Climate variability and change on precipitation in Bulgaria by means of stochastic precipitation model

Neykov, N., Neytchev, P., Zucchini, W.[1], and Hristov, H. P.

National Institute of Meteorology and Hydrology
Bulgarian Academy of Sciences

[1] Dept. of Econometric & Statistics
University of Göttingen

Grant 436 BUL 113/136/0-1 within the framework of cooperation between the DFG and BAS

Outline

1. **Linking atmospheric circulation to daily precipitation patterns over Bulgaria**
    - **Methods and data;**
    - **Model fitting and inference;**
2. **Results and discussion**
    - **Climate variability and change;**
    - **Droughts and floods risk assessments;**
3. **Conclusions**

The aims of our work are:

- **To gain insights into inter-annual climate variability, detection and attribution to climate change for the cold half-year (October to March);**
- **To answer detailed specific questions relating to the occurrence and severity of rainstorm and drought related events;**

Approaches to extreme values analysis

- There are two approaches to analyzing the extremes of time series according to Embrechts et al. (1997):
    - The 1st one is based on the Extreme Value Theory that deals with the stochastic behavior of the extreme values in a process data, e.g., Coles (2001), Reiss and Thomas (2001);
    - The 2nd approach is to develop a time-series model for the complete data process and then determine not only its standard statistics but its extremal behavior either analytically or by simulation of long sequences of artificial data treating them as if it were a very long real record;
- In this study we followed the 2nd approach to answer detailed specific questions relating to severe weather events over the territory of Bulgaria.
- For this purpose we developed a hidden Markov model for linking synoptic scale patterns to daily precipitation amounts over the territory of Bulgaria.

GoTo Back Next

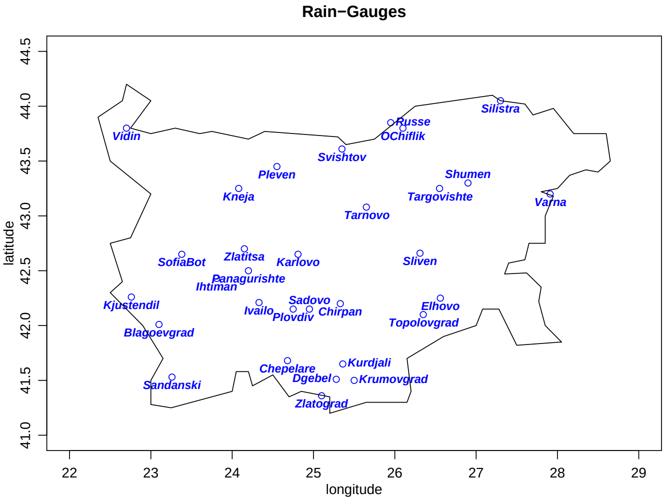


Figure 1: Map of 31 rain gauges broadly covering the territory of Bulgaria. Daily precipitation totals for the cold half years (October - March) 1960-2000 are used. The period 1960-1990 was used for model fitting, while the period 1991-2000 was reserved for model validation.

GoTo Back Next

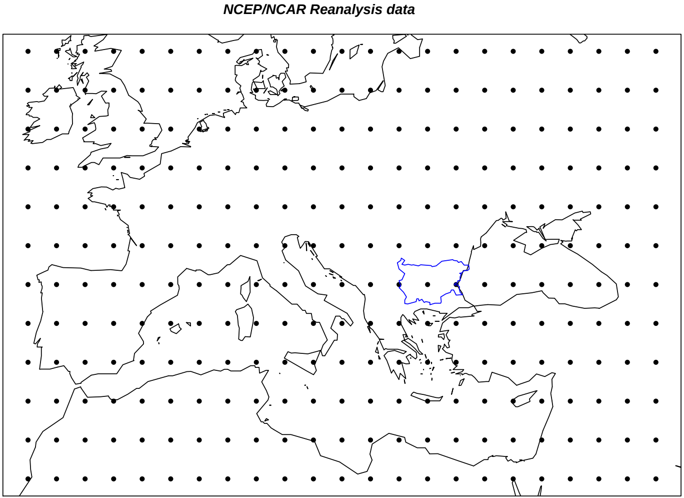


Figure 2: 2.5^o × 2.5^o gridded data within the window (30^{o}W - 60^{o}E, 20^{o}N - 70^{o}N). At each of 276 nodes - slp; hgt at 500, 700 and 850 hPa; air temperature at 850 hPa; relative humidity at 700 and 850 hPa.

GoTo Back Next

Precipitation downscaling and hidden Markov models

- Let $\mathbf{X_{1:T}} = (\mathbf{X_1}, \ldots, \mathbf{X_T})'$ be the matrix of daily atmospheric data;
- Let $\mathbf{R_{1:T}} = (\mathbf{R_1}, \ldots, \mathbf{R_T})'$ be the matrix of daily precipitation totals;
- $\mathbf{R_t}$ at time t is assumed to be generated by an unobserved state process $\mathbf{S_t} \in \{\mathbf{1}, \mathbf{2}, \ldots, \mathbf{K}\}$ with daily Markovian transitions from state to state influenced by a set of synoptic-scale atmospheric predictors $\mathbf{X_t}$:

$$\begin{tikzcd}
\cdots \arrow[r, "\mathbf{X_{t-1}}"] & \mathbf{S_{t-1}} \arrow[r, "\mathbf{X_t}"] \arrow[d] & \mathbf{S_t} \arrow[r, "\mathbf{X_{t+1}}"] \arrow[d] & \mathbf{S_{t+1}} \arrow[r, "\mathbf{X_{t+2}}"] \arrow[d] & \cdots \\
& \mathbf{R_{t-1}} & \mathbf{R_t} & \mathbf{R_{t+1}} &
\end{tikzcd}$$

- Spatial dependence is explained by the common state $\mathbf{S_t}$, i.e., $\mathbf{Pr}(\mathbf{R_t} | \mathbf{S_{1:T}}, \mathbf{R_{1:t-1}}, \mathbf{X_{1:T}}) = \mathbf{Pr}(\mathbf{R_t} | \mathbf{S_t})$;
- $\mathbf{X_t}$ and the Markov evolution of $\mathbf{S_t}$ account for the temporal dependence, i.e., $\mathbf{Pr}(\mathbf{S_t} | \mathbf{S_{1:t-1}}, \mathbf{X_{1:T}}) = \mathbf{Pr}(\mathbf{S_t} | \mathbf{S_{t-1}}, \mathbf{X_t})$

Model fitting

- The likelihood of the observed data given the atmospheric variables is

$$\begin{aligned}
\mathbf{L}(\theta) &= \mathbf{Pr}(\mathbf{R_{1:T}}|\mathbf{X_{1:T}},\theta) = \sum_{\mathbf{S_1,\ldots,S_T}} \mathbf{Pr}(\mathbf{R_{1:T}},\mathbf{S_{1:T}}|\mathbf{X_{1:T}},\theta) \\
&= \sum_{\mathbf{S_1,\ldots,S_T}} \mathbf{Pr}(\mathbf{S_{1:T}}|\mathbf{X_{1:T}},\theta_\mathbf{1})\mathbf{Pr}(\mathbf{R_{1:T}}|\mathbf{S_{1:T}},\mathbf{X_{1:T}},\theta_\mathbf{2}) \\
&= \sum_{\mathbf{S_1,\ldots,S_T}} \mathbf{Pr}(\mathbf{S_1}|\mathbf{X_1})\prod_{\mathbf{t=2}}^{\mathbf{T}}\mathbf{Pr}(\mathbf{S_t}|\mathbf{S_{t-1}},\mathbf{X_t},\theta_\mathbf{1})\mathbf{Pr}(\mathbf{R_t}|\mathbf{S_t},\theta_\mathbf{2}) \\
&= \sum_{\mathbf{S_1}}\mathbf{Pr}(\mathbf{R_1}|\mathbf{S_1})\mathbf{Pr}(\mathbf{S_1}|\mathbf{X_1})\prod_{\mathbf{t=2}}^{\mathbf{T}}\sum_{\mathbf{S_t}}\mathbf{Pr}(\mathbf{S_t}|\mathbf{S_{t-1}},\mathbf{X_t},\theta_1)\mathbf{Pr}(\mathbf{R_t}|\mathbf{S_t},\theta_2)
\end{aligned}$$

- $\mathbf{T}$ is usually large and computation of $\mathbf{L}(\theta)$ is intensive. Details are given in Hughes et al. (1999) [6] and McDonald and Zucchini (1997)[7].
- Note: Hidden Markov models are just a generalization of the more familiar Neural Network Models.

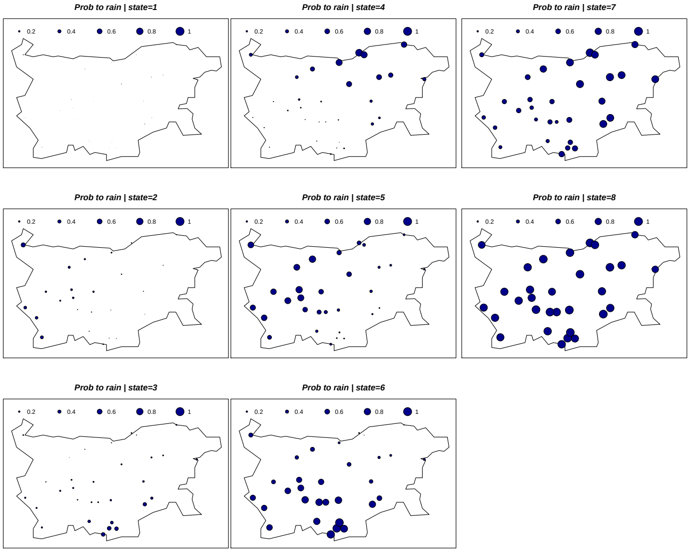


Figure 3: Diameters of circles indicate precipitation occurence probabilities. The sequences of states transitions 5 → 8 → 3, 5 → 8 → 7, 6 → 8 → 7 or 6 → 8 → 3 represent realistic well-known synoptic situations of Mediterranean cyclones.

GoTo Back Next

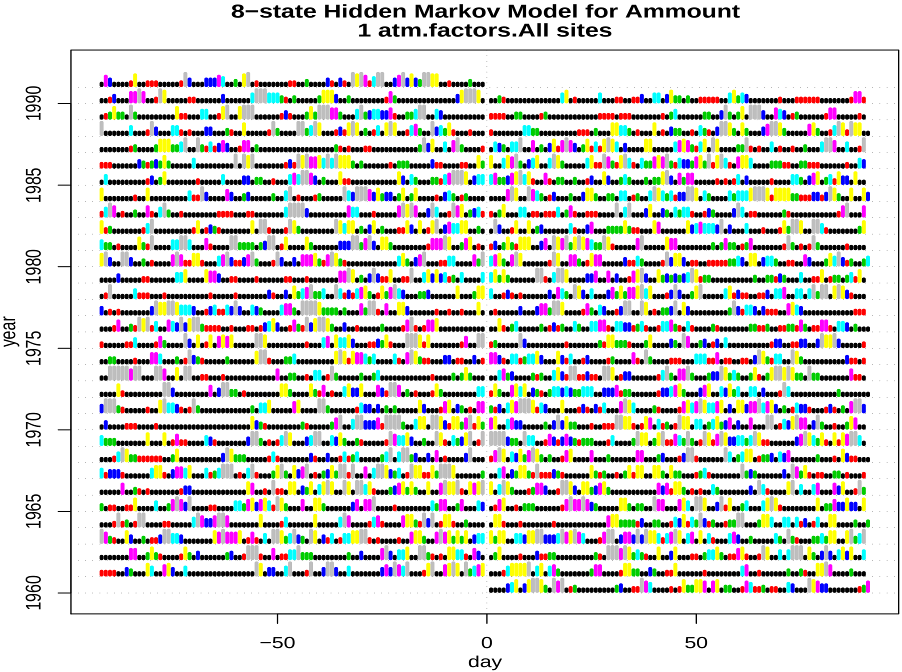


Figure 4: The estimated state sequence by the Viterbi algorithm. The bar-colors correspond to the state numbers.

GoTo Back Next

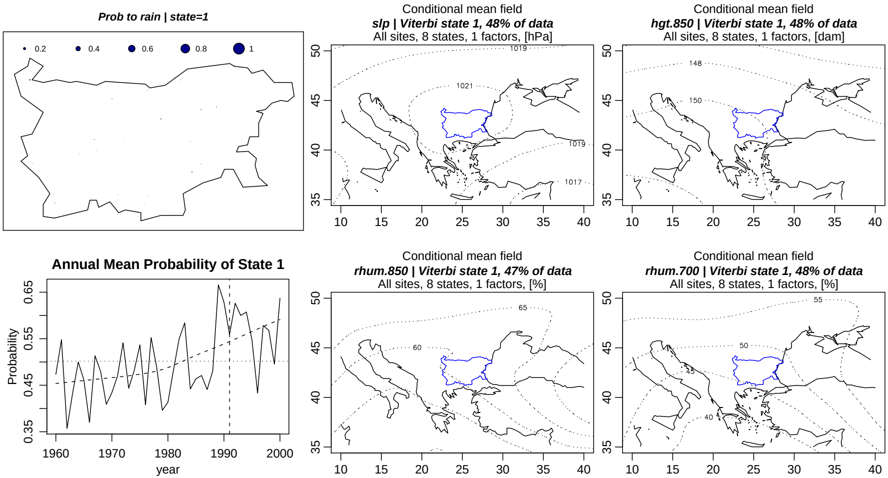


Figure 5: The synoptic pattern associated with state 1 shows a typical dominant high pressure system centered at Balkan Peninsula. Composite fields averaged over all days classified under each state. **Annual Mean Probability of State 1 series for cold half-years. Short dashed line is the smoothed fit. State 1 has become steadily more frequent during the period.**

GoTo Back Next

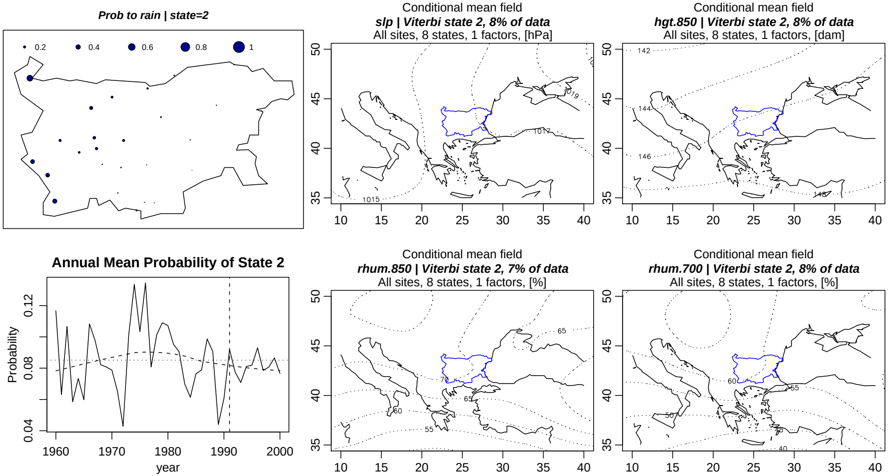


Figure 6: The weather pattern related with State 2 can be associated with Mediterranean cyclones centered over Northern Italy moving to Hungary due to southwestern flow. In such synoptic situations, the precipitations are limited over Western Bulgaria and the slopes of mountain opposite to wind, according to *hgt*.850 plot. **Annual Mean Probability of State 2 is charecterised with a grear variability and declining since 1970s.**

GoTo Back Next

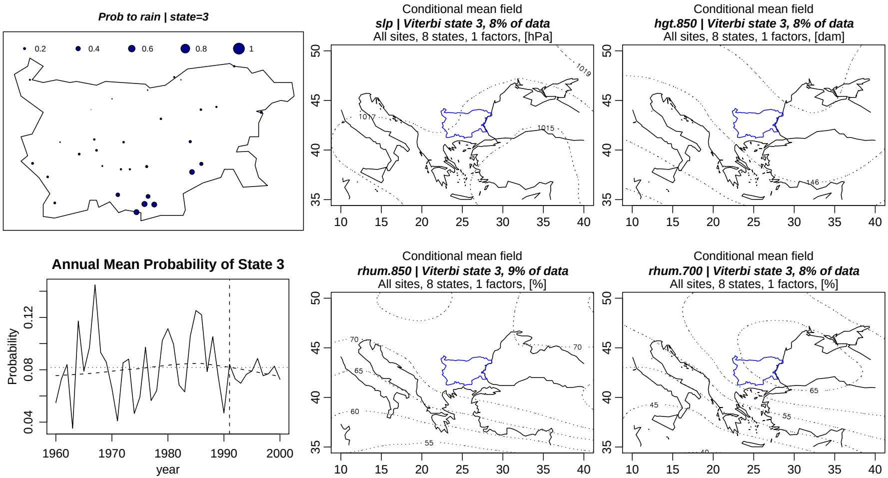


Figure 7: In state 3 the precipitation is localized in the southeast part of the country and is associated with a stationary frontal system along the Bosphorus strait. **Annual Mean Probability of State 3 series for cold half-years. Short dashed line is the smoothed fit. State 3 has become steadily more frequent although a great variability.**

GoTo Back Next

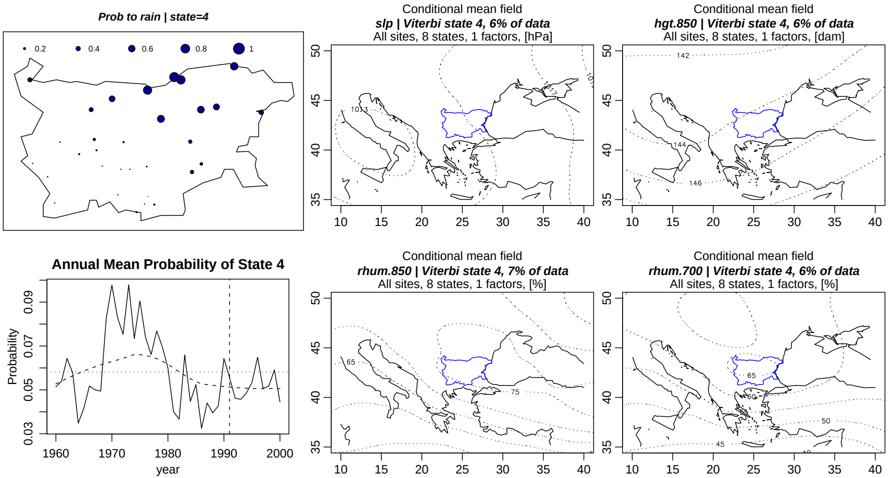


Figure 8: In state 4 the precipitations occur in the northeast half of the country. The precipitations are due to a cold front crossing the country and can be associated with a cyclonic generation in the northwest Black Sea. **Annual Mean Probability of State 4 series for cold half-years. Short dashed line is the smoothed fit. State 4 is charecterised with great variability and declined since 1970**.

GoTo Back Next

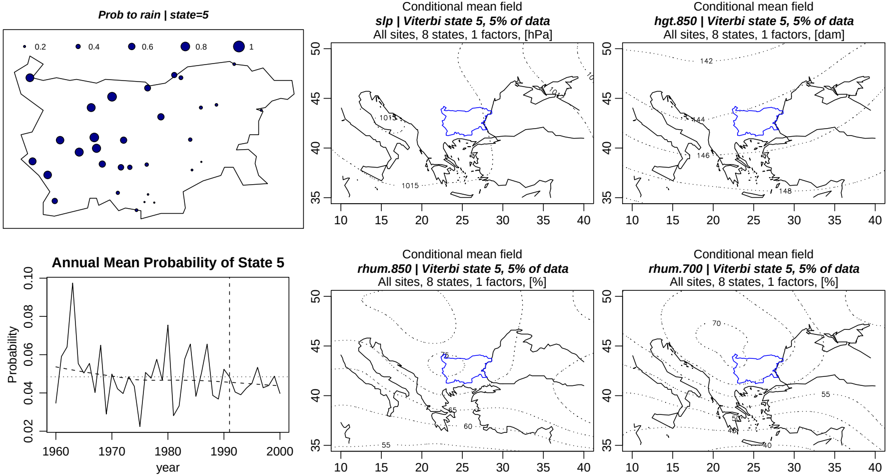


Figure 9: The weather state 5 is associate with a depression centered over the central Mediterranean and Sought–Italy in the mean sea–level pressure field and an upper–level trough with an amplitude and tilt in the geopotential height at 850 hPa. **Annual Mean Probability of State 5 series for cold half-years. Short dashed line is the smoothed fit. State 5 fluctoates around its multiannual mean.**

GoTo Back Next

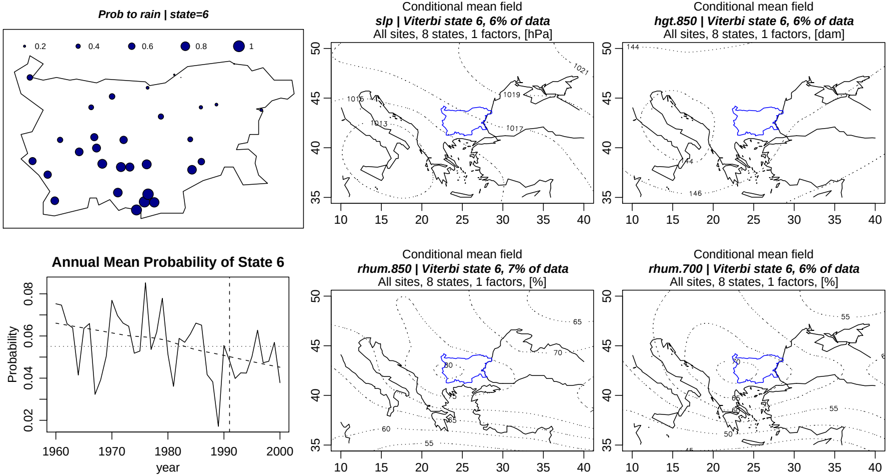


Figure 10: In state 6 the depression is shifted westwards and therefore touches only the southwest part of Bulgaria where the precipitations occur. **Annual Mean Probability of State 6 series for cold half-years. Short dashed line is the smoothed fit. State 6 has declined steadily during the periods**.

GoTo Back Next

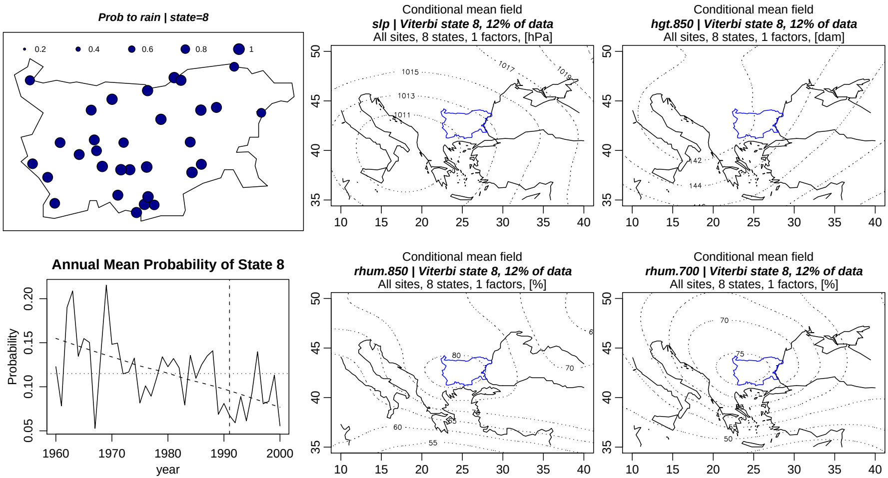


Figure 11: The warm front cloudiness of the cyclone over Ionian Sea causes the precipitation over all the territory of Bulgaria. **Annual Mean Probability of State 8 series for cold half-years. Short dashed line is the smoothed fit. State 8 has declined steadily during the periods**.

GoTo Back Next

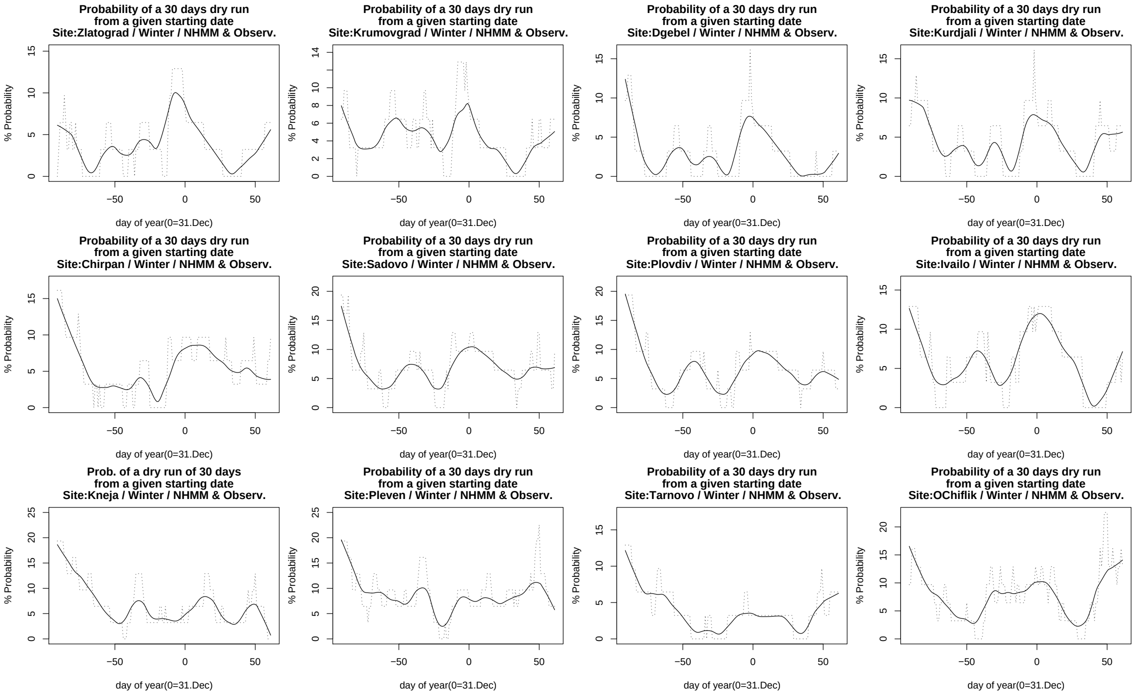
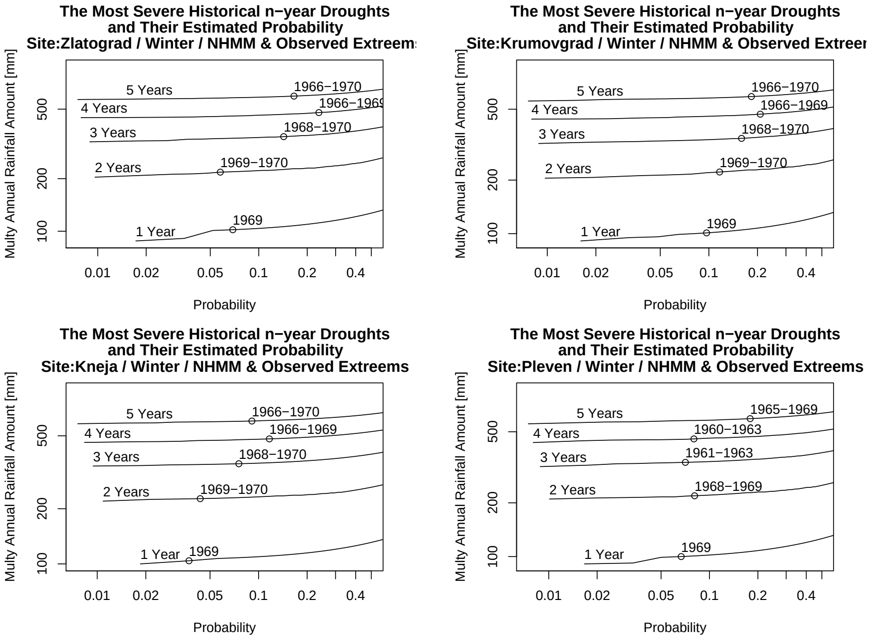


Figure 12: Drought risk assessment. Dotted and smoothed lines are based on historical and simulated data.

GoTo Back Next



The Most Severe Historical n−year Droughts
and Their Estimated Probability
Site:Zlatograd / Winter / NHMM & Observed Extreem

The Most Severe Historical n−year Droughts
and Their Estimated Probability
Site:Krumovgrad / Winter / NHMM & Observed Extree

The Most Severe Historical n−year Droughts
and Their Estimated Probability
Site:Kneja / Winter / NHMM & Observed Extreems

The Most Severe Historical n−year Droughts
and Their Estimated Probability
Site:Pleven / Winter / NHMM & Observed Extreems

Figure 13: The most severe historical n-years droughts and their estimated probability of exceedence. The tiny circles correspond to the lowest precipitattion cumulative sum for the period October-March.

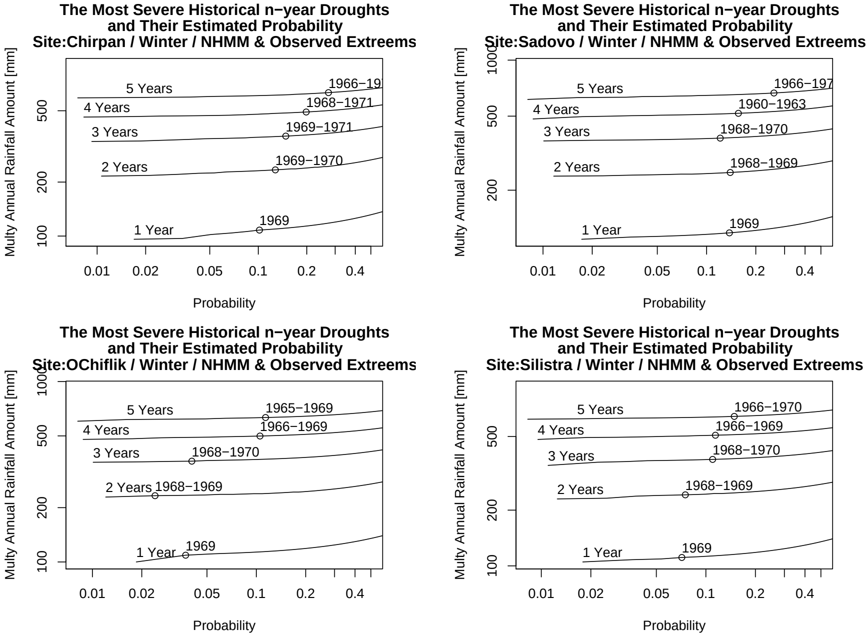
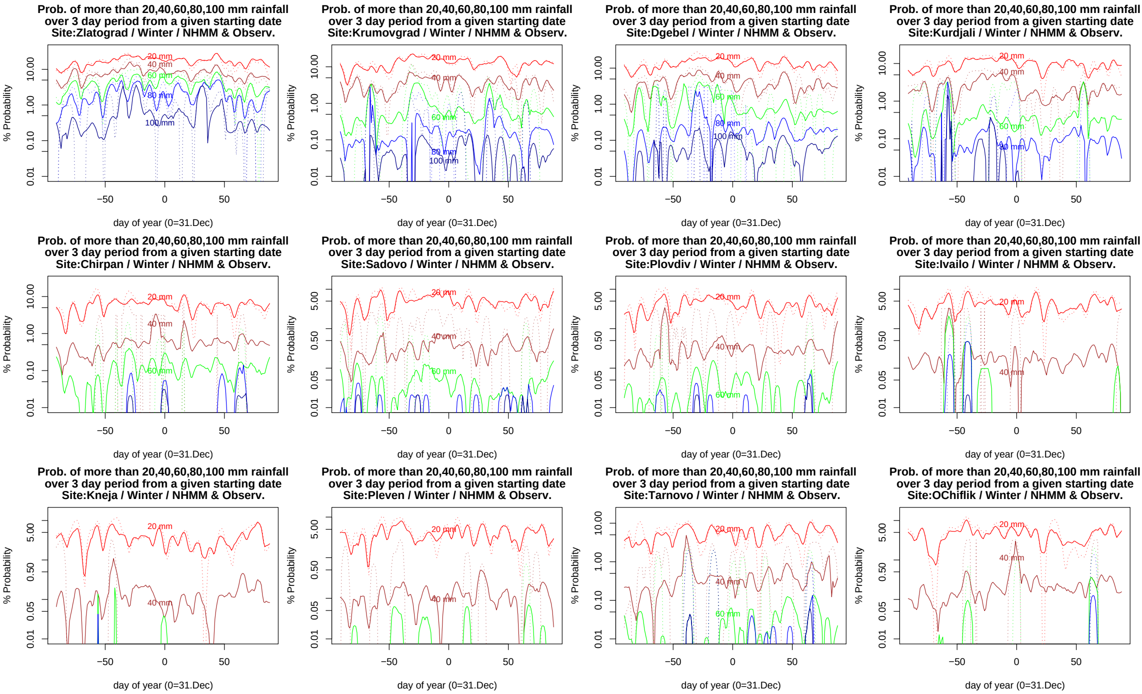


Figure 14: The most severe historical n-years droughts and their estimated probability of exceedence. The tiny circles correspond to the lowest precipitattion cumulative sum for the period October-March.



Prob. of more than 20,40,60,80,100 mm rainfall over 3 day period from a given starting date Site:Zlatograd / Winter / NHMM & Observ.

Prob. of more than 20,40,60,80,100 mm rainfall over 3 day period from a given starting date Site:Krumovgrad / Winter / NHMM & Observ.

Prob. of more than 20,40,60,80,100 mm rainfall over 3 day period from a given starting date Site:Dgebel / Winter / NHMM & Observ.

Prob. of more than 20,40,60,80,100 mm rainfall over 3 day period from a given starting date Site:Kurdjali / Winter / NHMM & Observ.

Prob. of more than 20,40,60,80,100 mm rainfall over 3 day period from a given starting date Site:Chirpan / Winter / NHMM & Observ.

Prob. of more than 20,40,60,80,100 mm rainfall over 3 day period from a given starting date Site:Sadovo / Winter / NHMM & Observ.

Prob. of more than 20,40,60,80,100 mm rainfall over 3 day period from a given starting date Site:Plovdiv / Winter / NHMM & Observ.

Prob. of more than 20,40,60,80,100 mm rainfall over 3 day period from a given starting date Site:Ivailo / Winter / NHMM & Observ.

Prob. of more than 20,40,60,80,100 mm rainfall over 3 day period from a given starting date Site:Kneja / Winter / NHMM & Observ.

Prob. of more than 20,40,60,80,100 mm rainfall over 3 day period from a given starting date Site:Pleven / Winter / NHMM & Observ.

Prob. of more than 20,40,60,80,100 mm rainfall over 3 day period from a given starting date Site:Tarnovo / Winter / NHMM & Observ.

Prob. of more than 20,40,60,80,100 mm rainfall over 3 day period from a given starting date Site:OChiflik / Winter / NHMM & Observ.

Figure 15: Flood risk assessment. Dotted and smoothed lines are based on the historical and simulated data.

GoTo Back Next

Conclusions

- The results of this study confirm that the NHMM is a useful research tool for investigating the relationship between large-scale climatic processes and local climate variables, such as precipitation;
- Results for a 32-site network over Bulgaria indicate that the NHMM can successfully reproduce the at-site and inter-site statistics of daily precipitation;
- The identified precipitation states provide a regional climatology for Bulgaria, representing the dominant spatial patterns of daily precipitation occurrences;
- These precipitation states are related to climate variability via a small set of atmospheric predictors;
- The model preserves well the geographical distribution of the precipitation and related extreme events as droughts and floods over the territory of Bulgaria;
- Future applications of this technology can be used to assess water resource management in Bulgaria as a function of current and projected future climate.

References

[1] Bellone, E., Hughes, J. P. and P. Guttorp. (2000). A hidden Markov model for downscaling synoptic atmospheric patterns to precipitation amounts. *Climate Res.*, **15**, 1-12.

[2] Charles, S. P., Bates, B. C., Smith, I. N. and Hughes, J.P. (2004). Statistical downscaling of daily precipitation from observed and modelled atmospheric fields. *Hydrol. Process.*, **18**, 1373-1394

[3] Embrechts, P., Kluppelberg, C. and Mikosch, T. (1997). *Modelling Extremal Events for Insurance and Finance*. Springer.

[4] Hughes, J. P., and P. Guttorp (1994a) . A class of stochastic models for relating synoptic atmospheric patterns to regional hydrologic phenomena. *Water Resour. Res.*, **30**, 1535-1546.

[5] Hughes, J. P., and P. Guttorp (1994b). Incorporating spatial dependence and atmospheric data in a model of precipitation. *J. Appl. Meteor.*, **33**, 1503-1515.

[6] HUGHES, J.P., GUTTORP, P. AND CHARLES, S.P. (1999). A non-homogeneous hidden Markov model for precipitation occurrence. *Appl. Stat.*, **48**, 15-30.

[7] MACDONALD, I. L., AND ZUCCHINI, W. (1997). *Hidden Markov and Other Models for Discrete-valued Time Series.* Chapman & Hall,

[8] NEYKOV, N.M., NEYTCHEV, P., ZUCCHINI, W. AND HRISTOV, H. (2008). Stochastic Downscaling of Daily Precipitation Over the Territory of Bulgaria by Means of Hidden Markov Models. In: 3rd International Conference on Water Observation and Information System for Decision Support, 27-31 May 2008, Ohrid, Republic of Macedonia, 11 pages paper available on the conference website: $http://balwois.com/balwois/infosys/publication2008.php$

[9] NEYTCHEV, P., ZUCCHINI,W., HRISTOV, H. AND NEYKOV, N.M. (2006) Development of a multisite daily precipitation model for Bulgaria using hidden Markov models. In: Proc. of the XXIIIrd conference of Danubian countries on the hydrological forecasting and hydrological bases of water management. Belgrade, Serbia, 28-31 August, S. Bruk and T. Petkovic (eds.). (The full paper of 12 pages is available on the conference CD).

GoTo Back Next

[10] Neytchev, P., Neykov, N., Zucchini, W. and Hristov, H. (2008). Statistical Linkage of Daily Precipitation in Bulgaria to Atmospheric Circulation. In: Proc. of the XXIV Conference of the Danubian Countries on the Hydrological Forecasting and Hydrological Bases of Water Management, 2-4 June, Bled, Slovenia,(The full paper is available on the conference CD).

[11] Neytchev, P.N., Neykov, N.M, Zucchini W. and Hristov, H. (2008). Climate Variability and Change in Bulgaria: An Approach Based on Stochastic Downscaling of Atmospheric Fields. In: Proc. of the international conference on "Global Environmental Change: Challenges to Science and Society in Southeastern Europe", 19-21 May 2008, Sofia, Bulgaria. Valkov, N. and A. Jotova (eds.) (The full paper of 12 pages is available on the conference CD).

[12] Reiss, R.D. and Thomas, M. (2001). *Statistical Analysis of Extreme Values: with Applications to Insurance, Finance, Hydrology and Other Fields.* 2nd Edition. Birkhauser.

[13] Zucchini W. and Guttorp P.(1991). A hidden Markov model for space-time precipitation. *Water Resour Res.*, **27**, 1917–1923.

GoTo Back Next