Climate System Studies

Final Report to the U.S. Department of Energy

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Climate System Studies: Natural Variability and Climate Change Detection

Accomplishments

We carried out four major tasks:

- 1) examined the characteristic patterns of decadal and longer timescale variability in the atmosphere-ocean system, and the forcing mechanisms responsible for these changes. Both of these topics are among the primary science questions identified by the WMO-CLIVAR DEC-CEN Program as critical research issues.
- 2) examined changes in the spatial structure and frequency of occurrence of a suite of major atmospheric circulation features, such as the El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) patterns in the climate record, and for equivalent measures in model data to ascertain whether congruent changes are present.
- 3) examined changes in the amplitude and phase of the annual cycle of instrumental temperature and precipitation data, to compare with model simulated data for equivalent changes in doubled CO₂ experiments.
- 4) evaluated changes in daily, monthly, seasonal and annual values of surface temperature and precipitation for continental land areas over the past century to determine whether changes have occurred in the probability distributions of these basic climatic elements.

This work built on our previous research for the Department of Energy, which has focused on:

- high quality database construction (Bradley et al., 1985; Bradley and Jones, 1986; Eischeid et al., 1991; 1993)
- analysis of spatial and temporal variability of climate (Bradley et al, 1987a; Bradley et al., 1992a, 1992b; Diaz, 1986, 1990; Diaz et al., 1989, Diaz and Kiladis, 1992; Diaz and Pulwarty, 1992, 1994; Diaz and Bradley, 1995; Karl et al., 1989, 1990; Mann et al., 1995)
- the relationship of these variations to forcing mechanisms (Bradley et al., 1987b; Bradley, 1988; Bradley and Jones, 1992a; Diaz and Kiladis, 1995; Diaz and Markgraf, 1992), and
- the long-term evolution of climate, leading up to the 20th century (Bradley, 1991, 1994a,b, 1995; Bradley and Jones, 1992b, 1993, 1995, Hughes and Diaz, 1994; Jones and Bradley, 1992a,b).

[references cited are listed in Appendix 1)

Here we briefly summarize some of the major conclusions of our work during the period 1995-1998. **Appendix 1** provides a more extensive bibliographic summary of papers arising from this grant (indicated by asterisks) as well as from our previous work supported by the Department of Energy.

Results

Elements of the first two tasks were goals in a study of possible causal mechanisms for observed widespread retreat of alpine glaciers and melting of tropical ice cap margins (Diaz and Graham, 1996). The inferred warming is consistent with oxygen isotopic changes ($\delta^{18}\text{O}$) that indicate significant warming in the past 100 years, with the greatest change occurring in the past few decades (Hastenrath and Kruss, 1992; Brecher and Thompson, 1992; Schubert, 1992; Oerlemans, 1994; Thompson *et al.*, 1993; 1995; Haeberli, *et al.*, 1994). The study also compared temperature changes in the tropics based on instrumental records for the past 3-4 decades, to the results of a modeling study where the model atmosphere was forced by the observed global pattern of sea surface temperature in a 19-yr simulation. In particular, the time evolution of the height of the freezing-level surface (FLS; the height of the 0°C isotherm) in the GCM was compared with the evolution of this critical level derived from radiosonde measurements taken during a similar period of time. Comparison of temperature changes in high elevation environments were also made by using 40-45 years of surface temperature records from sites situated above 1000 m in elevation. The results suggest that freezing-level heights in much of the tropical region have risen ~100-200 m **since the mid-1970s** and are consistent with the apparent rise in freezing-levels at selected high-elevation tropical ice caps, particularly in the Andes, where changes in oxygen-isotope profiles taken several years apart (Thompson, 1995) indicate an upward displacement of the firn-line by ~150m.

The pattern of freezing level height changes in the higher resolution model strongly resembles the upper-tropospheric anomaly pattern that occurs during the course of El Niño events in the tropical Pacific Ocean (Yulaeva and Wallace, 1994). Some of the greatest simulated warming occurs in the region of Peru where both the Quelccaya and Huascarán ice caps are located. One question considered in Diaz and Graham (1996), was whether these changes are mainly associated with the recent ~20 year episode of generally above average SST in the tropical Pacific, which has been amply documented (Graham, 1994, 1995; Trenberth, 1990; Miller, *et al.*, 1994). Graham (1995) and Morrissey and Graham (1996) using a synthesis of observational and model data, have provided evidence indicating that the increases in tropical SST during this period

resulted in an enhancement of the tropical hydrologic cycle. One manifestation of such an enhancement is a trend towards large temperature increases with height in the tropical troposphere, a consequence of a tendency for the vertical temperature structure to more closely approach a moist adiabatic lapse rate. The annual mean FLS changes for the set of 10 long-term radiosonde stations in South America suggest a jump in FLS heights that occurred around 1976-77. Since tropical SST changes in the 1970s have been implicated in a variety of anomalous geophysical events since then (Miller *et al.*, 1994), the observed changes in tropical SST, from the 1950s to the 1990s, were compared to the corresponding changes in FLS in South America. These and the other results referenced above suggest a fairly tight coupling of the tropical SSTs (arising mostly from changes in the tropical Pacific Ocean) and the freezing level heights over South America. This study strongly indicates that the recent observed changes in freezing level heights, both as deduced from the melting of high-elevation tropical ice cores, and from radiosonde and surface temperature measurements throughout the tropics, are related to a long-term increase of sea surface temperature in the tropics and the resulting enhancement of the tropical hydrologic cycle.

Although changes in temperature are likely the dominant mechanism producing this melting, there is also evidence from both observations and models that the changes in temperature have been accompanied by widespread increases in moisture content in the lower troposphere (Gaffen, *et al.*, 1991); these increases would also contribute to accelerated melting rates. By inference, based on the very long isotopic records obtained from the various tropical ice cap cores (on the order of several centuries to several thousand years), the level of warmth being recorded in the tropical oceans in the last several decades may be unprecedented since perhaps the mid-Holocene, 3000-4000 yr BP (Thompson *et al.*, 1995).

Additional efforts focused on the question of differential changes of atmospheric temperature with elevation (Beniston *et al.*, 1997), are the subject of a special issue of the journal *Climatic Change* that we co-edited (also released as a book: Diaz *et al.*, 1997). High elevation sites are sensitive indicators of climatic change and have not received the attention that these remote observations deserve. The volume addresses these matters explicitly and makes recommendations to the W.M.O. for continued support of high altitude observations.

Additional studies focused on tasks 1 & 2, include Lean *et al.* 1995; Bradley, 1996; Barnett *et al.* 1996; Mann *et al.* 1995, 1997a, 1997b; Diaz and Bradley, 1997). They represent an effort to evaluate changes in natural modes of climatic variability in the last millennium, using paleoclimatic records. We have developed databases of proxy

records and have applied new approaches to the reconstruction of global temperature in the centuries prior to anthropogenic effects on greenhouse gases. This allowed us to evaluate the effects of various forcing mechanisms (solar, volcanic, orbital) on temperature variations before greenhouse gases became significantly altered. These results suggest that solar irradiance changes may have played a more important role in natural climatic variability than has hitherto been recognized (Lean, Beer and Bradley 1995). Further studies, involving GCM experiments on solar variability and volcanic forcing are currently underway. Analysis of the spatial patterns associated with these forcings are being undertaken (Waple et al., 2000).

Work on Task 3 focused on changes in the seasonality of precipitation, particularly in the tropics (Diaz, 1996). An important measure of the reliability of simulated precipitation fields by general circulation models will be their ability to reproduce the more important features of observed precipitation, including its spatial distribution, annual cycle characteristics, and the more salient features of its interannual variability. In addition, considerable interests has been expressed regarding the impact of interannual to decadal changes in precipitation at the scale of moderate to large river basins. An analysis of some potential impacts of precipitation and related streamflow variability in the Colorado River Basin was published by Diaz and Anderson (1995).

Related research by M. Mann (partly supported at the University of Massachusetts by a DOE Alexander Hollaender post-doctoral fellowship) examined trends in the phase and amplitude of the seasonal temperature cycle in long-term observational data and in transient enhanced greenhouse scenario model simulations (Mann *et al*, 1996a). The primary conclusion of this study was that a decisive "fingerprint" could not be found with the existing observational database. Nonetheless, with more widespread, albeit shorter data, spanning the past few decades, it may be possible to more confidently identify a possible anthropogenic signal. This is particularly true for precipitation, where dramatic recent trends have been observed (Rajagopalan and Lall, 1996). Some important characteristics of the large-scale variability of observed precipitation fields during the past few decades over land, and for the last 15 years over ocean areas, based on satellite measurements, are described in this study. One such feature is an enhancement of the semiannual cycle in the tropics. A second is the strong influence of the El Niño/Southern Oscillation in modulating rainfall patterns globally. A third salient feature is the decline of precipitation over some parts of the tropics since the mid-1970s, which in turn, appears to be connected to the prevalence of warm ENSO conditions in the Pacific during that time.

The goals of Task 4 were addressed by focusing on the topic of changes in daily to annual extreme values in surface temperature and precipitation records (Eischeid et al. 2000; Easterling et al. (1999).— Changes in the frequency of occurrence of extreme events on different time scales is highly dependent on spatial scales and geographical location. Significant changes in the frequency of occurrence of extremes on different time scales is also highly dependent on sample size, as, by definition, extremes comprise the tails of the frequency distribution and therefore are the rarer types of events.

A second effort aimed at identifying regions around the globe that display the greatest sensitivity to global scale climatic variations in the last century (e.g. the northern treeline). Various comparisons were made, based on observations, and output from GCM experiments of natural patterns of climatic variability (Bradley, 1996; Diaz 1996). In the first study, we used long (1000+ year) GCM simulations to identify key locations for proxy data which can be used in long-term paleoclimate reconstruction. In the second one, a similar analysis was carried out using global gridded surface temperature records for the last hundred years. This will assist our efforts in establishing robust estimates of the magnitude of natural variability in both the instrumental and paleoclimate record, and in analysing their characteristic patterns of spatial variability (Mann, Bradley and Hughes, 1997, 1998; Bradley and Diaz, 1997).

This should help with current efforts to detect greenhouse-gas induced climatic changes from the noisy background of natural climate variations.

Recent high-frequency episodes of warm sea surface temperature in the equatorial Pacific (El Niño events), such as have occurred in the 1990s are likely to impact hydrologic and ecological balances throughout the world, not just in the tropical regions. A review of changes in the climate system over the past few centuries and linkages to the ENSO system can be found in Diaz and Kiladis (1995).

We have also considered changes in the frequency distribution of extreme events for both temperature and precipitation at different time scales over the last 100 years, in order to ascertain whether the evolution of the climate of the 20th century exhibits changes in the higher order moments, as well as in the mean values (Diaz and Bradley, 1996).

In addition to these studies, we contributed to national and international goals on global change research via our membership on various key committees, for example our contributions to the IPCC, and Bradley's membership of the National Academy of Sciences panel on Decade to Century Scale Climate Change (Martinson et al., 1999), NSF's Earth System History Advisory Panel and the International Geosphere Biosphere Programme on Past Global Change (IGBP-PAGES). We also organized an international

meeting historical records of climate variability and climate impacts (in Barcelona, Spain).

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APPENDIX 1
Comprehensive list of publications
arising from Department of Energy support, 1992-98

Results from DoE funding 1995-98 (Agreement No. DE-FG02-89ER69017)
indicated by asterisks

A. Books

- Diaz, H.F. and V. Markgraf (eds.), 1992: *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*. Cambridge University Press, Cambridge, UK, 476 pp.
- *Diaz, H. F. and R. S. Pulwarty (eds.), 1997: *Hurricanes: Climate and Socioeconomic Impacts*. Heidelberg: Springer-Verlag, 292 pp.
- *Diaz, H.F., M. Beniston and R.S. Bradley (eds.) 1997: *Climatic Change at High Elevation Sites*. Kluwer Academic, Dordrecht, 298pp.
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- *Jones, P.D., R.S. Bradley, J. Jouzel (eds.), 1996: *Climate Variations and Forcing Mechanisms of the Last 2000 Years*. Springer-Verlag, Berlin, 649pp.
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B. Journal Articles and Book Chapters

- *Barnett, T.P., B.D. Santer, P.D. Jones, R.S. Bradley and K.R. Briffa, 1996: Estimates of low frequency natural variability in near-surface air temperature. *The Holocene* 6, 255-263.
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C. Other Relevant Publications (not refereed)

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