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Abstract

The authors describe the construction of a comprehensive set of high-resolution grids of monthly climate at spatial resolutions of 10 minutes for Europe and 0.5 degrees for the global land surface. Five climate variables are included: temperature, diurnal temperature range, precipitation, vapour pressure, and cloud cover. The set comprises the observed climate record (1901–2000), a control scenario (1901–2100) and 16 scenarios of projected future climate (2001–2100). The 16 climate change scenarios represent all combinations of four emissions scenarios and four global climate models (GCMs), covering 93% of the range of uncertainty in global warming in the 21st century published by the Intergovernmental Panel on Climate Change. Thus these scenarios permit users to assess the implications for climate impacts of some of the major sources of uncertainty in future climate. The scenarios were constructed by combining time-series of global warming and patterns of change from GCMs with the baseline climate and sub-centennial variability from the observed record. Thus these grids provide homogenous 200-year transient scenarios (1901–2100) for users projecting the future impacts of climate change using environmental models. These grids are publicly available through the Climatic Research Unit (http://www.cru.uea.ac.uk).

1 Introduction

It is desirable that any study of the potential consequences of future climate change should use the best available information about projected climates. These projections are most commonly obtained from global climate model (GCM) simulations of the climate response to a given scenario of future greenhouse gas and aerosol emissions into the atmosphere. Future emissions depend on human actions and are inherently unpredictable. In addition, the effects of changing emissions on climate are not yet properly understood and cannot be modelled with confidence. For these reasons, model projections of climate change are described as scenarios rather than predictions (Mearns et al, 2001; Carter et al, 2001).

The earliest studies of the potential impacts of global warming in Europe were based on idealised equilibrium GCM simulations (usually 2 x CO2). Sometimes results from only one model were used to illustrate potential impacts in a single study (e.g. Emanuel et al, 1985 for global natural vegetation zones) or across a range of impact studies to ensure consistency (e.g., the IIASA/UNEP studies of impacts on agriculture in selected countries — Parry et al, 1988). Other studies recognised inter-model uncertainties and adopted outputs from several GCMs (e.g. Santer, 1985 for impacts on biomass potential in western Europe; Rotmans et al, 1994 for impacts on various sectors in Europe using the ESCAPE model).

Later climate scenarios were based on more realistic transient GCM simulations. Transient simulations permitted impacts to be expressed in terms of rates of change as well as magnitudes (e.g. Carter et al, 1991; Barrow, 1993; Arnell, 1998), and climate change to be related to concurrent non-climatic changes (e.g. Barrow et al, 1996 for climate and CO2 concentration; Parry et al, 2000 for climate, CO2 and socio-economic futures in the ACACIA project). An alternative approach was to use a composite scenario based on results averaged across several GCMs (e.g. Saelthun et al, 1998 for impacts on energy production in the Nordic region). Recent studies have also stressed the importance of capturing additional sources of uncertainty attributable to multi-decadal natural variability (e.g. Hulme et al, 1999).

One feature of most of these scenario construction exercises was a focus on particular time horizons in the future, often 30-year periods, for which impacts were estimated and compared to impacts during a baseline period (commonly 1961–90). Some employed a pattern scaling technique (Santer et al, 1990, and see review by Mitchell, 2003) to scale the GCM pattern of climate change obtained for a given emissions scenario to represent higher or lower emissions or to represent earlier or later time periods in the future.

Most scenarios provided monthly climate information on a regular grid, which limited their immediate value for impacts sensitive to climate at higher temporal and spatial scales. The information presented was either at the GCM’s native grid resolution or else interpolated to the resolution of the relevant observed climate data. Techniques were advocated for obtaining high resolution data at individual sites using weather generators (Wilks, 1992) or statistical downscaling (Wilby and Wigley, 1997). The ESCAPE model computed impacts from scenarios obtained by combining a database of GCM patterns of climate change and a database of climate observations (Rotmans et al, 1994).

This paper describes a set of high-resolution gridded data-sets (‘grids’) of monthly climate information based on climatological observations and on outputs from transient coupled atmosphere-ocean GCM simulations. An initial set of gridded scenarios (referred to as TYN SC 1.0) was developed at a 10 minute spatial resolution (2001–2100) for Europe. These grids were constructed as part of the ATEAM project, to permit a vulnerability assessment of ecosystems and their services during the 21st century in Europe. These ATEAM climate scenarios were developed in conjunction with scenarios of atmospheric composition and land use change to estimate potential impacts on natural vegetation, agriculture, forests, runoff and biodiversity (ATEAM, 2003). The data set was subsequently extended to the global land surface — except Antarctica — at a 0.5 degree resolution (TYN SC 2.0) for purposes of biogeochemical modelling.

To produce the scenarios and enhance their utility, it was necessary to provide comparable observed grids (1901–2000) for Europe (10 minute: CRU TS 1.2) and the globe (0.5 degree: CRU TS 2.0), and to calculate the mean climate (‘climatology’) for 1961–90 across the globe (10 minute: CRU CL 2.1). To provide a more convenient data-set for large-scale socio-economic applications, the global half-degree grids were also converted into country averages for a set of 289 countries and territories, following Mitchell et al (2002): TYN CY 1.1 uses the observed grids (CRU TS 2.0), and TYN CY 3.0 uses the scenario grids (TYN SC 2.0).

The grids were designed for flexible application with a wide variety of impact models, such that:

1. Analysts may apply part or all of the scenario time series from 1901–2100 for any of the five climate variables included: temperature, diurnal temperature range, precipitation, vapour pressure and cloud cover.

2. By combining four emissions scenarios with four GCMs, the resulting 16 scenarios incorporate much of the uncertainty in future climate change.

3. The grid-based design permits the data to be directly applied at grid-box resolution (e.g. Arnell, 1998), as regional means (e.g. Mitchell et al., 2002). Finer resolution information may be derived by spatial (e.g. Zaidman et al, 2002) or temporal (e.g. Pidgeon et al, 2001) resampling; statistical downscaling or weather generators might also be used.

The design of the grids is described first (section

2). The data and methods for the 20th (section 3) and 21st (section

4) centuries are treated separately. The grids themselves are presented in section 5, followed by some concluding remarks (section 6). The algebraic notation and acronyms are summarised in the Appendix.

2 Design

The period covered subdivides neatly into two centuries: the 20th (1901–2000) and 21st (2001–2100). Since our aim was to satisfy impact modellers, it was not a priority to supply observed data up to the present day. It was sufficient to use observations for the 20th century (section 2.1) and present scenarios for the 21st century (section 2.2). A parallel control scenario that covers both centuries permits improvements in experimental design (section 2.3).

2.1 20th century: observations

The observed 20th century is a reference data-set needed for impact model evaluation; it also provides a realistic spin-up for transient impact models. Gridded observations, already available for 1901–1995 (New et al, 2000), will be extended to 2000 by updating the underlying databases.

2.2 21st century: scenarios

The scenarios for the 21st century were designed to provide as full a representation of the uncertainties in projections of regional climate change as possible. Two sources of uncertainty are addressed directly, a third is treated partially, and a fourth possible source is acknowledged, but not considered. A scenario is presented for each permutation of emissions (4) and GCM (4). This scenario structure allows the implications of different sources of uncertainty to be considered systematically. The sources of uncertainty are now briefly described.

2.2.1 Emissions

The SRES report (IPCC, 2000) provides a comprehensive set of 40 socio-economic futures, and details their consequences for anthropogenic emissions of greenhouse gases and other pollutants. The full set is too large for our purpose, so we adopt four of the six illustrative scenarios (A1FI, A2, B2, B1). These four represent 68% of the range of uncertainty in emissions published by SRES, as measured by the cumulative carbon dioxide emissions (1990–2100), compared to the full set of 40 SRES scenarios (IPCC, 2000, Table SPM-3a).

2.2.2 Climate models

A more important source of uncertainty in global and regional climate changes arises from differences between climate models. In this study four different GCMs represent the time-series of global warming and the patterns of change in the mean.

2.2.3 Internal variability of the climate system

The magnitude of anthropogenic climate change projected for the globe lies well outside modelled natural variability — from decades to centuries — under all SRES scenarios (Mitchell et al, 1999). However, at spatial scales from continental down to a grid box, and especially for variables other than temperature, substantial multi-decadal variations may make it difficult to detect a climate change signal (e.g. Carter et al, 2000).

Some of this uncertainty is addressed by using an ensemble of simulations from a GCM, but ensembles were not available for all GCMs or all emissions scenarios. However, the scenario design makes it possible for the user to remove the effects of multi-decadal variability on their results. Here, the variability observed in the 20th century is superimposed on the the mean changes projected for the 21st century, so comparison between equivalent periods in the two centuries removes all but anthropogenic climate changes. One consequence of this approach is that possible future changes in multi-decadal or inter-annual variability are not included in these scenarios.

2.2.4 Non-linearities

Although experiments with GCMs have explored non-linear behaviour in the climate system (e.g. Cox et al, 2000; Thorpe et al, 2001), GCM simulations forced with SRES emissions scenarios have exhibited markedly linear behaviour. The extent to which this is the case may be judged by the accuracy of pattern scaling techniques (Mitchell et al, 1999; Mitchell, 2003). Although it is possible to develop gridded scenarios from GCM simulations that include non-linear behaviour, this cannot be achieved within the SRES structure, since such GCM simulations usually involve arbitrary and large perturbations of particular aspects of the GCM. Therefore this source of uncertainty must be omitted.

2.3 Control scenario

Since the scenarios are intended to allow the investigation of the possible impacts of climate change, a control scenario is provided, in which centennial (not sub-centennial) climate change is eliminated. The control scenario (1901–2100) assumes no changes in radiative forcing. This is not a plausible scenario, but it offers the opportunity to calculate the future — or present — impacts of climate change in an absolute sense (i.e. compared to an absence of climate change), rather than in merely a relative sense (i.e. the comparison of one climate change scenario with another).

The convention is to calculate impacts relative to the recent past, most commonly 1961–90 (e.g. Mearns et al, 2001). This period also has the advantage of the best observational record (e.g. Figure 1, discussed below). Therefore the observed 1961–90 climate is made the fixed average around which climate varies through the course of the control scenario.

Previously, long control simulations have been used to assess the effects of natural climate variability (Hulme et al, 1999; Carter et al, 2000). Had long control simulations from the four GCMs been readily available, an expanded set of control scenarios could have represented natural variability on multi-decadal and centennial time scales.

3 Data and methods: 20th century

3.1 Data

Our design requires three new data-sets of gridded observations, identified in section Table *2: The sources of station observations from which the CRU databases were updated. See Table 7 for acronym meanings.*

3.2. The new grids belong to a series of data-sets based on a single set of observational databases, the result of the work of a number of individuals over a long period of time, held by the Climatic Research Unit (CRU) of the University of East Anglia (UK). Figure 1 indicates the temporal extent of the databases. In order to provide greater clarity to users, we have developed a consistent form of identification for these data-sets (Table 1). We — including the lead authors of all the data-sets concerned — urge the adoption of these labels wherever possible. These data-sets are publicly available (CRU, 2003).

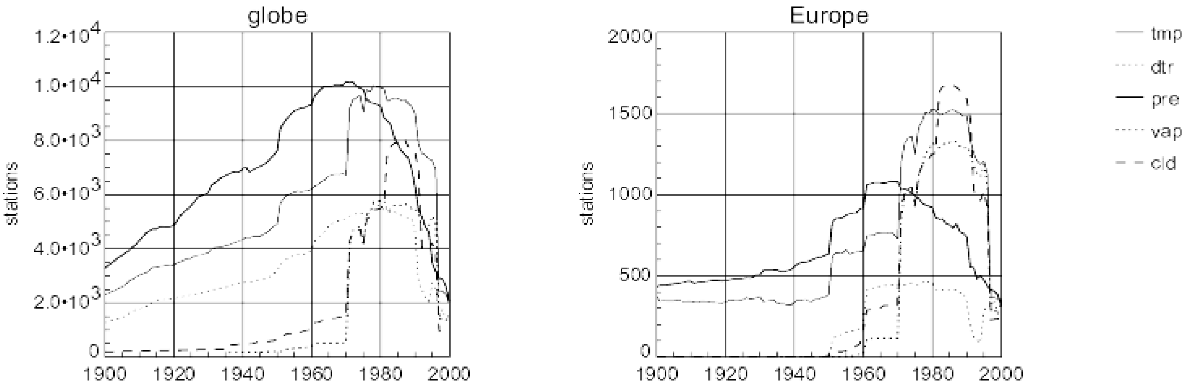


Figure 1: The average number of station observations available in the CRU databases (per month), as a function of climatic variable and time, for the global land surface (left) and Europe (right).

data-set	Space	time	variety	reference
CRU CL 1.0	0.5°	1961–90	climatology	New et al, 1999
CRU CL 2.0	10’	1961–90	climatology	New et al, 2002
CRU CL 2.1	10’	1961–90	climatology	this paper
CRU TS 1.0	0.5°	1901–1995	time-series	New et al, 2000
CRU TS 1.1	0.5°	1996–1998	time-series	New et al, 2000; extended
CRU TS 1.2	10’ Europe	1901–2000	time-series	this paper
CRU TS 2.0	0.5°	1901–2000	time-series	this paper
TYN SC 1.0	10’ Europe	2001–2100	scenarios	this paper
TYN SC 2.0	0.5°	2001–2100	scenarios	this paper
TYN CY 1.1	Country	1901–2000	countries	this paper
TYN CY 2.0	Country	2070–2099	countries	Mitchell et al, 2002; extended
TYN CY 3.0	Country	2001–2100	countries	this paper

Table 1: Identification, specification and source of UEA high-resolution gridded monthly climate data-sets. The identifying label is made up of the institution of origin, a label denoting the type of data-set, and a version number. The institutions are the Climatic Research Unit (CRU) and the Tyndall Centre for Climate Change Research (TYN). The type of data-set may be a climatology (CL), an observed time-series (TS), a set of scenarios (SC), or a set of country averages (CY).

The new grids are based partly on the observed grids summarised in Table 1, and partly on updates to the CRU databases. The most important sources of additional data are summarised in Table 2.

source	variables	reference
Jones and Moberg	Tmp	Jones and Moberg, 2003
Hulme and Lister	Pre	Mike Hulme, pers. comm.
CLIMAT	pre, dtr, sun, vap	UK Met Office, pers. comm.
GHCN v2	tmp, pre, dtr	Peterson et al, 1998
Hahn	cld, tmp, vap	Hahn and Warren, 1999
MCDW	Sun	William Angel, pers. comm.

Table 2: The sources of station observations from which the CRU databases were updated. See Table 7 for acronym meanings.

3.2 Method

3.2.1 10 minute climatology (globe)

Additional observed climatologies (1961–90) were calculated for cloud cover and vapour pressure for Europe at 10 minute resolution (CRU CL 2.1). These were obtained from the existing climatologies of sunshine and relative humidity (CRU CL 2.0) by simple conversions, as described by New et al (1999).

3.2.2 10 minute time-series (Europe)

Time-series (1901–2000) were calculated for the five climate variables — temperature, diurnal temperature range, precipitation, vapour pressure and cloud cover — for Europe at 10 minute resolution (CRU TS 1.2).

The CRU databases were updated from the sources in Table 2. Except Hahn, all sources supplied monthly values (averages or totals) for individual meteorological stations. Since Hahn supplied synoptic (i.e. 3-hourly) values, these were converted into monthly means using a two-pass procedure: first the climatology was calculated by synoptic hour, using all available data; then the daily and monthly anomalies were calculated, and the climatology and anomalies then added together.

Time-series up to 1995 (1998 for temperature and precipitation) were already available at 0.5 degree resolution (CRU TS 1.0 and 1.1). These existing 0.5 degree grids were extended to 2000 for Europe only, by applying the methodology of New et al (2000) to the updated databases. The 0.5 degree grids (1901–2000) were expressed as anomalies, smoothed to a 10 minute resolution for Europe, and recombined with the 1961–90 climatology at the same 10 minute resolution (CRU CL 2.1 and 2.2).

3.2.3 0.5 degree time-series (globe)

Time-series (1901–2000) were calculated for the five climate variables for the globe at 0.5 degree resolution (CRU TS 2.0). The additions made to the CRU databases warranted a full revision of the (anomaly) time-series, rather than merely an extension to 2000. Therefore this data-set replaces the previous versions (CRU TS 1.0 and 1.1), except for wet day and frost day frequencies. These grids have also been converted into country averages (TYN CY 1.1) for a set of 289 countries and territories, following Mitchell et al (2002).

A similar method to New et al (2000) was employed, except for cloud cover. A dense network of high-quality cloud data was limited to the period 1971–1996 (Hahn and Warren, 1999); this was augmented by sunshine duration data for 1991–2000 (Table 2: CLIMAT and MCDW). These data were initially converted to anomalies relative to the periods 1971–1995 and 1991–1995 respectively, and gridded. The sunshine anomaly grids (1996–2000) were converted to cloud cover anomaly grids under the assumption that the anomalies have the same magnitude, but opposite signs. The cloud cover anomaly grids for 1971–1996 and 1996–2000 were adjusted to be relative to 1961–90 using CRU TS 1.0, combined with the climatology from CRU CL 1.0, and appended to the 1901–1970 grids from CRU TS 1.0.

4 Data and methods: 21st century

4.1 Data

The scenarios presented here are based on representations of the climate system obtained from four GCMs (Table 3). These four were selected because they were the only GCMs for which any SRES simulations had been performed and deposited with the IPCC Data Distribution Centre (DDC) at the time of scenario construction. A simple climate model (MAGICC: Wigley and Raper, 1987; Raper et al, 2001) extended the range of simulations covered by these models. The data required for the scenarios comprise:

1. a set of GCM-based patterns (section Table *3: The GCMs used to construct the scenarios. The IPCC number refers to the index of that model in Tables 8.1 and 9.1 in IPCC (2001). The spatial resolution of the GCM in the bottom layer of the atmosphere is also noted. See Table 7 for acronym meanings.*

   4.1.1);
2. a set of time-series of future global warming (section Table *4: The size of the ensemble of GCM simulations used to construct the patterns (p) for each of the 16 scenarios. Four combinations, unsimulated by the GCM, were filled by copying another (normalised) pattern. See Table 7 for acronym meanings.*

   4.1.2);
3. the observed climatology (CRU CL 1.0, 2.0, 2.1; Table 1);
4. the observed time-series (CRU TS 1.2, 2.0; Table 1).

acronym	IPCCresolution	reference
CGCM2	73.8 by 3.8 degrees	Flato and Boer, 2001
CSIRO2	103.2 by 5.6 degrees	Gordon and O’Farrell, 1997
HadCM3	232.5 by 3.75 degrees	Mitchell et al, 1998
PCM	302.8 by 2.8 degrees	Washington et al, 2000

Table 3: The GCMs used to construct the scenarios. The IPCC number refers to the index of that model in Tables 8.1 and 9.1 in IPCC (2001). The spatial resolution of the GCM in the bottom layer of the atmosphere is also noted. See Table 7 for acronym meanings.

4.1.1 Spatial Patterns

The construction of each climate change scenario required a GCM-based pattern for each of the five climate variables — temperature, diurnal temperature range, precipitation, vapour pressure, and cloud cover. Each pattern was of the absolute change relative to the 1961–90 mean, and was expressed in units per degree Celsius of warming, using the equivalent annual global-mean temperature anomaly.

However, in many cases the climate variables deposited with the IPCC DDC are neither consistent between GCMs, nor the most useful for examining the impacts of climate change. Therefore to obtain an internally consistent set of patterns, it was necessary to make some bold assumptions and perform some complex manipulations, which are described below. The grids presented would be more accurate, and could have been constructed more efficiently, if a consistent and more useful set of climate variables were deposited with the IPCC DDC by the relevant climate modelling centres.

The set of patterns (*p*) was obtained as follows:

1. Vapour pressure (e) was derived from whatever moisture information was available from the models. For CGCM2 and PCM specific humidity (q) and sea level pressure (slp) were combined under an approximate relation derived from the gas laws:

$$e=\frac{q*slp}{0.62} \tag{1}$$

   Relative humidity (RH) was available for HadCM3, and was converted to vapour pressure using its relationship with saturated vapour pressure (e_s):

$$e=\frac{RH*e_s}{100} \tag{2}$$

The saturated vapour pressure (e_s) was estimated from daily mean temperature (T) using the Magnus equation:

$$e_s=6.107exp\left(\frac{17.38T}{239+T}\right) \quad whereT_w \geq 0 \tag{3}$$

$$e_s=6.107exp\left(\frac{22.44T}{272.4+T}\right) \quad whereT_w<0 \tag{4}$$

An approximate estimate of the wet-bulb temperature (T_w) was required to select between frozen and liquid water. Since daily minimum temperature (T_{min}) was available from HadCM3, it was assumed — following New et al (2000) — that this might be used as a proxy for dew-point temperature (T_d), and an approximate empirical relationship was employed:

$$T_w=\frac{3T_d+2T}{5} \tag{5}$$

No atmospheric moisture information was available for CSIRO2. Therefore T_{min} was again taken as a proxy for dew-point temperature (T_d) in equation 5, and vapour pressure was obtained through substituting e for e_s and T_d for T in equations 3 and 4.

2. Patterns of anomalies (m') on the native model grids were constructed from the available simulations. The ensemble mean was used if more than one simulation was available, to improve the signal-to-noise ratio and thus improve the accuracy of the pattern scaling that will be used at a later stage (Mitchell, 2003). Although the averaging will result in a slight loss of physical consistency between climate variables, this loss is much smaller than the loss suffered from combining high-resolution observations with low-resolution GCM information. For each variable (v) — except cloud cover — absolute anomalies were calculated:

$$\mu_{v}^{'}=\mu_{v.2070\text{-}99}-\mu_{v.1961\text{-}90} \qquad (6)$$

For downward short-wave flux (dsf) a fractional anomaly was calculated:

$$\mu_{dsf}^{'}=\frac{\mu_{dsf.2070\text{-}99}}{\mu_{dsf.1961\text{-}90}} \qquad (7)$$

3. Since the GCM-based patterns ($m^{'}$) had a substantially coarser spatial resolution than the 0.5 degree resolution of the scenarios (Table 3), it was necessary to decide whether to provide a smooth interpolated surface, or to retain the granularity of the original GCM. A compromise was necessary to balance the need to avoid discontinuities between 0.5 degree grid boxes, and the need to minimise the influence of ocean GCM grid boxes on land 0.5 degree grid boxes. Therefore the patterns were interpolated to the 0.5 degree resolution using a Delaunay triangulation of a planar set of points. Additional smoothing was required to transform from 0.5 degrees to 10 minutes over Europe.
4. The cloud cover patterns were obtained by combining GCM-based patterns ($m^{'}$) of downward short-wave flux with the observed climatology of cloud cover (o_{cld}) on the 0.5 degree (CRU CL 1.0) or European 10 minute (CRU CL 2.1) grid (Table 1). An estimate was made of the equivalent observed climatology of the sunshine received (spc):

$$o_{spc}=100-o_{cld} \qquad (8)$$

It was assumed that a percentage change in the downward short-wave flux represented by the model corresponds to an equal percentage change in the sunshine received:

$$\mu_{spc}^{'}=o_{spc}*\mu_{dsf}^{'} \qquad (9)$$

By reversing the sign the absolute change in cloud cover was obtained:

$$\mu_{cld}^{'}=-\mu_{spc}^{'} \qquad (10)$$

5. The final set of patterns (p) were constructed as ratios relative to the equivalent annual global-mean temperature anomalies ($t^{'}$), which are calculated below (section Table *4: The size of the ensemble of GCM simulations used to construct the patterns (p) for each of the 16 scenarios. Four combinations, unsimulated by the GCM, were filled by copying another (normalised) pattern. See Table 7 for acronym meanings.*

4.1.2).

$$p=\frac{\mu^{'}}{t^{'}} \qquad (11)$$

	PCM	CGCM2	CSIRO2	HadCM3
A1FI	=A2	=A2	one	one
A2	one	one	one	three
B2	one	one	one	two
B1	=B2	=B2	one	one

Table 4: The size of the ensemble of GCM simulations used to construct the patterns (p) for each of the 16 scenarios. Four combinations, unsimulated by the GCM, were filled by copying another (normalised) pattern. See Table 7 for acronym meanings.

4.1.2 Time-Series

MAGICC was used to emulate the time-series (2001–2100) of annual global-mean temperature change in various GCMs (see Cubasch et al, 2001: Appendix 9.1). MAGICC was used, rather than GCM outputs, in order to extend the range of simulations and to reduce internal variability. The temperature anomaly (t') in each year (y), GCM (g), and under each SRES scenario (s) was obtained as follows:

$$t'_{gsy} = t_{gsy} - t_{g.1961\text{-}90} \tag{12}$$

Since CGCM2 has not been emulated by MAGICC, t' was estimated for this particular GCM (ca) by taking the shape of the time-series from the mean of the other three models, and the magnitude from the CGCM2 A2 and B2 simulations in the period 2070–2099. The estimate for A2 was as follows:

$$t'_{ca.A2.y} = \sum_{g=1}^{3} t'_{A2.y} * \left(\frac{t'_{ca.A2.2070\text{-}99}}{\sum_{g=1}^{3} t'_{A2.2070\text{-}99}} \right) \tag{13}$$

To obtain B2 one may substitute $B2$ for $A2$ in the above equation. Since no A1FI or B1 simulations were available for CGCM2, it was assumed that the ratio of global climate change between the A1FI and A2 scenarios (and between the B1 and B2 scenarios) would be the same from one GCM to another. Thus the estimate for A1FI was as follows:

$$t'_{ca.A1FI.y} = \sum_{g=1}^{3} t'_{A2.y} * \left(\frac{t'_{ca.A2.2070\text{-}99}}{\sum_{g=1}^{3} t'_{A2.2070\text{-}99}} \right) * \left(\frac{\sum_{g=1}^{3} t'_{A1FI.2070\text{-}99}}{\sum_{g=1}^{3} t'_{A2.2070\text{-}99}} \right) \tag{14}$$

To obtain B1 one may substitute $B1$ for $A1FI$ and $B2$ for $A2$ in the above equation.

4.2 Method

The principles that guided the construction of the scenarios are described first (section 4.2.1). The control scenario (section 4.2.2) is constructed in the same way as a climate change scenario (section 4.2.3), but omitting the spatial pattern of anthropogenic climate change. The key equations are 18 (control) and 19 (climate change), which are discussed in their respective sections.

4.2.1 Principles of construction

Scenarios of future climate are conventionally constructed from unmodified GCM outputs, perhaps after interpolation onto a more convenient grid. A different approach is adopted here, for three reasons:

- There are insufficient GCM simulations available to represent each of the 16 scenarios.

- Not all of the required variables were directly represented in the stored GCM outputs.
- Since the recently observed and modelled climates differ in both their mean and their variability, the use of direct outputs from GCMs would introduce inhomogeneities between the 20th and 21st centuries.

Therefore the scenarios present future climates in which the multi-decadal changes are taken from GCMs, but the baseline climate and inter-annual variability are taken from observations. The information present in the scenarios may be broken down into four components:

1. The observed climatology from 1961–90 (CRU CL 1.0, 2.0, 2.1; Table 1) represents the baseline climate. This baseline is adopted for the scenarios as well as the observed record, in order to preserve homogeneity between the 20th and 21st centuries.
2. The GCMs (via MAGICC) represent changes in global climate, as expressed by the time-series of annual global-mean temperature change.
3. The GCM patterns of climate change at the end of the 21st century express the spatial variations between the scenarios. It is assumed that the pattern of anthropogenic climate change is constant within a GCM simulation, but the magnitude of the pattern varies linearly with the amount (not rate) of global-mean temperature change. Under this assumption, pattern scaling can be used to combine this spatial pattern with the time series of global warming. This approach has been shown to be reasonable by Mitchell et al (1999) and Mitchell (2003).
4. The observed variations in climate during the 20th century (CRU TS 1.2, 2.0; Table 1) provide plausible sub-centennial variability during the 21st century.

The use of observed rather than modelled inter-annual variability has a number of disadvantages:

- Any modelled changes in variability remain unrepresented in the scenarios. However, it might prove possible to reduce this problem in the future by extending the pattern scaling technique to patterns of change in inter-annual variability (Mitchell, 2001), not just patterns of change in the mean.
- Impossible values may be introduced through combining modelled and observed information. For example, a modelled absolute reduction in precipitation may coincide with a very dry year from the observed variability, resulting in negative precipitation. Therefore at the end of the process, the calculated values were checked and corrected where necessary. The ranges of values taken by precipitation and vapour pressure were truncated at zero and cloud cover was restricted to values between 0 and 100%. Diurnal temperature range was truncated at 0.1°C because values of 0.0°C are not meaningful.
- Where observations were scarce in the early 20th century and the observed time-series had already been ‘relaxed’ towards a zero anomaly (New et al, 2000), some sub-centennial variability will be missing from the early 21st century for some variables.

However, using the observed variability avoids introducing differences (inhomogeneities) between the representation of 20th and 21st century climate. The GCM inter-annual variability may be substantially different from that observed:

- in the spatial resolution — the GCM variability is restricted to scales of at least a few grid-boxes;
- in the underlying magnitudes — for example, GCM estimates of the inter-annual standard deviation of Niño 3 SSTs include 0.4°C (GFDL R30) and 1.1°C (HadCM3), compared to an observed value of 0.7°C (McAvaney et al, 2001: Table 8.2);
- in the transitions — for example, GCMs underestimate the speed of warming during the 1997–98 El Niño event (McAvaney et al, 2001).

Spatial patterns of absolute, rather than relative, change were chosen. This is the obvious choice for most climate variables, but not necessarily precipitation, as discussed by Mearns et al (2001). Absolute changes were applied to all variables for the sake of consistency.

4.2.2 Control scenario

The control scenario is not merely a fixed average, but includes plausible sub-centennial variability taken from the observed time-series. The difficulty is to avoid including the anthropogenic climate changes experienced during the 20th century. In order to achieve this the observed 20th century is detrended, assuming that the observed centennial climate changes at the grid-box level are linearly related to changes in annual global-mean temperature. (This assumption has been shown to be reasonable for GCMs by Mitchell et al (1999) and Mitchell (2003).)

The method for the European 10 minute grids is described first (TYN SC 1.0). The 1901–2000 observed time-series (*o*: CRU TS 1.2) was split into the 1961–90 climatology (*o*: CRU CL 2.0 and 2.1) and the time-series of anomalies (o') for each variable (*v*), grid box (*i*), year (*y*), and month (*m*) in the 20th century:

$$o_{viym} = o'_{viym} + o_{vim} \tag{15}$$

The anomaly time-series (o') was modified (giving $\tilde{o}'$) by removing any values that were the result of relaxation to zero in the earlier part of the 20th century (New et al, 2000), and smoothing the genuine data with a Gaussian filter at 30 years. The trend (*b*) in $\tilde{o}'$, as a function of the global-mean temperature anomaly (t') in the observed record (Jones and Moberg, 2003), was calculated using a least squares method:

$$\tilde{o}'_{viym} = b_{vim} * t'_y \tag{16}$$

The residuals ($\dot{o}'$) were calculated, but zeros were retained where values in o' had been relaxed to zero:

$$\dot{o}'_{viym} = o'_{viym} - \left(t'_y * b_{vim}\right) \tag{17}$$

The control scenario (*c*) was formed by combining these high-frequency residuals with the observed climatology:

$$c_{viym} = \dot{o}'_{viym} + o_{vim} \tag{18}$$

The control scenario for the globe at 0.5 degrees (TYN SC 2.0) was also constructed following the above method. The only deviations were to begin with CRU TS 2.0 (rather than CRU TS 1.2), and to restrict the calculations to the period 1951–2000. When *c* had been calculated for 1951–2000, this period was duplicated into 1901–1950. The reason for the duplication was to minimise the effects of relaxation to zero anomalies in the construction of the observed time-series (New et al, 2000). The relaxation was in data-sparse places and times, and resulted in an absence of any inter-annual variability for the affected variables. If reflected in the time series of *c*, an abrupt transition in variability would be introduced from one century to the next. This problem is relatively small in Europe, so for TYN SC 1.0 advantage was taken of the larger sample of interannual variability available from the entire 20th century.

In both data-sets it is assumed that in the absence of radiative forcing, sub-centennial climate variability would be similar from one century to the next. Therefore the control scenario in the 21st century is a replica of the 20th century.

4.2.3 Climate change scenarios

The climate change scenarios (x) have the same climatology (o: Equation 15) and variability ($\dot{o}'$: Equation 17) as in the control scenario (c; Equation 18); these do not vary between scenarios. The choice of scenario is determined by the choice of GCM (g) and SRES emissions (s), which in turn determine the pattern of change (p: Equation 11) and the global temperature anomalies (t': Equation 12) by which the pattern is scaled. Thus the climate change scenario is given by:

$$x_{vgsiym} = o_{vim} + \dot{o}'_{viym} + \left(p_{vgsim} * t'_{gsy}\right) \tag{19}$$

These grids were also converted into country averages (TYN CY 3.0) for a set of 289 countries and territories, following Mitchell et al (2002).

5 Results

The global climate changes in the 16 scenarios are represented in Figure 2. The 16 scenarios cover 93% of the range of uncertainty in global warming in the TAR (1760–2100), compared to the full set of combinations of the 35 SRES emissions scenarios with complete greenhouse gas emissions and the seven GCMs for which a simple model was tuned (Cubasch et al, 2001, Figure 9.13).

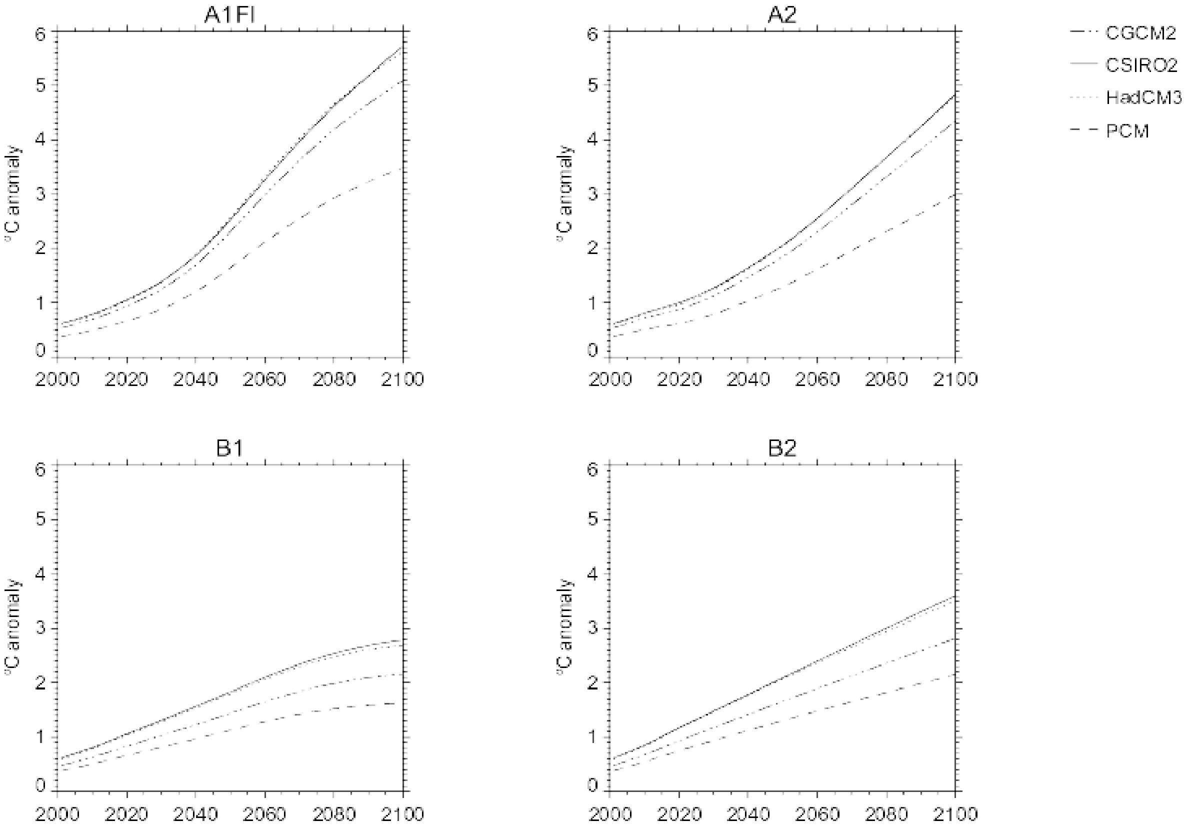


Figure 2: The changes in annual global-mean temperature (relative to 1961–90) for the 16 scenarios. This statistic is t' *from Equation 19.*

The inter-pattern differences are much greater between GCMs than between SRES emissions, so the Table 5 summarises the former. The GCMs agree on the sign of the change at this large scale, with the notable exception of precipitation in CGCM2. Nonetheless, these statistics confirm the considerable diversity among the GCMs. The temperature patterns reflect the differential rates of warming between land and ocean, especially in CGCM2 and HadCM3. There is greater diversity between the GCMs in the precipitation patterns; in many parts of the world the range includes both drying and moistening. This Table also records the number of corrections required to keep values within the bounds of the physically possible, which did not exceed 1% for any variable.

		CGCM2	CSIRO2	HadCM3	PCM	corrections
cld	1/100	-1.23	-1.15	-1.15	-1.83	0.1 %
dtr	°C	-0.07	-0.16	-0.03	-0.14	0.008 %
pre	mm/month	-0.14	1.02	0.18	1.79	0.8 %
tmp	°C	1.24	1.15	1.21	1.15	none
vap	hPa	0.51	0.84	0.10	0.71	0.8 %

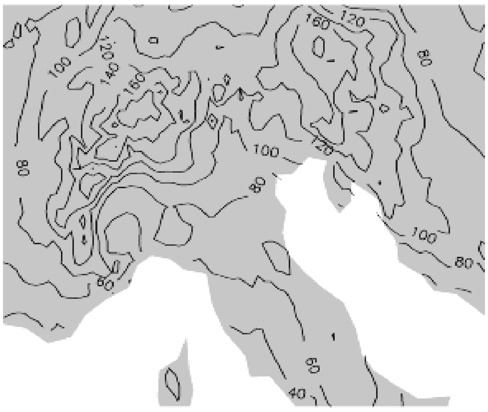
Table 5: The area-weighted annual mean, over the global land surface, of the patterns of change (units per °C of change in annual global-mean temperature) for the four A2 scenarios and for each of the five variables. This statistic is a summary of p from Equation 19. The number of instances in which a value in a 0.5 degree grid was corrected to the minimum or maximum possible value is also recorded, as a percentage of the instances possible. See Table 7 for acronym meanings.

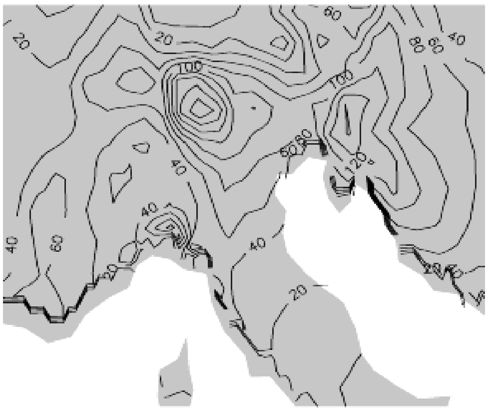
Figure 3 illustrates the spatial scales of the different elements contributing to the scenarios. Alpine precipitation in August 2095 is built from the three components shown and the annual global-mean temperature anomaly (4.53°C, not shown). These sources of information are at 10 minutes, 0.5 degrees, the GCM resolution (2.5° by 3.75°) interpolated on the 0.5 degree grid, and the global scale respectively. These spatial scales are appropriate for their respective climate variables; for example, greenhouse-gas-related climate change may be expected to occur on large spatial scales, relative to local variations in mean climate. Finer-scale observed data-sets (e.g. Schmidli et al, 2001) include even more detail.

However, in some places the complex orography and land-sea distribution may introduce substantial local variations to future climate changes. For example, there may be substantial differences between the changes in Alpine valleys and on Alpine ridges. Such variations are unrepresented in these scenarios because they are unrepresented in the GCMs; many variations are also unrepresented at the typical 50km scale of RCMs. However, statistical downscaling could be used to derive finer-scale information if necessary.

Figure 4 illustrates the time scales of the different elements contributing to the scenarios, using the example of July precipitation in Norwich. The creation of an areal average (top-right) from point data (e.g. top-left) reduces the inter-annual standard deviation from 32.8 mm to 29.5 mm. The control scenario (mid-right) was developed by removing the global-warming related trend from the observed series (top-right). In this case the trend is a drying, shown (mid-left) by the changes from the observations to the control: drier in the mid-20th century, and wetter in the late-20th century. The HadCM3 A2 scenario (bottom-right) was constructed by combining the variations from the control — both inter-annual (mid-right) and multi-decadal (mid-left) — with the centennial changes obtained from the GCM (bottom-left).

The result is a scenario for the 21st century with a baseline climate, centennial changes, inter-annual variations and multi-decadal variations that are consistent with the observed record from the 20th century. When the two centuries are combined into a single 200-year series, the transition between them is smooth and plausible. However, there are some data-sparse places and variables in which the transition is not as smooth (see section 4.2.2). The use of the same time-series of $\overset{.'}{o}$ to represent inter-annual variability (Equation 19) results in considerable similarity between the different scenarios.





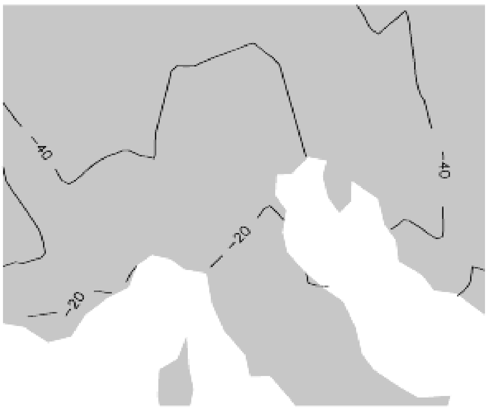


Figure 3: The components of the precipitation (mm) in August 2095 under the HadCM3 A2 scenario (10 minute) for the Alps and northern Italy: the 1961–90 mean (top: o), the residual from 1995 (centre: $\dot{o}'$), and the pattern of 21st century change under HadCM3 A2 (bottom: p).

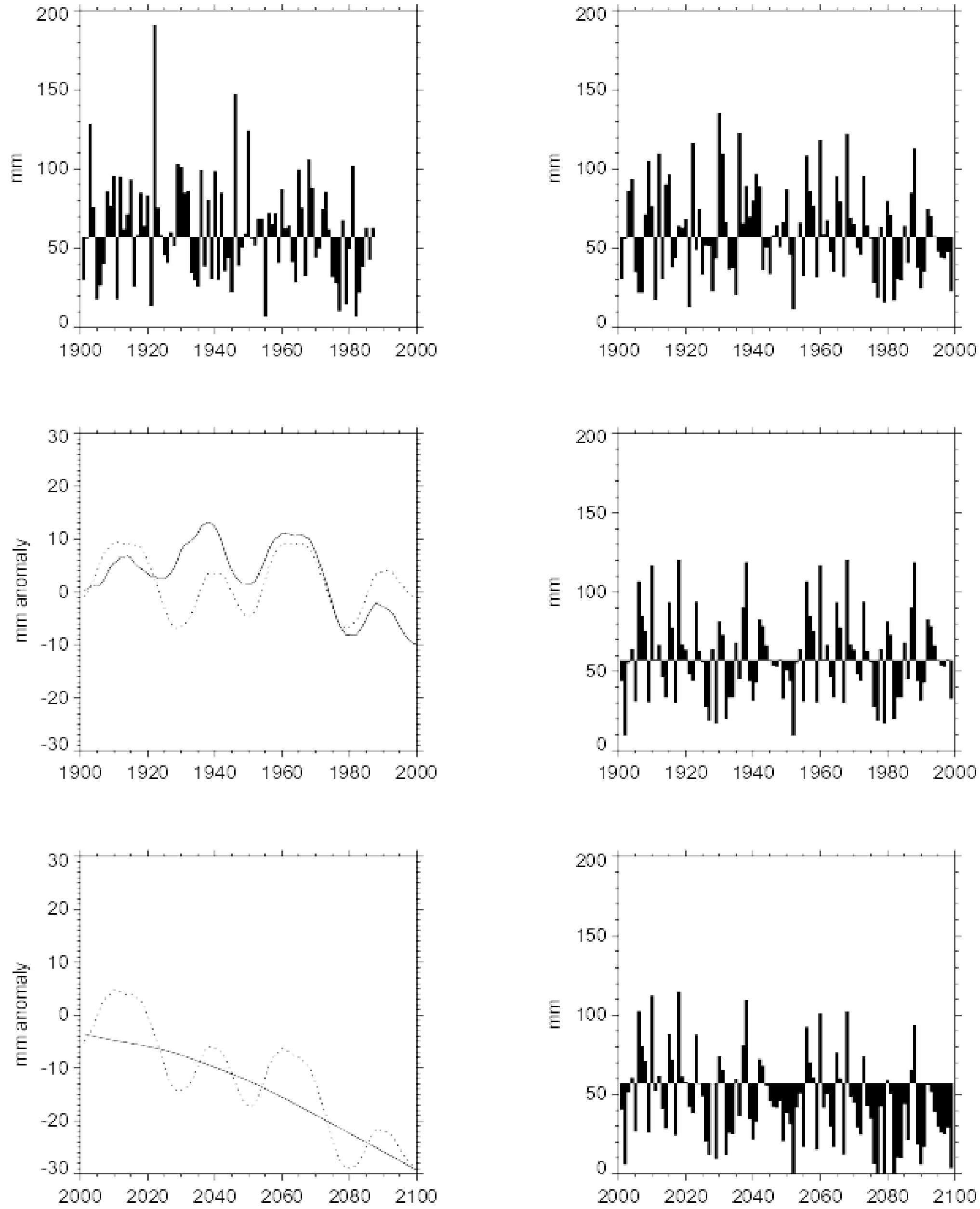


Figure 4: July precipitation in the 0.5 degree grid box containing Norwich (UK). All anomalies are calculated relative to the observed mean in 1961–90 (o: 56.9 mm) from the grid box; the bars emphasise this mean. An observed station record (Norwich Weather Centre) is at top-left. The observed grid-box record (o) is at top-right, and the control scenario (c) is at mid-right. The grid-box observations (õ′ :

solid) and control (dotted) are also displayed (mid-left) as anomalies, smoothed with a Gaussian filter at 30 years. The HadCM3 A2 scenario (x) is displayed at bottom-right, and also as smoothed anomalies (bottom-left, dotted); it was constructed by duplicating the control scenario (mid-right) and adding the product (bottom-left, solid) of the GCM pattern (p: -6.1 mm year^{-1}*) and the GCM time-series of global temperature (t').*

6 Conclusion

The grids described in this paper provide, for the first time, an opportunity to standardise much of the climatic information used in large-scale climate impact assessments. This opportunity has arisen through developing high-resolution grids of monthly climate for a number of variables, providing the historical climate record, representing the main sources of uncertainty in future climate, and doing all this in a coherent way.

These sets of grids are quite versatile. The realistic month-by-month variations are ideal for numerical methods involving iteration through time, or alternatively periods from the time-series may be averaged into time-slices. The grids may be used directly or regionalised by aggregating grid boxes. The grids may also be combined with station observations to introduce finer spatial scales through statistical downscaling. For example, scenarios for a study site could be developed as follows:

1. use the first half of the record from a local meteorological station to construct a predictive relationship with the corresponding period from a local aggregation of grid boxes;
2. use the second half of the record to assess the skill of the relationship;
3. use the scenario grids and the predictive relationship to develop local scenarios.

Using gridded surface variables as predictors may provide less predictive skill than using upper-air variables directly from a GCM (e.g. Wilby and Wigley, 1997). However, our method may have considerable advantages, particularly if extremes change similarly to means: notably the ability to represent emissions scenarios unsimulated by the GCM, and the ability to use multiple GCMs without constructing a separate predictive relationship for each GCM.

These monthly grids are not directly applicable to impacts dependent on daily variability. However, finer temporal scales could be incorporated by applying a weather generator or some form of statistical downscaling. The grids representing the full range of GCMs and emissions scenarios could then be used to perturb the parameters of the algorithm used, to simulate daily climate for the future.

The grids may be used in a variety of types of assessment.

- The environmental and socio-economic impacts of changes in regional climate (‘climate impacts’) in the past may be explored.
- The climate impacts of multi-decadal natural variability may be assessed by comparing adjacent periods in the control simulation.
- The evolution of climate impacts during the 21st century, as represented by a variety of climate models, may be explored.
- The climate impacts of alternative emissions pathways may be contrasted.
- The climate impacts resulting from anthropogenic influence may be identified by comparing climate change scenarios with the control.
- The climate impacts from anomalous periods in the 20th century may be contrasted with the impacts from periods with equivalent anomalies in the 21st century, but with additional anthropogenic changes to the climate.
- The importance of multi-decadal natural variability, relative to anthropogenic climate change, may be assessed by comparing the climate impacts from climate change scenarios with those from the control.

A further paper (Mitchell and Carter, 2003) explores how these grids may be used in some detail, notably in conjunction with scenarios of concurrent changes in atmospheric composition and land use.

The observed grids (1901–2000) are not suitable for climate monitoring, the detection of climate change, or the attribution of changes to anthropogenic influences, such as in IPCC (2001). There are a number of features of the observed grids that make them unsuitable for these purposes:

- Data were used from all available stations, including stations influenced by urbanisation and land-use change, stations that are no longer active, and stations that are not routinely reported in real time.
- At times and in places where no station data were available, the grids were ‘relaxed’ to a zero anomaly, relative to the 1961–90 climatology, following New et al (2000). Any improvement in this respect requires open access to existing data-sets and digitisation of paper records.
- Fluctuations over time in the numbers and locations of adjacent stations may lead to abrupt and incorrect changes in the climate of an individual grid box, particularly changes in variability.

Therefore alternative data-sets should be used for monitoring, detection and attribution purposes: examples include Jones and Moberg (2003) for temperature and Hulme et al (1998) for precipitation. The observed grids presented here are intended to complement such alternative data-sets, by providing spatially and temporally complete grids that incorporate all the available information about the actual changes in climate experienced over the last century, irrespective of cause. These same features make it important for analysts of impacts to be aware of the characteristics of the climatic time-series of the grid boxes of interest. In particular, analysts should check whether values have been ‘relaxed’ to a zero anomaly, or whether there are changes over time that are related to fluctuations in the number of adjacent stations. Metadata supplied with the observed grids indicate how many stations potentially contributed to each individual value.

This data-set is capable of improvement in a number of ways. Among the most desirable improvements for the future include:

- extending the time scale to a daily resolution, which will only be possible for the observed period in data-rich regions — possibly with the assistance of weather generators — and will require RCMs for future scenarios;
- extending the number of climatic variables included;
- extending the number of climate models represented;
- improving the observed records, to enhance the historic record and the representation of interannual variability;
- incorporating modelled changes in the interannual variance (Mitchell, 2001), rather than merely changes in the multi-decadal mean.

The authors of this data-set welcome dialogue in two directions in particular:

1. with those who wish to use the data-set to examine the possible effects of future climate change;
2. with those who wish to deploy the concepts explained in this paper to develop similar data-sets.

7 Acknowledgements

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8 Appendix

Symbol	Variable	Units
b	trend	climate variable units per degree Celsius
c	control scenario	
ca	a particular GCM, CGCM2	
cld	cloud cover	percentage (%)
dsf	downward shortwave flux	watts per square metre (Wm^{-2})
e	vapour pressure	hector Pascals (hPa)
e_s	saturated vapour pressure	hector Pascals (hPa)
g	GCM	
i	grid box	
m	month	
$\bar{o}$	observed climatology	climate variable units
o [$\acute{o}$]	observed [anomaly] time-series	climate variable units
$\acute{\tilde{o}}$	smoothed observed anomaly time-series	climate variable units
$\acute{o}'$	residuals from the detrended time-series	climate variable units
p	pattern of change	climate variable units per degree Celsius
q	specific humidity	kilogram per kilogram
RH	relative humidity	percentage
s	SRES scenario	
slp	sea-level pressure	hector Pascals (hPa)
spc	sunshine	percentage of possible
t [t']	annual global-mean temperature	degree Celsius (^{o}C)
T	daily mean temperature	degree Celsius (^{o}C)
T_{min}	daily minimum temperature	degree Celsius (^{o}C)
T_{max}	daily maximum temperature	degree Celsius (^{o}C)
T_d	dew-point temperature	degree Celsius (^{o}C)
T_w	wet-bulb temperature	degree Celsius (^{o}C)
v	climate variable	
x	climate change scenario	
μ	GCM mean	climate variable units
μ'	GCM anomaly	climate variable units

Table 6: Algebraic notation

Acronym	In full

ATEAM	Advanced Terrestrial Ecosystem Analysis and Modelling
cld	cloud cover
CGCM2	Canadian Global Climate Model version 2
CSIRO2	Commonwealth Scientific and Industrial Research Organisation GCM mark 2
CLIMAT	World Meteorological Organization monthly climate bulletin
CRU	Climatic Research Unit
DDC	Data Distribution Centre
DJF	December, January, February
dtr	diurnal temperature range
GCM	Global Climate Model or General Circulation Model
GHCN	Global Historical Climatology Network
HadCM3	Hadley Centre Coupled Model version 3
IPCC	Inter-governmental Panel on Climate Change
JJA	June, July, August
MAGICC	Model for the Assessment of Greenhouse gas Induced Climate Change
MCDW	Monthly Climatic Data for the World
PCM	National Centre for Atmospheric Research Parallel Climate Model
pre	precipitation
RCM	Regional Climate Model
sun	sunshine hours
SRES	Special Report on Emissions Scenarios
SST	sea-surface temperature
TAR	Third Assessment Report
tmp	daily mean temperature
TYN	Tyndall Centre for Climate Change Research
UEA	University of East Anglia
vap	vapour pressure

Table 7: Acronyms and abbreviations

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The trans-disciplinary Tyndall Centre for Climate Change Research undertakes integrated research into the long-term consequences of climate change for society and into the development of sustainable responses that governments, business-leaders and decision-makers can evaluate and implement. Achieving these objectives brings together UK climate scientists, social scientists, engineers and economists in a unique collaborative research effort.

Research at the Tyndall Centre is organised into four research themes that collectively contribute to all aspects of the climate change issue: Integrating Frameworks; Decarbonising Modern Societies; Adapting to Climate Change; and Sustaining the Coastal Zone. All thematic fields address a clear problem posed to society by climate change, and will generate results to guide the strategic development of climate change mitigation and adaptation policies at local, national and global scales.

The Tyndall Centre is named after the 19th century UK scientist John Tyndall, who was the first to prove the Earth's natural greenhouse effect and suggested that slight changes in atmospheric composition could bring about climate variations. In addition, he was committed to improving the quality of science education and knowledge.

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- Centre for Ecology and Hydrology
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