LONG-TERM CLIMATE MONITORING AND EXTREME EVENTS

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Abstract. Problems with long-term monitoring of various extreme meteorological events (including tropical and extratropical cyclones, extreme winds, temperatures and precipitation, and mesoscale events) are examined. For many types of extreme events, the maintenance of long-term homogeneity of observations is more difficult than is the case for means of variables. In some cases, however, a strategy of using more than a single variable to define an event, along with the careful elimination of biases in the data, can provide quantitative information about trends. Special care needs to be taken with extreme events deduced from meteorological analyses, because changes in analysis and observation systems are certain to have affected extremes. Also, compositing of observations from more than one station, using differences in means (of temperature for instance) to produce a single long-term site, may not remove the biases in the extremes. These problems, along with ambiguities in defining extreme events, and difficulties in combining different analyses from different sites, complicate (and perhaps invalidate) attempts to determine whether extreme weather is becoming more frequent. The best that is likely to be achieved, even with increased emphasis on attaining the high-level of homogeneity necessary in the observations, is to monitor long-term variations in certain important extreme events, in select locations with high-quality data. Regional indices of important extreme events, selected on the basis of their damage potential and capable of adequate monitoring, may be established. If, in the future, we are to answer the question "Are extreme weather events becoming more frequent?", we must establish and protect high-quality stations capable of monitoring the most important extreme events (perhaps with such regional indices), and ensure that changes affecting the recording of extreme events (e.g., changes in exposure) are meticulously documented.

Introduction

Many of the deleterious impacts of a global climate change may result from changes in frequency or intensity of extreme weather events such as tropical cyclones, wind storms, heavy rainfall, and extreme temperatures, rather than from changes in mean values of atmospheric variables such as temperature. Already, these extreme events cause considerable damage and loss of life. Numerical model simulations of the climatic effects of an enhanced greenhouse effect suggest that the frequency and intensity of some extreme events may change. It is important, therefore, that there exist effective methods for the monitoring of changes in extreme events. Only then can we answer the frequently-posed question "Are extreme weather events becoming more frequent or severe?".

Karl *et al.* (1995a) note the difficulties involved in monitoring most aspects of the climate system. Monitoring extreme events is even more difficult than monitoring changes in climate means, in many cases. Serious problems with past and present monitoring systems prevent or complicate the credible estimation of changes or variations of many types of extreme events. In this paper the problems

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of monitoring extreme events are discussed, for an illustrative range of extreme events. The problems are not uniform across all types of extreme events. Nor are the potential solutions. For some types of events the difficulties and the potential solutions are rather simple, or are similar to the solutions necessary to ensure adequate monitoring of changes in means of variables. For others, inadequacies in the monitoring system appear to be more severe, and less amenable to ready solution. Some possible methods for overcoming the potential problems, and for long-term continuous monitoring of extreme events, are considered.

For the purposes of this paper an extreme weather event is defined as a short-lived meteorological phenomenon capable of causing loss of life or substantial damage. 'Short-lived' is assumed to include time-scales up to a few days, thereby encompassing tropical cyclones and mid-latitude wind storms. The definition excludes very long events which could still result in severe economic or social damage, such as droughts.

The various extreme meteorological events can be categorised in a variety of ways. In this paper the following types of extreme events are considered separately:

- Tropical cyclones;
- Extratropical cyclones;
- Strong winds;
- Heavy precipitation;
- Extreme temperatures;
- Mesoscale disturbances (eg., tornadoes, thunderstorms);

These categories involve some overlap: tropical cyclones and tornadoes are usually associated with extreme winds and sometimes with heavy rains. The methods of monitoring the various types noted above are, however, different, and have their own range of problems. Monitoring the number of tropical cyclones as well as the number of extreme wind events, therefore, can provide extra useful information, despite their overlap. The types of extreme events selected for consideration here include the best-documented, and the most damaging. The discussion here of these 'representative' extreme events also indicates the type and seriousness of the difficulties involved in monitoring almost all types of extreme weather events.

Tropical Cyclones

Intense Atlantic hurricane activity over the period 1970–87 was less than half that in the period 1947–69 (Gray *et al.*, 1992). A similar quiet period had occurred in the western North Pacific, suggestive of a decrease in the number of very intense tropical cyclones. Bouchard (1990) and Black (1992), however, demonstrated that this apparent change in intensity in the western North Pacific was an artefact, due to a change around 1970 in the method used to derive wind estimates from pressure estimates. Chen (1990) independently determined that the historical typhoon data sets were biased and required correction prior to 1970, if they were to be compred with recent behaviour. Black found that when a consistent method for determining wind estimates was used throughout the period of record, then the pre-1970 data was statistically indistinguishable from the post-1970 data. Bouchard used estimates of surface pressure to determine the number of very intense typhoons (defined as a cyclone with a central pressure below 910 mb), and found no evidence of any strong trend in the number of very intense typhoons, although the 1980s had, on average, more very intense typhoons than earlier decades. Landsea (1993) suggested that Atlantic hurricane intensity record was probably also biased. Winds were five kt higher before 1970, compared with hurricanes with the same minimum pressure after 1970. This suggests that the apparent drop in Atlantic hurricane activity may, at least partially, also be an artefact, as in the northwest Pacific. Landsea found, however, that after adjusting for this bias a substantial downward trend in intense hurricane activity is still apparent. There remains a possibility that not all the bias in the Atlantic records has been removed, and that this drop in activity is artificial. However, a similar drop in activity around 1970 was also observed in the frequency of storms hitting the U.S.A. These storms were categorised by using minimum sea level pressure recorded at landfall. Such observations should not be as suspect as observations over the ocean. Also, the decrease in hurricanes appears to reflect a relationship between hurricane activity and Sahel rainfall (Landsea and Gray, 1992), which has also been low since about 1970. Finally, hurricane activity is also weaker during El Niño episodes. The tendency for the El Niño-Southern Oscillation to remain more frequently in the El Niño mode since the mid-1970s (Trenberth, 1995) would, therefore, have led to a tendency for weak hurricane activity. There are strong grounds, therefore, for concluding that much of the decrease in intense Atlantic hurricane activity is real (Landsea *et al.*, 1995). However, it is worth pointing out that our confidence in this conclusion rests partly on empirical relationships between hurricane activity and other meteorological variables.

Apparent changes in cyclone frequency elsewhere may be artefacts. The Southern Oscillation Index (SOI) is a good predictor of tropical cyclone numbers in the Australian region. Nicholls (1992) demonstrated that the relationship between the SOI and cyclone numbers apparently changed around 1986. After this year the numbers of tropical cyclones appeared to be consistently lower than would be expected from the relationship with the SOI derived only with data beforethis date, although the interannual variations were still closely related. The sudden change in this cyclone-SOI relationship is suspicious, and may be due to changes in the analysis of cyclones. Figure 1 shows a time series of the number of named tropical cyclones in the Australian region (105° E–165° E) between 1949 and 1994. The influence of the El Niño–Southern Oscillation, which affects interannual variations in cyclone numbers, has been removed from these data, to facilitate identification of trends. The steady upward trend in cyclone numbers from 1949 to the mid 1980s seems likely to be at least partly artificial, reflecting improvements in observing systems (e.g., the progressive introduction of improved meteorological satellites over this period). On the other hand, tropical cyclone activity around Australia is also related to sea surface temperatures (Nicholls, 1984), and these increased over this period (Figure 2). So perhaps part of the apparent upward trend in cyclone activity is real. The 'spike' in 1962 is the result of some weak storms being identified as tropical cyclones. In previous and later years such systems would not have been named as cyclones. The sudden drop in cyclone numbers in 1986 is probably at least partly artificial, reflecting a change in policy of which tropical storms will be named as cyclones. However, there is some evidence of a real drop in activity, again from other data. Tropical cyclones often bring good rains to northern Australia, and summer rainfall was low through the mid to late-1980s. This may reflect a decrease in cyclone frequency, supporting the apparent decrease seen in Figure 1. The gradual increase in cyclone numbers in the most recent years may also be real, based on higher rainfalls after the late-1980s. This example demonstrates the difficulties in even establishing numbers of tropical cyclones in recent years, let alone examining changes over decades. This applies even to a good observing network, on the Australian coast and surrounding islands. Obstacles in establishing whether observed trends in cyclone numbers in, for instance, the south Indian Ocean and the south central Pacific, are even more severe. However, the use of proxy variables, such as rainfall and station pressure, may provide evidence in support of apparent changes in cyclone activity determined from analyses.

As was the case with the monitoring of the numbers of cyclones, there are grounds for believing that the changes in observing and analysis techniques over the past few decades may have biased the trends in cyclone intensity. Figure 3 shows the maximum sustained wind speed attained each year in Atlantic hurricanes (C. W. Landsea, pers. comm., 1994). There is no obvious trend. After 1970, however, the spread of maximum wind speeds increased: in some years the maximum wind speed was relatively weak, while in others very high maximum wind speeds (higher than had been observed prior to 1970) were reached. The suddenness of the change around 1970 suggests that it might be the result of changes in the observing techniques, specifically the introduction of satellite monitoring. A similar change in spread is not apparent in the *mean* maximum sustained wind speed attained each year in Atlantic hurricanes. This suggests that the changes in the observing systems may be causing problems for an occasional very weak or very strong storm.

Observing and analysis techniques will continue to change in the future. A fresh approach to monitoring cyclone numbers and intensity is therefore necessary, if we are to be able to credibly claim that we have a clear picture of variability and change. One possible approach is to parameterise tropical cyclone numbers in terms of a few large-scale variables, i.e. extending the approach of Gray and his colleagues. If such a parameterisation was successful, the changes in the large scale variables could then be used to deduce the changes in cyclone numbers, or to verify such changes. Changes in these variables could then be used to deduce changes in tropical cyclone activity.

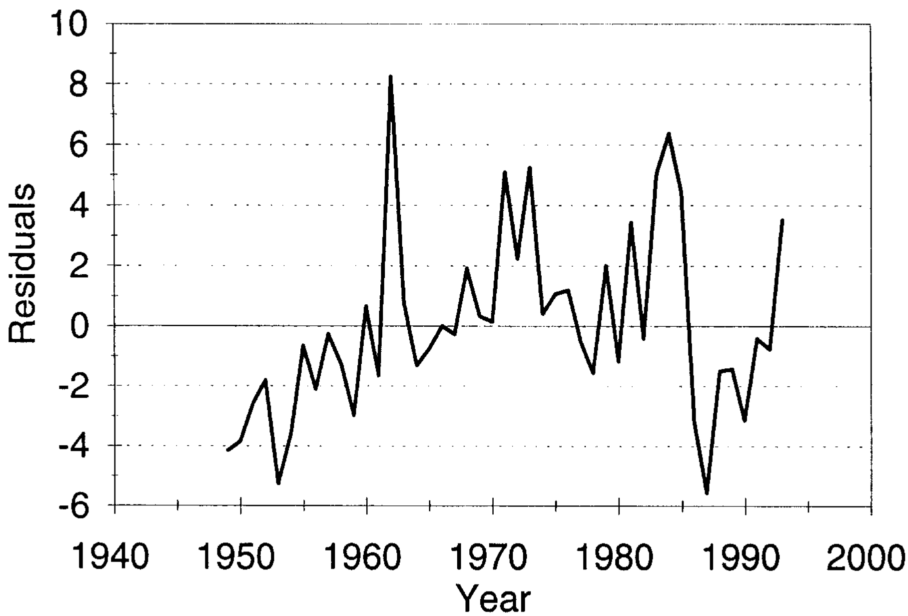

Fig. 1. Time series of the number of named tropical cyclones in the Australian region (105° E–165° E) between 1949 and 1994. The influence of the El Niño–Southern Oscillation, which affects interannual variations in cyclone numbers, has been removed from these data by linear regression, to facilitate identification of trends.

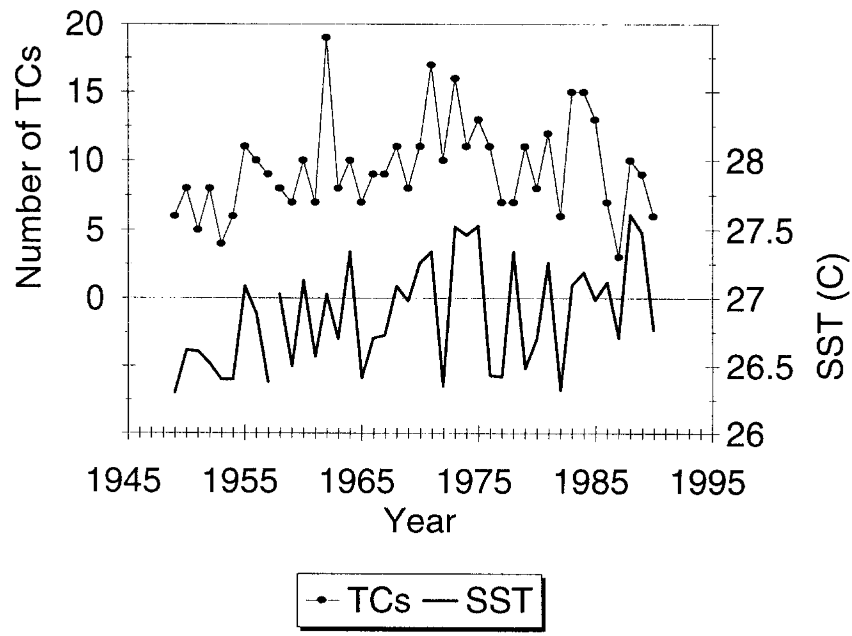

Fig. 2. Time series of the number of named tropical cyclones in the Australian region (105° E–165° E) between 1949 and 1991, and September sea surface temperatures in the box 120–160° E, 5–15° S.

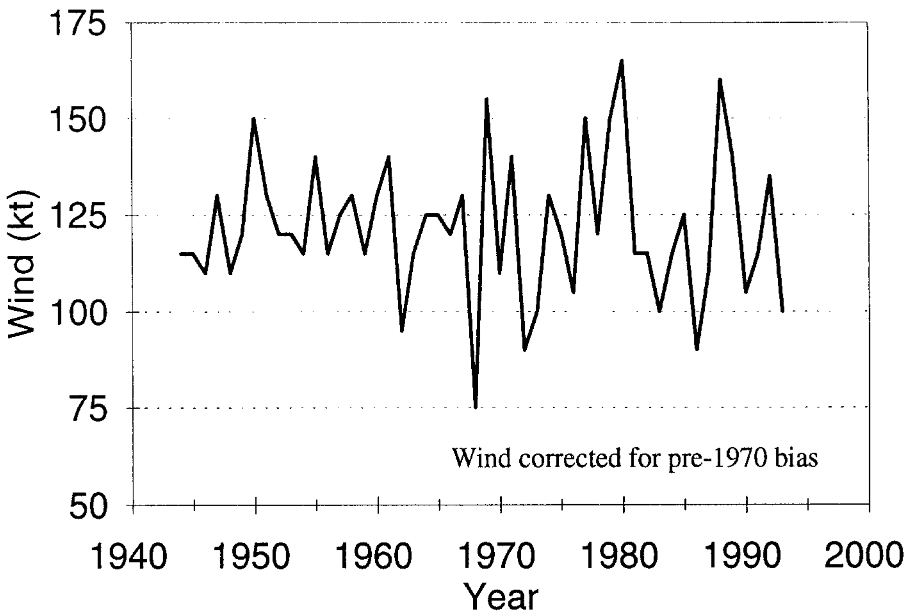

Fig. 3. The maximum sustained wind speed attained each year in Atlantic hurricanes (C. W. Landsea, per. comm.).

A different approach is to rely on deductions about numbers or intensity of cyclones from stable, land-based observations. As noted earlier, the sharp decrease in North Atlantic hurricane activity after 1970 was also observed in the frequency of storms hitting the U.S.A. Such landfall observations should not be as suspect as observations over the ocean, and they therefore provide partial confirmation of the reality of the changes discussed above. Another approach (suggested by F. Woodcock) is to define systems as tropical cyclones if a satellite image indicates a clear 'eye', and to base long-term monitoring of numbers of cyclones on this simple criterion.

Extratropical Cyclones

Cyclonic depressions in higher latitudes rarely cause as much damage as a severe tropical cyclone. However, they can still be extremely destructive. The most obvious method for monitoring extratropical cyclone occurrence is to use historical weather maps. Schinke (1993) used once-daily analyses (U.S.A. analyses (1939–1964; thereafter German analyses) to count the number of storms below certain thresholds. Agee (1991) combined data from three previous studies of cyclone and anticyclone frequency around North America to examine trends.

Schmidt and von Storch (1993) note, however, that the use of operational analyses for the studies cited above may be complicated by the possibility of improvements in the analyses resulting from more and better observations and other improvements in monitoring the state of the troposphere. Trenberth (1995) notes some of the changes in analysis systems in recent decades. The use of analysis systems over longer periods is fraught with dangers, especially for deducing changes in frequency or intensity of extreme events such as extratropical depressions. More detailed mapping, for instance, would tend to result in cyclones with lower central pressures. Such a change might arise because of improved observational systems, or because of improvements in the analysis systems. Because of the doubts caused by changes in observing/analysis techniques, other data are needed to confirm any deduced changes. Changnon and Changnon (1992) used insurance data and found that temporal variations in winter storm disasters closely matched the trends in cyclone numbers for North America (Agee, 1991). Insurance data, however, are themselves inhomogeneous, because of changes in insurance coverage, as well as other factors reflecting social rather than weather changes.

As with tropical cyclones, parameterisation of cyclone activity in terms of variations of other variables, with stable observing characteristics, might provide more credible estimates of changes and variations. Hopkins and Holland (1995) determined the numbers of cyclones affecting the Pacific coast of Australia with an objective method of specification based on a consistent set of observing stations spread along the coast. They found a clear upward trend in the numbers of cyclones between 1958 and 1992. Such a trend, if deduced from analyses, would be suspect; the use of the consistent synoptic observations, however, lends credibility to the trend.

Reanalysis projects provide some hope for improved determination of trends in extratropical circulation systems. Modern meteorological computer analysis techniques produce globally-complete data-sets. The techniques used in such analysis have, however, changed with time, thereby introducing a further set of biases. Several groups plan to create historical grid-point data-bases by reanalysis of recent historical data using fixed numerical models and analysis techniques (cf., Kalnay and Jenne, 1991). Trenberth (1995) describes these reanalysis projects in some detail. The reanalysis projects will remove the biases associated with the analysis techniques, but will inevitably still contain time-varying biases because some temporally heterogeneous data, for example from radiosondes, will be supplied to the models. Techniques for producing globally-complete fields have not so far treated biases explicitly (as opposed to random errors), so these must be removed first, if the reanalysis projects are to produce data free of time-varying biases. But even with these time-varying instrumental problems, the reanalyses should improve confidence in our ability to determine trends or variations in extreme events, such as extratropical depressions. Doubts about the homogeneity of the analyses due to possible changes in at least some observing system could be addressed by examining how well the analyses can reproduce those data known to be homogenous over time, e.g., global lower tropospheric temperatures derived from microwave sensor unit (MSU) observations since 1979.

Strong Winds

Wind records are amongst the worst in terms of consistency over long periods. Fairly small changes in exposure would significantly affect wind speeds. As well, during times of strong winds, weather equipment malfunctions are more likely, but vary with the type and exposure of the equipment. So, progressive strengthening of equipment might lead to artificial biases in strong winds. Schmidt and von Storch (1993) suggest that local studies with homogenous air pressure data may provide more definite answers, at least for specific regions, because of the uncertainties with direct observations of winds. They used daily air pressure observations at three stations in the southeast North Sea to calculate the annual distributions of daily geostrophic wind speeds and concluded that the frequency of extreme storms in this area has not changed in the past 100 years. There are numerous areas of the world where long-term surface pressure observations could be used in this way, to assess the possibility of changes in extreme wind speeds.

Again, other variables (which might themselves be more robust than wind speeds) might provide confirmation of changes, or lack of changes, in wind speeds. Von Storch *et al.* (1993) also examined high water levels at Hoek van Holland, after removing the effects of tides and sea level changes. The resultant time series should reveal storm-related surge heights. No trend was found in the frequency of extreme surge heights. Of course, high water levels may also be affected by inhomogeneities, thereby invalidating their use to monitor trends in extreme wind speeds. Comparison of extreme wind records and nearby storm-surge records goes, however, provide an avenue for checking the consistency of both forms of data.

Heavy Precipitation

Karl *et al.* (1995c) analysed the trends in the percentage of total seasonal and annual precipitation occurring in heavy daily rainfall events (days with rainfall exceeding 50.8 mm/day) over the U.S.A., the former Soviet Union, and China. A significant trend to increased percentages of rainfall falling in heavy events was evident in the U.S.A., largely due to a strong increase in extreme rainfall events in summer. However, the accumulation of rainfall totals over more than one day can complicate such studies. For instance, in some countries rainfall reports at some stations are not taken on weekends. As a result the Monday report is an accumulation of rainfall since Friday. In some countries this tendency has occurred more frequently in recent years than in the past, at some stations. This will bias the estimation of trends in extreme rainfalls in a complicated fashion. Careful checks of documentation regarding station observing/reporting schedules, conducted as part of a general check on station quality and consistency (eg., Lavery *et al.*, 1992) should reveal whether such accumulations were likely to bias the results of any apparent trend in rainfall occurrence. It may be possible to model the rainfall distribution statistically, and use this model to calculate the likely influence of the increased prevalence of accumulation on extreme event frequency.

Karl and Knight (1995) used a different approach to check whether the accumulations were biasing their results. They repeated their calculations with 3-day rainfalls to check the possibility that the 1-day rainfall results simply reflected a trend to increased numbers of 'accumulated' totals, i.e., totals reflecting more than a single day of rainfall. A similar trend was apparent in heavy rainfall events calculated from 3-day total rainfalls, to that from the 1-day totals. They concluded, on this basis, that accumulations were not substantially affecting their results. Note that this accumulation problem is unlikely to affect determination of trends in mean rainfall, except insofar as evaporation from the gauge over several days reduces observed precipitation.

Changes in instrumentation may also bias the results. IPCC (1990, 1992) note that precipitation is generally underestimated by conventional measuring devices, typically by 10 to 15%, and that progressive improvements in instrumentation have introduced artificial, systematic increases in estimates of precipitation, especially in areas where the proportion of solid to liquid precipitation is relatively high. Karl *et al.* (1995a) discuss the effects of changes in instrumentation, and instrument bias, in precipitation measurements. Very important for the measurement of heavy rainfalls would be biases due to changes in wind protection. Strong winds will often accompany heavy rainfall and snowfall. Any changes to minimise losses due to wind-induced turbulence over the orifice of a raingauge would be likely to result in artificial trends in extreme precipitation. So, in some areas, determination of trends in heavy rainfalls might be more difficult than is the case for total rainfall.

Some changes in instrumentation might affect the apparent frequency of heavy rains, relative to days with light falls. For instance, Australian rain gauges were changed in 1974 to metric units. There are grounds for concern (Nicholls and Kariko, 1993) that this change may have led to an increase in the numbers of days with very light rainfall. So, even though this change would not have led to an artificial change in the absolute numbers of heavy rainfalls (or of the total rainfall recorded in some extreme events), it may have led to an artificial change in the relative frequency of heavy events compared to light rainfall days. Nicholls and Kariko calculated an average intensity of rainfall events, by simply dividing the total rainfall by the number of rain days. If the number of light rainfall days had increased artificially this might have led to an artificial decrease in average intensity, which might be assessed, incorrectly as evidence of decreasing relative frequency of heavy rainfall.

Some supporting evidence regarding heavy rainfalls may be obtained from flood heights of extreme streamflow records. Care would need to be taken, of course, to ensure that such records are not affected by changes in rivers, dams, or vegetation and building changes in catchments.

Extreme Temperatures

Stone *et al.* (1995) examined daily temperature series for several stations in inland eastern Australia and found a significant decrease in the numbers of days with minimum temperatures below 0 °C, and the date of last frost, over the 20th century. They also found similar decreases in frequency for other low temperature thresholds. Similar changes in frost frequency have been noted in several other studies.

There are concerns, however, with such studies. Increased urbanisation may result in increased minimum temperatures, including a reduction in the frequency of very low minimums. Other effects, e.g., increased spray irrigation, or increased vegetation round observing sites, might also reduce the number of frost observed. These effects might be even more prevalent in rural areas than urban areas (despite the widespread concern about the effects of urbanisation). For instance, many rural observations in Australia are from farms, where the thermometer screen is sited nearby the farm buildings. Even if the site is well separated from buildings, this area often features more large trees and more complete vegetation cover than the surroudning areas. The trees will have grown over long periods and their influence on local winds may have influenced the temperature recordings. So, the increasing height and cover in the area around the screen might be expected to bias the extreme temperatures. Note that this may be a problem even if correct standards are applied for siting of screens, especially for extreme temperatures can be accompanied by strong winds. It may be that long-term phenomenological reports, e.g. visual reports of heavy frosts on fields, may provide at least confirmatory evidence of changes in extreme events. Such reports, in some cases, may be more reliable than temperature recordings from screens, as they are more likely to represent conditions some distance from the screen, and therefore may be less-affected by such factors as the growth of trees near the instrument enclosure.

A common problem with long-term station records is that a high-quality station may have closed at some time, and have been replaced by another station nearby. Overlapping periods can be used to compare the two stations, and to produce a composite station, with the data at one station adjusted to take into account the differences between the sites. This is commonly done with monthly or annual mean data, and can produce good composite sites for estimation of trends in mean temperatures. However, inter-station differences in extreme temperatures can be very different to the differences in the means and this may confound the use of composite sites in estimating trends in extreme temperatures (Trewin and Trevitt, 1995). Since even a change in exposure, or a slight shift in location, at a specific station may result in a need for adjustments, this problem will affect many, if not most, sites used for long-term monitoring of temperatures. For example, sheltering by a tree might affect extreme maximum temperatures more than mean temperatures. So, correcting the 'sheltered' part of the record by adjusting mean temperatures may not result in adequate corrections of the extreme temperatures.

Trewin and Trevitt (1995) have proposed an approach to compositing stations likely to overcome such problems.

Changing the exposure of the thermometers (e.g., from the Glaisher stands common in the 19th century to Sevenson screens) introduces different biases to the mean, maximum, and minimum temperatures (Parker, 1994). Such changes could have affected the extremes differently to the mean temperatures. For instance, Laing (1977) found differences of around 2 °C between Stevenson and Glaisher maxima on some very warm days, even though the difference in the annual mean temperatures was statistically insignificant (Parker, 1994). Laing's results suggest that correction of historical records to ensure homogeneity of extreme temperatures, despite changes in screens, may be more difficult than for mean temperatures. Again, as long as overlapping records from the various exposures are available, the data can be combined as suggested by Trewin and Trevitt (1995).

Mesoscale Disturbances

The final type of extreme weather events considered here consists of events normally subject only to visual reports, rather than resulting from quantitative readings on conventional meteorological observing equipment. The apparent prevalence and intensity of such events depend crucially on the objectivity, availability and consistency of the observers. Identification of trends in such data is likely to be problematic, because of doubts about consistency of observer's behaviour and reactions over very long periods such as several decades.

Ostby (1993) examined the U.S.A. data base of reports of tornadoes from 1953–1992, for evidence of changes in frequency or intensity. He noted that tornado reports are probably the most 'noisy' and biased of all meteorological data. There appears to have been an increase in the reporting of weak tornadoes, perhaps the result of increased population, eagerness in reporting, or improved reporting procedures.

Similar problems plague determination of changes or variations in the frequency of thunderstorms, dust storms, and other mesoscale meteorological events. For at least some such events, truly global monitoring systems may soon be available. For instance, monitoring lightning strikes from space appears to be feasible. Alternatively, tropical thunderstorm activity leads to electrification of the fair-weather atmosphere through what is known as the atmospheric electrical circuit. So measurements of the atmospheric electrical circuit may be able to provide information on thunderstorm and lightning activity (e.g., Williams, 1992; Price, 1993).

Some General Problems

One problem with assessing possible changes in extreme events, to answer such questions as "Are extreme weather events becoming more frequent", is that such questions must be addressed at numerous individual locations. It is difficult to establish protocols for combining information regarding extreme events at the various locations. The behaviour may be very different at various locations. Thus, Karl *et al.* (1995c) found a significant trend to increased percentages of rainfall falling in heavy events in the U.S.A., but not in the former Soviet Union nor in China, making it difficult to conclude whether there has been an overall (global?) increase in extreme rainfall events.

Investigators may have used very different criteria in their considerations of extreme events. For instance, a variety of approaches to the study of intense rainfalls have been taken in Australia in recent years. Yu and Neil (1991) examined whether daily rainfalls above a certain intensity threshold were likely to behave in the same way as rainfall totals (e.g., seasonal or annual rainfall), in a changing climate. Cumulative rainfalls in excess of 40 m/day were calculated for stations in southeast Australia. In this area there has been an increase in rainfall totals through the 20th century (e.g., Nicholls and Lavery, 1992). However, Yu and Neil found no trend in the amount of rainfall received in intense rainfall events. Nicholls and Kariko (1993) calculated an average rainfall intensity (total rainfall divided by number of rain days) for stations in eastern Australia and also found no trend in intensity through the 20th century. They noted that the changes in rainfall totals reflected increases in the number of rain events, rather than a change in intensity. Yu and Neil compared the rainfall in excess of various intensity thresholds in this region during the 1920s, with the situation in the 1950s. The 1950s had higher total rainfall, but the 1920s had more falls of high intensity (at all thresholds above 30 mm/day). Yu and Neil (1993) examined the relationship between total rainfall and high intensity falls for the southwest of Australia, an area where rainfall has been decreasing in recent decades (Nicholls and Lavery, 1992). They did not find a concurrent decrease in high intensity rainfall. In fact high intensity rainfall increased in summer, offsetting a decrease in winter. Lough (1993) however found that for the northeast Australia, interannual variations in rainfall totals are closely related to variations in rainfall intensity, as well as to the number of events. This area is tropical and received much of its rainfall in only a relatively few events. Lough (1993) found no evidence of a trend to more intense rainfall, or for greater numbers of heavy rain days between 1921 and 1987. However, Suppiah and Hennessy (1995) examined trends between 1910 and 1989 across tropical Australia and found that most stations revealed positive trends in the 90th percentile rainfall intensity and frequency, although few were statistically significant. It is difficult to decide how much of the difference between the conclusions of these studies represent real geographical variations, and how much is due simply to the approaches used in the various studies.

Different criteria (what is an extreme event?), when used on the same data, may lead to different conclusions, reflecting the fact that changes in extremes and variability on different time scales do not necessarily have to be identifical. It might be, for instance, that intensities of say, 10-minute ranfalls, might increase without a concomitant increase in intensity measured with 24-hour rainfall totals. Yu and

Neil (1991) analysed 6-minute rainfall data from Canberra Airport, Australia to test this possibility. The rainfall volume occurring above a given intensity threshold in the 6-minute data was compared with that above the same threshold from daily data. Annual high-intensity rainfall volumes, derived from the two data sets, with an intensity above a certain threshold are positively correlated but the correlation decreases as the threshold is increased. For a threshold of 20 mm/day the r^2 is 0.92, but it decreases to 0.76 for intensity greater than 40 mm/day. It is feasible, therefore, that results of studies of trends in intense rainfalls using daily data may not reflect trends in shorter period intense rainfalls. Such problems might also arise at longer time-scales. For instance, a trend in one-day extreme rainfalls might not be reflected by a similar trend in 3- or 30-day extreme rainfalls. Similarly, temperature extremes might be defined as the number of days exceeding a certain threshold, or alternatively as the highest temperature recorded during a given period (e.g., a year). Trends in such different 'extremes' might not be identical.

Care is also required in extrapolating observed trends in extremes even to nearby regions. Grace and Curran (1993) showed that for many southern Australian coastal sites, the frequency distribution of daily maximum temperatures was a combination of maritime and continental airstreams, with each distinct airstream having a separate normal distribution. A change in the intensity or frequency of one of these airstreams (e.g., more frequent maritime stream) might result in a change in extreme temperatures at the coastal sites, but perhaps not further inland (where the maritime stream might be less influential). So, a change in extreme temperatures at the coastal sites could be very different to the situation at a nearby inland site.

These problems, and those discussed earlier for the specific types of extreme events, mean that it is unlikely that we will be ever be able to answer, on a global basis, the question "Are extreme weather events becoming more frequent?". The difficulty of combining such disparate information as trends in tropical cyclone activity, trends in extreme temperatures (e.g., frosts), etc., probably renders the question meaningless in any case. Even if one form of extreme weather event changes in frequency, it is likely that this will be offset be an opposite change, either in a different sort of event at the same location or elsewhere. The only tactic that seems likely to realise useful results is to concentrate on important extreme events and to determine for specific regions (e.g. an ocean basin), whether this subset of extreme events is canging in frequency or intensity. The array of problems discussed earlier clearly demonstrates that even such a limited, location-specific and variable-specific approach is difficult. With care, however, and the use of supporting evidence from a variety of data types, this does seem feasible, at least for some types of extreme events, in some areas.

It may then be possible to select a subset of important, but well-monitored, extreme weather events from a specific region. These could then be used to form an index of extreme weather for that region, and be routinely monitored for future changes. Karl *et al.* (1995b) used this approach to develop an index of extreme weather for the U.S.A. They included the area with very high or very low maximum and minimum temperatures, the area with very dry or very wet conditions, the area with a large proportion of rainfall falling in extreme rainfalls, and the area with very large or very small number of rainfall days. These were combined into an index which was calculated for every year on record. In the same way an index of extreme weather events could be developed for other countries or regions or even ocean basins (e.g., the Atlantic). The specific extreme events to be included in such indices, and their relative weighting, should be developed a priori, based on an estimate of their relative importance or destructiveness.

Improved consistency of routine meteorological observations, and intensified efforts to remove past inconsistencies and biases in these data, will however be needed, even for such studies. The prevalence of these problems in historical data, however, does not preclude the development of such indices for monitoring *future* changes in extreme weather events. Care will need to be taken in the development of the indices, to ensure that a consistent and reliable data base for calculation of the indices is available in the future. This will require that sufficient high-quality observing stations are either established or protected from future changes liable to introduce artificial changes in the time-series. If this is done we may, in the future, have more evidence of whether or not extreme weather events have been changing, possibly even on a quasi-global scale.

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