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Anthropogenic forcing is a plausible explanation for the observed surface specific humidity trends over the Mediterranean area

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We investigate whether the observed surface specific humidity (q) trends over the Mediterranean region in the period 1974-2003 are consistent with what climate models (CMIP3, CMIP5) simulate as response of q to anthropogenic forcing (Greenhouse gas and sulphate aerosols). The natural (internal) variability is estimated using 6,000-year of pre-industrial control simulations. With the exception of winter, the increases in annual and seasonal q over this region are very unlikely (with less than 1% chance) due to natural (internal) variability or natural forcing alone. Using several climate models and ensemble means, we demonstrate that the large-scale component (spatial-mean trend) of the anthropogenic forcing is detectable (at 1% level) in the annual and seasonal trends of q (expect winter). However, the smaller-scale component (spatial anomalies about the mean trend) of anthropogenic signal is detectable only in warm seasons (spring and summer). We further show that the spread of projected trends based on A1B scenario derived from 13 CMIP3 models encompasses the observed trend of area-averaged q. This may have important implications for the extreme precipitation, potential intensity of cyclones and surface hydrology over the Mediterranean region.

1. Introduction

We here examine to what extent the observed climate trends in the Mediterranean region are already an indication of the conditions described by the climate change scenarios (A1B) at the end of this century. The approach used here has been earlier applied to near-surface temperature [Barkhordarian et al., 2012], precipitation (Barkhordarian et al., revised) and mean sea level pressure [Barkhordarian, 2012]. In the present study we investigate the surface specific humidity (q) trends, which is the principal source for free-troposphere water vapor and has important implications for earth radiation and energy budget and therefore climate sensitivity (Willett et al. [2010] and references therein). It is also one of the key variables in the hydrological cycle and in a possible intensification of precipitation extremes [Allen and Ingram, 2002]. On global scale, near-surface q has been found to have increased significantly by 0.07 g/Kg per decade over the time period 1973-2003 parallel to rising temperature (T), with relative humidity remaining approximately constant (Willett et al. [2008]). The spread of 20th century runs of CMIP3 models encapsulates the observed changes (1974-1999) in the global mean, Northern Hemisphere extratropical mean (20°N – 70°N) and tropical mean [Willett et al., 2010]. Large scale averages over all seasons show the greatest q increase in the extratropical Northern Hemisphere, coincident with the largest increase in T [Willett et al., 2010]. At the global scale the rise in surface q is attributable mainly to anthropogenic GHG forcing [Willett et al., 2007]. However, regional feedbacks and local forcings can lead to very different climate changes in different parts of the world. Successful adaptation will necessitate increased understating of such regional differences [Stott et al., 2010]. Here we analyze changes of q over the Mediterranean

region, among the regions likely to experience major climatic changes in the 21st century as a result of the global increase in GHG concentrations [Giorgi , 2006]. Over the southern European land area that is part of the Mediterranean region, moistening (1973-1999) is found to be very close to the Clausius-Clapeyron scaling of saturated specific humidity ($\sim$7% K^{-1}) and high correlations (0.85) are found between q and T [Willett et al., 2010]. In this study we investigate for the first time whether the observed trends in q in the Mediterranean are consistent with climate change projections.

1.1. Data and Method

The Mediterranean area is defined here as the region from 30°N to 55°N and 10°W to 40°E. Observed humidity data are from HadCRUH [Willett et al., 2008]: a quality controlled and homogenized land and marine monthly mean anomaly 5° by 5° gridded data set of surface specific humidity (q) available for the period 1973-2003. Global simulations with coupled AOGCMs, provided through the WCRP CMIP3 [Meehl et al., 2007] and CMIP5 [Taylor et al., 2012] are used to estimate the response of humidity to different forcing (Supplementary Tables 1 and 2).

We follow the same approach as presented in [Barkhordarian et al., 2012]. In the first step we assess whether the observed changes in q is compatible with an undisturbed stationary climate and, if not, whether they are consistent with the modelled response to anthropogenic and natural forcing. Comparison is carried out using un-centred correlation statistics (Supplementary Eq.1). We also use un-centred and centred regression indices (Supplementary Eqs. 2 and 3), which, unlike the correlation statistics, also includes information about the relative magnitude of the observed and model simulated trend

patterns. The un-centred statistic measures the similarity of two patterns without removal of the spatial mean, whereas the centred statistic refers to the similarity of deviation patterns where the spatial mean has been subtracted [Santer et al., 1995].

The response to external forcing is defined either as the simulated trends in the observational period or as the trend simulated in future climate simulations. On the one hand we use transient simulations derived from CMIP3 and CMIP5 archive over the period 1974 to 2003. We consider 3 groups of simulations. One group (GS) includes 11 simulations conducted with 6 models forced with estimates of historical anthropogenic forcing only, including greenhouse gases and sulphate aerosols. A second group (GHG) includes 24 simulations conducted with 7 models forced with historical well-mixed greenhouse gases. A third group (NAT) includes 24 simulations conducted with 7 models forced with natural external forcing only; including volcanic aerosols and solar irradiance change.In the multi-model ensembles mean of 7 models (24 GHG (NAT) simulations), the internal variability in reduced by about 90 percent, which leads to increasing the signal-to-noise ratio in estimated signal patterns (Supplementary material). On the other hand, we use time-slice climate change experiments and define the anthropogenic climate change signal (GS) as the difference between the last decades of the 21st century (2071-2100, SRES A1B scenario) and the reference climatology (1961-1990). We assume a linear development in multi-decadal running means from 1961-2100 and the resulting signal is scaled to change per year [Bhend and von Storch, 2008] (For details see supplementary Sect 1 and Table 2).

2. Results

2.1. Detection of externally forced changes

Observations show an upward trend in q in all seasons over the Mediterranean region, with maximum increase in summer and minimum in winter (Fig. 1). The area mean q increases by 0.04, 0.12, 0.29 and 0.13 g/Kg per decade over the period 1974-2003 in DJF, MAM, JJA and SON, respectively. In contrast to specific humidity, relative humidity remains approximately constant. The observed record shows a -0.1, -0.5, -0.5 and +0.03 %/decade changes in DJF, MAM, JJA and SON, respectively, which could be solely explained by internal variability (with 1% risk of error). High positive time correlations between the observed surface temperature (HadCRUT3v; Brohan et al. [2006]) and surface humidity changes, correlation coefficient being +0.77, +0.92, +0.94 and +0.90 in DJF, MAM, JJA and SON, respectively, is suggesting that temperature (T) and humidity (q) are acting in concert. This is also suggested by Peterson et al. [2011], who indicates that the ratio of latent and sensible heat content of surface atmosphere energy is positive over the Mediterranean land area, pointing to the concert behavior of q and T. Following the Clausius-Clapeyron relation, changes in q with increasing T should be largest in warm seasons if RH remains approximately constant. This is consistent with finding maximum trend of q in summer and higher T-q correlation in warm seasons. Furthermore, in low latitudes and warm seasons, where the mean temperature is warmest, latent heat is the dominant component in the total atmospheric energy budget at surface [Peterson et al., 2011], which leads to faster increase in q with changing temperature.

The increase in q is pronounced throughout the region, although small areas of decreasing q are notable in DJF and MAM (See Supplementary Fig. 1). Increasing trends in

q have been observed and also simulated in response to GS and GHG forcing, while the observed positive trends are distinct from the predicted response to natural forcing (NAT) (Fig. 2).The natural response is likely dominated by the effect of volcanoes, which induce a cooling for a few years after the eruptions, and which in turn decreases q [Santer et al., 2007]. Over land area, where moisture sources are restricted, the response of q to GS forcing are found to be somewhat smaller than over the sea where moisture supplies are not limited (Supplementary Fig. 1).

Here, we assess whether the observed trend of q can be due to natural (internal) variability alone. This is achieved by testing the null hypothesis H_0=zero trend. To do so, annual and seasonal observed trends are compared with estimated natural (internal) variability derived from control integrations of CMIP3 climate models, which are pre-industrial control experiments with all forcing held constant. (The number of years used from the control integration of each model is presented in supplementary Table 2). From 6,000-year control runs we draw 194 non-overlapping 30-year segments to estimate natural (internal) variability of 30-year trends. Rejecting the null hypothesis (H_0) at 98% significant level will indicate that there is less than 1% chance (one-sided test) that natural (internal) variability rather than external drivers are responsible for the observed changes. The results plotted as red whiskers in Fig. 1 indicate that no single sample of 194 segments yield a positive trend of specific humidity as strong as that observed during the period 1974-2003, in all seasons except winter. From this we conclude that it is unlikely that the observed positive trends of q can be attributed to natural (internal) variability alone, and thus that externally forced changes are significantly detectable (with less than 1% risk)

in all seasons except winter. The lack of winter season detection of a q trend is because the observed trend is too small (0.04 g/kg per decade); in addition the internal variability term is higher given the higher cold season temperature variance [Barkhordarian et al., 2012].

Having established that externally forced changes are detectable in the observed record of q, we determine in a second step whether these results are consistent with what climate models describe as expected response to anthropogenic (GS, GHG) or natural (NAT) forcing. The distribution of regression indices is assessed from fits of regression models (Supplementary Eqs. 2 and 3) to 194 non-overlapping control run segments derived from 6,000 year control simulations. The quantiles of the centered (R) and un-centred (UR) regression indices of 194 control run segments (O_i in Supplementary Eqs. 2 and 3) onto the all projected and historical anthropogenic and natural climate change signal patterns (P_i in Supplementary Eqs. 2 and 3) are used to test the H_d hypothesis that the distribution of regression indices does not include "zero" but includes "1". When there is insufficient evidence to reject H_d, the consistency of changes to the respective forcing is claimed.

2.1.1. Consistency of spatially averaged observed and climate change signal patterns

In spring (MAM) the uncentered correlation (UC) between the observed trend pattern and 13 climate change projections are in the range of [0.70, 0.84]. The correlation with the historical GS response pattern is 0.70 and with the historical GHG response pattern the correlation is 0.88 (Supplementary Table 3). These correlations are larger than the

95th %tile distribution of correlation coefficients of 194 patterns of unforced trends with anthropogenic signal patterns. However, the highest positive correlations are found in summer, correlation coefficients being in the range of [0.82, 0.92] with 13 projections, 0.87 with the GS response pattern and 0.91 with the GHG response pattern. The correlation between the anthropogenic signal patterns with the 194 patterns of unforced trends is never as high as with observed trends (significant at 98% level). Also in autumn the observed trend patterns show a high positive correlation with anthropogenic signal patterns; correlations are in the range of [0.77, 0.86] with 13 projections, 0.85 with the GS response pattern and 0.74 with the GHG response pattern. These coefficients are also found to be larger than the 95th %tile distribution of control run correlations. Indeed such correspondence can hardly be expected to occur if the effect of anthropogenic forcing were not present in the observed record (with the probability of error of less than 2.5% in spring and autumn, and 1% in summer). However, the observed record shows a zero or negative correlation with natural-forcing-only simulations (NAT), correlations 0.0, -0.29, 0.0 and 0.1 in DJF, MAM, JJA and SON, respectively, indicating that the observed q trends are distinct from the predicted response to natural forcing (NAT).

Figure 2 (left column) displays the uncentered regression indices (UR) and the 98th %tile uncertainty range, derived from fits of the regression model (Supplementary Eq.2) to 194 independent control run segments based on 6,000-year control integrations. As shown in Fig. 2 (left column) in spring, summer and autumn the uncertainty interval of uncentered regression indices (UR) does not include zero , but includes unity in the case of all the 13 projections (black bars), the simulated GS signal patterns (green bars)

and the simulated GHG signal patterns (blue bars). Therefore, as the regression indices within all the 15-anthropogenic signal patterns are significantly greater than zero and compatible with a value of unity, we conclude that the large-scale component of anthropogenic (GS, GHG) signal is detectable in the observed positive seasonal trends of surface specific humidity at 98% significant level in all seasons, except winter. Natural-forcing-only simulations (volcanic aerosols and solar irradiance change, NAT) display near zero or negative regression indices and large uncertainty ranges in all seasons, indicating an opposite response (decreasing q) to the observations. The uncertainty range derived from the NAT simulations is considerably larger than the range estimated for GS or GHG forcing (Fig. 2, left column). This could imply that the signal is dominated by the GHG (GS) response, which makes it difficult to separate the smaller NAT contribution from the internal climate variability.

2.1.2. Consistency of observed and climate change signal anomaly patterns

As shown in Fig. 2 (right column), when removing the area mean change and comparing the anomaly patterns, the small-scale component (spatial anomalies about the spatial mean trend) of GS signal is detectable in observed data only in 4 out of 13 projections in spring, in 5 projections in summer and 3 projections in autumn. For the rest of the models the regression indices are either negative or not significantly different from zero. It is notable that in spring and summer the detection of the historical GHG forcing in the observed record is robust against the removal of the area mean change. As shown in Fig. 2 (right column) the uncertainty range of centred regression indices (R) in spring and summer are inconsistent with "zero" and are also not significantly different from "1",

indicating the detectability of the anomaly component of GHG forcing at 98% significant level. In spring both historical GHG and NAT regression coefficients are found to be inconsistent with "zero", suggesting a detectable response to both historical GHG and natural forcing (NAT). The fact that the detailed spatial signature in response to anthropogenic (GHG, GS) forcing is hard to detect in observed anomaly patterns may be due to three factors. First, the influence of small-scale phenomena is not average out as at spatial-mean scale. This leads to a decrease in the signal-to-noise ratio of externally forced changes [Zwiers and Zhang, 2003]. Second, spatial representativeness of the observation together with model errors at grid-box-scale play important roles in the similarity of anomaly patterns. Third, local forcing such as the emission of aerosols related to industry or traffic and/or forcing from land-use changes are locally more important [Stott et al., 2010].

3. Conclusions

The influence of anthropogenic (GHG, GS) forcing is detectable in annual and seasonal trends (expect for winter) in the spatial-mean of q; these annual and seasonal (except in winter) increasing trends of q in the 1974-2003 over the region cannot be explained by natural (internal) variability or natural forcing alone. However, the regional pattern of trends (deviations from the spatial mean) contradicts the null hypothesis of natural variability or natural forcing only in warm seasons (spring, summer). We further show that the observed trends of q are within the range of changes described by 13 climate change projections based on A1B scenario; therefore we conclude that observed upward trend of surface specific humidity serves as an illustration of plausible future change in

this region [Barkhordarian et al., 2012]. This may have important implications for the extreme precipitation [Allen and Ingram, 2002], potential intensity of cyclones, surface hydrology [Gedney et al., 2006] and human heat stress Willett and Sherwood [2012].

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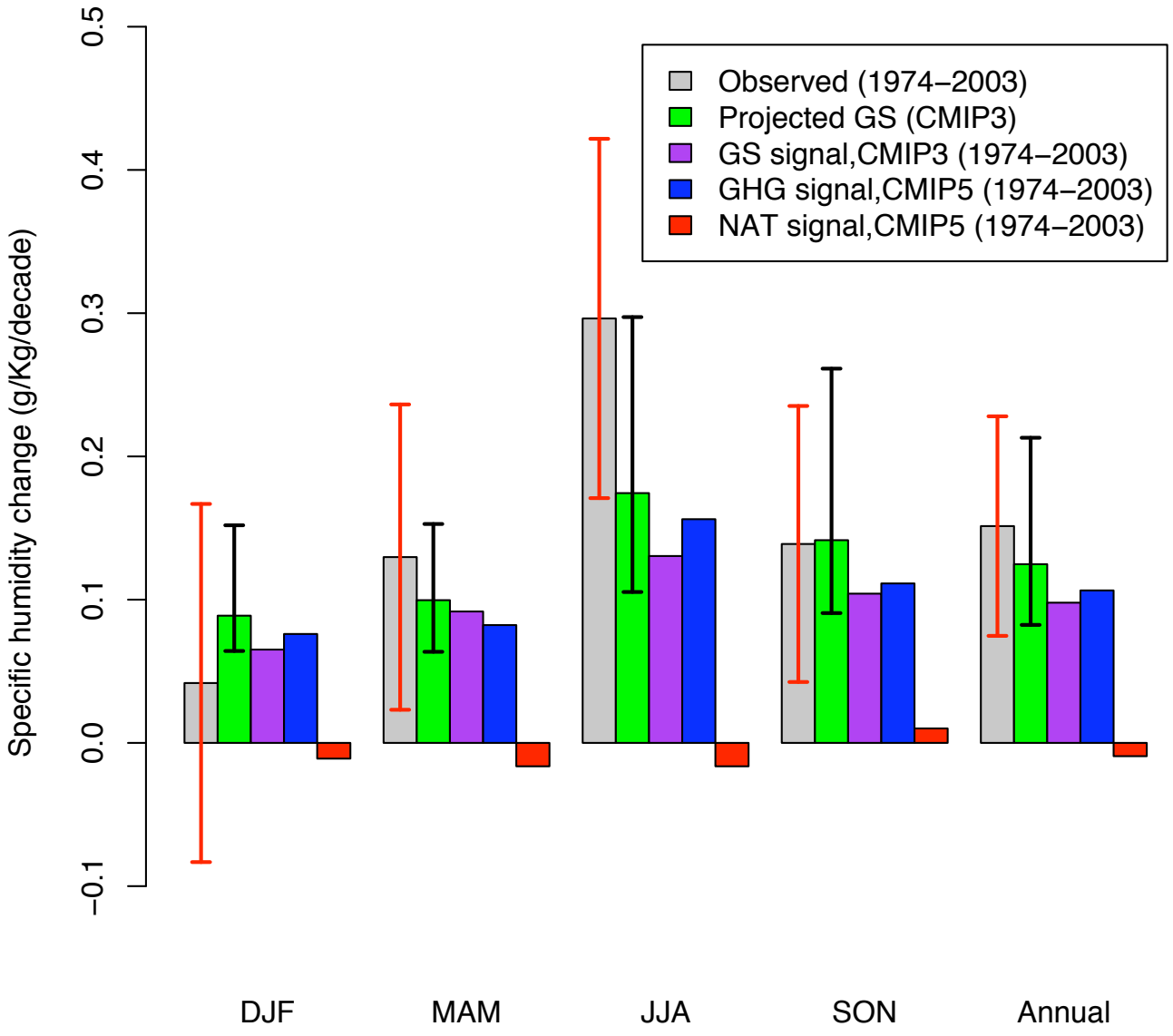

Figure 1. Observed area mean changes of surface specific humidity over the period 1974-2003 (grey bars) in comparison with 13 climate change projections estimated from time slices experiment, SRES A1B scenario (green bars), the ensembles mean of 11 historical GS forcing only simulations (purple bars), the ensembles mean of 24 historical GHG forcing only simulations (blue bars) and the ensembles mean of 24 historical natural forcing only simulations (red bars). The black whiskers indicate the spread of trends of 13 projections. The red whiskers indicate the 98th %tile uncertainty range of observed trends, derived from 6,000-year control runs. Units are g/Kg per Decade

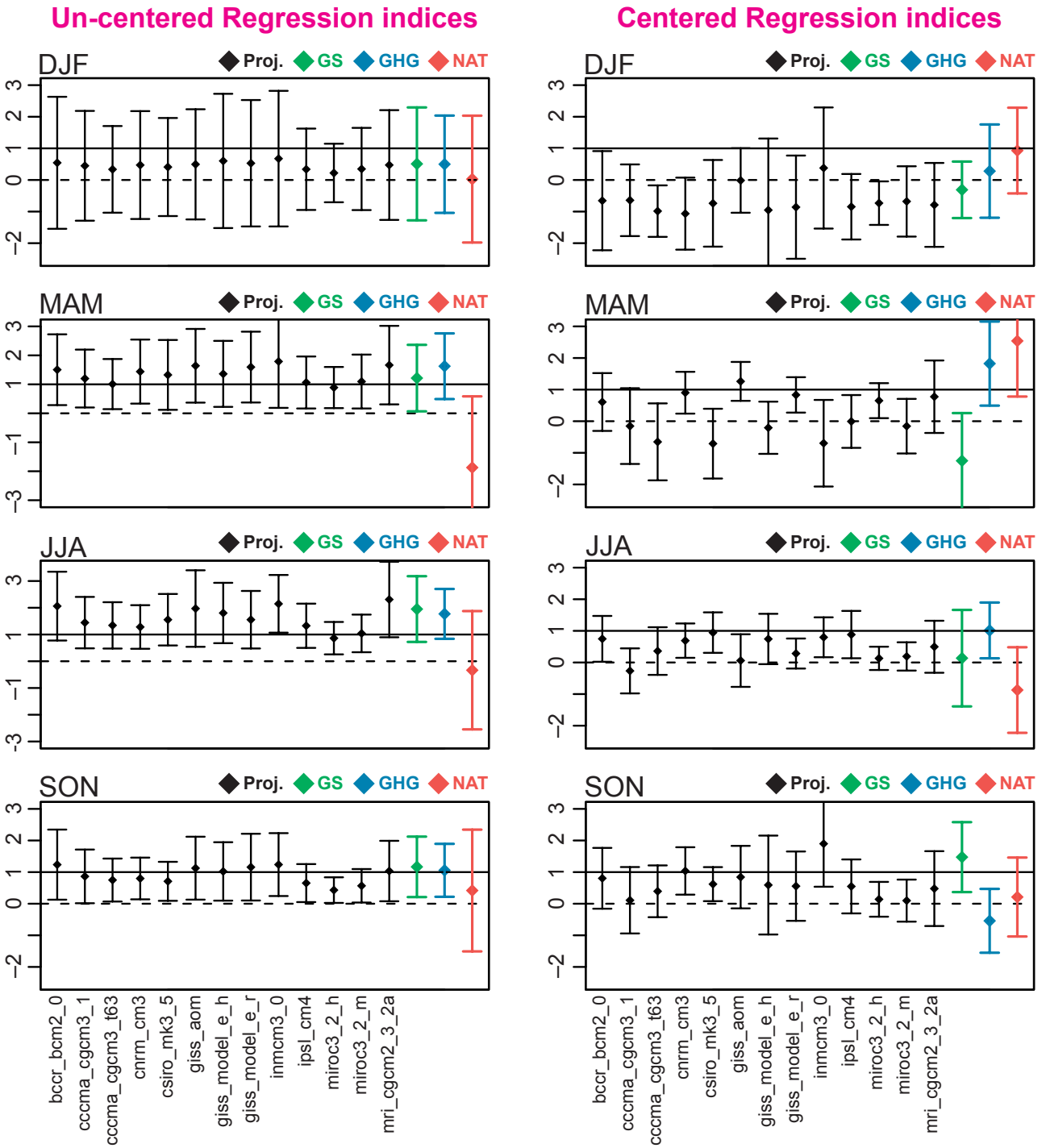

Figure 2. Seasonal un-centred regression indices (left column) and centred regression indices (right column) of observed specific humidity changes against the 13 climate change signal patterns base on SRES A1B scenario (black bars), against the simulated GS signal (green bars), the GHG signal (blue bars), and the NAT signal (red bars). The 95th %tile uncertainty range of regression indices is derived from 6,000-year pre-industrial control simulations.