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Validation of precipitation events in a regional climate model simulation using methods from complex systems theory

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With 5 Figures

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Summary

[1] We show that daily precipitation is characterized by a behaviour regulated by power laws. Both for the frequency distribution of both event intensity and drought duration. In this respect, precipitation appears to follow self-organized criticality laws, much as other geophysical phenomena such as avalanches and earthquakes. We use this feature to validate the simulation of daily precipitation events in a multi-decadal regional climate model experiment for the European region. Our focus is on the Italian peninsula and we show that both the model results and the station observations for daily precipitation intensity and drought length follow power laws with comparable values of the relevant parameters. We suggest that complex systems theory can provide useful tools for the validation of precipitation statistics in climate models.

1. Introduction

Nested regional climate models (RCMs) have been extensively used over the last decade to produce information on the regional response to global warming (Giorgi and Mearns, 1999). In particular, because of their relatively high horizontal resolution, RCMs can be especially useful in the simulation of daily precipitation events, including extremes (Huntingford et al., 2002). It is thus important to assess the performance of RCMs, and in fact of climate models in general, to simulate different statistics of daily precipitation.

A new way to approach the issue of validation of simulated precipitation events is offered by the observation that rain can be considered as a phenomenon that follows self-organized criticality laws (Peters et al., 2002). In this context, precipitation is essentially viewed as a relaxation non-equilibrium process of characteristics similar to those of earthquakes and avalanches. Such phenomena are driven by a slow energy input which is released via intermittent bursts of large activity. In the case of precipitation, energy is stored in the atmosphere in the form of water vapor evaporated from the ocean and land surface and it is released when the water vapor condenses and precipitates. As discussed in Peters and Kristensen, self-organised criticality refers to the tendency of slow driven non-equilibrium systems to evolve into a state of scale free behaviour. Among other behaviours, it gives rise to power law frequency distributions of the intensity of events and of the length of time intervals between events. This power law is of the type

$$f \approx x^{-\alpha} \tag{1}$$

where f is the frequency distribution and x is in our case the intensity of precipitation events or the length of dry periods between events (droughts). For example, analysing data at one-minute resolution Peters et al. (2002) showed that this power law is followed by precipitation observations, with the coefficient α being 1.36 and 1.42 for precipitation intensity and drought length, respectively. More recently, Bove et al. (2004) found power law distributions of precipitation intensity and drought length in fifteen minute resolution rain gauge data, with coefficients of 2.35 and 2.1 for intensity and drought, respectively.

The evidence is thus rising that observed precipitation exhibits self-organized criticalityomplexity-like behaviour, at least at fine temporal scales. This can therefore be a useful feature for the validation of precipitation simulated by climate models. Following this premise, in this work we analyse the criticality-like behaviour of daily precipitation events in a regional climate simulation for the European region and validate it against observed daily precipitation data at a number of gauge stations distributed throughout the Italian peninsula. In this approach, self-organized criticality concepts can thus provide a tool for improving our confidence in the ability of climate models to simulate the precipitation process.

2. Model experiment and observations

The experiment analysed here was conducted as part of the project PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risk and Effects, Christensen et al. (2002)). The simulation was completed with the regional climate model RegCM described by Giorgi et al. (1993a, b) and Pal et al. (2000), and covers the 30-year period of 1961–1990. The lateral boundary conditions necessary to run the RegCM are obtained from a global time-slice simulation carried out with the Hadley Centre atmospheric model HadAM3H (Pope et al., 2000) using observed sea surface temperatures for 1961–1990. The RegCM domain covers the entire European region at a horizontal grid point spacing of 50 km, however the area of interest in this work is limited to the Italian Peninsula. For this area Fig. 1 shows both the model land grid points and the location of 67 observing stations used for validation of the model results. These stations were chosen from the Italian Weather Service network and include daily precipitation data for the 1961–1990 period; with a sensitivity of 1 mm. The data are collected from standard pluviometers. From Fig. 1 it can be seen that a subset of stations are outside the land-mask of the model, particularly

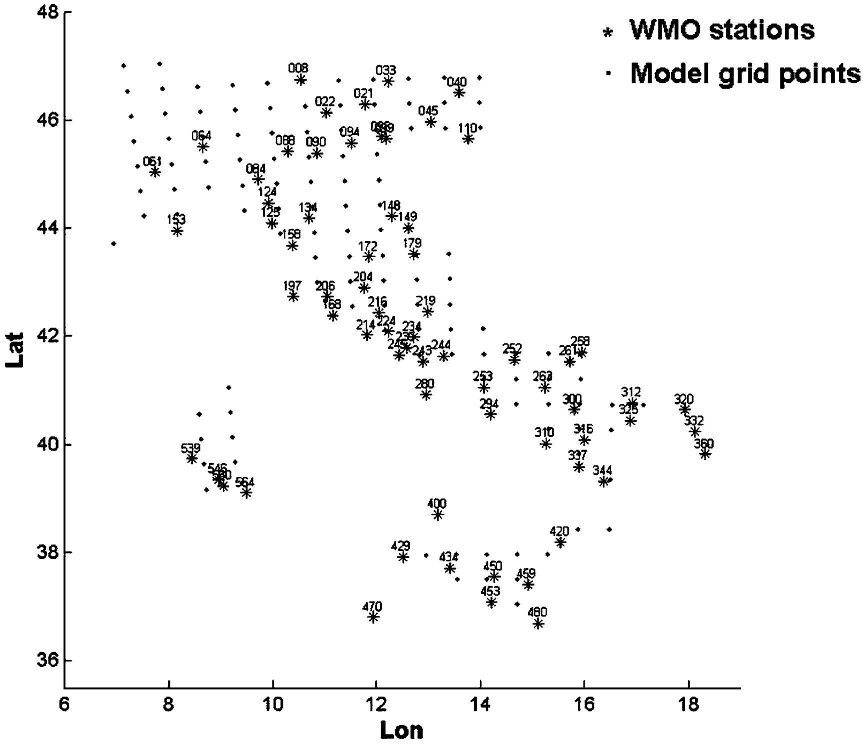


Fig. 1. Weather stations (with their WMO code) and model grid points (land only) considered in this study

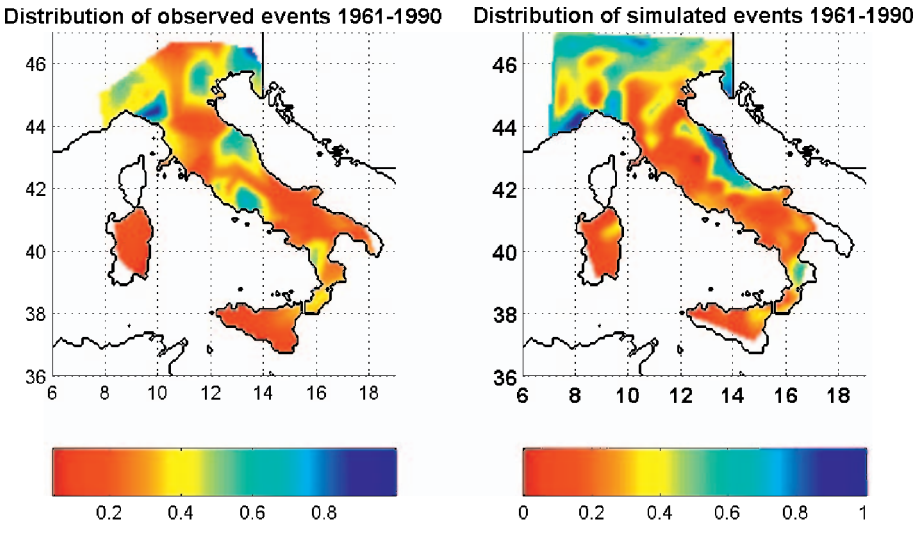
in south-eastern Italy. The HadAM3H fields and RegCM experiment over the full domain are analysed by Giorgi et al. (2004), and the reader is referred to that paper for more details.

3. Results

As an illustrative example of how the model simulates the intensity of precipitation events over the interest area, particularly for high intensities, Fig. 2 shows the simulated and observed spatial distribution of the number of daily precipitation events with intensity greater than 30 mm for the full 1961–1990 period. Both simulated and observed data are interpolated onto a common grid covering the Italian territory (except for the Apulia region were the model does not have any land grid points) using a linear interpolation procedure and are normalized by their maximum value to facilitate the intercomparison. The comparison shows that the model is capable of reproducing many aspects of the observed spatial distribution of high intensity events, as forced by topographical and geomorphological features. The Gulf of Genoa and the Ligurian coasts are centers of strong cyclogenesis and intense precipitation episodes (Buzzi et al., 2000), and the model captures this feature. Also captured are areas of maximum frequency of intense events over the central Adriatic coastal regions and the Calabria region in southern Italy. An observed maximum over the central Tyrrenean coasts is underestimated. Considering the different distribution of model grid points and observing stations, Fig. 2 shows a generally good agreement between observed and simulated geographical distribution of heavy precipitation events.

Figure 3 shows the seasonal distribution of observed (all stations) and simulated (all nearest grid points to the station locations) number of heavy precipitation events. A pronounced maximum of such events occurs in late summer and fall, and the model reproduces well this prominent feature. However, the model simulates a secondary maximum in frequency of intense events during the spring, which does not appear in the observations. Overall the number of simulated high intensity events is within 20–50% of observations in all months. A further analysis (not shown here for brevity) indicated a dependence of the model bias in simulating intense events on topography, with a prevailing overestimate at low elevations and underestimate at high elevations. This is likely tied to the relatively coarse model representation of topographical features of the Italian peninsula.

We now turn our attention to the validation of daily rain events using concepts from criticality theory. As discussed in Section 1, criticality in a dynamical system results in power law distributions for the intensity of events and for the distance between events (in our case the number of consecutive dry days, or drought length). To examine whether both the daily observations and the simulated fields follow criticality laws, Fig. 4 presents examples of distribution of precipitation intensity and drought length at three stations and corresponding nearest grid points. The data are



Distribution of observed events 1961-1990

Distribution of simulated events 1961-1990

Fig. 2. Comparison between observed (left) and simulated (right) frequency of events with intensity greater than 30 mm over the Italian peninsula (see text). Units are normalized to the maximum number of events, which is 389 for the observations and 448 for the model

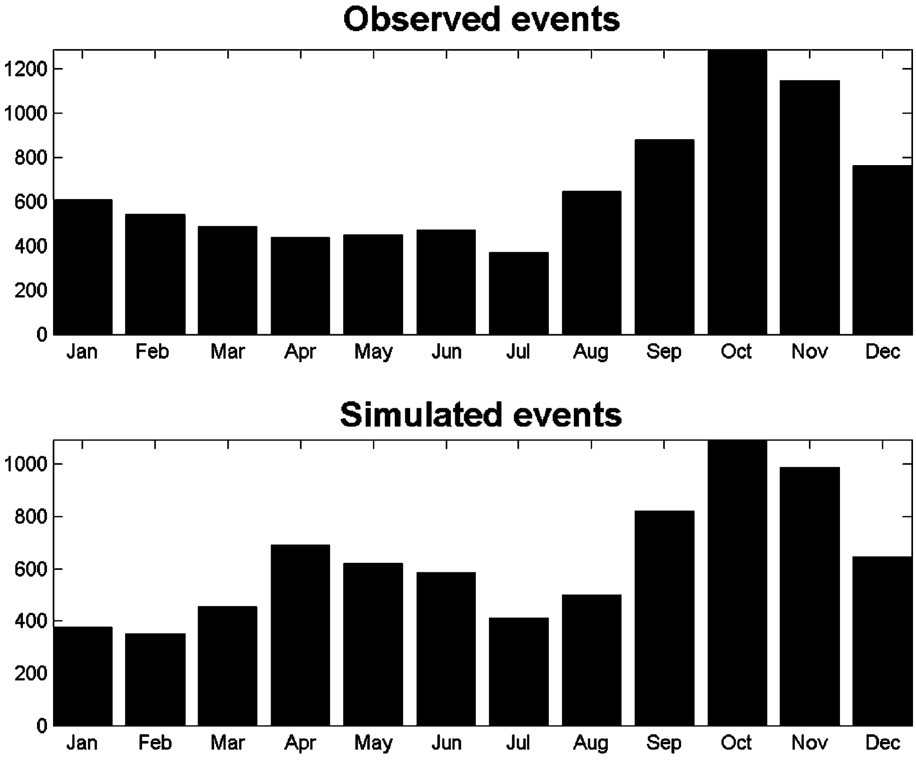


Fig. 3. Observed (top panel) and simulated (bottom panel) number of events with daily precipitation greater than 30 mm for different months of the year. The number is calculated by adding over all observing stations (or grid points closest to the observing stations for the simulated data) and all years in the 1961–1990 period

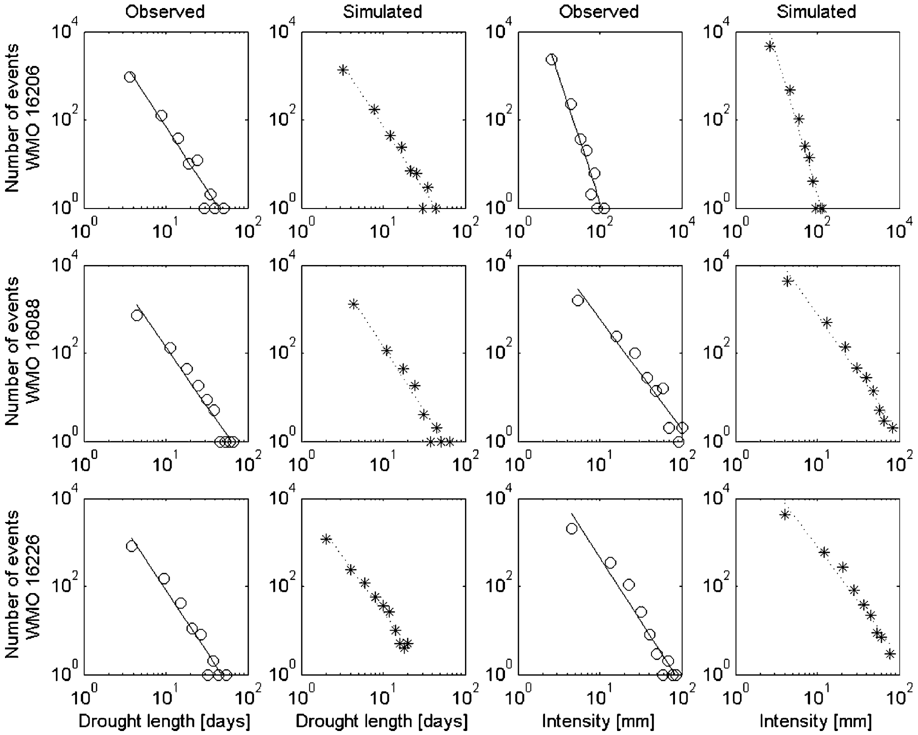


Fig. 4. Number density of rain events and drought duration for the observations (circles) and the simulation (asterisks) at three weather stations, (WMO 16206 Grosseto, WMO 16088 Brescia-Ghedi, 16216 Viterbo) and nearest model grid-points on a double logarithmic scale. Also shown are the best-fit lines to the data

presented on logarithmic scales, where a straight line indicates a power law function. Although a greater range of intensities and drought durations would be desirable to better identify power laws, we can see that both the observed and simulated rainfall data and drought events follow quite closely power-law distributions with a difference in the magnitude of exponents between model and

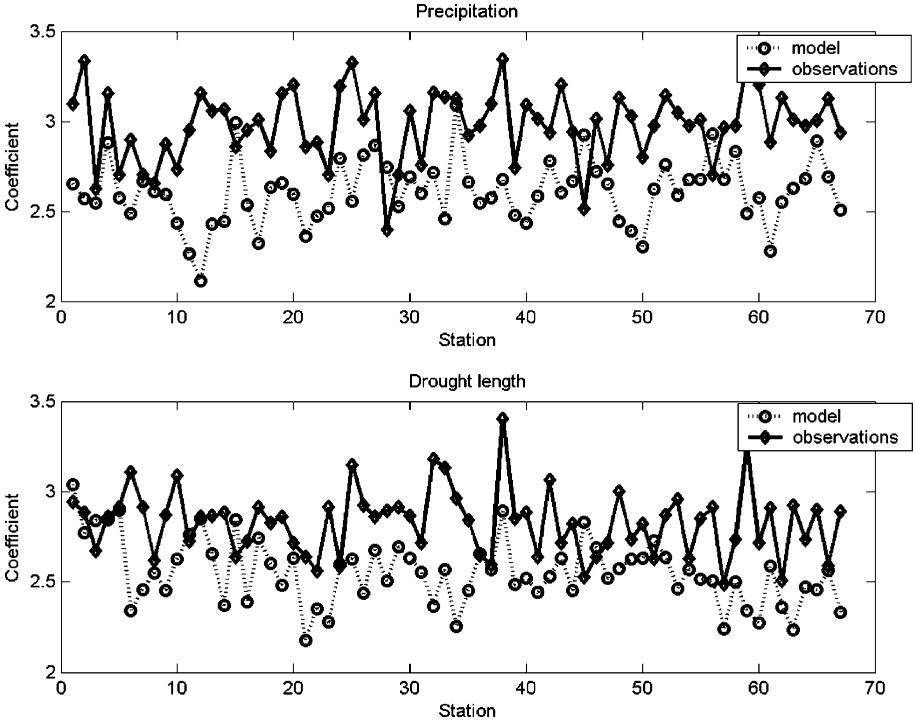


Fig. 5. Precipitation (top) and drought length (bottom) coefficients of the power distributions for all observing stations and corresponding closest model grid points

observations lower than *0.5* for both drought length and rain intensity.

In Fig. 5 the drought and rain intensity exponents of the power law distributions are displayed for all observation stations and for the corresponding closest model grid points. These exponents were calculated as the slope of the best linear fit of data reported on log–log plots similar to those of Fig. 4. The exponents for observed precipitation intensity vary between 2 and 3, with an average value of 2.61. The observed drought exponents vary approximately in the same range, but with the smaller average value of 2.55. These exponent values are greater than those found by Peters et al. (2002) but it should be recalled that their study analyzed data series at a different location (Baltic coast); moreover our results are comparable to those of Bove et al. (2004) who used data at much finer temporal scales but in the same geographical area (Italy). This consideration, along with the variability across stations of the exponents (see Fig. 5) suggest that the values of the exponents in the power law distributions may be dependent on the climatic regimes that determine the time series. This can be expected in view of the differences in the fundamental mechanisms that for example lead to tropical convective precipitation vs. mid-latitude synoptic scale precipitation.

Both for precipitation intensity and drought duration, the simulation exhibits generally larger magnitudes of exponents than observed, in the range of 2.5 to 3.5, and with grid point averages of 2.97 and 2.83, respectively. However, at a number of stations the exponents for the observations and the simulation are quite close to each other. Also, in agreement with observations (and with previous studies) the magnitude of the exponent is greater for drought than for intensity. The larger simulated than observed exponent for drought length is consistent with a model overestimate of precipitation frequencies. This can be at least partially attributed to the fact that while the observations are point values, the simulations refer to grid box averages of 50 × 50 km. Consistently with this result, the greater magnitude of exponent for the intensities implies a general underestimate of precipitation intensities by the model, a result at least partially attributable to the scale difference between the observed and modelled data as well as deficiencies in the model representation of the precipitation process. It is worth noting, however, that because of the power-laws, the gap between the distribution functions $f_{\mathrm{mod}} \approx x^{-\alpha}$ and $f_{\mathrm{obs}} \approx x^{-\beta}$ is greater for low x values and therefore the model underestimate of intensities decreases as we move towards more intense and extreme events.

4. Summary and conclusions

In this paper we have used results from complex systems theory to validate daily precipitation statistics in a regional climate model simulation. While previous work had demonstrated that observed precipitation at fine temporal scales follows power distributions determined by self-organized criticality behaviour, such an analysis had never been conducted on model output. In this work we show that also at the daily scale observed precipitation intensity and drought length follow power distributions and that such distributions are reproduced reasonably well in a regional climate model simulation. The exponents of the distributions are generally greater in the model than in the observations, which is likely due to the scale difference between the model grid point average and the station point observations as well as deficiencies in the model parameterization of precipitation. Indeed, in many locations, the observed and simulated exponents are very close to each other. Our results, as well as their comparison with previous work, are also suggestive of a dependence of the exponents on the station location, and thus on the specific climatic regime of the location under consideration.

Overall, our analysis indicates that precipitation in the RegCM approximately follows self organized criticality laws in a similar way as in the observations, and this adds confidence to the capability of the model to describe the precipitation process. We suggest that the use of self organized criticality concepts can provide a valuable tool to evaluate a model simulation of the precipitation process.

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References

Bove R, Pelino V, De Leonibus L (2004) Complexity in rainfall phenomena. Communications in Nonlinear Science and Numerical Simulation (accepted)

Buzzi A, Foschini L (2000) Mesoscale meteorological features associated with heavy precipitation in the southern Alpine region. Meteorol Atmos Phys 72: 131–146

Christensen JH, Carter TR, Giorgi F (2002) PRUDENCE employs new methods to assess European climate change. EOS 83: ■–■

Giorgi F, Mearns LO (1999) Introduction to special section: Regional climate modeling revisited. J Geophys Res 104: 6335–6352

Giorgi F, Marinucci MR, Bates GT (1993a) Development of a second generation regional climate model (RegCM2). Part I: Boundary layer and radiative transfer processes. Mon Wea Rev 121: 2794–2813

Giorgi F, Marinucci MR, Bates GT, De Canio G (1993b) Development of a second generation regional climate model (RegCM2). Part II: Convective processes and assimilation of lateral boundary conditions. Mon Wea Rev 121: 2814–2832

Giorgi F, Xunqiang B, Pal J (2004) Mean, interannual variability and trends in a regional climate change experiment over Europe. I: Present day climate (1961–1990). Clim Dyn 22: 733–756

Huntingford C, Jones RG, Prudhomme C, Lamb R, Gash JHC, Jones DA (2003) Regional climate model predictions of extreme rainfall for a changing climate. Quart J Roy Meteor Soc 129: 1607–1622

Pal JS, Small EE, Eltahir EAB (2000) Simulation of regional scale water and energy budgets: representation of subgrid cloud and precipitation processes within RegCM. J Geophys Res 105: 29579–29594

Peters O, Christensen K (■) Rain viewed as relaxation events to be published in special issue of Journal of Hydrology (available in http://www.cmth.ph.ic.ac.uk/people/k.christensen/pub.html)

Peters O, Hertlein C, Christensen K (2002) A complexity view of rainfall. Phys Rev Lett 88: ■–■

Pope VD, Gallani ML, Rowntree PR, Stratton RA (2000) The impact of new physical parameterizations in the Hadley Centre climate model. Clim Dyn 16: 123–146

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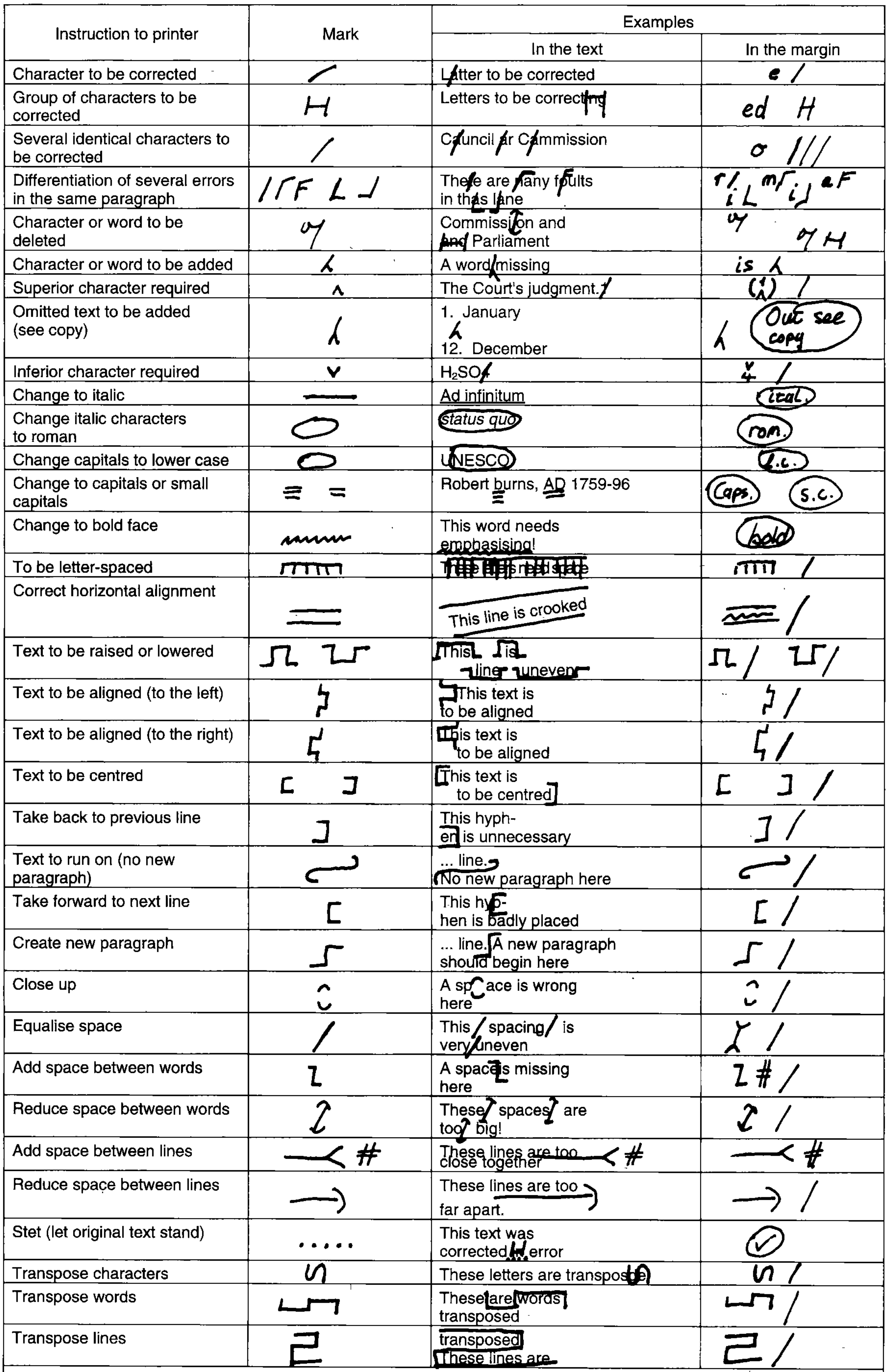

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