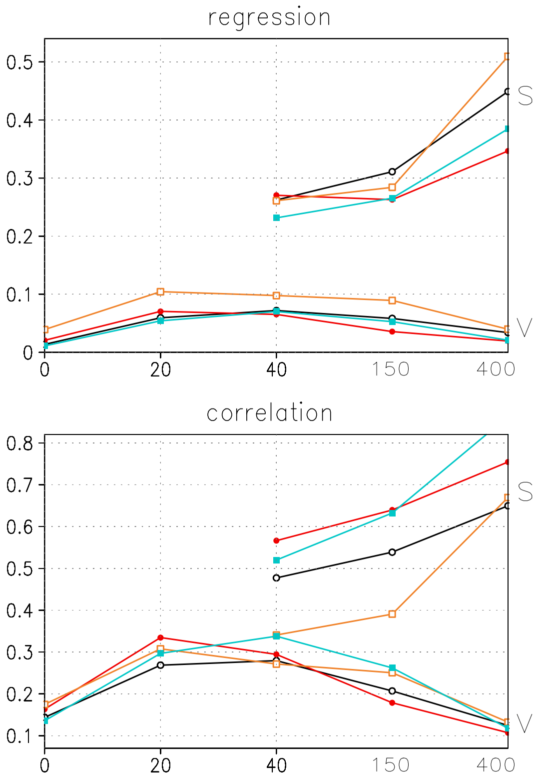

Fig. 3. Same as Fig. 2, but now for the reconstructed temperature records of Jo98 (yellow line), Ma99 (red line), Ma03 (greenblue line) and Cr00 (black line).