THEME SPA.2013.1.1-05

EUCLEIA

(Grant Agreement 607085)

EUropean CLimate and weather Events: Interpretation and Attribution

Deliverable D5.1

Analogue flow analyses for temperature and precipitation

Summaries on a seasonal basis

Deliverable Title		*Analogue flow analyses for temperature and precipitation summaries on a seasonal basis*
Brief Description		*The detection of a change in a given extreme season (for temperature or precipitation) can be analyzed using observations or reanalyses by quantifying how the amplitude would have been with similar flows in past climate periods. This can be achieved via the so-called “analog method”. In this deliverable, we explain the formalism of analogs, show a few examples of how it can be used for detection or attribution in singular events, and describe the potential products that can be developed in an operational system.*
WP number		5
Lead Beneficiary		*CNRS*
Contributors		*Robert Vautard, CNRS* *Pascal Yiou CEA* *Nils Hempelmann, CNRS*
Creation Date Version Number Version Date		
Deliverable Due Date Actual Delivery Date		31 December 2015 31 December 2015
Nature of the Deliverable	x	*R – Report*
		P – Prototype
		D – Demonstrator
		O – Other
Dissemination Level/ Audience	x	*PU – Public*
		PP - Restricted to other programme participants, including the Commission services
		RE - Restricted to a group specified by the consortium, including the Commission services
		CO - Confidential, only for members of the consortium, including the Commission services

Table of Contents

List of Tables

1. Executive Summary

A method based on flow analogs is developed in order to estimate how temperature and precipitation events would have changed in past (or counterfactual) climates as compared to current (or factual) climate. The method is based on the comparison of events in the two climate periods but for similar flows. The method allows distinguishing the dynamical and other contributions to the changes.

It can be applied to observations of different climate periods, for a detection problem, or to model simulations, for an attribution problem. To illustrate the methodology, beyond previous studies, the method is applied to the case of extreme rainfall season of 2013-2014 in the U. K.

2. Project Objectives

With this deliverable, the project has contributed to the achievement of the following objectives (DOW, Section B1.1):

No.	Objective	Yes	No
1	Derive the requirements that targeted user groups (including regional stakeholders, re-insurance Companies, general public/media) have from attribution products and demonstrate the value to these users of the attribution products developed under EUCLEIA.		x
2	Develop experimental designs and clear ways of framing attribution studies in such a way that attribution products provide a fair reflection of current evidence on attributable risk.	x	
3	Develop the methodology for representing the level of confidence in attribution results so that attribution products can be trusted to inform decision making.	x	
4	Demonstrate the utility of the attribution system on a set of test cases of European weather extremes.	x	
5	Produce traceable and consistent attribution assessments on European climate and weather extremes on a range of timescales; on a fast-track basis in the immediate aftermath of extreme events, on a seasonal basis to our stakeholder groups, and annually to the BAMS attribution supplement.	X	

3. Detailed Report

3.1 Science questions

Extreme events generally result from an ensemble of processes involving specific atmospheric dynamics (large-scale flows) and other and regional to local-scale processes, which interact with one another. These other contributions are often called “thermodynamical contributions”. The processes involved are described in Deliverable D6.2. For instance, in the development of summer heat waves, a large-scale flow characterized by persisting anticyclonic and stagnant conditions is necessary. This brings high radiation heating the ground and allowing accumulation of heat day after day. However during such conditions temperature strongly depend on the state of soil moisture [Quesada et al., 1992]. Under dry conditions, feedbacks take place [Seneviratne et al., 2010] and temperature rises fast while with wet soils temperature rise remains limited. Changes in the frequency of impacting events such as heavy precipitations or heat/cold waves are therefore potentially affected by both changes in large-scale circulations and changes in “thermodynamics”.

In the mid-latitudes, daily weather is governed by the variability of the atmospheric circulation, which is often represented in terms of “weather regimes” [Michelangeli et al., 1995] for the sake of simplification. Such regimes are areas of the phase space where the atmospheric state “likes to stay”. A season can be characterized by the duration of each regimes and alternation between regimes. Exceptional seasonal mean temperatures, rain amounts or frequency of events generally results from the persistence of a given weather regime.

For instance, we have shown that the winter of 2013-2014, where repetitive storms and heavy rainfalls pounded the U. K. and Brittany, was dominated by one of the four weather regimes, the “ZONAL weather regime” (Figure 1 from [Schaller et al., 2016]), according to the classification of [Michelangeli et al., 1995]). The persistence of this regime leads to an extension of the jet towards Western European coasts. It had a large contribution to the extreme weather observed during this winter in Western Europe.

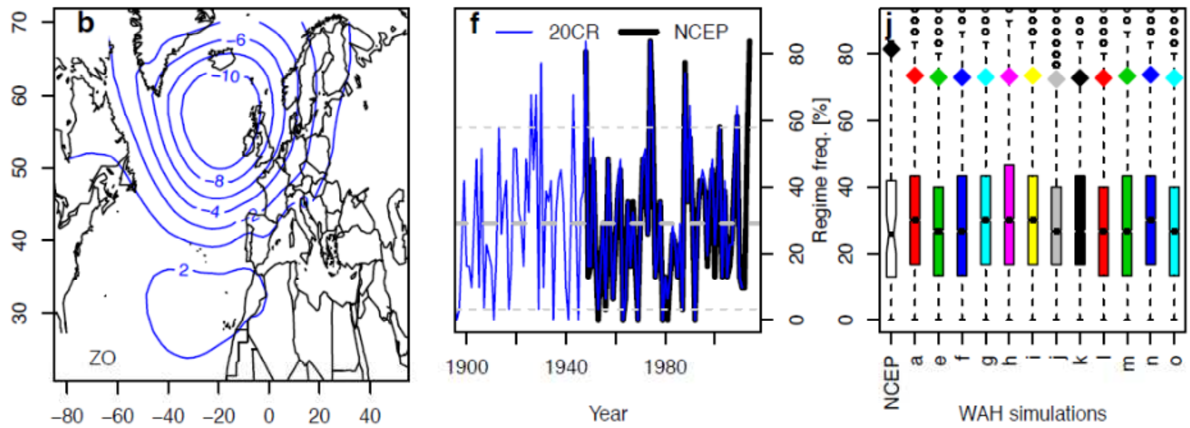

Figure 1 (after Schaller et al., 2016): (a) Spatial pattern of the ZO weather regime cluster centroid (SLP anomaly); (b) occupancy in % of days of the ZO regime for all January months since 1900 from two reanalyses (20CR and NCEP/NCAR); (c) frequency of ZO regimes in January in factual (a) and counterfactual simulations e-o) from the HadAm model run by the Oxford group.

When such an extreme season occurs (in terms of rain or temperature), three legitimate questions arise:

- Does seasonal persistence or occurrence of such flows have a long-term trend?,
- Was there a long-term change in the response to such flows, enhancing (or mitigating) temperature and precipitation amounts?
- How would have been the “same” season in past climate periods (provided we can define what “same” means)?

The “flow analog” method allows to address these issues. Iwas developed initially for a number of type of problems in meteorology (weather predictability [Lorenz, 1969]; downscaling [Zorita and von Storch, 1999], …); it is more general than the weather regime approach and can provide answers, or at least partial answers to detection/attribution in general, as initially demonstrated by Yiou et al. [2007], Vautard and Yiou [2009] and Cattiaux et al., [2010]. The analogue method provides information on conditional attribution. This deliverable develops here the concepts and shows how such methods could be integrated, at least for seasonal-scale events, in an operational detection/attribution service.

3.2General formalism of flow analogs

Concept

The central concept is the decomposition of the probability distribution function of a climate variable *x* (eg. rain, temperature) into flow-conditioned probabilities (hence the term: conditional attribution). This can be formally written in terms of density distributions as:

(1) $\rho(x) = \int_F \rho(x/F).\rho(F)$,

where the integral bears on all possible states of the flow, $\rho(x)$ is the unconditional density distribution of the variable *x*, $\rho(x/F)$ is the conditional distribution of *v* given a flow *F* and $\rho(F)$ is the density distribution of the flow *F*. For instance, if the flow is represented by two weather regimes, and if *x* is the temperature, the distribution of the flow is discrete, $\rho(F)$ is the frequency of each regime, and $\rho(x/F)$ *F=F1, F2*, is the distribution of all possible values of the temperature in each regime.

A change $\delta\rho(x) = \rho_2(x) - \rho_1(x)$, between two climates C1 and C2, in the distribution of the variable *x* can be then decomposed as the sum of a change in the conditional distributions and a change in the distribution of flows:

(2) $\delta\rho(x) = \int_F \delta\rho(x/F).\rho(F) + \int_F \rho(x/F).\delta\rho(F)$

The term $\int_F \rho(v/F).\delta\rho(F)$ can be interpreted as the contribution of the change in *x* due to the change in dynamics, and the term $\int_F \delta\rho(v/F).\rho(F)$ can be interpreted as the contribution of the change in *v* by the other factors. For an attribution problem, the two climates C1 and C2 can be respectively the counterfactual and factual climates.

As an example using our two-regime case as above, the contribution of flow changes to changes in temperature is obtained as the sum of the difference in regime frequencies multiplied by the conditional probability of temperature exceeding threshold in each regime. The “thermodynamical” contribution is symmetrically obtained as the sum of the differences in conditional probabilities multiplied by regime frequencies.

The “flow analog” method generalizes the regime examples above and may be used to estimate both contributions in Equation (2). The conditional distribution of *x* for a given flow *F,* $\rho(x/F)$*,* can be estimated by the distribution of the values of *x* for flows neighbouring *F*. This can be calculated by establishing a metrics, for instance the Euclidian distance, to compare flows and selecting analogs for each flow within a ball of fixed distance. Often also a fixed number of analogs is taken, regardless of their distance to *F*.

In practice

Assume that we have a long enough record of *n* observations of the flows in the two climates, (for C1: $F_{1,1}$, $F_{2,1}$, … $F_{n,1}$ and for C2: $F_{1,2}$, $F_{2,2}$, … $F_{n,2}$), and corresponding climate variables (for C1: $x_{1,1}$, $x_{2,1}$, … $x_{n,1}$ and for C2: $x_{1,2}$, $x_{2,2}$, … $x_{n,2}$). Assume that we are interested in changes of an event defined as "x exceeds a threshold x_o". We want to calculate changes in the probabilities and the dynamical and thermodynamical contributions. For each flow $F_{i,j}$ in each climate, let us denote by $P_{1,i,j}(x>x_o)$ and $P_{2,i,j}(x>x_o)$ the respective flow-conditioned probabilities of exceedance given the flow, estimated by counting the frequency of exceedance in its analogs. Then one can estimate the probability $P_{ff}(x > x_o)$ of the event in the factual climate as the average of flow-conditioned probabilities over all flows encountered:

(3) $P_{ff}(x > x_o) = \frac{1}{n}\sum_{i=1}^{n} P_{2,i,2}(x > x_o)$.

The same can be done for the counterfactual climate:

(4) $P_{cc}(x > x_o) = \frac{1}{n}\sum_{i=1}^{n} P_{1,i,1}(x > x_o)$.

Replacing in (4) the counterfactual flow-conditioned probabilities by the factual ones, one obtains the probability of exceedance that would obtain with the "thermodynamics" of the factual world and the flows of the counterfactual world. This can be estimated by searching analogues of the counterfactual flows in the factual climate.

(5) $P_{fc}(x > x_o) = \frac{1}{n}\sum_{i=1}^{n} P_{1,i,2}(x > x_o)$

The difference $P_{ff}(x > x_o)$ - $P_{fc}(x > x_o)$ can be interpreted as the dynamical contribution of the change in exceedance probability.

Similarly, the probability of exceedance that might have be obtained with factual flows but conditional probabilities of the counterfactual period as:

(6) $P_{cf}(x > x_o) = \frac{1}{n}\sum_{i=1}^{n} P_{2,i,1}(x > x_o)$

and the thermodynamical contribution of the change can be estimated as $P_{ff}(x > x_o)$ - $P_{cf}(x > x_o)$. The two contributions may not be additive in practice due to nonlinear interactions between dynamical and other processes and feedbacks.

For extreme seasons, in practice, only a limited number of seasons is available, from observations or reanalyses, while lots of daily values are available. It is not possible to calculate directly analogs of seasonal mean flows. Then for seasonal statistics, such as rainfall amount, frequency of rainy days, mean temperature, the conditional probabilities can be estimated by taking daily analogs and reconstructing seasonal statistics.

Technical aspects

This formalism is quite general and many technicalities come in practice, such as the number of analogs or the ball radius, the climate periods, whether one should detrend first flows or climate variables, how to account for seasonality. So far no single approach is being used, as the method is still currently under intensive testing on EUCLEIA test cases. However some previous applications led us to a few conclusions (see also Stott et al., 2015):

Application to real observations :

In this case one generally have reliable data over 60 years since the middle of the 20th century. Thus a “counterfactual” world is defined as the first 30 years and an “actual world” as the last 30-year period. The question is a detection question because human-induced climate change may not be the only driver of changes. The best 10 to 30 analogs are being used, and analogs are sought within a calendar month of the date of the flow.

Application to model data:

In this case one uses simulations of the factual (C2) and counterfactual (C1) worlds. In the w@h simulations usually thousands of seasons are generated, leaving many possibilities for analogs. The application to the 15-member ensemble of HdaGEM data will be considered for operations. Two periods of 30 years could be used, which would give a set of 30x15=450 seasons, enabling a good selection for daily analogs, and less for monthly analogs.

Only one application so far has been done using the w@h data generated in the Schaller et al. [2016] study. Another one is currently being tested for elevated temperatures in December 2015.

In previous studies the formalism was not developed and often changes in amplitudes of seasonal means was studied only and not changes in probabilities. The actual anomaly was compared to that of a reconstruction from analogs all over the available data period, thus comparing a given season extreme with what would be obtained from analog combinations taken from flows at any time across the data period (in general starting in the second half of the 20th century.

For instance, in Yiou et al., [2007], Cattiaux et al. [2009], Cattiaux et al. [2010], the respective extreme warmth of the Fall & Winter 2006-2007, cold of the 2009-2010 winter were compared to reconstructed seasons from daily analogs. In Vautard and Yiou [2009], the contribution of dynamical changes to changes in temperature, precipitation and other variables in Europe was analyzed using analogs taken also all along the data period.

In Chrstidis and Stott, the role of circulation in the extreme rain of Winter 2013/2014 is investigated using the single flow itself and its analogs in the factual and counterfactual world of the HadGEM model. Then, the study estimates whether, under these similar flows, one can detect a change between actual and counterfactual climates. This estimates the "thermodynamical" contribution, for this singular flow.

We now present some applications of this formalism. The examples taken are drawn from yet unpublished work. We also present propositions for an operational detection service using the analog methodology.

The full formalism will be applied for WP7 official case studies.

3.3 An illustrative case study: the wet Winter 2013-2014

Observational estimations

The case taken here is that of the Winter 2013/2014 and the repeated heavy rainfalls in the South of U. K. that led to floods in the Thames river basin [Huntingford et al., 2014; van Oldenborgh et al., 2014]. The rank of the winter season precipitation amount in several gauges in Southern U. K. was the first at many sites as shown by Figure 2.

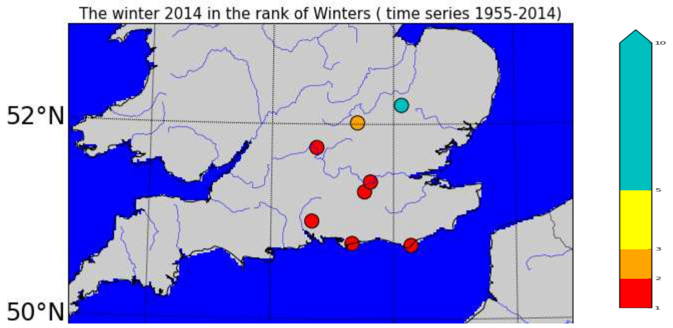

Figure 2: Rank of the seasonal rainfall amount at several sites in South-Eastern U.K. Thanks to the U.K. Met Office and T. Legg.

An index of mean seasonal amount was built by averaging amounts over the rain gauge measurements in order to characterize the event. The same index can be calculated from cumulated daily rainfall from flow analogs taken across the 1955-2014 period. This is shown in Figure 3. The observed interannual variability of seasonal amounts is clearly well reproduced using either one reconstruction from each day's best analog or the average over the best 10 analogs, in this case taken all along the data period. It is also clear that the anomaly observed in 2013-2014 (the last point in the graphs) can be well reconstructed from flow analogs, showing that the anomalous circulation is the main driver of the extreme seasonal rain.

Figure 3 (bottom) also shows the difference between the two reconstructions obtained when restricting the analog selection to either half of the data. When taking analogs in the first data half, the amount reconstructed is generally smaller than when taking analogs in the second half. This indicates that there is a change in conditional distribution of seasonal amount of rain between the first and the second data half. For a given series of flows along the winter season, accumulated rainfall would have been lower in the earlier climate than in the later climate indicating a thermo-dynamical change. As seen on Figure 3, the average change in amount is in the order of 10 mm (about 5%).

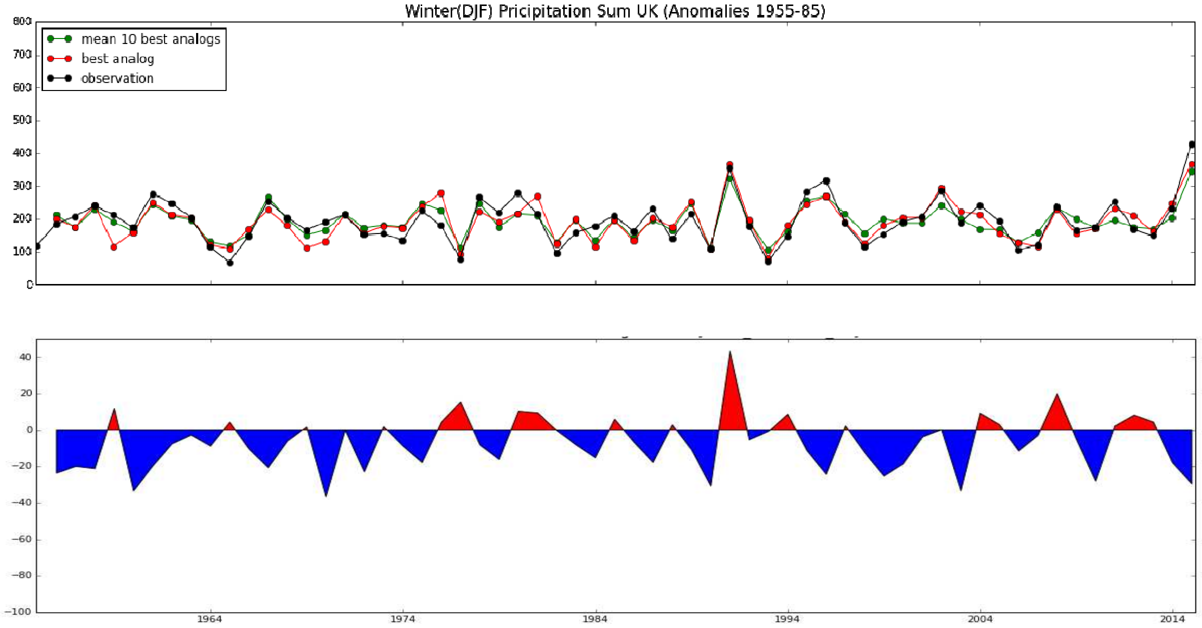

Figure 3: (top) Evolution of observed and reconstructed seasonal amounts of rainfall over the rain gauges shown in Figure 2. Two analog reconstructions are shown, one using the best analog and the other one using the average over the best 10 analogs; (bottom) Difference between the best analog reconstruction using analogs in the earlier half of the period and analogs in the later half.

The quantification of extreme distribution changes can be made in terms of extreme value theory, by plotting return values vs. return periods for the observations, the reconstructed series from analogs in the two halves of the data period (Figure 4). Reconstructions are slightly underestimating observed extreme cases (can be seen on Figure 3, top panel), which makes the analog return values lower than observed for given return periods. Equivalently, for a given return period, the corresponding return value is about 10mm higher in the later climate than in the earlier climate. However the comparison between reconstructions with analogs taken in the first and the second half only shows significant differences in return periods smaller than about 50 years, or return values smaller than about 300 mm.

This example shows how the flow analog method can help estimating changes in extreme statistics from thermodynamics for seasonal events. The method will be generalized for all types of extremes in WP7. The estimation of the dynamical contribution was not done from observation but from a model study.

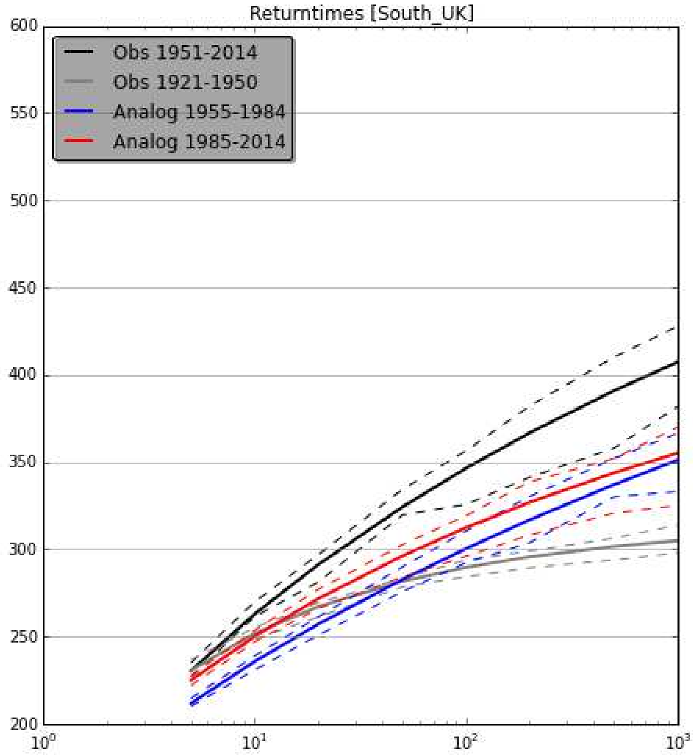

Figure 4: Return values vs. return period from observed winter seasonal amounts averaged over the South U. K. stations of Figure 2. Reconstructions are taken either from the first or the second half of the data period. Dashed lines indicate confidence intervals.

Model estimations of dynamical/thermo-dynamical change contributions

Another study was conducted using the potential provided by the large ensembles designed in Schaller et al. [2016]. Instead of considering daily analogues and aggregating at seasonal time scale, we now consider monthly-mean flow analogs from model data consisting in about 17000 winter simulations for the factual climate, using actual SST conditioning, and more than 100000 simulations from 11 ensembles, using de-anthropogenized SST conditioning. The results from the 11 ensembles are averaged here. Monthly January amounts were used here for consistency with Schaller et al. [2016] analysis. The metrics used for analog calculation is a weighted average of Sea level pressure RMS with weights proportional to the correlation between SLP grid point and the monthly amount over the model area where rainfall is considered (a square box covering South-East U. K).

We apply the formalism developed in Section 3.2, and calculate the distribution of monthly amounts using the factual or counterfactual sets of w@h simulations. This led to estimates of the distribution tails, calculated directly from the data instead of extreme value theory. Results are shown in Figure 5. In this case C1 is the counterfactual climate (simulated by de-anthropogenized SSTs) and C2 is the factual climate (actual SSTs). We calculated, for each flow of C2, the conditional probability $P_{ff}(x>x_o)$ of amounts exceeding a value x_o searching analogs also in C2. In a similar manner $P_{cc}(x>x_o)$ is also calculated for the C1 climate, as well as the cross estimates $P_{cf}(x>x_o)$ and $P_{fc}(x>x_o)$.

By comparing probabilities from factual flows with factual analogues and probabilities from counterfactual flows with factual analogs one obtains the change of exceedance probability solely due to the change of flows (the difference between green and red curves). Comparing the red curve with the black curve (probabilities from factual flows with counterfactual analog search), one obtains the thermodynamical contribution of the change. In the example here (Figure 5) the contribution from change in dynamics is about 20% of the total change. This is in excellent agreement with the results presented in Schaller et al., where dynamical and thermo-dynamical contributions were calculated from a simple index of circulation: the value of sea level pressure in the center of the winter anomaly (North West of Scottland).

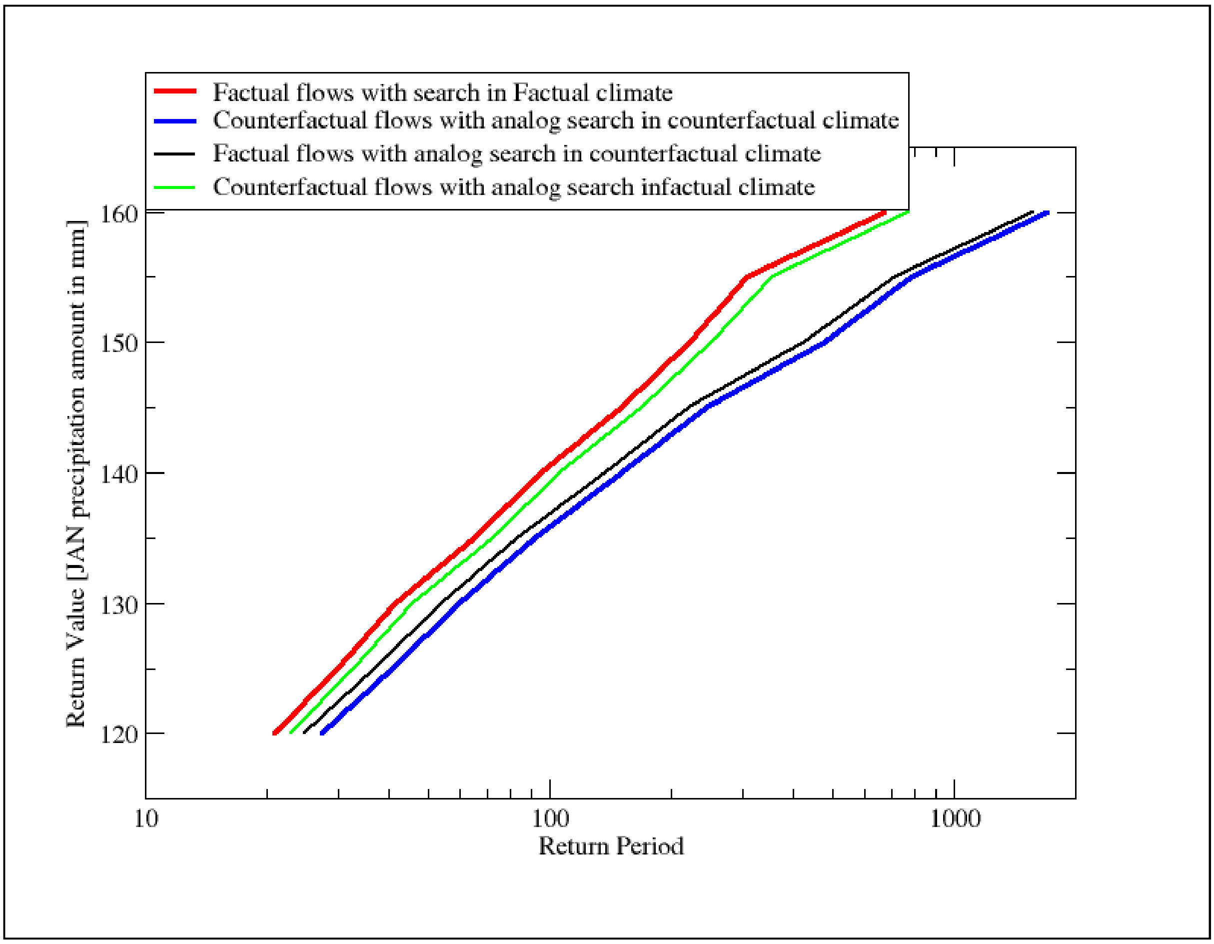

Figure 5: Return value vs. return period for the factual climate (red), the counterfactual climate (blue). These are calculated from monthly precipitation amounts searching respectively analogs in their respective climate. The black curve shows the distribution of extreme values by selecting flow analogs of the factual flows in the counterfactual period. The green curve shows the distribution of extreme values by selecting flow analogs of the counterfactual flows in the factual period. The difference between the black and blue curves represent the contribution due to dynamical changes while the

difference between the red and black curves shows the "thermo-dynamical" contribution. This difference is rather similar with that between red and green curves.

Discussion

These examples can be generalized to other types of extremes as the formulation is quite general. This will be applied for test cases of WP7. So far the analog method was found to be fairly successful for wintertime seasonal events (precipitation or temperature). This is due to the strong dependence of seasonal events on large-scale circulation. However such success is not guaranteed for short-term events or summertime events as other factors enter into play. In the summer case, the state of soil moisture, which depends on rainfall in previous months is also a major driver of hot seasons [Vautard et al., 2007; Seneviratne et al., 2010; Quesada et al., 2012], and for short-term convective events the large-scale situation and corresponding flow shape may not be as important as the convergence of moisture and vertical stratification of the atmosphere. The extension and testing of these concepts will be conducted through test cases of WP7.

3.4 Potential operational service application

There is a potential for operational application of flow analog method in the fast-track mode (however only for seasonal events), provided near real-time observations are accessible. There is however a need to evaluate the method against other methods in test cases before establishing confidence in the method for all types of events.

From observation and reanalysis alone, the analysis conducted for the wet winter can be generalized to other regions, and calculations can be done within a few hours. While analog metrics have been defined for Europe, they need to be tested with different domains for other regions of the world. It is not clear, in particular, that the method would properly work in tropical areas dominated by convection.

In fast track modes, graphs such as presented above from observations could be easily produced. The distinction between dynamical and thermo-dynamical contributions with large model ensembles in factual and counterfactual can be generalized but will not be easily implemented in real time unless precooked ensembles are ready. The size of the ensembles should not be too big otherwise calculations will be too long for fast-track attribution.

References

Cattiaux, J., Vautard, R., Cassou, C., Yiou, P., Masson-Delmotte, V., & Codron, F. (2010). Winter 2010 in Europe: a cold extreme in a warming climate. *Geophysical Research Letters*, *37*(20).

Cattiaux, J., Vautard, R., & Yiou, P. (2009). Origins of the extremely warm European fall of 2006. *Geophysical Research Letters*, *36*(6).

Huntingford, Chris, et al. "Potential influences on the United Kingdom's floods of winter 2013/14." *Nature Climate Change* 4.9 (2014): 769-777.

Lorenz, E. N. (1969). Atmospheric predictability as revealed by naturally occurring analogues. *Journal of the Atmospheric sciences*, *26*(4), 636-646.

Michelangeli, P. A., Vautard, R., & Legras, B. (1995). Weather regimes: Recurrence and quasi stationarity. *Journal of the Atmospheric Sciences*, *52*(8), 1237-1256.

van Oldenborgh, G.-J., D. B. Stephenson, A. Sterl, R. Vautard, P. Yiou, S. S. Drijfhout, H. von Storch and H. van den Dool, 2015: comment on 'Potential influences on the United Kingdom floods of Winter 2013/2014 by Huntingford et al', Nature Climate Change, 5, 490-491.

Quesada, B., Vautard, R., Yiou, P., Hirschi, M., & Seneviratne, S. I. (2012). Asymmetric European summer heat predictability from wet and dry southern winters and springs. *Nature Climate Change*, *2*(10), 736-741.

Schaller, N., A. L. Kay, R. Lamb, N. R. Massey, G.-J. van Oldenborgh, F. E. L. Otto, S. N. Sparrow, **R.** Vautard, P. Yiou, A. Bowery, S. M. Crooks, C. Huntingford, W. Ingram, R. Jones, T. Legg, J. Miller, J. Skeggs, D. Wallom, S. Wilson & M. R. Allen, 2015, Human influence on climate in the 2014 Southern England winter floods and their impacts. Nature climate change, in press.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., & Teuling, A. J. (2010). Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews*, *99*(3), 125-161.

Vautard, R., & Yiou, P. (2009). Control of recent European surface climate change by atmospheric flow. *Geophysical Research Letters*, *36*(22).

Yiou, P., Vautard, R., Naveau, P., & Cassou, C. (2007). Inconsistency between atmospheric dynamics and temperatures during the exceptional 2006/2007 fall/winter and recent warming in Europe. *Geophysical Research Letters*, *34*(21).

Zorita, E., & Von Storch, H. (1999). The analog method as a simple statistical downscaling technique: comparison with more complicated methods. *Journal of climate*, *12*(8), 2474-2489.

4. Lessons Learnt

- positive lessons:

It was found possible to distinguish dynamical vs. thermodynamical contributions in winter monthly to seasonal precipitation events. We found that within a few decades, regional seasonal amounts have increased by a few %, due to thermodynamical changes. This is quite consistent with what was found with other methods, for instance with large ensembles. Other methods involving regional modeling experiments are being carried out and also exhibit similar results.

- negative lessons:

The operational application in near real time for observations remains difficult due to long homogeneous data, including the last days, being difficult to access. For model applications, several applications must be conducted in order to gain confidence in the approach.

5. Links Built

The application of the methods will be made within WP7.