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Extending North Atlantic Oscillation reconstructions back to 1500

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Abstract: Monthly (1659–1995) and seasonal (1500–1658) North Atlantic Oscillation (NAO) indices were estimated using instrumental and documentary proxy predictors from Eurasia. Uncertainty estimates were calculated for the reconstructions, and the variability of the 500-year winter NAO has been assessed. The late twentieth century NAO extremes are within the range of variability during earlier centuries.

Keywords: North Atlantic Oscillation, reconstructions, uncertainty ranges, variability.

1. INTRODUCTION

The climate of the North Atlantic and adjacent landmasses exhibits considerable variability on a wide range of time-scales (Hurrell, 1995). Improved understanding of this variability is essential to estimate the likely range of future climate fluctuations and to assess their predictability and the potential impact of anthropogenic forcing (Hurrell *et al*., 2001).

The North Atlantic Oscillation (NAO) is the dominant pattern of atmospheric circulation variability over the North Atlantic basin (van Loon and Rogers, 1978; Wallace and Gutzler, 1981; Barnston and Livezey, 1987; Kushnir and Wallace, 1989; Hurrell, 1995). Its pronounced

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Table 1. Reconstructed North Atlantic Oscillation indices (in chronological order of publication).

Authors	Reconstruction period	Time resolution	Predictors
Appenzeller *et al.* (1998)	1648–1990	Annual (April–March)	Greenland ice accumulation records
Cook *et al.* (1998)	1701–1980	Winter (DJF)	Tree-ring width records from the Eastern United States and Europe
Luterbacher *et al.* (1999)	1675–1990	Monthly	Instrumental station pressure, temperature and precipitation measurements plus documentary proxy data
Cullen *et al.* (2000)	1750–1979	Winter (DJF)	Multiproxy approach using tree-rings, ice cores and instrumental records
Proctor *et al.* (2000)	907–1993	Annual	Stalagmite growth rate from NW Scotland
Cook *et al.* (2001)	1400–1979	Winter (DJFM)	Tree-ring data from eastern North America, Morocco and Europe plus Greenland ice-core data
Rodrigo *et al.* (2001)	1501–1997	Winter (DJF)	Reconstructed precipitation from documentary records from southern Spain (Andalusia)
Glueck and Stockton (2001)	1429–1983	Winter (DJF)	Tree-ring data from Morocco and Finland and GISP2 δ^{18}O annual series and GISP2 snow accumulation record

seasonal variation in position, intensity and shape reflects the strength of the westerlies across the Atlantic basin into Europe (Barnston and Livezey, 1987; Portis *et al.*, 2001).

Better understanding of the NAO variations over the past centuries in comparison to recent times is of interest to paleoclimatology and the climate modelling community (Appenzeller *et al.*, 1998; Luterbacher *et al.*, 1999; Cullen *et al.*, 2000; Jones *et al.*, 2001*a*).

Index timeseries reflecting the state of the NAO can be derived from instrumental data back to the early nineteenth century (Rogers, 1984; Hurrell, 1995; Jones *et al.*, 1997, 2001*b*). NAO indices for earlier periods have been statistically reconstructed based on paleoenvironmental data (Table 1).

Except for Luterbacher *et al.* (1999) none of the existing reconstructions consider a monthly resolution of the annual cycle and seasons other than winter. Here we extend the monthly NAO reconstructions of Luterbacher *et al.* (1999) back to 1659 and add seasonal reconstructions back to 1500 using updated and additional predictors from various sites in western Eurasia. We evaluate the overall reliability of our reconstructions and provide time-dependent uncertainty ranges about each single estimated NAO value. Finally the observed NAO variability towards the end of the twentieth century is discussed in the context of our 500-year reconstructions.

2. DATA AND METHODS

Figure 1 presents the locations of the predictors used for the NAO reconstructions (see Luterbacher *et al.*, 2001 for a description of the data including sources). We used some additional station pressure series from Nothern and Central Europe (Schmith *et al.*, 1997; Auer *et al.*, 2001) (Circles indicate time-varying monthly instrumental time-series of pressure (in blue), temperature and precipitation. Triangles mark

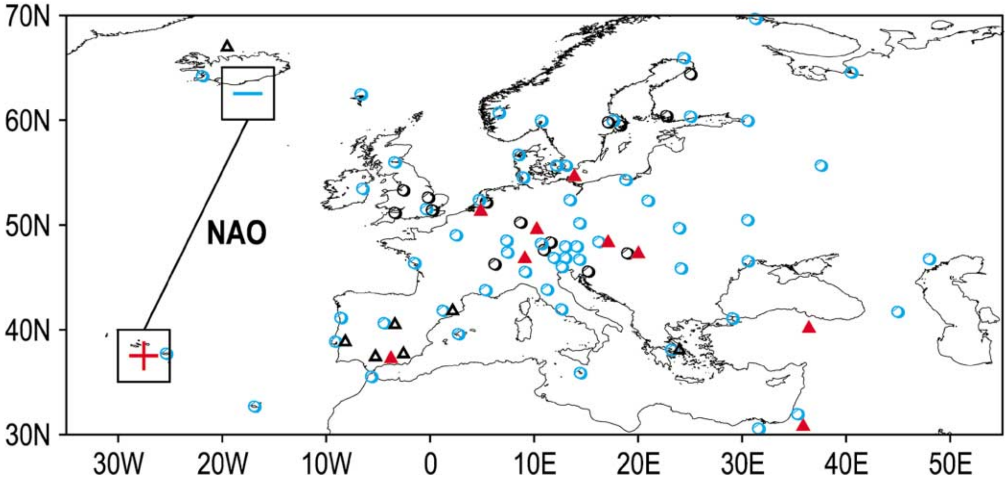

Figure 1. Distribution of the predictors and the defined NAO to be reconstructed (see text for details). Circles mark instrumental data series (pressure (in blue), temperature and precipitation), triangles mark data series mostly estimated from high resolution documentary evidence (see Luterbacher *et al.*, 2001). Red triangles indicate available predictors for parts or the entire pre-1659 period.

indexed time-series that are not direct measurements. These indexed series are estimated from documentary evidence (estimates from observations of cloud cover, snow and ice features as well as phenological and biological observations). Before 1659 only 11 reconstructed climatic indices (temperature, precipitation and sea ice conditions from the western Baltic area, Fig. 2b)—mostly on a seasonal resolution—are available (red triangles). These seasonal predictors based on documentary data were prepared according to the method outlined in Glaser *et al.* (1999). This involved constructing timeseries of categorized intensities of some parameter (e.g. snowcover) based on the pre-instrumental data. The categories used in these timeseries construction were defined in an instrumental period (1901–1960) when the variance of the measured data to the variance of the categorized (indexed) data can be compared.

The NAO index is defined as the standardized (1901–1980) difference between the SLP average of four gridpoints on a $5^\circ \times 5^\circ$ longitude-latitude grid over the Azores and over Iceland (Luterbacher *et al.*, 1999) from the dataset of Trenberth and Paolino (1980, data are available through: http://dss.ucar.edu/datasets/ds010.1/data/).

Over the calibration period (1901–1960), empirical orthogonal functions (EOFs) explaining 90% of the variance of the predictor data were regressed against the NAO index timeseries. The number of winter EOFs retained (Fig. 2b) ranged from 5 (1500–1658) to 14 (20th century). Due to the time-varying database (Figure 2b) of the monthly predictors (period 1659–1995), 310 regression models had to be developed. These regression equations were applied to the corresponding predictor variables for the verification period 1961–1995. For the seasonal reconstructions from 1500 to 1658, the same method was applied but regressing the seasonal mean of the NAO against all the retained seasonal predictor EOFs. In this case 18 series of equations for the different networks were developed.

The skill of each of these 328 models was assessed over 1961–1995 (Figure 2a) by the reduction of error (RE) (Cook *et al.*, 1994) statistic which is the expected proportion of the variance of the predictand, given by the predictor. The range of RE is $(-\infty, +1)$ with a zero value

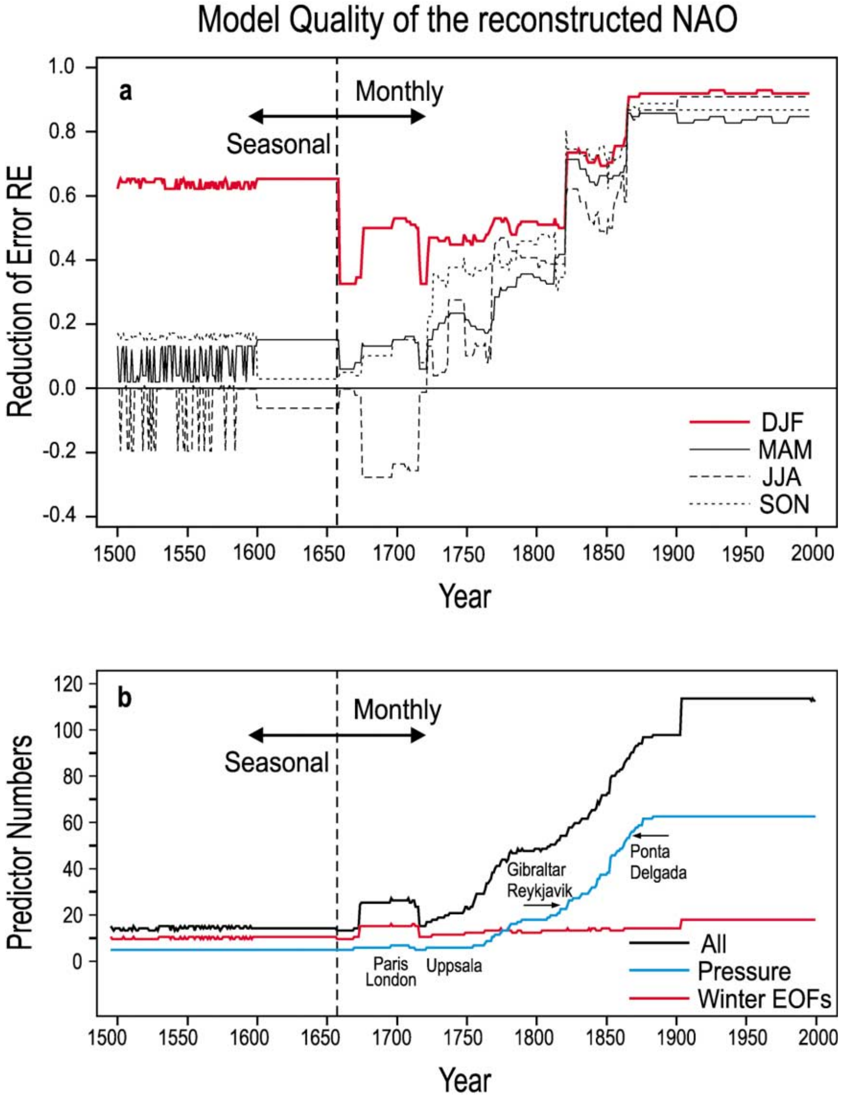

Figure 2. (a) Model performance (RE) for the reconstructed NAO plotted against the time period for which a given statistical model (verification period 1961–1995) was used. (b) Counts of the predictor numbers used for the reconstructions. The black line corresponds to all and the blue line stands for station pressure predictors. The red line indicates the number of winter EOFs retained for the 328 different statistical models.

representing the skill of climatology and increasingly positive RE representing increased regression skill. A RE of +1 is a perfect reconstruction, whereas a RE of −1 is a random guess from a properly fitted distribution and $-1 < \mathrm{RE} < 0$ is better than random choice.

After assessment we recalibrated over 1901–1995 in order to derive monthly (1659–1995) and seasonal (1500–1658) NAO indices. For a detailed mathematical treatment of the reconstruction method, the reader is referred to Jones *et al.* (1999) and Luterbacher *et al.* (2001).

Uncertainty ranges for the predicted winter NAO index values were computed in terms of ± 2 standard error (SE; for calculation see von Storch and Zwiers, 1999; Briffa *et al.*, 2001) using statistics from the final calibration period (1901–1995). SE quantifies the uncertainty in the regression coefficients and the residual variance that is not captured by the reconstructions. Prediction for each time step is obtained by fitting a regression model with the predictor data available for that particular month (season). This allows time-dependent estimations of uncertainty that illustrate how addition or removal of specific predictors affects the strength of the calibration (Briffa *et al.*, 2001; Jones *et al.*, 2001*a*). The residuals of the regression do not show any significant autocorrelation such that the uncertainty ranges were not further adjusted.

3. RESULTS

Quality of the NAO reconstructions

Figure 2a presents the evolution of the seasonal RE in the verification period 1961–1995. The best model performance was obtained for winter with RE values generally higher than 0.3. For the pre-1659 period, the spring, summer and autumn regression models showed only small predictive skill. Meaningful spring, summer and autumn NAO estimates start in the 1720s.

The biggest increases in skill for most of the seasons are due to the inclusion of the pressure series of Paris (1671) and London (1697, Slonesky *et al.*, 2001a), Uppsala (1722, Bergström and Moberg, 2001), Gibraltar and Reykjavik (1821, Jones *et al.*, 1997) and Ponta Delgada (1865, Rogers, 1984) (Figure 2a, b), respectively.

Winter NAO variability 1500–2001 and uncertainty ranges

We focus on winter (DJF), for which the most reliable reconstructions were obtained. Figure 3 shows the winter NAO reconstructions from 1500–1995, and the indices derived from the gridded SLP data of Trenberth and Paolino (1980) from 1996 to 2001. The SE (± 2) of the unfiltered reconstructions is also indicated.

Over the last 500 years strong decadal to interdecadal variations of the NAO are evident. The filtered (nine-point low pass filter) timeseries reveals persistent negative NAO values (weaker westerlies) from the mid-1500s to 1700, in the second part of the eighteenth century and in the middle of the twentieth century. Positive NAO estimates are prevalent at the beginning of the sixteenth and eighteenth centuries, around 1850, the beginning and the last decades of the twentieth century.

Uncertainties decrease with time mostly after 1820 with the inclusion of the station pressure series of Gibraltar and Reykjavik (Figure 2b; Jones *et al.*, 1997) and in 1865 (Ponta Delgada). Before 1821, the proportion of NAO variability not related to the available predictors becomes rather large, so that the possible range of plausible NAO values in these times is hardly constrained.

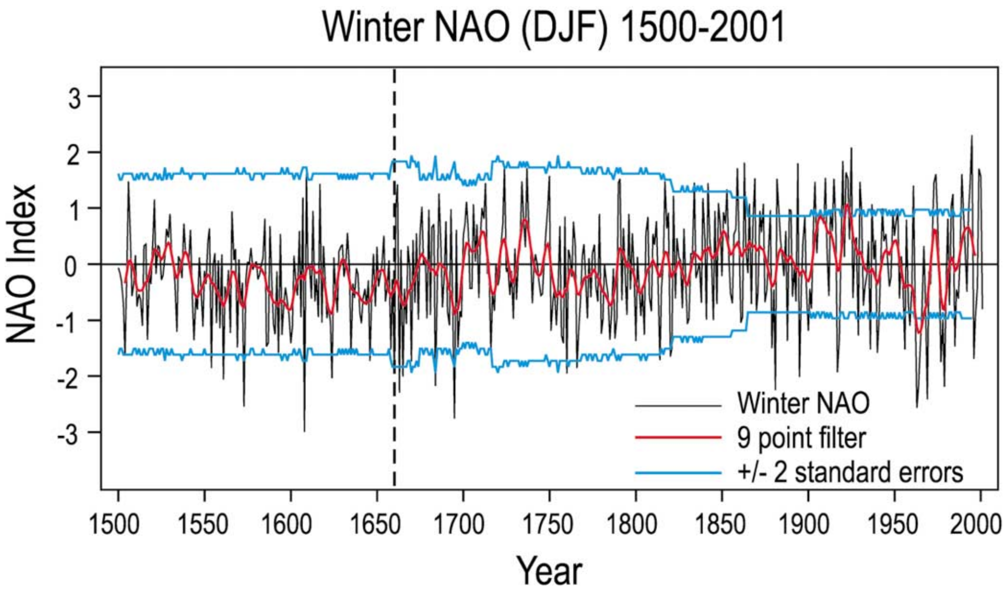

Figure 3. Normalized winter North Atlantic Oscillation index (thin black line) from 1500 to 1995. The 1996–2001 winter values have been added. Values from 1659 to 2001 are DJF means and the pre-1659 estimates are winter (DJF) values. Winters dated by the January. The thick red line is a nine-point low pass filter. The thick blue lines shows the ± 2 SE of the unfiltered reconstructions on either side of the zero line rather than on either side of the reconstructed values.

Correlations among published NAO indices

Table 2 provides significant (95% level) correlations between our winter NAO index and Cook *et al.* (1998, pers. comm.) Cullen *et al.* (2000), Rodrigo *et al.* (2001) and Glueck and Stockton (2001). However, Cullen *et al.* (2000) and our database used several common predictors. Low or even negative correlations were found with Appenzeller *et al.* (1998) and Proctor *et al.* (2000).

4. DISCUSSION

Quality of the reconstructions

The quality of our 500-year reconstructions of the NAO index depends on the season number and the spatial distribution of the predictors (Figure 2).

The generally higher RE values for winter indicate the greater spatial coherence of the atmospheric circulation over the eastern North Atlantic/European area and of climate variables during the cold season. The decrease of the RE from the winter season reconstructions to the monthly estimates (i.e. from 1659 onwards) is outstanding. We found that the reconstructions based on seasonal winter averages

Table 2. Correlation coefficients between the reconstructed winter NAO of this study and other proxy based NAO indices.

	Winter Cook98	Winter Cook01	Winter CullenR4	Winter Glueck01	Winter Rodrigo	Yearly Appenzeller	Yearly Proctor
This study	0.30*	0.57* (0.24*)	0.51*	0.19* (0.02)	0.46*	−0.16	0.01
This study	0.16	0.52*	0.35*	0.05	0.37*	−0.04	−0.12

First line: Cook *et al.* (1998; Cook98) winter (DJF) reconstruction for 1701–1980, Cook *et al.* (2001; Cook01) winter (DJFM) reconstruction for 1659–1979, in brackets (1500–1658); Cullen *et al.* (2000; CullenR4) multiproxy winter reconstruction for 1750–1979; Glueck and Stockton (2001; Glueck01) winter (DJF) reconstructions for 1659–1983, in brackets (1500–1658); Appenzeller *et al.* (1998) yearly (April–March) reconstruction for 1648–1990; Proctor *et al.* (2000) yearly (December–November) reconstruction for 1500–1993; Rodrigo *et al.* (2001) winter (DJF) reconstruction for 1659–1995. No correlation was calculated with Rodrigo *et al.* (2001) for the pre-1659 period since their predictor (Andalusian precipitation) was used for our reconstructions.

Second line as first line, but correlations are calculated only for the pre-calibration period (i.e. before 1901).

*indicate significant correlations (95% level).

sometimes lead to better results (higher REs, smaller SEs) than monthly estimates. This can be related to the smaller seasonal variability of the NAO compared to each single month within the season. Another reason for the high quality seasonal winter reconstructions (1500–1658), is the addition of temperature in the Low countries (present-day Belgium, the Netherlands and Luxembourg, van Engelen *et al.* 2001) and the precipitation from southern Spain (Rodrigo *et al.*, 2001). Since these two important seasonal winter predictors were not available on a monthly resolution, this might explain the discontinuous decline of the RE in Figure 2a in 1659.

For the seasonal reconstructions (pre-1659), validity of the constructed timeseries of categorical (indexed) data (based on documentary evidence) was judged by comparing the spatial correlations of the categorical data during a pre-instrumental and instrumental period. Since these spatial correlations compared favourably between the two periods, this lends credibility to the indexed predictors. However, the indexed predictor can only approximate the variance of measured predictor. Therefore, the skill of the seasonal NAO reconstructions, which are based on measured predictor data from 1901 to 1995, are probably inflated. However, we cannot quantify this effect as the quality of documentary data varies in an unknown way through time.

For the monthly reconstructions (post-1658), instrumental station pressure data are the most important. The station pressure series for Uppsala (Bergström and Moberg, 2001) improved the monthly reconstructions of Luterbacher *et al.* (1999) for the period from 1722 to the late eighteenth century.

Our estimation method minimizes the expected error, i.e. the squared error averaged over many model fits; however, we cannot be sure whether the error in the specific fit is really small or not. Based on the limited evidence of the available data, we provide a best guess, although statements should not be made on the probability of our reconstruction being close to the real values. As long as we do not have better evidence, it is acceptable to use the reconstruction prudently, though revisions will likely be required as soon as new data become available. The only quality control we could do was to perform a cross validation in the twentieth century. Reassuringly, in about 95% of the cases, the true values were included in the uncertainty ranges.

Another benchmark for the reconstruction quality is consistency with data that was not used in the reconstruction. Negative (positive) winter NAO indices are known to be cold (warm) over Eurasia. The extended period of negative NAO values between around 1550 and the beginning of the eighteenth century (Figure 3) are consistent with colder winters in western Russia, the Ukraine (Lyakhov, 1987) and Estonia (Tarand and Nordli, 2001).

Variability of the NAO index

Figure 3 indicates that the high positive NAO values at the beginning and the end of the twentieth century are not unusual in terms of the 500-year reconstructions. Therefore we cannot detect a clear change in the secular trends during the industrial era compared to previous centuries.

The problem of non-stationarity in the NAO teleconnection (both spatially and temporally) with proxy reconstructions is of obvious concern (Luterbacher *et al.*, 1999; Cullen *et al.*, 2000; Schmutz *et al.*, 2000; Cook *et al.*, pers. comm.). Loss of correlation between different estimators of the NAO was considered indicative of non-stationarity of the NAO teleconnection. However, in view of the wide range of uncertainties of the reconstructions, the dissimilarity of two estimates could also reflect the presence of large NAO contributions not related to the predictors. Changes in proxy data might occur through changes in the NAO, but they could also occur through alterations in the influence of the NAO on local climate (Barnett and Jones, 2000; Jones et al., 2001*a*,*b*). The best of the natural proxy reconstructions (in terms of correlation) compared to our NAO estimations was found to be the Cook *et al.* reconstruction (pers. comm.), where information from other geographic regions affected by the NAO (Hurrell, 1995; Hughen *et al.*, 1996; Sutton and Allen, 1997; Portis *et al.*, 2001) was included. Cook *et al.*'s reconstruction mainly shows positive values prior to 1800, whereas our winter NAO estimates imply more negative values. Cook *et al.* find small but stable relationship between their proxy-based reconstruction and our documentary- and instrument-based estimations prior to the nineteenth century implying that there is compatibility between them. The task still remains to merge proxy and documentary proxy and early instrumental data from both sides of the Atlantic Basin that should produce a more coherent picture of the past NAO variability. Cook *et al.* have achieved this for trees and ice cores for winter.

Osborn *et al.* (1999), Slonosky *et al.* (2001b) and Jacobeit *et al.* (2001) report on the probable change of the NAO's influence on surface temperature and precipitation at specific locations. Jones *et al.* (2001*a*) argue that changes in SSTs, are only incorporated to the extent that such variability is reflected in the predictor data used. Using surface air temperature data to estimate our NAO back in time may introduce more persistence in the reconstruction due to links with Atlantic SSTs and winter snow cover, whereas the reconstructions by Cook *et al.* were statistically modelled to match only the observed persistent structure in the SLP-based NAO index. In this sense, climate models can offer a test of the limitations of deducing large-scale circulation indices from different types of local predictors.

5. CONCLUSIONS

Combined long-term early instrumental timeseries and documentary proxy data were used to extend and improve previous monthly NAO indices back to 1659. Seasonal estimates were obtained back to 1500.

Although the verification results illustrate skill in the NAO reconstructions over the last centuries, the uncertainty ranges are rather high before 1820. Even 19 available pressure series in 1820 did not help account for much of the NAO variability, although the inclusion of

Gibraltar and Reykjavik station pressure as predictors in 1821 leads to a significant increase in confidence of the estimates. It is possible that the current uncertainty in the first three centuries of the record can be reduced with the inclusion of early instrumental data (especially pressure series) from Europe and other areas sensitive to the NAO.

Despite their limitations, our reconstructions of past NAO intensities can be taken as current best guess estimates. They reveal that the high positive NAO values at the beginning and the end of the twentieth century are not unusual in terms of the 500-year reconstructions.

We note that we focused on the interannual variability of the NAO. Different conclusions might be drawn with regard to low-frequency variations, since not only the variability but also the SE of our reconstructions become smaller when considering low-pass filtered timeseries.

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The reconstructed NAO values are available from the Climatic Research Unit data homepage http://www.cru.uea.ac.uk/cru/data/

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