MONITORING CHANGES IN CLIMATE EXTREMES
A Tale of International Collaboration

by Thomas C. Peterson and Michael J. Manton

THE NATURE OF THE PROBLEM. The Second Assessment Report (SAR) of the Intergovernmental Panel on Climate Change (IPCC), published in 1996, concluded that the available data and analyses were inadequate for any assessment to be made about the nature of global changes in extreme climate events. Since the SAR, a number of international projects have moved the focus of climate analysis from monthly to daily data so that today there is a better understanding of the extent and character of changes around the world in extreme climate events, such as heavy rainfall and heat waves.

Because of the traditional focus of climatologists on monthly data and the proprietary view many countries have toward data on shorter time scales, the international exchange of long-term daily climate records has been limited, and in 1996 there was no international dataset of long-term daily terrestrial data available. Analyses of extremes were primarily limited to data from Canada, the United States, the former Soviet Union, China, and Australia. Furthermore, any analyses of extremes from these countries were hard to compare because the analyses used different measures of extremes.

TWO-PRONGED SOLUTION. At the November 1999 meeting of what is now known as the joint1 Expert Team on Climate Change Detection and Indices (ETCCDI; www.clivar.org/organization/etc-cdi/etcddi.php), it was recognized that a two-pronged approach was needed to promote further work on the monitoring and analysis of daily climate records to identify trends in extreme climate events.

The first task was internationally coordinating the exact formulation of a suite of agreed indices of climate extremes from daily data. The use of agreed indices would allow comparison of analyses conducted in any part of the world.

Secondly, the ETCCDI decided to promote the analysis of extremes around the world by organizing regional climate-change workshops following the model pioneered in December 1998 at an Asia-Pacific Network for Global Change Research (APN) meeting in Melbourne. That meeting brought together world-recognized experts in climate change analysis to guide participants from a dozen countries in the Asia-Pacific region. The participants brought their long-term daily data, history about the observing stations, and a willingness to learn about quality control, homogeneity testing, and climate analysis.

PROGRESS IN INDICES. The index formulation primarily—but not solely—focused on extremes. One of the key approaches involved the number of days in a year exceeding specific thresholds. Across large regions, the numbers of days above or below a categorical threshold, such as 0°C, is unlikely to be evenly distributed; moreover, such thresholds may never be exceeded in some regions. On the other hand, the number of days exceeding the 90th percentile of daily temperature at each station is more evenly distributed and is a meaningful index in every region. Therefore, many of the ETCCDI’s indices were

1 The expert team is jointly sponsored by the World Meteorological Organization (WMO) Commission for Climatology (CCL), the World Climate Research Programme (WCRP) project on Climate Variability and Predictability (CLIVAR) and, since 2006, the Joint WMO-Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) Technical Commission for Oceanography and Marine Meteorology (JCOMM).
based on percentiles with thresholds set to assess moderate extremes that typically occur a few times every year rather than high-impact, once-in-a-decade weather events.

The specifications for the 27 agreed indices developed by the ETCCDI are available from http://cccma.seos.uvic.ca/ETCCDI along with software to calculate them. Many of the models run for the IPCC Fourth Assessment Report (AR4) computed a subset of these indices in part because they provide a metric for validation of how well the models simulate extremes. Also, projected changes in the indices are indicative of future climate change in extremes. The original workshop software to calculate the indices was written in 2001 by Byron Gleason of NOAA’s National Climatic Data Center, and used spreadsheet macros. Because some current indices require bootstrapping calculations, which are too intensive for a spreadsheet to handle efficiently, Xuebin Zhang of Environment Canada produced new software using the open source statistical package called R (www.r-project.org). This software continues to be enhanced, and its effective use of R graphing capabilities enables visual inspection for both homogeneity and data quality.

**PROGRESS IN WORKSHOPS.**

**Workshops held.** Table 1 lists the workshops on climate extremes that have been held over the last decade. Between 1998 and 2004, APN sponsored a total of five workshops in Melbourne to promote this activity in Southeast Asia and the South Pacific. ETCCDI coordinated workshops in the Caribbean and Africa. Owing to a number of difficulties (including initial restrictions on the sharing of climate indices), only the results of the Melbourne meetings were available in time to contribute to the “global” extremes analysis prepared for the IPCC Third Assessment Report.

A second series of ETCCDI workshops provided input to AR4. The first of this series was hosted by the University of Cape Town, South Africa, in June 2004. It was supported by the International Global Change System for Analysis, Research and Training (START) and World Climate Research Programme (WCRP), and it involved most of southern and eastern Africa. The U.S. State Department, to support IPCC, provided funding through the Global Climate Observing System (GCOS) to organize four additional workshops in the following eight months in Brazil, Turkey, Guatemala, and India. The results contributed to the global analysis of extremes used by the IPCC AR4 as shown in Figs. 1 and 2.

**Fig. 1.** Trends (in days per decade, shown as a map) and annual time-series anomalies relative to 1961–1990 mean values (shown as a plot) for annual series of percentile temperature indices for 1951–2003 for warm nights (index TN90p). Trends were calculated only for the grid boxes with sufficient data (at least 40 years of data during the period, and the last year of the series is no earlier than 1999). Black lines enclose regions where trends are significant at the 5% level. The orange curve on the plot is a nonlinear trend estimate obtained by smoothing using a 21-term binomial filter. The figure, which is from Alexander et al. (2006) and also IPCC AR4, includes indices from workshops held prior to 2006.
Workshop format. These regional workshops involve participants from neighboring countries as well as several well-qualified experts from around the world to provide guidance on the analysis of the climate data. Participants present data from a few of their countries’ sites to be quality controlled, checked for homogeneity, and analyzed at the workshop. This allows participants to quickly assess the climatology and data availability across the whole region, and thus to recognize the benefit of preparing a consistent regional analysis built on each national database.

The core of the meeting is the hands-on analysis of national data. The first step in the analysis is basic quality control (QC) involving a variety of graphical and statistical analyses. However, these routines require human intervention. For example, the basic test of maximum temperature being less than minimum temperature may identify the existence of a problem, but the participant must examine the actual data to determine the nature of the problem and its possible solution.

Once the data have passed the QC tests, participants assess the temporal homogeneity of the data. Changes in instruments or observing site often cause inhomogeneities, and so the station history metadata are vital for resolving such problems. Sites with such artificial changes are removed from the analysis.

Participants are then able to use the software to calculate the agreed indices for each station in their country. An expert collates all the results and gives an overview of the trends and variability in extremes across the whole region. The benefits of working across national borders become obvious when similar results from neighboring countries verify the analyses.

The painstaking task of preparing a peer-reviewed paper about extremes in the region requires access to the data after the workshop. Almost all participants have allowed time series of their indices to be publicly shared (see http://cccma.seos.uvic.ca/ETC-CDI for available calculated station-level indices). Unfortunately, some countries do not allow access to the data from their individual sites. Nevertheless, releasing indices, such as the amount of precipitation that fell each year from events greater than the 95th percentile, provides a great deal of information on how weather and climate extremes are changing.

**FUTURE.** ETCCDI is continuing the two-pronged strategy of index development and regional workshops to the extent that resources permit. Almost every workshop ends with a request for additional workshops. Often that initial workshop was the first time the participants extracted climate-change information from their historical data. Time after time this demonstration of the value of historical climate data has led to increased digitization of a country’s archive. For example, Cameroon’s digital daily data available for the workshop were from 1966 through 2005 and only about 80% complete. Three months after the

![Trend in contribution from very wet days (% per decade) 1951-2003](image)

**Fig. 2.** As in Fig. 1, but for heavy precipitation; specifically, the percent of annual precipitation on days that received precipitation equal to or greater than the 95th percentile of daily precipitation.
Table 1. List of regional workshops held over the last decade to promote the monitoring and analysis of extreme climate events, their sponsors, and the peer-reviewed publications that resulted from the workshops.

<table>
<thead>
<tr>
<th>Date</th>
<th>Host</th>
<th>Region</th>
<th>Sponsors</th>
<th>Journal Publications</th>
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<tbody>
<tr>
<td>Dec 1998</td>
<td>BMRC, Melbourne, Australia</td>
<td>S.E. Asia &amp; S. Pacific</td>
<td>APN</td>
<td></td>
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<tr>
<td>Dec 1999</td>
<td>BMRC, Melbourne, Australia</td>
<td>S.E. Asia &amp; S. Pacific</td>
<td>APN</td>
<td>Manton et al. (2001)</td>
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<td>Jan 2001</td>
<td>University of West Indies, Jamaica</td>
<td>Caribbean</td>
<td>WMO, NOAA, NASA</td>
<td>Peterson et al. (2002)</td>
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<tr>
<td>Feb 2001</td>
<td>Moroccan Meteorological Service, Casablanca, Morocco</td>
<td>North Africa</td>
<td>WCRP</td>
<td></td>
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<tr>
<td>Apr 2001</td>
<td>BMRC, Melbourne, Australia</td>
<td>S.E. Asia &amp; S. Pacific</td>
<td>APN, START</td>
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<tr>
<td>Mar 2004</td>
<td>BMRC, Melbourne, Australia</td>
<td>S.E. Asia &amp; S. Pacific</td>
<td>APN</td>
<td>Griffiths et al. (2005)</td>
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<td>Nicholls et al. (2005)</td>
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<tr>
<td>Aug 2004</td>
<td>Universidade Federal de Alagoas, Maceio, Brazil</td>
<td>South America</td>
<td>US DOS, GCOS, IAI(^a)</td>
<td>Haylock et al. (2006)</td>
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<td>Vincent et al. (2005)</td>
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<tr>
<td>Oct 2004</td>
<td>Turkish State Meteorological Service, Alanya, Turkey</td>
<td>Middle East</td>
<td>US DOS, GCOS</td>
<td>Zhang et al. (2005)</td>
</tr>
<tr>
<td>Nov 2004</td>
<td>CRRH, Costa Rica, and INSIVUMEH, Guatemala</td>
<td>Central America</td>
<td>US DOS, GCOS</td>
<td>Aguilar et al. (2005)</td>
</tr>
<tr>
<td>Feb 2005</td>
<td>IITM, Pune, India</td>
<td>Central &amp; South Asia</td>
<td>US DOS, GCOS</td>
<td>Klein Tank et al. (2006)</td>
</tr>
<tr>
<td>Jan 2006</td>
<td>GCISC, Islamabad, Pakistan</td>
<td>South Asia</td>
<td>APN</td>
<td></td>
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<tr>
<td>Apr 2007</td>
<td>Brazzaville, Congo</td>
<td>Central Africa</td>
<td>Met Office, WCP-WCDMP(^b)</td>
<td>Aguilar et al., in prep.</td>
</tr>
<tr>
<td>Feb 2008</td>
<td>Republic of Korea</td>
<td>Eastern Asia</td>
<td>APN</td>
<td></td>
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\(^a\) Inter-American Institute for Global Change Research

\(^b\) WMO World Climate Programme-World Climate Data and Monitoring Program
workshop, the data were about 95% complete and covered the period 1951 through April 2007. Similarly, prior to the workshop, the Meteorology Agency of the Democratic Republic of Congo had digital daily time series for only 7 stations. Six months later they had 22. A major incentive for participation in this process is the need for countries to be able to adapt to climate change. As demonstrated in the APN workshops, establishing a continuing series of workshops in a region expands that region’s climate-change and data expertise. Two additional workshops were held last year under the auspices of the ETCCDI, in Central Africa and Southeastern Asia, and additional workshops are being organized.

Ideally, all countries would allow the data from their individual sites to be shared, but unfortunately many countries still restrict access to their data even though this is covered by WMO Resolution 40 on the free and unrestricted access of meteorological data for research purposes and for the support of WMO programs. The importance of such access has also been highlighted in the Implementation Plan for the Global Observing System for Climate in Support of the United Nations Framework Convention on Climate Change (UNFCCC). The sharing of core climate data across all countries will be essential for each country and region to develop the capability to adapt to climate change in an economically sustainable manner. Nevertheless, releasing climate indices does provide useful information on trends and variability in extreme events. Sharing the ETCCDI’s indices of extremes is a giant step in the right direction, and the indices have already been of great use to scientists working on adaptation and climate model validation.

FOR FURTHER READING


Yoshikazu Sasaki’s Pivotal Contribution: Data Assimilation

During the early- to mid-1950s when numerical weather prediction (NWP) set the meteorological world abuzz, there came the attendant need to provide initial conditions for deterministic models—first the quasigeostrophic (filtered) models and later the physically more-meaningful primitive-equation models. These methods for finding the initial conditions were first labeled objective analysis schemes or numerical weather map analyses and only later became known as data assimilation. Ideally, these analyses would be untouched by human hands and programmed for execution on high-speed computers. Despite the absence of computational power during this period in post-WWII Japan, Yoshi Sasaki, then a graduate student at the University of Tokyo, developed the variational method of data assimilation—a method that sought to combine observations under the constraint of dynamical law. His innovative technique is the cornerstone of present-day four-dimensional data assimilation (labeled 4DDA or 4DVAR)—the best representation of the real and fluid atmosphere available today.

Sasaki’s fundamental training in physics and his fascination with the application of calculus of variations to relativity and quantum mechanics led him to investigate the applicability of this methodology to geophysical fluid dynamical systems. In principle, this work is tied to Carl Gauss’s early nineteenth-century development of the method of least squares under constraint. Although Sasaki was unable to use a computer to solve these initial-value problems, he solved the governing analysis equations graphically in the spirit of Ragnar Fjortoft’s pioneering work with NWP in the early 1950s. In a tour de force that combined the theory of calculus of variations with the practical problem of typhoon track prediction, Sasaki and his colleague Kikuro Miyakoda established a line of research in 1954 that stimulated the worldwide community of operational and research meteorologists.

Sasaki’s theoretical development is best viewed in the context of operational objective analysis and numerical weather prediction. In fact, as one examines modern-day data assimilation, there is a clear connection to two theoretical lines of research, one based on determinism (Sasaki’s approach) and one based on a stochastic view. Arnt Eliassen introduced the meteorological community to the stochastic approach to data assimilation in 1954 while grappling with the problem of observational network design for the World Meteorological Organization.

The fundamental difference in these variational methods is...