Extreme change: an analysis of past, present and future changes in global temperature and precipitation indices

Julie Arblaster[1,3] and Lisa Alexander[2,3]

[1]National Center for Atmospheric Research, Boulder, USA
[2]Hadley Centre, Met Office, Exeter, UK
[3]Bureau of Meteorology Research Centre, Melbourne, Australia

Observations

The analysis of observed changes in global climate extremes is particularly demanding because of the reluctance of some institutions to part with daily data. A recent initiative by the joint World Meteorological Organization Commission for Climatology (CCl)/ World Climate Research Programme (WCRP) project on Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) aimed to address gaps in data availability and analysis in previous global studies [e.g. *Frich et al.*, 2002]. One way they did this was through the international coordination of the development of a suite of climate change indices which primarily focus on extremes. In all, 27 indices derived from daily temperature and precipitation data were defined and standard software packages were developed which are freely available to the international research community. By setting an exact formula for each index and by using the same software package, analyses done in different countries or different regions can fit together seamlessly.

The ETCCDMI also coordinated regional workshops in data sparse regions modeled on the Asia Pacific Network (APN) workshops [*Manton et al.*, 2001; *Peterson et al.*, 2001]. Between 2001 and 2005 workshops were held in Jamaica (to cover the Caribbean region), Morocco (Africa), South Africa (southern and east Africa), Brazil (southern South America), Turkey (the Middle East), Guatemala (northern South America and central America) and India (central and south Asia). Scientists from different countries within a region brought their own daily data to the workshops. Under guidance from international experts, during the workshop, they conducted data quality control and computed indices using a standard procedure and software. Careful post-workshop analysis was also applied to the data.

Although some participants chose not to share their original daily data they made the derived indices series available for regional and global analyses. High quality data from international institutions were combined with the workshop results using exactly the same software package. In total data from over 2200 temperature and nearly 6000 precipitation stations were analysed. The results were collated for a study which provided a previously unseen global picture of observed changes in temperature and precipitation extremes during the 20th century [Alexander et al., 2005].

Results from this study showed large scale significant changes in temperature extremes over the second half of the 20th century, especially from those indices derived from daily minimum temperature. There have been large scale significant decreases in the annual occurrence of frost (Figure 1a) and the annual occurrence of warm nights (Figure 1b) have significantly increased by more than 50% with some regions e.g. North Africa, experiencing a more than doubling of these extremes. This contrasts with a similar reduction in the trends of cool nights implying a shift in the distribution of global minimum temperature. Extremes derived from maximum temperature indicate similar change but with smaller magnitude (not shown). As expected, precipitation extremes did not have such large scale coherence but some indicators such as the annual trends in number of consecutive dry days (Figure 1c) and trends in heavy precipitation (Figure 1d) were remarkably coherent over large areas.

Probability distributions of indices derived from approximately 200 temperature and 600 precipitation stations, with near-complete data for 1901-2003 and covering a very large region of the Northern Hemisphere mid-latitudes (and parts of Australia for precipitation) were analysed for the periods 1901-1950, 1951-1978 and 1979-2003. Results indicate a significant warming throughout the 20th century (Figure 2). Differences in temperature indices distributions are particularly pronounced between the most recent two periods and for those indices related to minimum temperature. An analysis of those indices for which seasonal timeseries are available shows that these changes occur for all seasons. Precipitation indices show a tendency towards wetter conditions throughout the 20th century.

Comparison of observations with models

The study of extremes, in both the observations and climate models has been hampered until now by a general lack of available daily data. The ETCCDMI addressed this issue for the observations. On the modelling side and in order to facilitate multi-model analysis prior to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR4), the Joint Steering Committee (JSC)/CLIVAR Working Group on Coupled Models requested that modelling groups worldwide submit a subset of the output from their climate simulations to a central archive in California. Along with raw model output from the atmosphere, ocean, sea-ice and land components of the coupled models, extremes indices based on the definitions of Frich *et* al. [2002] were calculated and submitted by a number of the modelling groups. Tebaldi *et al.* [2005] analyse these historical & future (see below) indices of climate extremes, as derived from an ensemble of nine coupled climate models. The study concentrates on the general consensus of the models as to the direction and significance of changes in the extremes indices. Twentieth century trends in the model indices generally agree with the changes found by Frich *et al.* [2002] and Alexander *et al.* [2005], providing a basic sense of reliability for the GCM simulations (Figure 3). Recent work by *Kiktev et al.* [2005] shows that the observed changes in temperature extremes are reasonably well simulated by multi-model ensembles although the models studied showed much less skill in reproducing precipitation extremes. This conclusion is supported by the Tebaldi *et al.* [2005] study with trends in the precipitation based extreme indices being less significant and more variable amongst the models than those based on temperature. The studies discussed here are the first comparison of extremes between models and observations undertaken in a globally and computationally consistent framework. Previous and ongoing studies [e.g. *Kiktev et al*., 2003 and *Christidis et al*., 2005] indicate that only the inclusion of both natural and anthropogenic forcings can account for the observed changes in temperature extremes. Further studies are planned to compare the observational and modelled indices in more detail.

Future changes in extremes

Tebaldi *et al*. [2005] find that the trends in temperature extremes that began to be detected above the noise in the late 20th Century will continue and intensify into the future, regardless of which climate model is analysed or IPCC SRES emissions scenario is followed (Figure 4). Spatial patterns of change in the temperature extremes are very stable, with the changes increasing in magnitude as the rate of emissions increases (not shown), demonstrating a strong relationship between greenhouse gas emissions and the magnitude of potential impacts. Models also agree with the observations that there is a trend towards a world characterised by intensified precipitation, with a greater frequency of heavy-precipitation and high-quantile events and longer dry spells, although with substantial geographical variability and more inter-model variability than the temperature indices. Taken together the precipitation indices offer a picture of regions whereby little to no change in mean precipitation could mask a simultaneous increase in both dry day periods and heavy rainfall events conducive to flooding conditions.

Summary

Estimates of changes in temperature and precipitation extremes are of key importance to assessments of the potential impacts of climate change on human and natural systems. Recent observational and modelling studies have been presented and show that, in general, the warmest (coldest) temperature extremes, particularly those derived from minimum temperature, have significantly increased (decreased) over the 20th century and will continue to increase (decrease) throughout the 21st century. Although changes in precipitation extremes are less coherent, the evidence suggests that globally there have been more flood/drought-inducing events which are set to continue in the future.

Descriptions of all the observational climate indices, details of quality control procedures, references to relevant literature, software packages and station data are available from http://ccma/seos.uvic.ca/ETCCDMI. Gridded datasets are available from http://www.hadobs.org. The Tebaldi *et al.* [2005] study and additional figures can be downloaded from http://www.cgd.ucar.edu/ccr/publications /tebaldi-extremes.html. Extremes indices from the 9 climate models used in the study are available from http://www-pcmdi.llnl.gov (registration required).

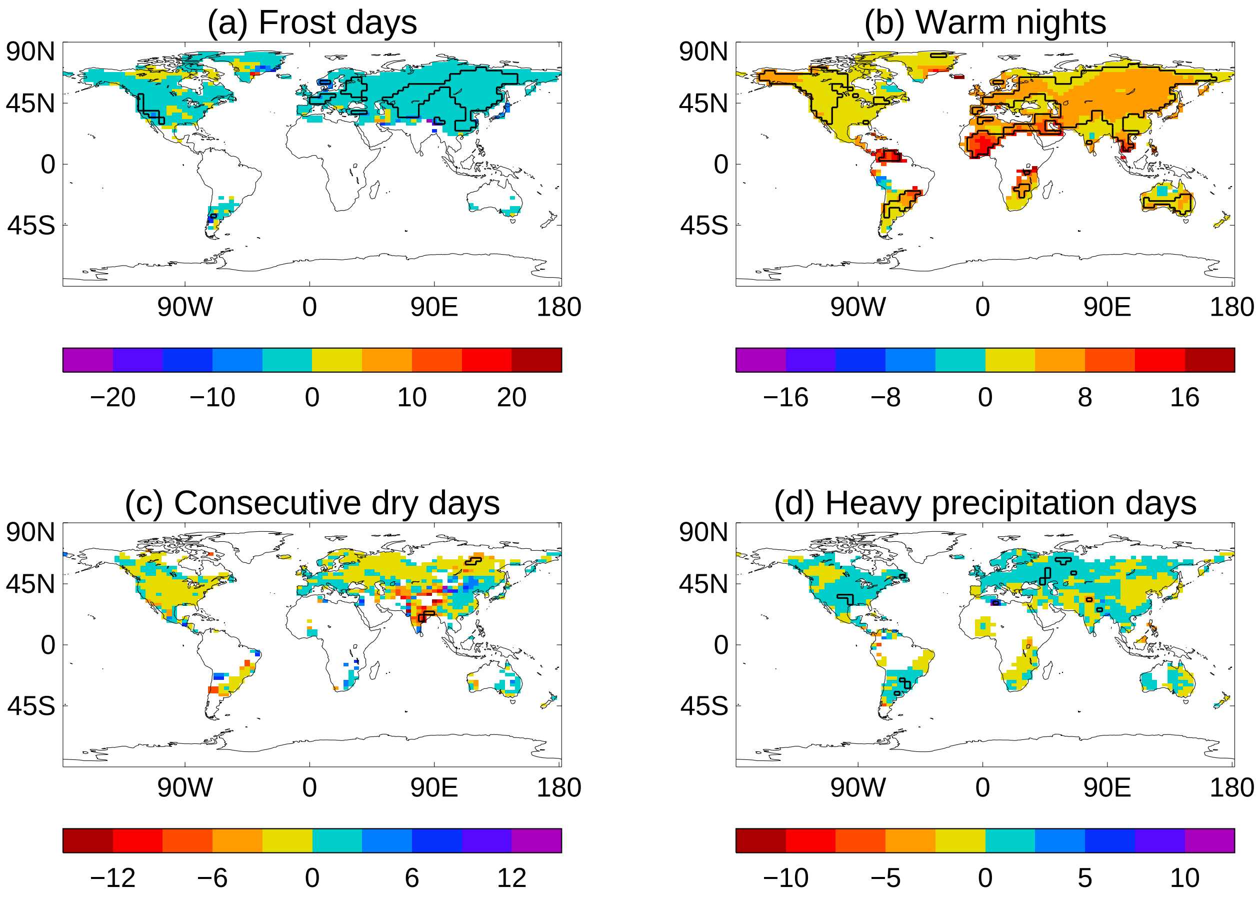

Figure 1: Decadal trends (days) between 1951-2003 for (a) annual occurrence of days with Tmin < 0ºC (FD), (b) annual occurrence of Tmin > 90th percentile of 1961-1990 reference period (TN90p), (c) annual maximum consecutive number of days < 1mm (CDD) and (d) annual occurrence of days > 10mm (R10). Black lines enclose regions where trends are significant at the 5% level.

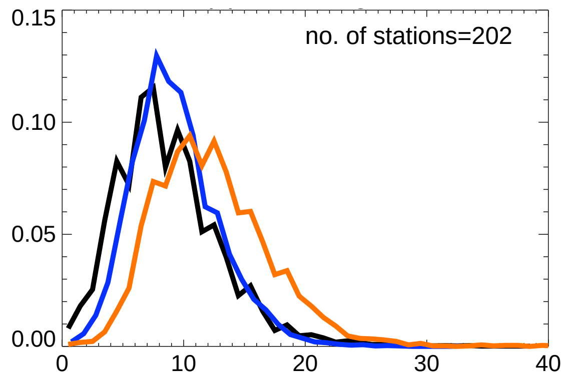

Figure 2: Annual probability distribution functions for warm nights index (TN90p) for a subset of global stations with at least 80% complete data between 1901 and 2003 for 3 time periods: 1901-1950 (black), 1951-1978 (blue) and 1979-2003 (red). The x-axis represents the percentage of time during the year when the index was above the 90th percentile.

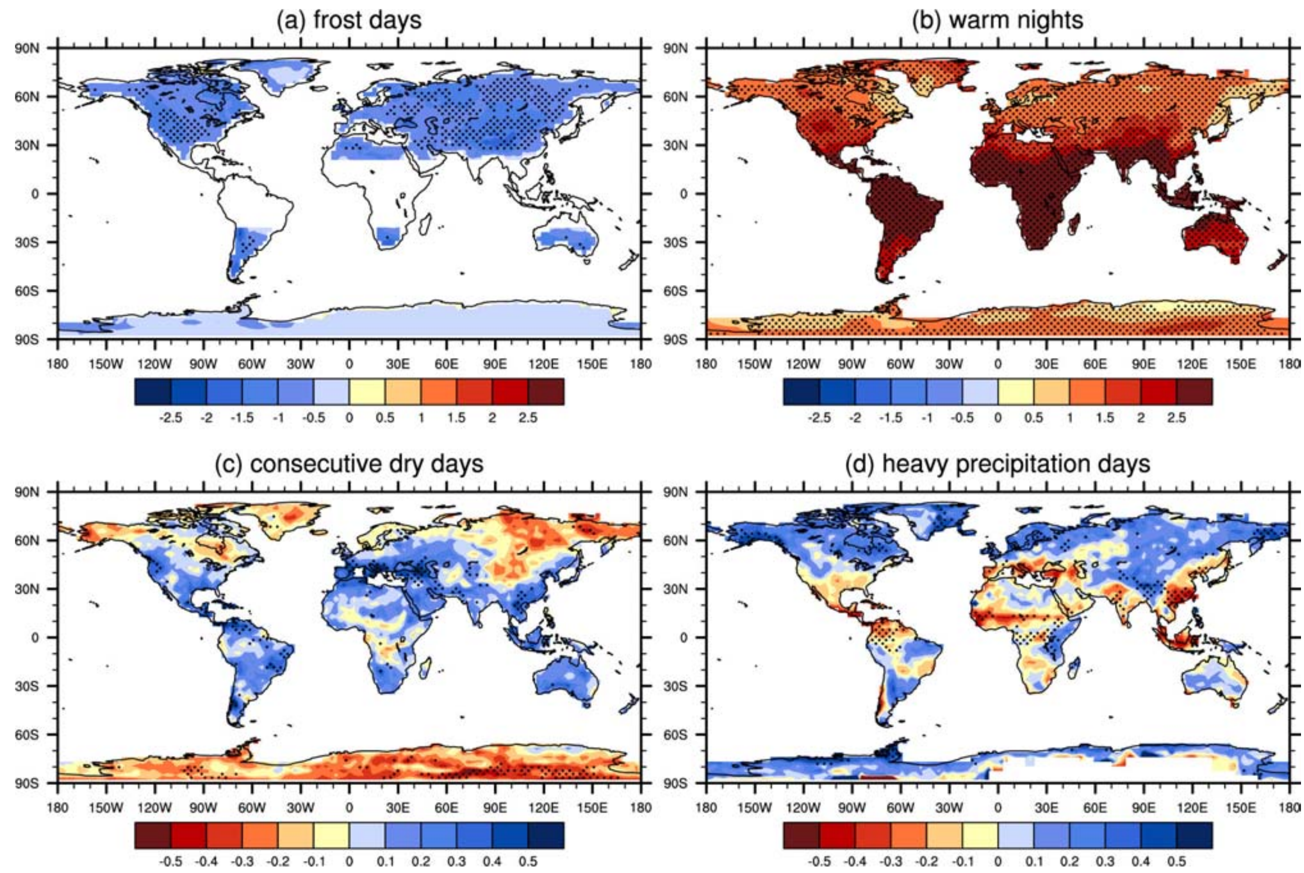

Figure 3: Multi-model averages of spatial patterns of change at the end of the 20th century for significant (a) annual occurrence of days with Tmin < 0ºC (FD), (b) annual occurrence of Tmin > 90th percentile of 1961-1990 reference period (TN90p), (c) annual maximum consecutive number of days < 1mm (CDD) and (d) annual occurrence of days > 10mm (R10). Shown is the difference between two twenty-year averages (1980-1999 minus 1900-1919). Each gridpoint value for each model has been standardised first, then a multi-model simple average is computed. Stippled regions correspond to area where at least five of the nine models concur in determining that the change is statistically significant. Note that standarised units are used to form multi-model averages and cannot be compared quantitatively with those in Figure 1.

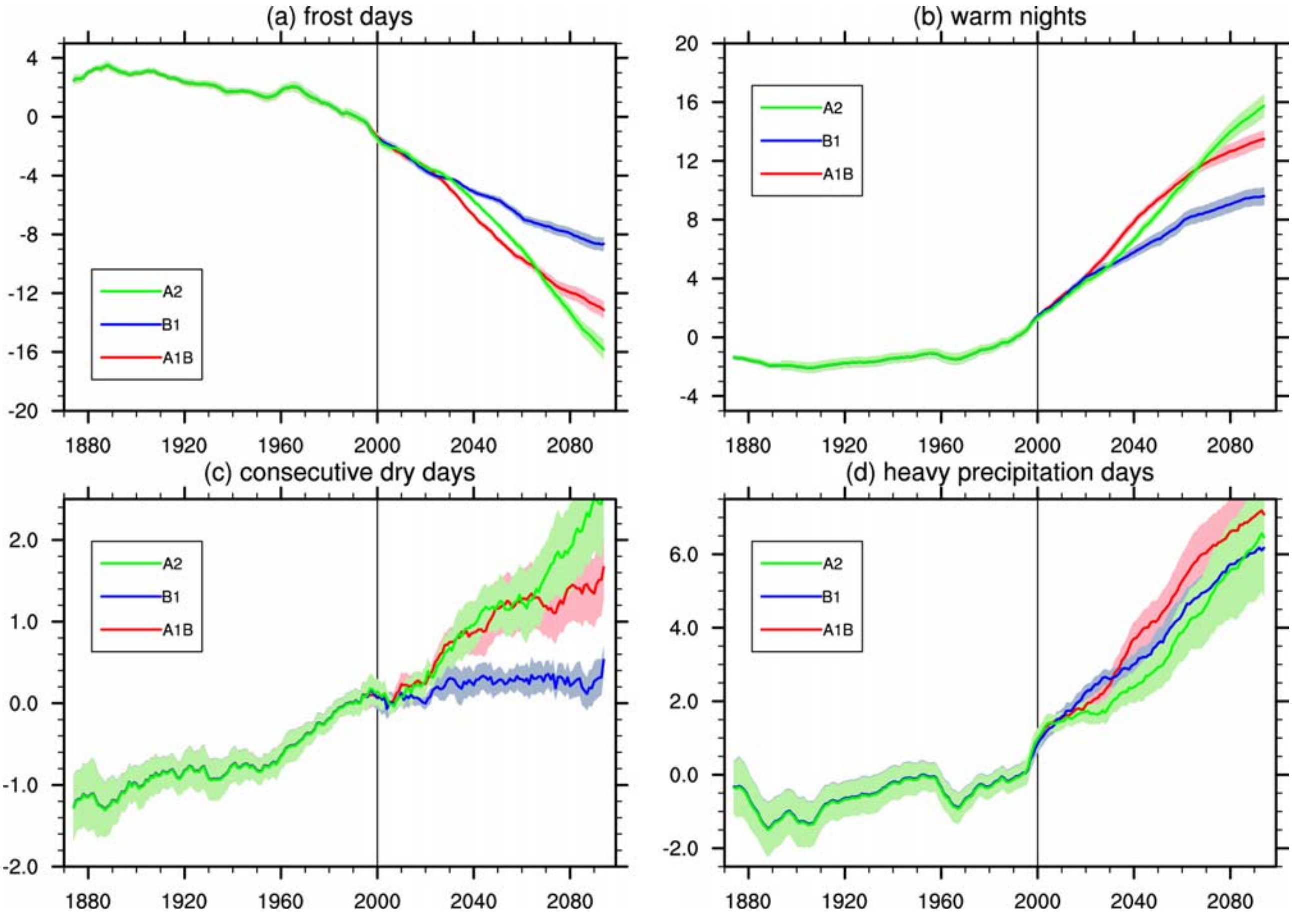

Figure 4: Time series of globally averaged (land only) values of (a) frost days (b) warm nights, (c) consecutive dry days and (d) heavy precipitation days extremes indices. Three SRES scenarios are shown in different colours for the length of the 20th and 21st Centuries. The values have been standardised for each model and then averaged and smoothed by a 10-year running mean. The shading represents one standard deviation of the ensemble mean, as a measure of inter-model variability.

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