STARDEX

downscaling climate extremes

Executive summary

STARDEX is one of three projects which ran from 2001/02 to 2004/05, funded under the European Union Framework 5 Programme, which focused on the key question: How will the frequency and intensity of extreme weather events change by the end of the 21st century in response to global warming?

Based on extensive analyses of observed and climate model data, supported by an understanding of the underlying changes in atmospheric circulation and other physical processes, STARDEX convincingly demonstrated that:

- spatially coherent and, in many cases statistically significant, changes in European temperature and rainfall extremes have occurred and had an impact over the last 40 years, and major changes are projected for the future

- there are uncertainties in regional scenarios of extremes due, in part, to the method used to downscale from the relatively coarse global climate model scale to the finer spatial scale required for many impacts assessments

- there is, therefore, a need to take a multi-model approach to regional scenario construction, whether using statistical and/or dynamical downscaling methods.

STARDEX produced a set of application, robustness and performance criteria which allow identification of the most appropriate and better performing downscaling methods for any particular climate impacts assessment study. The STARDEX recommendations and points of good practice should thus be of interest to all developers and users of regional scenarios of extremes.

Contents

What is the STARDEX project?

How will the frequency and intensity of extreme weather events change by the end of the 21st century in response to global warming? This is the major question addressed by the European Union-funded STARDEX project using state-of-the-art climate modelling and regional downscaling techniques developed during the course of the project.

The climate of the 21st century is likely to be significantly different from that of the 20th because of human-induced climate change. Thus climate change scenarios are needed to assess the impacts of these changes on human activities and the environment. Global climate models provide the starting point for construction of these scenarios. Climate scenarios should not be viewed as forecasts, but rather as coherent, internally consistent and plausible descriptions of possible future states of the world.

The contrasting extremes of floods in central and eastern Europe and drought in southwestern Europe experienced during the summer of 2005 graphically illustrate the major impacts and damages associated with extreme weather events. Thus there is growing recognition that changes in the frequency and intensity of extreme events are likely to have more of an impact on the environment and human activities than changes in mean climate.

This has created a growing demand for more reliable, high-spatial resolution scenarios of extremes. This issue was the major focus of a cluster of three projects running from 2001/02 to 2004/05 and funded under the European Union Framework 5 Programme:

- MICE (Modelling the Impacts of Climate Change) http://www.cru.uea.ac.uk/projects/mice
- PRUDENCE (Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects) http://prudence.dmi.dk
- STARDEX (STAtistical and Regional dynamical Downscaling of EXtremes for European regions) http://www.cru.uea.ac.uk/projects/stardex

PRUDENCE focused on the development and application of regional climate models and MICE on the use of global and regional climate model output in climate change impacts studies. The twelve STARDEX partners *(page 20)* focused on two major objectives:

- To rigorously and systematically inter-compare and evaluate statistical and dynamical downscaling methods for the construction of scenarios of extremes for European regions;
- To identify the more robust downscaling techniques and to apply them to provide reliable and plausible future scenarios of temperature and rainfall-related extremes for European regions.

Bern, Switzerland, August 2005

What type of extreme weather events can we make statements about?

In an unchanging climate, extreme weather events are, by definition, rare. This is particularly so for the rarest and potentially the most catastrophic events. The summer of 2003, for example, was probably the hottest in Europe since at least AD 1500. Clearly, it is very difficult to draw general conclusions from very small sample sizes. In such situations, statistical techniques, such as the analysis of trends, must be used with great care. Thus STARDEX focused on relatively moderate extremes rather than the most extreme events. A set of ten core indices of extremes *(six for rainfall and four for temperature)* was used *(Table 1)*.

Many of the indices are based on thresholds defined using percentile values rather than fixed values. This makes them transferable across the range of climatic regimes experienced across Europe. The core set was carefully chosen to encompass magnitude (e.g., hot-day threshold), frequency (e.g., heavy rainfall days) and persistence (e.g., longest dry period) of extremes.

Extreme events such as the August 2002 floods in Central and Eastern Europe and the severe heatwaves experienced across many parts of Europe in August 2003 make headline news because of the associated losses of life, high economic damages and disruption, not because of their statistical properties. According to Munich Re, for example, the August 2002 floods were responsible for economic losses of 21.1 billion Euro and insured losses of 3.4 billion Euro, together with over 100 deaths. Although the STARDEX indices of extremes are defined primarily from a climatic perspective (and relatively moderate), they are still highly relevant in terms of impacts. The greatest 5-day rainfall amount, for example, is an important measure of extreme from the point of view of flooding in a large basin like the Rhine. The actual impacts of extremes will, however, depend on the particular susceptibility or vulnerability of the local population and environment. Thus defining extremes in terms of climatic variables rather than their impacts gives more objective and consistent indices.

The statistical downscaling of extreme events is a very new area of study. Thus the STARDEX project focused on the two most common climate variables: temperature and rainfall. A somewhat different set of indices of extremes, including storm-related indices, was used by the MICE project on the impacts of climate change. The annual number of days with wind speed above a threshold of 25 m/s, for example, was used as a measure for the frequency of high winds.

Table 1: The STARDEX indices of extremes.

The STARDEX rainfall-related indices of extremes		**User-friendly name**
pq90	90th percentile of rainday amounts (mm/day)	Heavy rainfall threshold
px5d	Greatest 5-day total rainfall (mm)	Greatest 5-day rainfall (amount)
pint	Simple daily intensity (rain per rainday)	Average wet-day rainfall (amount)
pxcdd	Maximum number of consecutive dry days	Longest dry period
pfl90	% of total rainfall from events > long-term 90th percentile	Heavy rainfall proportion
pnl90	Number of events > long-term 90th percentile of raindays	Heavy rainfall days
The STARDEX temperature-related indices of extremes		
txq90	Tmax 90th percentile (°C) – the 10th hottest day per season	Hot-day threshold
tnq10	Tmin 10th percentile (°C) – the 10th coldest night per season	Cold-night threshold
tnfd	Number of frost days Tmin < 0 °C	Frost days
txhw90	Heat wave duration (days)	Longest heatwave

What is downscaling and why is it needed?

Global climate models are grid-box models, developed from numerical weather forecasting models, and provide the starting point for constructing climate scenarios. Their relatively coarse spatial resolution (typically 300 km by 300 km over Europe – Figure 1), means that downscaling is required to the finer spatial scales relevant for studying the impacts of climate change. This might be much finer resolution grids (e.g., 50 km or even 1 km) or individual points (for consistency with instrumental station locations).

River Trent and M1 motorway, UK, 10 November 2000

Grid-box averages provided by global climate models are just that. In the case of rainfall, for example, they provide area-averaged values which differ in their statistical properties to point values. The former will tend to give more wet days and generally lower magnitude extreme events, for example, than observed at a single point. Thus downscaling is particularly needed in the case of rainfall extremes and in regions with complex topography (compare the top two panels in Figure 2).

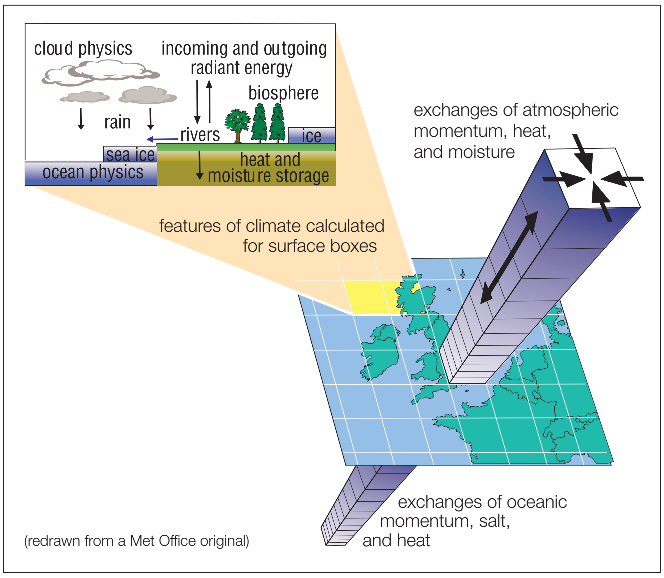


Figure 1: Conceptual structure of the HadCM3 global climate model.

To be worthwhile, downscaling should provide added value and should reflect the sub-grid scale processes that are lacking from global climate models. Thus downscaling should involve more consideration of physical processes, and should give more skill, than simple linear interpolation of grid-box averages to point locations.

The STARDEX work is based on the suite of climate models developed by the Hadley Centre, UK Met Office. The first in this suite of models is the HadCM3 global model (Figure 1) which has a horizontal resolution in the model atmosphere of 2.5° latitude by 3.75° longitude – giving only nine grid points over the UK, for example. The Hadley Centre has used output from HadCM3 to drive the HadAM3P global atmospheric model which has a grid-box resolution equivalent to about 150 km by 150 km over Europe. It is output from HadAM3P that provides the starting point for the STARDEX downscaling activities.

What downscaling methods are available?

Two major approaches to downscaling, dynamical and statistical, began to be developed and tested 5-10 years ago by a number of different research groups and were shown to offer good potential for the construction of high-resolution climate change scenarios. Initially, work on both approaches focused on their use in the construction of scenarios of change in mean climate. The major goal of STARDEX was to explore the utility of these approaches, and to develop improved methods, for the construction of scenarios of extremes.

Dynamical downscaling involves the nesting of a finer-scale regional climate model within the coarser global climate model. Statistical downscaling involves the application of relationships identified in the observed climate, between the large and smaller-scale, to climate model output. It is based on two major assumptions. The first assumption is that the observed relationships are applicable to a future warmer climate (this is known as the stationarity assumption). The second assumption is that the large-scale circulation patterns are better represented than the local weather patterns in global climate models.

In all, 22 different statistical downscaling methods were developed and tested by STARDEX. These are grouped into the following categories:

- multiple linear regression
- canonical correlation analysis
- artificial neural networks
- multivariate autoregressive models
- conditional resampling and other analogue-based methods
- methods based on a 'potential precipitation circulation index' and 'critical circulation patterns'
- a conditional weather generator
- local scaling and dynamical scaling

The methods range from standard linear regression methods, through methods focusing on spatial patterns (such as canonical correlation analysis), to non-linear neural network methods and other novel methods, including analogue-based methods. STARDEX provides the most systematic evaluation of these particular approaches to date. The 22 STARDEX methods can be divided into 'daily' methods, where daily time series are downscaled and indices of extremes calculated, and 'seasonal' methods where seasonal indices of extremes (Table 1) are downscaled directly.

The state-of-the-art regional climate models run in the PRUDENCE project have a spatial resolution of 50 km, giving improved representation of, for example, rainfall extremes in mountainous areas compared with the underlying global model (Figure 2). Since many of the PRUDENCE simulations were also driven by the same Hadley Centre global models as used for statistical downscaling in STARDEX, this permitted a direct comparison of the two general approaches to downscaling.

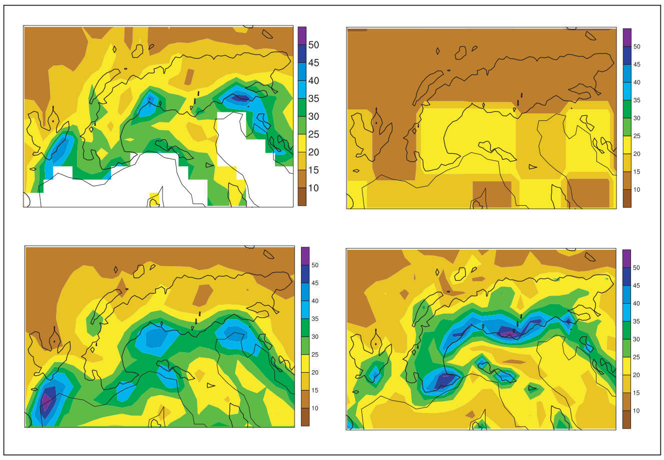


Figure 2: The autumn heavy rainfall threshold (mm per day) simulated by the HadAM3P global climate model (top right), the Swiss CHRM (lower left) and UK HadRM3H (lower right) regional climate models, compared with observed gridded data (top left).

Have changes in extremes occurred over the last 40 years?

STARDEX analysed trends over the last 40 years in the core indices of extremes using observed station data for six case-study regions, and a specially-constructed dataset of 491 European-wide daily station records. These analyses show that spatially coherent and, in many cases, statistically significant changes in European temperature and rainfall extremes have occurred over the last 40 years.

The temperature indices indicate a general shift to warmer conditions with more hot and fewer cold extremes, e.g., fewer frost days (Figure 3a) and longer heatwave duration (Figure 3b). In the German Rhine, for example, the hot-day threshold has increased by 2.7°C and 1.1°C in winter and summer respectively (Figure 4). The European-wide changes in temperature extremes can be summarised as follows:

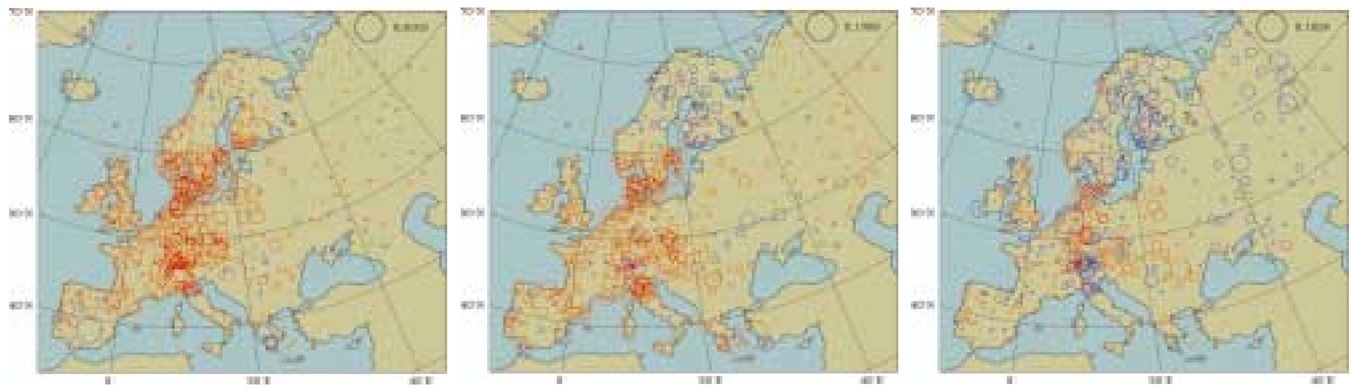
Winter:

- Extreme maximum temperature increased over most of the region except the southeast
- Extreme minimum temperature increased over the entire region, apart from small decreases in parts of Greece, the Iberian Peninsula and Scandinavia
- Extreme minimum temperature increased to a larger degree than the corresponding extreme maximum temperature

Summer:

- Extreme maximum temperature increased in most areas, except in northern Scandinavia, Eastern Europe and Russia
- Extreme minimum temperature increased in most areas, except that a few stations showed a decrease.

The rainfall trends are more spatially and seasonally variable. Results for the case-study regions (Table 2) indicate trends towards more extreme rainfall in winter and autumn in Switzerland, for example, contrasting with negative trends in winter and spring and positive trends in summer and autumn in Emilia Romagna to the southeast. In Switzerland, however, the winter/autumn increase is restricted to northerly (Figure 5) and westerly regions and contrasts with a decrease in rainfall in the Mediterranean part of the Alps. For the UK and the German Rhine, there is a contrast between the strong winter trend to more extreme rainfall and the summer trend towards drier conditions. In the German Rhine, the greatest 5-day rainfall amount has risen by 37% on average across the basin in winter (Figure 6) and fallen by 11% in summer. These spatial complexities are further revealed in the European-wide analyses (Figure 3c), which can be summarised as follows:



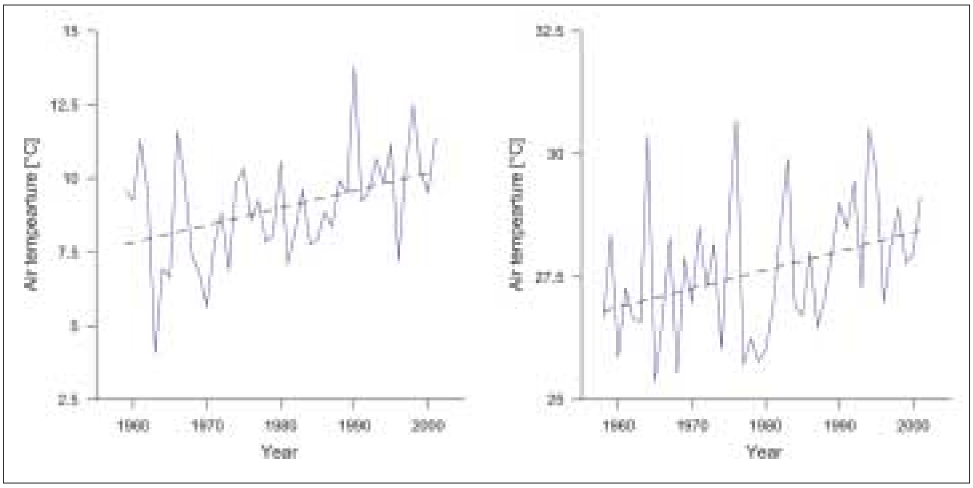
(a) Winter frost days
Red is decreasing

(b) Summer heatwave duration
Red is increasing

(c) Summer heavy rainfall days
Blue is increasing

Figure 3: 1958-2000 trends in indices of extremes for 491 European stations. Scale is days per year. Thus the circles in the top-right of each figure indicate a total change over the 1958-2000 period of 35, 8 and 4.5 days respectively.

Figure 4: 1958-2001 trend in the hot-day threshold (°C) for 232 German Rhine stations in winter (left) and summer (right).



The dried-up River Töss, Central Switzerland, 28 August 2003

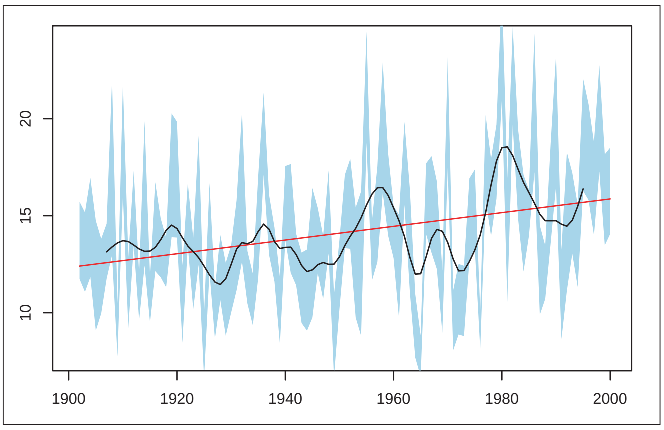


Figure 5: Trend in the winter heavy rainfall threshold (mm per day) for stations in the Swiss Central Lowlands and the northern fringes of the Alps.

Winter longest dry period:

- Increased in the southern part of the region
- Decreased in the north

Summer longest dry period:

- Less coherent signal
- Most stations in the central part, the UK, and southern Scandinavia showed an increase

Winter heavy rainfall extremes:

- Increased in central Europe, the UK and Scandinavia
- Decreased in Eastern Europe, Greece and western part of the Iberian Peninsula

Summer heavy rainfall extremes:

- Increased across northern Scandinavia and northwestern Russia
- Decreased across the UK and NE Europe
- Increased across SW Europe
- Decreased across the northern Iberian Peninsula

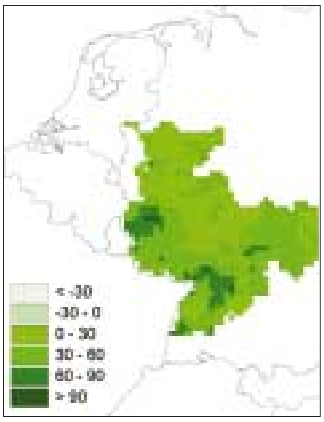


Figure 6: Percentage change over the period 1958-2001 in the greatest 5-day winter rainfall (mm) for 611 German Rhine stations.

	Winter	Spring	Summer	Autumn
UK (SE and NW England)	++		--	
German Rhine	++	+	--	+
Northern Italy (Emilia Romagna)	-	-	+	+
Greece	-	-		
Switzerland	++	Variable	Variable	++
French Alps	Variable	Variable	Variable	+

Table 2: Summary of changes in extreme heavy rainfall indices for the STARDEX case-study regions
+ = positive/increasing trend, - = negative/decreasing trend
++ and - - indicate strongest, most significant trends

Can these changes in extremes be related to changes in circulation and other aspects of the atmosphere?

As well as analysing past changes in extremes, STARDEX investigated relationships between these changes and changes in large-scale circulation patterns, focusing on potential predictor variables for statistical downscaling. It was found that, in part, the observed changes in extremes can be explained by changes in large-scale circulation and other predictors.

The relationships tend to be stronger in winter than in other seasons, particularly for rainfall. Two examples of the relationships identified are presented here.

The first example focuses on relationships between the North Atlantic Oscillation (widely recognised as a major influence on European mean winter climate) and spatial patterns in European-wide trends in the number of heavy winter rainfall days (Figure 7) and the longest dry period. This reveals that the North Atlantic Oscillation is an important influence on extreme rainfall, as well as mean rainfall, across Europe in winter. The similarity of the spatial patterns of the indices (indicated by canonical correlation patterns), and the linear trends in the indices (indicated by their principal components), suggests that it is mainly changes in the North Atlantic Oscillation that have caused the observed changes in the indices. In particular, the trend towards increased heavy winter rainfall in northern Europe and decreased heavy rainfall in southern Europe, is consistent with the trend of the North Atlantic Oscillation towards positive values, which is associated with lower pressure anomalies over Scandinavia and higher pressure anomalies centred over the Iberian Peninsula and extending over the Mediterranean, and hence with stronger westerly airflow over northwestern Europe (Figure 7).

It was not within the scope of the STARDEX project to determine whether the observed changes in extremes and/or

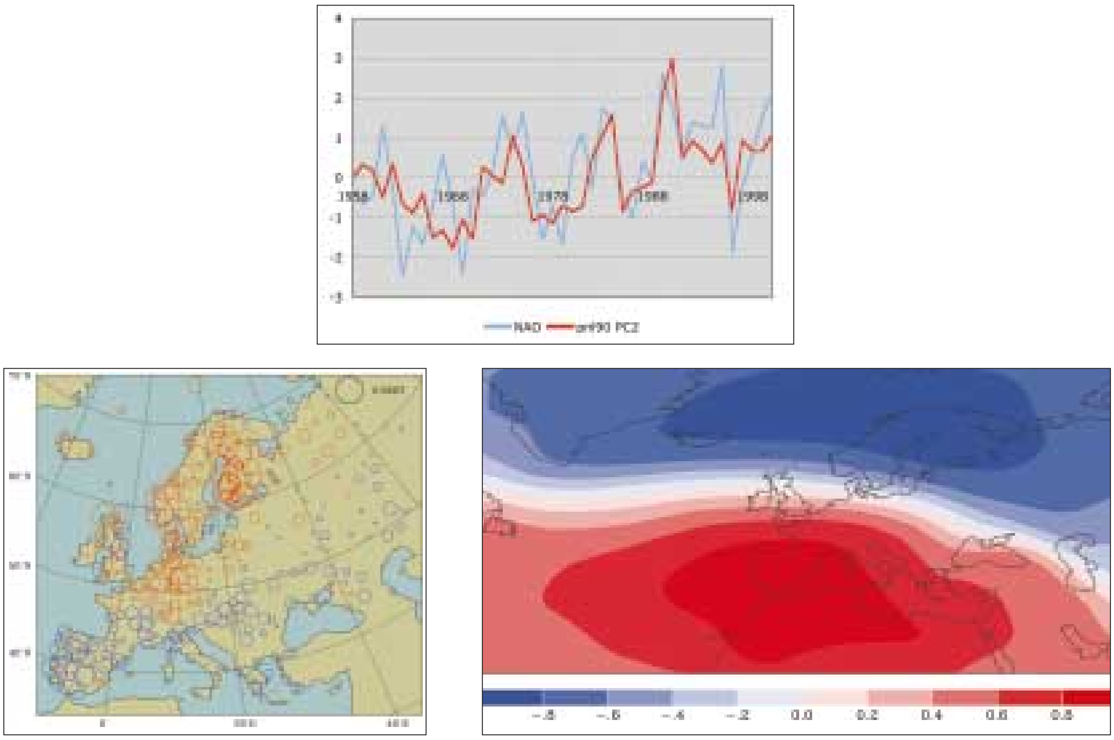


Figure 7: Correlation between the North Atlantic Oscillation (NAO, blue line) and the second principal component (PC2, red line) of the number of heavy winter rainfall days (top). First canonical pattern of heavy winter rainfall days (bottom left: red circle indicates a positive trend/relationship, blue circle a negative trend/relationship) and the associated sea level pressure anomaly pattern (bottom right – dimensionless units).

circulation can be attributed to human influence. However, comparisons between the observed North Atlantic Oscillation variability and that of climate models run under present conditions show that the recent strong positive trend is very improbable due to natural forcing only. This suggests that it is due to human causes. However, although climate models run with greenhouse gas forcings do show a change to more positive North Atlantic Oscillation values, the magnitude of the trend is less than that observed in recent decades. This suggests that either the Oscillation is more sensitive to the forcings than the models or that the trend has been enhanced by natural variability.

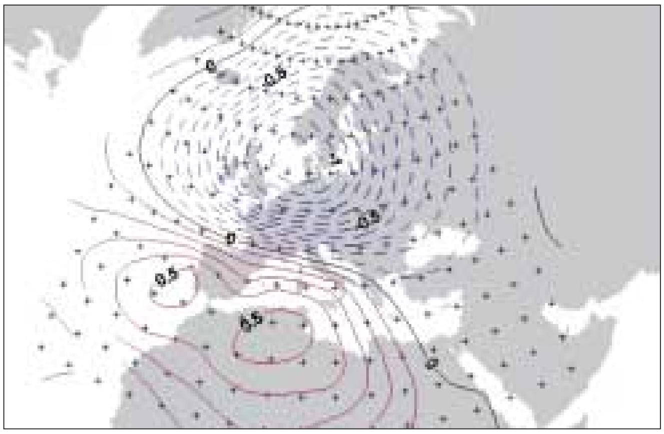


Figure 8: Sea level pressure anomalies of the objectively classified CP11 circulation pattern. CP11 is classified using reanalysis sea level pressure and runoff data for the Moselle river.

The second example concerns links between severe winter storms and river flooding in southwest Germany. The well-known West cyclonic (Wz) zonal circulation pattern is very similar to the objectively defined "critical" circulation pattern CP11 (Figure 8). These patterns are the most important for causing severe winter storms in Europe (including the series of winter storms in January and February 1990 and the 1999 winter storms Anatol, Lothar and Martin) and river flooding in southwest Europe. The "critical" CP11 has increased significantly in frequency and maximum persistence (Figure 9). Consistent with this, the longer record of Wz events (not shown), indicates that the risk of an 'extreme zonal winter' within the 'critical sector' (defined as winters with more than 35% Wz days and a maximum persistence of more than 13 days) has increased dramatically by a factor of more than 20 in the period 1982/83 to 2003/04 compared to the period 1881/82 to 1981/82.

These two examples demonstrate that relationships can be found between rainfall extremes and large-scale circulation patterns. STARDEX also found relationships with temperature extremes. The increased frequency of frost days over parts of the Greek mainland (Figure 3a), for example, is associated with an increased frequency of cold anticyclonic conditions at the surface with a long duration, thus explaining a localised trend which appears to contradict the more general warming.

Brienz, Switzerland, 24 August 2005

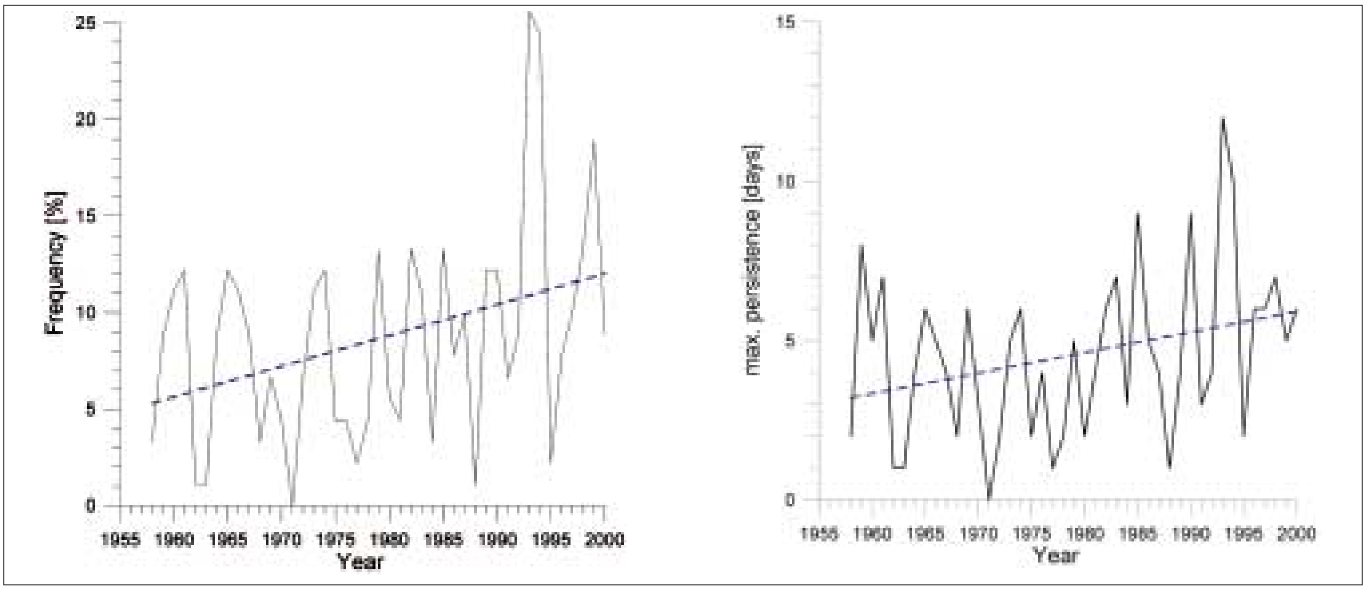


Figure 9: Critical circulation pattern CP11 in winter for the period 1958 to 2001 – frequency (left-hand side) and maximum persistence (right-hand side).

Can these extreme event/circulation relationships be used to project changes in extremes?

These relationships between extreme events and large-scale circulation patterns provide a sound basis for statistical downscaling, provided that the two underlying assumptions of statistical downscaling *(see page 5)* are met. In order to address the stationarity assumption it is considered important to incorporate additional predictor variables, particularly humidity-based variables, into downscaling models which are going to be used for climate-change applications.

Good predictor variables are defined by STARDEX as:
- Having strong, robust and physically-meaningful relationships with the local surface climate
- Having stable and stationary (in time) relationships with the local surface climate
- Explaining low-frequency (i.e., year-to-year and multi-year) variability and trends
- Being at an appropriate scale (in terms of both physical processes and global climate model performance)
- Well reproduced by global climate models (thus meeting the second assumption).

These considerations are incorporated in the STARDEX criteria for assessing the robustness of statistical downscaling methods. There are four components to these criteria: strength and stability; stationarity; uniformity of performance; and reliability of simulation of predictors. Key questions and recommended assessment methods for addressing them have been identified during the course of the project. The one issue that cannot be fully tested is stationarity, i.e., to what extent is it legitimate to extrapolate a statistical model based on present-day relationships to a future period which is projected to be warmer than any observed over the last 40 years?

Although the stationarity issue means that a stable statistical model which performs well for the present day is not necessarily the one that will perform best for the future, we can have greater confidence in models which do perform well for the large variability seen in the present day. Thus evaluating model skill using independent data is a crucial element of any statistical downscaling application. The STARDEX methods were extensively evaluated for present-day conditions using observed reanalysis data as the predictors and focusing on indices of extremes. Particular emphasis was given to how well year-to-year variability is reproduced (measured by correlations), since if it cannot be well modelled, this implies that relevant predictors may be missing or that noise far overshadows any model skill. Averaging the results across stations, indices, seasons and methods, allowed identification of a number of key messages:

- Skill varies from station-to-station (in particular), season-to-season, index-to-index, and method-to-method (Figure 10)

- But not systematically, which makes it hard to pick a single best method, particularly when working at the station scale

- Performance is generally better for temperature than rainfall, better for means than extremes, and best in winter and worst in summer (Figures 10 and 11)

- However, there are always exceptions to the rules, e.g., in Greece, the poorest rainfall results are for autumn

- A two-step European-wide analogue method performs well for temperature (Figure 11), as well as or better than locally developed methods

- The performance of non-linear neural network methods is quite good, particularly with respect to year-to-year rainfall variability (Figure 10)

- For rainfall extremes, measures of occurrence and persistence, notably the longest dry period, are better represented than intensity characteristics (Figure 10).

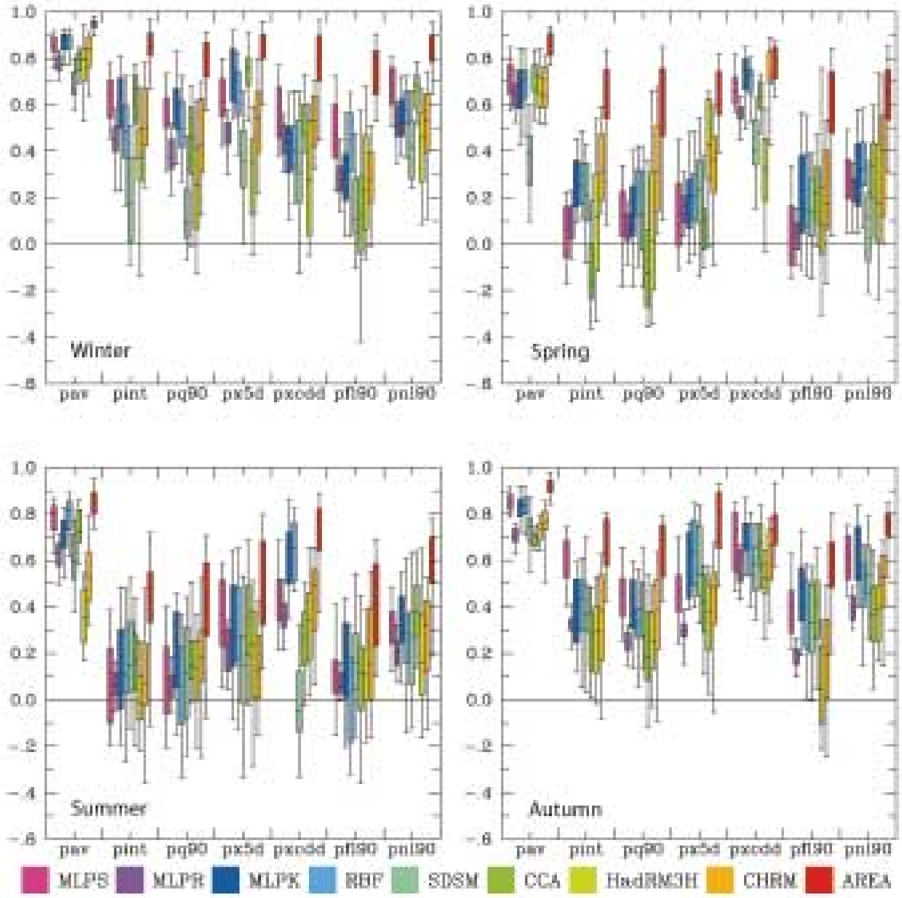


Figure 10: Correlation of modelled and observed rainfall indices (Table 1) for each season for SE England (28 stations) for the independent validation period 1979-1993. On the vertical axis, 0.0 indicates no correlation, 1.0 a perfect correlation. Coloured bars and vertical lines indicate the range across the stations. The first six methods are statistical (MLPR, MLPK and RBF are neural network methods), while HadRM3H and CHRM are regional climate models. AREA is the regional area average. pav is the average daily rainfall amount (mm).

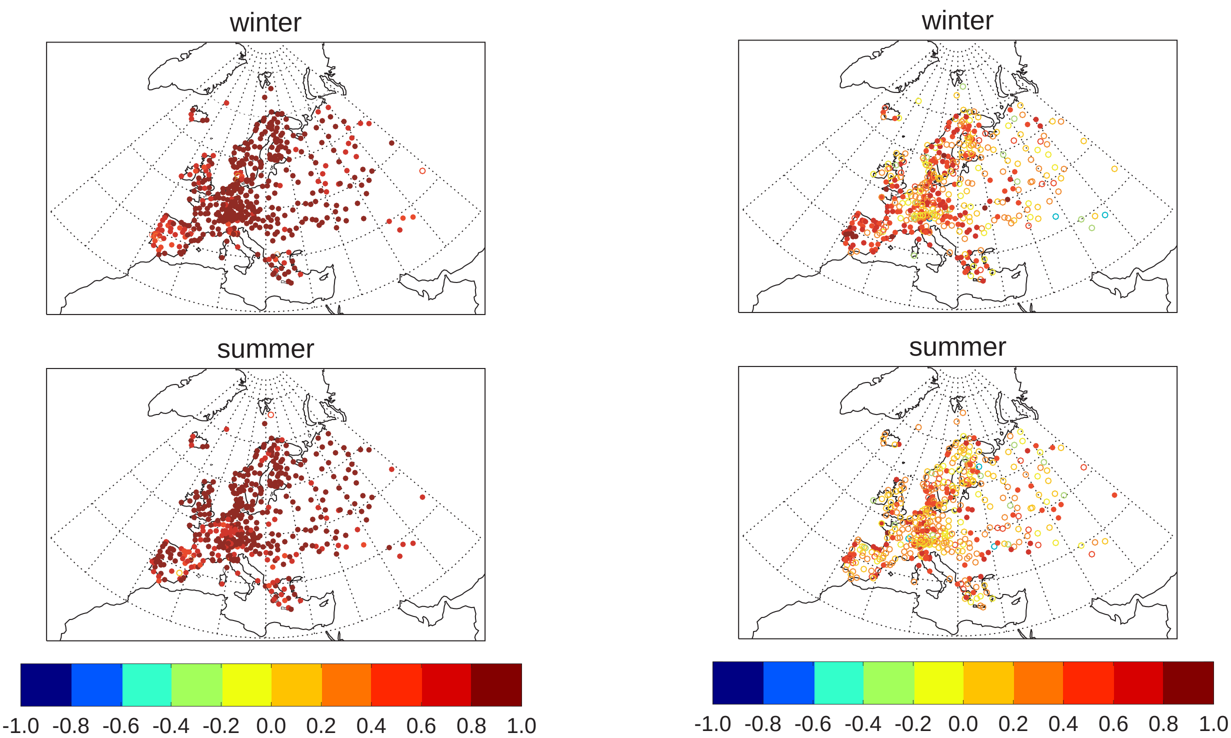


Figure 11: Correlations between observed and downscaled, using the FIC two-step analogue method, hot-day threshold (left-hand side) and greatest 5-day rainfall (right-hand side) for the European-wide dataset, for winter (upper panel) and summer (lower panel).

Will extremes become more frequent and/or intense in the future?

STARDEX has developed improved statistical downscaling methods which have been rigorously evaluated and inter-compared. The most robust of these methods, together with output from regional climate models (dynamical downscaling), have been used to construct scenarios of extremes for 2071-2100 (the 2080s) for the A2 and B2 emissions scenarios for the STARDEX case-study regions and Europe as a whole. According to these scenarios, major changes in extremes are projected for the future, though the nature of these changes, particularly for rainfall, varies from season-to-season and region-to-region.

The statistical relationships identified from observed data were applied to output from the HadAM3P global climate model in order to construct scenarios of extremes for two of the IPCC (Intergovernmental Panel on Climate Change) SRES (Special Report on Emissions Scenarios) scenarios: A2 – a medium-high emissions scenario, with atmospheric CO_2 concentrations reaching 715 ppm at 2100; and B2 – a medium-low scenario, with CO_2 reaching 562 ppm. Scenario changes for the six case-study regions are outlined below (more details are available from the STARDEX web site), focusing more on rainfall than temperature changes as the former tend to be more complex. Note that the results are based on just one global climate model, and are for the 2080s.

SE and NW England: we are confident that in winter both average and extreme rainfall are likely to increase by a factor of 1 to 1.25 in both regions, with a corresponding decrease in the longest dry period. In summer, we are less confident but the models indicate more of a decrease in both average and extreme rainfall.

German Rhine: Significant increases in temperature extremes are expected by the end of the 21st century with more severe increases in summer (Figure 12), accompanied by higher year-to-year variability. A similar increase is expected in the magnitude and frequency of occurrence of heavy rainfall in winter. The greatest 5-day winter rainfall, for example, is projected to increase by up to 50% for the A2 scenario (Figure 13). For other seasons, nothing can be said with confidence about the possible changes of rainfall extremes as the models do not agree on the direction of change.

Emilia Romagna: Significant increases are projected in temperature extremes during winter and autumn, when the minimum temperature increases more than the maximum. In contrast, maximum temperature increases more in spring. The number of frost days is projected to decrease, and heatwave duration to increase (particularly in summer). The rainfall scenarios indicate a slight increase during summer and autumn. A significant increase in the longest dry period is projected for autumn.

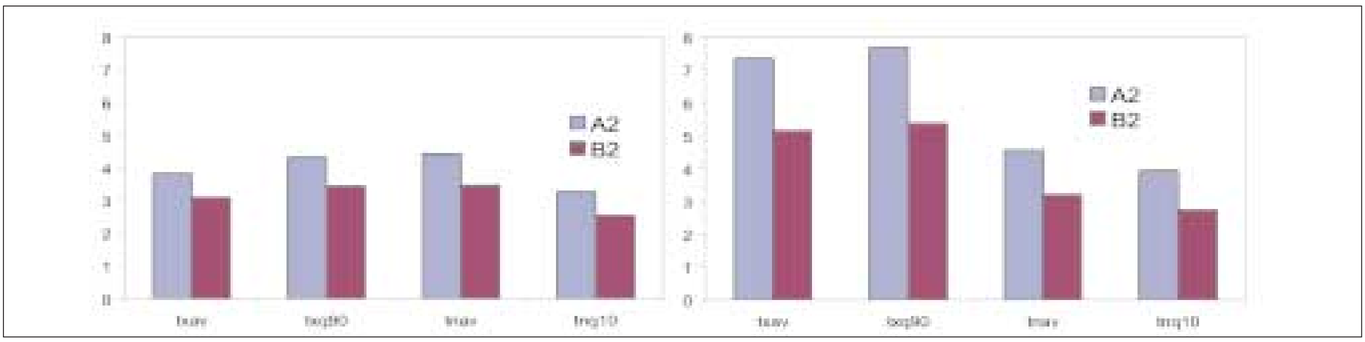


Figure 12: Statistically downscaled scenario changes in the mean values of the temperature indices – see Table 1 - (°C) averaged over German Rhine stations for winter (left-hand side) and summer (right-hand side). txav/tnav = average maximum/minimum temperature.

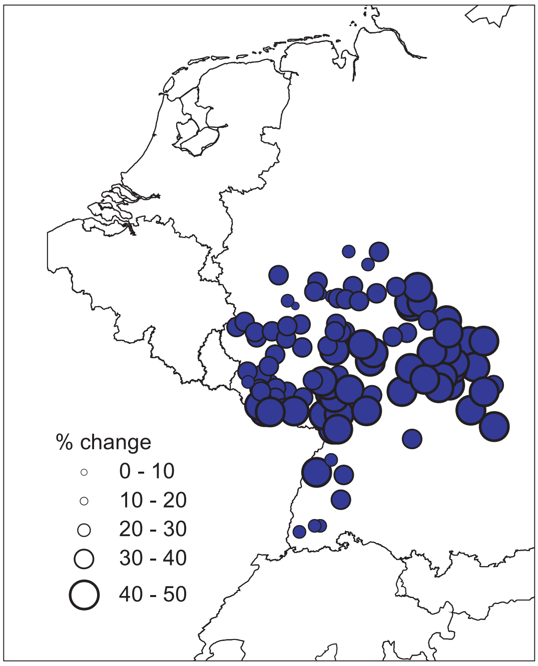


Figure 13: Percentage change in the statistically downscaled greatest 5-day winter rainfall for the German Rhine under the A2 emissions scenario. The blue infilling indicates that all changes are statistically significant.

Greece: Temperature means and extremes are projected to increase. For some indices of extremes, the changes for the B2 emissions scenario are comparable to those for the higher A2 scenario. An increase in rainfall extremes is projected for winter in central continental Greece and in part of the Aegean Sea (but a decrease in autumn). A decrease is projected in other parts of the country in winter. Longest dry periods are projected to lengthen in winter in all parts except the west (A2 scenario) and the south (B2 scenario).

Iberian Peninsula: For western Iberia, the projected rainfall changes are very small (a tendency towards slightly drier conditions) in winter, contrasting with large decreases in mean rainfall and most indices of extremes in the other seasons.

Changes in the longest dry period are, however, relatively modest and there is some indication of a slight increase in the proportion of rainfall coming from heavy events. All the high temperature extremes are projected to increase, with the exception of heatwave duration. Large decreases in the number of frost days are projected. For Southeast Spain, the projected changes indicate greater uncertainty, including some contradictory changes. This is related to the generally poorer evaluation results in this region of Spain.

Alps: A detailed comparison of rainfall scenarios constructed using statistical (six methods) and dynamical (three regional climate models) downscaling was undertaken for the Alps (Figure 14). There is reasonably good agreement between the two approaches for winter, showing that the scenario results (indicating generally wetter conditions with more intense extremes) are fairly reliable and robust. In summer, the differences between methods, particularly the statistical and dynamical models, are much larger. In general, however, a tendency towards drier conditions or little change is projected for summer.

Bätterkinden, Switzerland, August 2005

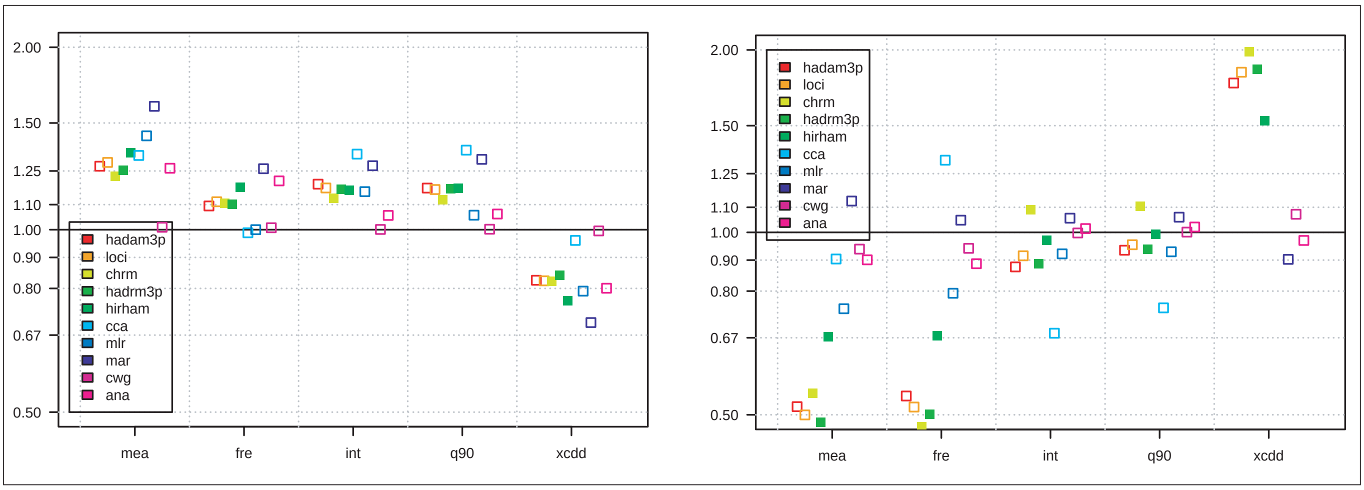


Figure 14: Simulated change (ratio of future to present day) for the A2 emissions scenario in winter (left-hand side) and summer (right-hand side) rainfall indices for the west Alpine region. Ratios > 1 indicate an increase, ratios < 1 a decrease. Filled symbols: regional climate models (chrm, hadrm3p, hirham), open symbols: statistical downscaling methods (loci, cca, mlr, mar, cwg, ana). Results for the underlying global climate model (hadam3p) are also shown. mea = mean rainfall, fre = frequency of rainfall; int = average wet-day rainfall, q90 = heavy rainfall threshold, xcdd = longest dry period.

Do these projected changes in extremes matter?

The STARDEX scenarios indicate increases/decreases in the frequency and intensity of hot/cold extremes throughout Europe, together with more spatially and seasonally variable changes in the occurrence of rainfall extremes (encompassing both wetter and drier conditions). Experience of recent extreme events, together with impacts modelling work, implies that these changes will have major impacts on the environment and human activities.

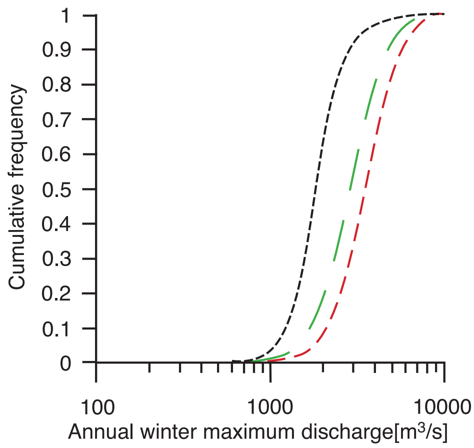


Figure 15: Statistically-downscaled flow duration curve for the Cochem gauge on the Mosel tributary of the River Rhine, for the present day (black curve), and 2071-2100 for the B2 (green curve) and A2 (red curve) emissions scenarios.

The economic losses associated with the Central and Eastern European floods of August 2002 have already been mentioned (page 3). Five of the winters in the 15-year period 1989/90 to 2003/04 fell within the 'critical sector' (see page 9) and according to estimates from Munich Re caused economic losses due to floods and winter storms of 40 billion $ US. The human impacts of extreme heatwave conditions are graphically illustrated by summer 2003 - estimates for the number of European heat-related deaths vary (reflecting the difficulty of directly linking extreme events and their human impacts), but could be as high as 40,000.

The MICE project focused on modelling the impacts of climate extremes. Amongst the impacts considered were Mediterranean forest fire, boreal forests, health, agriculture, wind storm damage, and implications for the energy, property insurance and tourism industries.

STARDEX did not specifically look at impacts. However, a regression-type statistical approach was used to relate winter maximum river discharge with seasonal indices of extreme rainfall calculated from regional series. Figure 15 shows the projected changes in flow duration for a gauge on the Mosel tributary of the River Rhine, while Table 3 summarises the corresponding changes in the 100 year return period winter discharges for this and four other tributaries. Substantial increases in extreme discharges are projected (although somewhat smaller for the Ruhr which is affected by upstream reservoirs), consistent with the projected increase in greatest 5-day winter rainfall (Figure 13), and the observed increase in this variable (Figure 6). These changes imply a substantial increase in flooding risk in these tributaries.

Table 3: Scenario changes in the 100 year return period winter discharge (Q100) for five gauges located in different tributaries of the River Rhine for the A2 and B2 emissions scenarios.

Gauge	Drainage area[km²]	% increase in Q100 relative to the control period	
		A2 scenario	B2 scenario
Rockenau (Neckar)	12655	109	55
Frankfurt (Main)	24764	103	53
Cochem (Mosel)	27088	104	69
Grolsheim (Nahe)	4013	109	65
Villigst (Ruhr)	2009	58	36

How confident can we be in these projections?

Although only the more robust statistical downscaling methods were used to construct the STARDEX scenarios of extremes, uncertainties still arise, particularly in the case of summer rainfall extremes. In many cases, the latter scenarios should be used with extreme care. STARDEX has demonstrated that uncertainties due to the statistical downscaling method need to be considered alongside the other sources of climate scenario uncertainty.

Uncertainties in climate scenarios are related to:

- The forcing emissions scenarios, i.e., inter-scenario variability
- The response of different climate models, i.e., inter-model variability
- Different realizations of a given forcing scenario with a given climate model, i.e., internal or intra-model variability (which is, in part, a reflection of natural climate variability)
- Sub-grid-scale forcings and processes, i.e., uncertainties due to downscaling method.

STARDEX explored a number of these uncertainties:

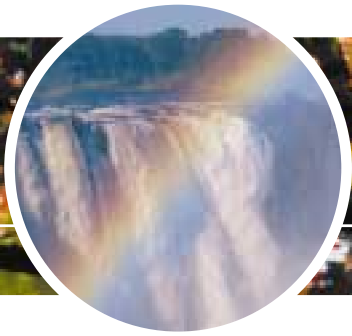
- **Emissions scenarios:** the A2 and B2 IPCC SRES scenarios were used
- **Intra-model uncertainty:** downscaled scenarios based on three ensemble members of HadAM3P A2-forced simulations were compared
- **Downscaling method:** scenarios were constructed using a number of different statistical downscaling methods for each region and inter-compared. For some regions, statistical and dynamical downscaling methods/scenarios were also inter-compared.

The main contribution of STARDEX to understanding the sources of uncertainty is with respect to the statistical downscaling method. Uncertainties arise due to choice of statistical method, predictors and their domain. Inter-model differences in the downscaled scenarios for a single station were shown to be at least as large as the differences between the emissions scenarios in some cases. Uncertainties tend to be smaller for temperature than rainfall, and the largest uncertainties are associated with summer rainfall scenarios. This is evident both in poorer evaluation results (Figures 10 and 11) and greater variability in scenario change across methods (Figure 14). This is likely to be related to the lower spatial coherence (and hence predictability) of summer rainfall.

One of the two headline conclusions from the evaluation analyses is that, for many regions and indices, the skill (or confidence) is unacceptably low for summer rainfall – thus scenarios are, at best, only indicative.

STARDEX did not address inter-model uncertainties associated with the choice of driving global climate model, since only the HadAM3P model was used. However, the PRUDENCE project has demonstrated that this is a major source of uncertainty with respect to dynamical downscaling, and this conclusion is also expected to be valid for statistical downscaling.

What is the most appropriate method of downscaling for my impacts study?



The second headline conclusion from the STARDEX evaluation studies is that, in the majority of cases, no consistently superior statistical downscaling model can be identified, particularly when working at the station scale. Thus a major recommendation is to use a range of the better statistical downscaling methods – just as it is recommended good practice to use a range of global/regional climate models for scenario construction.

Good practice in scenario development should include demonstration of the need for downscaling for each user's specific application. For some applications, this need will be more pressing, e.g., those requiring information about extremes at a high temporal and spatial resolution. The end-user needs will also help to determine which downscaling approach (dynamical or statistical) is most appropriate and, if statistical downscaling is adopted, which specific methods are most appropriate. The STARDEX application criteria have been developed for this purpose. They encompass spatial and temporal scale and consistency, together with resource (computing and data) requirements. Application criteria for the dynamical and statistical downscaling general approaches are shown in Table 4.

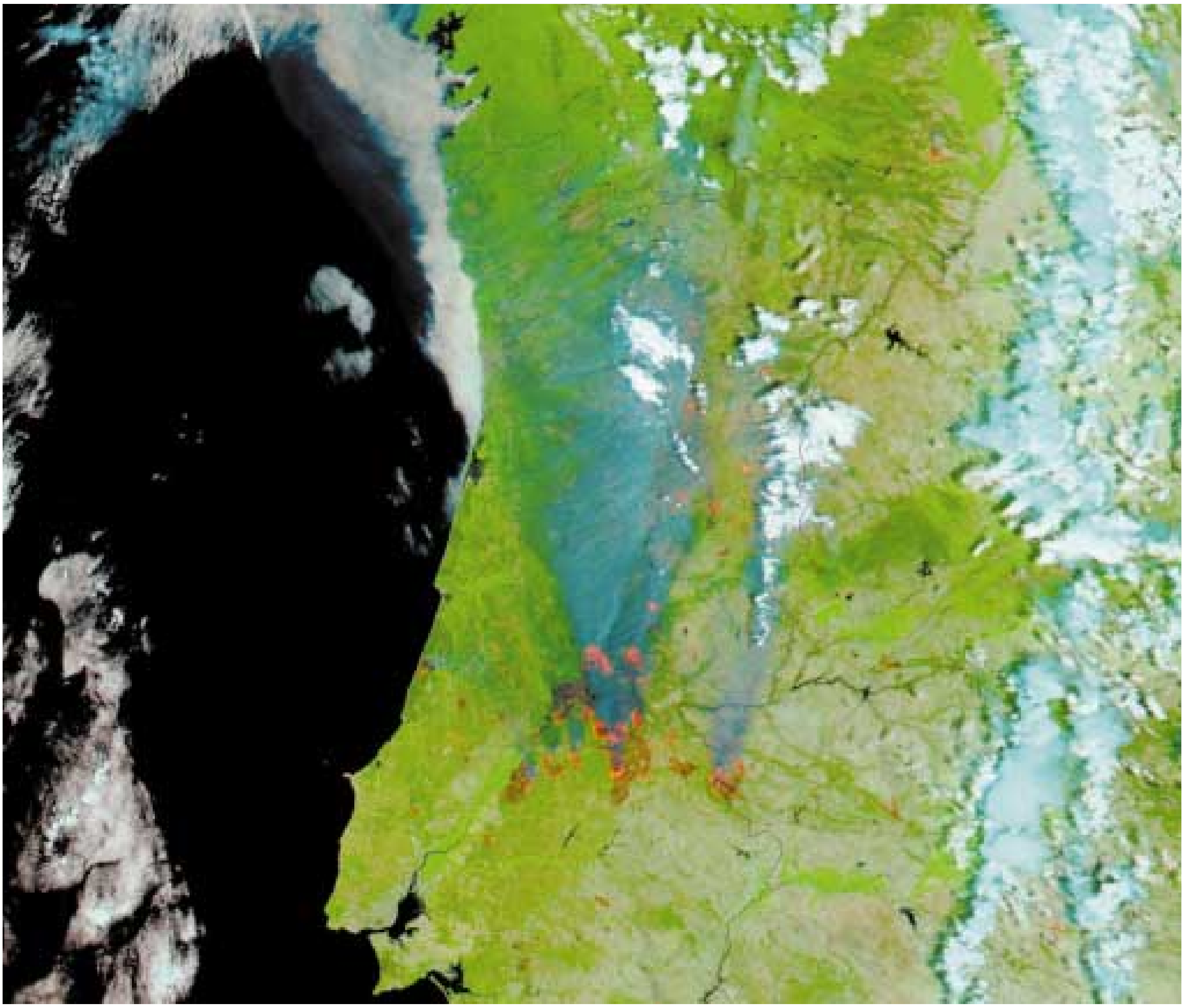
Application criteria for the specific statistical downscaling methods developed during the STARDEX project are available from the STARDEX web site as part of a report on 'Recommendations on the more robust statistical and dynamical downscaling methods for the construction of scenarios of extremes'. This report also describes the STARDEX robustness criteria (see page 10), together with the third set of criteria designed to guide developers and users of downscaled scenarios of extremes – the performance criteria. The latter summarise the relative performance confidence and overall performance of each method, as well as indicating the optimal spatial scale and recommended impact applications.

The three sets of STARDEX criteria (application, robustness and performance) allow identification of the most appropriate and better performing downscaling methods for a particular application. Wherever possible, it is strongly recommended that a range of the most appropriate/better methods, encompassing different statistical and/or dynamical methods (i.e., different regional climate models), is used. The report mentioned above provides further recommendations and points of good practice based on the STARDEX experience, and builds on the IPCC guidelines for statistical and dynamical downscaling.

Langnau, Switzerland, 22 August 2005

Method provides:	Dynamical downscaling	Statistical downscaling
Station-scale information	No	Yes
Grid-box information	Yes	Yes
European-wide information	Yes	Some methods
Daily time series	Yes	Yes – for 'daily' methods
Temperature and rainfall values which are physically consistent with each other on a daily/seasonal basis	Yes, in theory	Some methods available
Physically and spatially consistent values for multiple sites	Yes, in theory	A few methods available
Information at sites with no observations	Yes	No
Method requirements:		
Computing resources	High	Medium/low
Volume of data inputs	High	Medium/low
Availability of input data	Currently restricted to a few global climate models	Medium/low for observed data

Table 4: STARDEX application criteria for dynamical and statistical downscaling



Enhanced satellite image of fires and smoke across Portugal, 3 August 2003

What further research is needed?

STARDEX has undertaken a rigorous and systematic evaluation of improved statistical and dynamical downscaling methods and demonstrated that these can be used to construct scenarios of extremes. It has also been demonstrated, however, that there are uncertainties in these scenarios due, in part, to the downscaling method used. There is, therefore, a need to take a multi-model approach to regional scenario construction in the future, whether using statistical and/or dynamical downscaling methods.

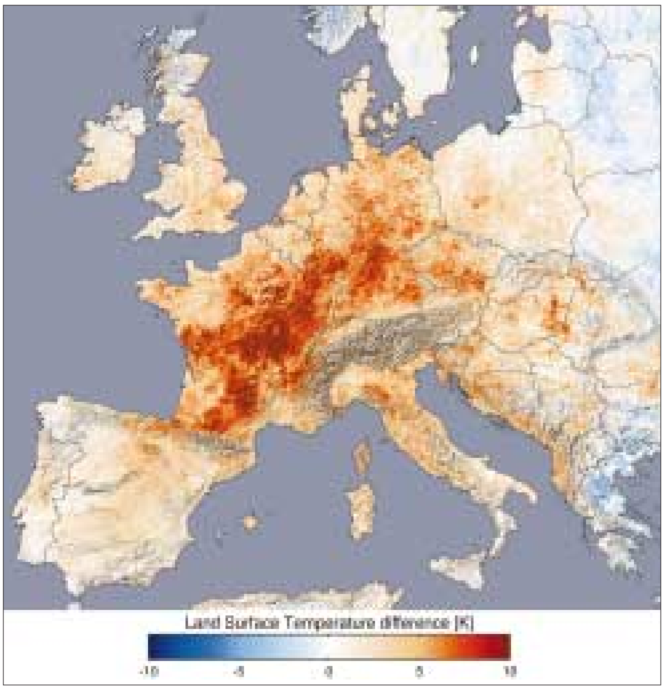
This implies a need for the development of new and efficient tools and techniques for combining output from multiple downscaling models. In STARDEX, simple averaging across methods was used, rather than, for example, attempting to weight each method in terms of its reliability. These are all issues related to the construction of probabilistic scenarios, which are being developed in the Framework 6 ENSEMBLES project (http://www.ensembles-eu.org) and for which STARDEX has provided a sound scientific starting point.

In STARDEX, statistical downscaling was based on output from global climate models. In theory, these methods can also be applied to regional climate model output (provided that the spatial scale of the predictors does not exceed the more restricted spatial domain of the regional models and that they still have physical meaning at these finer scales). This is another issue that will be explored in the ENSEMBLES project.

STARDEX focused on relatively simple indices of extremes based on single variables, i.e., temperature or rainfall. In terms of impacts, however, joint-probability events can be important (e.g., wind-driven rain), together with preceding conditions (e.g., a wind storm will cause more damage due to uprooted trees if the ground is already saturated) and sequences of events (e.g., a run of summers with heatwaves of comparable severity to 2003 would have major implications for health and infrastructure). The appropriateness of existing downscaling methods for such complex events requires assessment. The availability of suitable observed data sets may, however, impose some restrictions on the research that is possible.

The move towards developing publicly-available downscaling tools, together with the desirability of focusing more on those extreme events that are most relevant in terms of impacts, implies a need for scenario developers and end users to work more closely together. The STARDEX work was guided by external experts, including, for example, representatives from the European re-insurance industry. However, it is clear that more effort is needed in this respect. Hopefully this report will help to present the key scientific issues to a broader audience and thus pave the way for future fruitful dialogue and collaboration.

Finally, although STARDEX has illustrated the uncertainties associated with scenarios of extremes, the main findings of the project are clear – that major changes in extremes have occurred and had an impact over the last 40 years, and major changes are projected for the future.



Satellite image of temperature difference for July/August 2003 compared to the 2000-2002/2004 average.

Further reading and resources

Christensen, J.H. *et al.,* 2005: 'Evaluating the performance and utility of regional climate models in climate change research: Reducing uncertainties in climate change projections – the PRUDENCE approach', *Climatic Change,* submitted.

Goodess, C.M. *et al.,* 2005: 'An intercomparison of statistical downscaling methods for Europe and European regions – assessing their performance with respect to extreme temperature and precipitation events', *Climatic Change*, submitted.

Haylock, M.R. and Goodess, C.M., 2004: 'Interannual variability of European extreme winter rainfall and links with mean large-scale circulation', *International Journal of Climatology*, 24, 759-776.

Haylock, M.R. *et al.,* 2005: 'Downscaling heavy precipitation over the UK: a comparison of dynamical and statistical methods and their future scenarios', *International Journal of Climatology*, submitted.

Hundecha, Y. and Bárdossy, A., 2005: 'Trends in daily precipitation and temperature extremes across western Germany in the second half of the 20th century', *International Journal of Climatology,* 25, 1189-1202.

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Mearns, L.O. *et al.,* 2003: *Guidelines for Use of Climate Scenarios Developed from Regional Climate Model Experiments,* Intergovernmental Panel on Climate Change (IPCC) Task Group on Data and Scenario Support for Impacts and Climate Analysis (TGICA), available from: http://ipcc-ddc.cru.uea.ac.uk/guidelines/dgm_no1_v1_10-2003.pdf

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Schmidli, J. *et al.,* 2005: 'Statistical and dynamical downscaling of precipitation: Evaluation, intercomparison, and scenarios for the European Alps', *Journal of Geophysical Research,* in preparation.

Wilby, R.L. and Harris, I., 2005: 'A framework for assessing uncertainties in climate change impacts: low flow scenarios for the River Thames, UK', *Water Resources Research,* submitted.

Wilby, R.L. *et al.,* 2004: *Guidelines for Use of Climate Scenarios Developed from Statistical Downscaling Methods,* Intergovernmental Panel on Climate Change (IPCC) Task Group on Data and Scenario Support for Impacts and Climate Analysis (TGICA), available from: http://ipcc-ddc.cru.uea.ac.uk/guidelines/StatDown_Guide.pdf.

ENSEMBLES website: http://www.ensembles-eu.org

MICE website: http://www.cru.uea.ac.uk/projects/mice

PRUDENCE website: http://prudence.dmi.dk

STARDEX website: http://www.cru.uea.ac.uk/projects/stardex

The STARDEX website provides access to all public project outputs, including software for calculating indices of extremes, statistically-downscaled scenario data and non-restricted observed data, together with a number of technical reports (including one on trends in extreme daily rainfall and temperature across Europe in the second half of the 20th century) and non-technical information sheets. The latter include a set on the regional case-study scenario changes that are likely to be of particular interest to the readers of this report. The web site also includes a complete list of scientific papers based on the STARDEX work.

Contact details

For further information about STARDEX please visit the project website at http://www.cru.uea.ac.uk/projects/stardex or send an email to the STARDEX co-ordinator c.goodess@uea.ac.uk

STARDEX partners	Contact name	Postal address	Phone	Email
UEA: University of East Anglia	Clare Goodess	UEA, Norwich, NR4 7TJ, UK	44 1603 592875	c.goodess@uea.ac.uk
KCL: King's College London	Rob Wilby now with the Environment Agency	Environment Agency Trentside Offices, Nottingham, NG2 5FA, UK	44 115 8463727	rob.wilby@environment-agency.gov.uk
FIC: Fundación para la Investigación del Clima	Jaime Ribalaygua	C/Tremp 11 Esc. 3, 5ª, 28040 Madrid, Spain	34 91 4503393	fic@ficlima.org
UNIBE: University of Berne, Institute of Geography	Evi Schuepbach	Hallerstrasse 12, 3012 Berne, Switzerland	41 31 6318843	cabo@giub.unibe.ch
CNRS: Institut Non Lineaire de Nice_Sophia-Antipolis UMR6618 CNRS	Guy Plaut	1361 route des Lucioles, 06530 Valbonne, Sophia-Antipolis, France	33 492 96 73 10	guy.plaut@inln.cnrs.fr
ARPA-SMR: Servizio Meteorologico Regional, ARPA-Emilia Romagna	Carlo Cacciamani	Viale Silvani 6, 40122 Bologna, Italy	39 51 6497609	ccacciamani@smr.arpa.emr.it
ADGB: Atmospheric Dynamics Group, University of Bologna	Ennio Tosi	Viale Berti Pichat 6/2, 40127 Bologna, Italy	39 51 630 5214	e.tosi@adgb.df.unibo.it
DMI: Danish Meteorological Institute	Torben Schmith	Lyngbyvej 100, OE Copenhagen, Denmark	45 39 15 74 44	ts@dmi.dk
ETH: Swiss Federal Institute of Technology	Juerg Schmidli	Winterthurerstr. 190, CH-8057 Zürich, Switzerland	41 44 632 3495	schmidli@env.ethz.ch
FTS: Stuttgart University of Applied Sciences	Hans Caspary	Schellingstr. 24, D-70174 Stuttgart, Germany	49 721 892037	hans.caspary@hft-stuttgart.de
USTUTT-IWS: University of Stuttgart	Andras Bárdossy	Pfaffenwaldring 61, 70550 Stuttgart, Germany	49 711 6854663	bardossy@iws.uni-stuttgart.de
AUTH: Aristotle University of Thessaloniki	Panagiotis Maheras	University Campus, 54124 Thessaloniki, Greece	302 310 998471	maheras@geo.auth.gr

For further information about the European Commission research programme please contact the project officer Dr Georgios Amanatidis (Georgios.Amanatidis@cec.eu.int) or visit the following website: http://europa.eu.int/comm/research/environment/index_en.htm

Acknowledgements

The STARDEX consortium would like to gratefully acknowledge the continuing support and assistance provided by the European Commission in funding the project. Special thanks go to the Project Officer, Dr Georgios Amanatidis, and his predecessor Dr Ib Troen. In addition, STARDEX would like to acknowledge the Hadley Centre for Climate Prediction and Research, UK, for allowing the use of their climate model data. The European Union funded MERCURE and PRUDENCE projects are also thanked for providing regional climate model data.

Finally, STARDEX thanks the many external experts who attended the project meetings and who provided feedback and advice:

Alain Bourque – OURANOS, Canada
Simon Brown – Hadley Centre, UK
Erasmo Buonomo - Hadley Centre, UK
Pierre Carrega – University of Nice, France
Steve Charles – CSIRO, Australia
Andrew Dlugolecki – Climatic Research Unit Visiting Fellow, UK
Philippe Gachon – OURANOS, Canada
Pamela Heck – SwissRe, Switzerland
Richard Jones – Hadley Centre, UK
Wolfgang Kron – MunichRe, Germany
Linda Mearns – UCAR, USA
Taha Ouarda – OURANOS, Canada together with colleagues from the MICE (**Jean Palutikof** and **Clair Hanson**) and PRUDENCE (**Jens Hesselberg Christensen**) projects.

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for further information

STARDEX co-ordinator: Dr Clare Goodess
Email: c.goodess@uea.ac.uk
Website: www.cru.uea.ac.uk/projects/stardex/

Address:
Climatic Research Unit
School of Environmental Sciences
University of East Anglia
Norwich NR4 7TJ
United Kingdom

An EU Project funded under Framework Programme 5
European Commission DG Research
Contract number: EVK2-CT-2001-00115