Pergamon

Quaternary Science Reviews, Vol. 12, pp. 375–385, 1993.

0277-3791/93 $26.00

TOWARDS DEVELOPMENT OF A STRATEGY FOR DETERMINING THE ORIGIN OF DECADAL–CENTENNIAL SCALE CLIMATE VARIABILITY

Thomas J. Crowley* and Kwang-Yul Kim†
Applied Research Corporation, 305 Arguello Drive, College Station, TX 77840, U.S.A.

Although virtually all climate records with annual resolution record decadal–centennial scale climate fluctuations, their origin is obscure. Three candidates have been proposed — solar variability, volcanism and internal variability in the ocean–atmosphere system. A brief review of available evidence suggests that there is some support for the influence of solar variability, that the importance of volcanism may have been overestimated and that there is at present only limited information on the thermohaline circulation that suggests perhaps at most a 10–20% variation around its mean Holocene value. It is suggested that each of the above mechanisms has a different geographic signature of response in the surface temperature field. Some examples from energy balance model calculations indicate that: (1) solar variability has a near-global response, with the amplitude of response slightly larger over land; (2) volcanism has a proportionately larger amplitude of response over land than over ocean; and (3) the most oft-cited mode of internal variability, changes in the North Atlantic thermohaline circulation, has a hemispheric asymmetry in response. Preliminary comparison of solar results with observations indicates that, if the solar influence exists, it is not being manifested in terms of simple cooling; changes in the ocean–atmosphere system may be significantly modifying the response. Despite this disagreement it is proposed that climate model results can nevertheless be used to postulate key 'centers of action' that should be most sensitive to partitioning the effects of the above mechanisms. One example of a sampling strategy is presented. Although this strategy can be improved by further analysis of data and model calculations, it is hoped that it will contribute to imposing a

INTRODUCTION

The origin of decadal- to centennial-scale climate fluctuations is a major climate problem, for such oscillations hamper detection of a greenhouse signal. Unfortunately, instrumental records alone cannot be used to determine the origin of such variations, as there are too few oscillations in the last 100 years to definitively test models. Thus, proxy climate records of the last 1000 years represent an invaluable source of information.

Although virtually every proxy record with annual resolution records decadal- to centennial-scale fluctuations (e.g. Fig. 1), it is our opinion that processing of information on this time scale is hampered by lack of any general strategy for testing mechanisms. It is the purpose of this paper to review the different mechanisms that have been proposed, to briefly present evidence relevant to each of the mechanisms and to demonstrate with some climate model calculations that each of the mechanisms may have a distinctive geographic signature of response that should enable discrimination of origin. Based on these results an example of a sampling strategy is proposed and suggestions are made for further improvements in the strategy.

MECHANISMS OF DECADAL- TO CENTENNIAL-SCALE VARIABILITY

The three candidate mechanisms for decadal- to centennial-scale variability are solar forcing, volcanism and internal variations in the ocean–atmosphere system. As a considerable amount of recent reviews cover this topic (e.g. Crowley and North, 1991; Bradley and Jones, 1992; Diaz and Markgraf, 1992), this section will only briefly review some of the evidence and latest findings.

Although solar forcing has often been an unpopular mechanism to contemplate, there is a persistent occurrence of solar peaks in paleoclimatic records (e.g. Wigley and Kelly, 1990; see also Damon and Sonett, 1991). The solar peaks are inferred from variations in atmospheric ^{14}C levels, which correlate with solar activity fluctuations on multi-decadal time scales (e.g. Stuiver and Quay, 1980). Figure 2 compares the ^{14}C record from tree rings (Stuiver and Braziunas, 1989) with a number of paleoclimatic records (note that the 11-year solar cycle is damped in the radiocarbon record because the latter acts as a low-pass filter). Correlations and cross-spectral summaries are listed in Table 1.

Although there are obvious regions where sun–climate correlations are poor, some records, such as central China, have quite good correlations (–0.54), suggesting that a real sun–climate link may be buried within a considerable amount of weather noise. A ~120-year peak represents the most persistent occurrence of solar peaks in terrestrial records. A ~200-year peak is less often detected but strong when it is found (cf. Sonett and Suess, 1984; Peterson *et al.*, 1991). Although the 56-year solar peak has not received much previous attention, it also occurs in a number of paleoclimate records. In addition to those listed, it can be found in other tree ring records for western North America and also a varve record from the Santa Barbara Basin (Baumgartner *et al.*, 1992; Meko, 1992).

The interpretation of the influence of volcanism on

---

*Present address: Department of Oceanography, Texas A&M University, College Station, TX 77843, U.S.A.

†Present address: Climate System Research Program, Department of Meteorology, Texas A&M University, College Station, TX 77843, U.S.A.

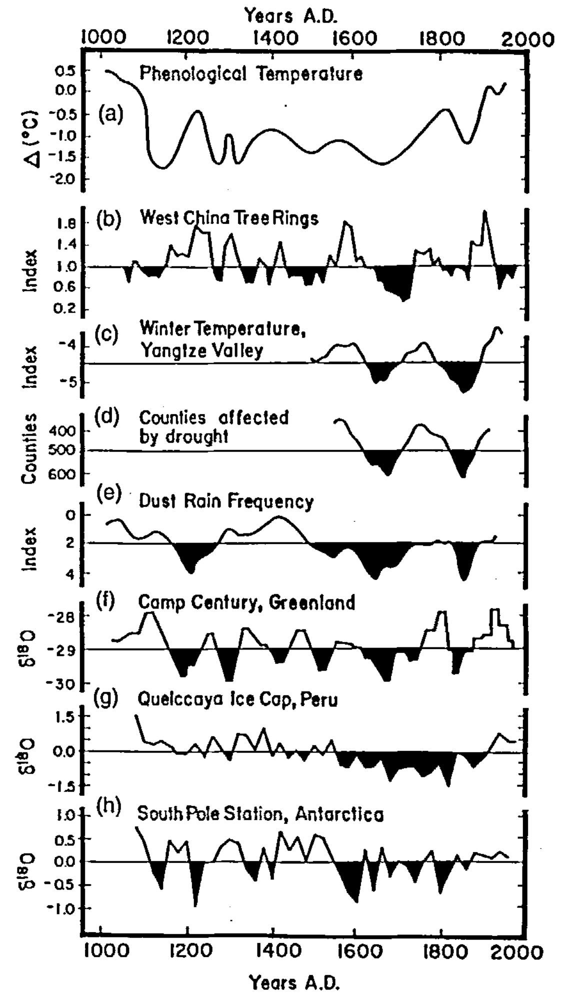

FIG. 1. Example of decadal- and centennial-scale climate variability. (a) The phenological temperature in China (after Zhu, 1973). This index is based on timing of recurrent weather-dependent phenomena, such as dates of flowering of shrubs or arrivals of migrant birds, or distribution of climatically sensitive organisms. (b) The growth ring index of a juniper tree from western China (after Wang *et al.*, 1983). (c) The winter temperature index in the lower reaches of the Yangtze River (after Zhang, 1980). (d) The number of Chinese counties affected by drought (after State Meteorological Administration, 1981). (e) The frequency curve of dust rains in China (after Zhang, 1984). (f) The $\delta^{18}O$ record from Camp Century, Greenland (after Johnsen *et al.*, 1970). (g) The $\delta^{18}O$ record from Quelccaya Ice Cap, Peru (Mosley-Thompson *et al.*, 1990). (h) The $\delta^{18}O$ record from the South Pole (Mosley-Thompson *et al.*, 1990). Shading equals cool intervals. (From Crowley and North, 1991.)

TABLE 1. Correlations between solar spectra in climate records.

Period	~420	~200	~120	-187	~56	r	r_{max}	
Glaciers	x		**X**	**X**		–0.11	0.15	(330)
Sierra TR			**X**		**X***	–0.10	0.22	(70)
China TR		**X***	x	x	x	–0.54	–0.54	(0)
Grn O18	**X**		**X**		**X***	–0.01	0.39	(45)
Peru O18			x	x	**X**	0.05	0.08	(15)
Spole O18		**X***	x	x	x	0.37	0.42	(–20)

A small 'x' indicates that solar periods occur but not consistently (as defined by variations in the amount of record smoothing). Bold **X**s refer to a more consistent occurrence, and bold **X***s refers to records that have coherences > 0.6. Parentheses after r_{max} refers to number of years the climate time series leads or lags at maximum correlation (minus sign indicates climate leads ^{14}C, the index of solar variability). ^{14}C record from Stuiver and Braziunas (1989); glacier record is a composite of alpine moraine fluctuations from Alaska, Scandinavia, the Alps, South America, the Himalayas, the Sierras, and New Zealand (after Röthlisberger, 1986); Sierra tree ring (TR) record from LaMarche (1974); China TR record from Wang *et al.* (1983; see also Fig. 1); Greenland $\delta^{18}O$ record from Camp Century (Johnsen *et al.*, 1970; see Fig. 1); Peru $\delta^{18}O$ record from Thompson *et al.* (1986; see Fig. 1); and South Pole $\delta^{18}O$ record from Mosley-Thompson *et al.*, 1990. (From Crowley and Howard, 1990.)

decadal-scale climate variability has varied with time. Meteorological observations now suggest a quite good link between volcanic eruptions and cooling for 1–2 years after the event (Bradley, 1988; Angell, 1990). However, the significance of volcanoes on longer time scales is more uncertain. Ice core studies of acidity variations in the Crete (Greenland) record suggested that volcanism may also influence climate variability on decadal- to centennial-time scales (Hammer *et al.*, 1980; Porter, 1986). The precise manner in which the short-term impulses were supposed to have caused a long-term response was not discussed.

One problem with the volcanism–climate link is that the oft-cited Crete ice core acidity record contains peaks due to volcanic activity and significant background variations reflecting other processes. Previous studies that smoothed the peaks and background variations may have introduced a bias into a volcanism–climate link. A re-examination (Crowley *et al.*, 1993) of the Crete conductivity record separated the peaks from the background and concluded that the correlation with climate was much lower than previously obtained (–0.24 vs. –0.54 in Hammer *et al.*, 1980). The higher correlation reflected the fact that the background record was also varying with climate (Fig. 3). The origin of the background variations is unclear; they may reflect dimethyl sulphide release from ocean plankton in the subpolar North Atlantic (Crowley *et al.*, 1993). If so, the background variations would represent a response to climate change rather than a forcing of the climate system.

Internal variations in the ocean–atmosphere system has been a theoretical possibility for some time (Hasselmann, 1976; Mikolajewicz and Maier-Reimer, 1990), but there is surprisingly little geologic data available for testing this concept in the Holocene. Boyle and Keigwin (1985–1986) illustrate some modest variations in cadmium/calcium ratios in a deep North Atlantic core that might reflect thermohaline changes (Fig. 4). But the variations have yet to be confirmed in other records and may well reflect bioturbation as much as climate change. If they are real, then there were slight reductions in NADW about 3.0, 4.5, 6.3, 6.9 and 7.7 thousand years ago. The 'events' around 3.0, 4.5 and 7.7 coincide with some millennial-scale cooling inferred from other records (Crowley and North, 1991).

Since ice-age variations in the same core are considerably larger than the Holocene variations, and the ice-age variations represent perhaps a 50% reduction in the North Atlantic thermohaline cell (Boyle and Keigwin, 1987), then the much smaller variations in the Holocene, even if real, would appear to place an upper limit of perhaps 10–20% in variations of the intensity of this mechanism (note that there is some nonlinearity in the rate at which cadmium is incorporated into the calcium carbonate lattice at low levels, so scaling from the glacial maximum has some uncertainty).

To summarize, there is some evidence for solar variability and the importance of volcanism has been downgraded. Ocean–atmosphere interactions require more docu-

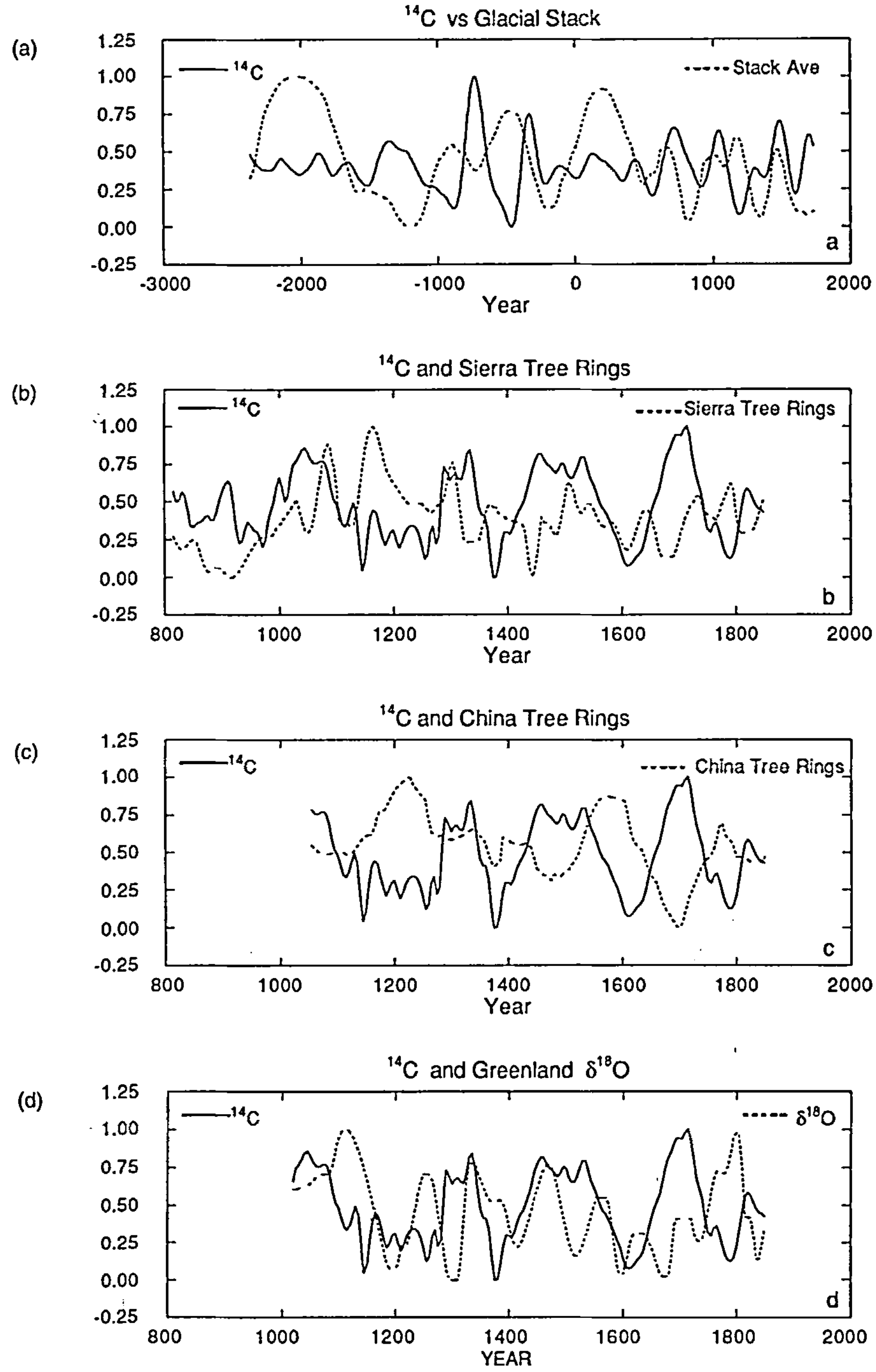

FIG. 2. Legend overleaf.

mentation, but a very limited amount of paleoceanographic data suggests that there may have been modest (10–20%) variations in overturn during the Holocene.

A STRATEGY FOR FURTHER TESTING MECHANISMS

The main purpose of this paper is to point out that the postulated different sources of forcing should be associated with unique geographic signatures that should be detectable in the geologic record (cf. Rind and Overpeck, 1993). To briefly summarize, solar forcing should have a near-global scale extent, volcanism should have a stronger land–sea contrast, and there should be a hemispheric asymmetry between sea surface temperatures (SSTs) in the northern and southern hemispheres as a result of changes in the thermohaline circulation.

Solar Forcing

The actual manner in which solar forcing should affect the atmospheric circulation is still a matter of conjecture. Direct observations of the solar constant over the last solar cycle show changes of only about 0.1% (Kyle *et al.*, 1993). However, there is some reason to believe that changes on

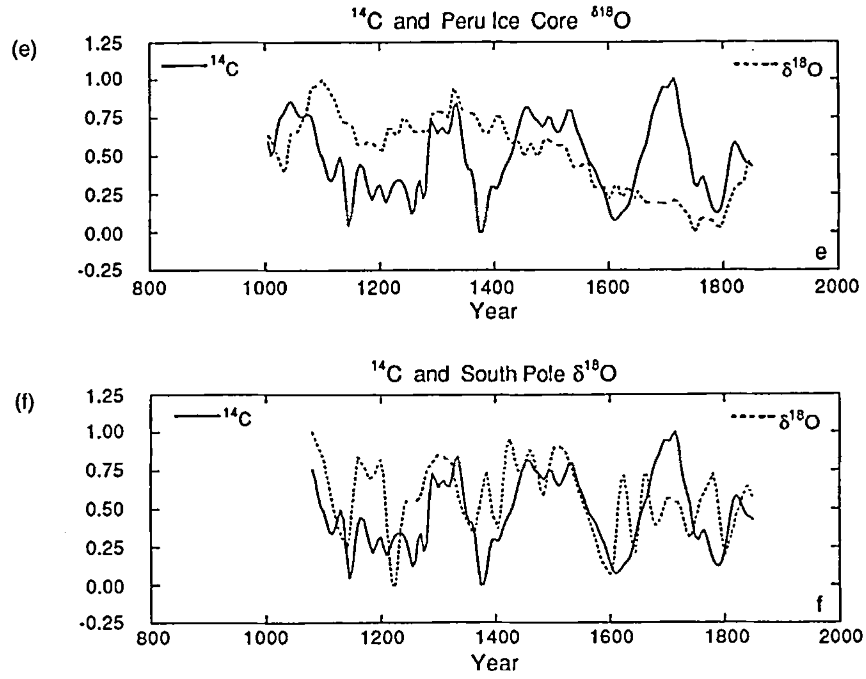

FIG. 2. Comparison of ^{14}C record of solar variability with six different indices of climate change: (a) a composite record of alpine glacial advances (Röthlisberger, 1986; see caption to Table 1 and discussion in Crowley and Howard, 1990); (b) and (c) tree rings from the Sierras and western China (LaMarche, 1974; Wang *et al.*, 1983); and (d–f) $d^{18}O$ records from Greenland, Peru, and Antarctica (Johnsen *et al.*, 1970; Thompson *et al.*, 1986; Mosley-Thompson *et al.*, 1990). (From Crowley and Howard, 1990.)

longer time scales could be as large as 0.4–0.5% (e.g. Baliunas and Jastrow, 1990; Lean *et al.*, 1992). There may be other pathways in which the sun influences climate, but at present these pathways are so obscure as to preclude the possibility of any a priori predictions. Conventional meteorological data sets may also be too short to test these alternate pathways.

In order to illustrate the potential effect of changes in solar forcing we therefore adopt a minimalist approach by assuming that the most testable manner in which the sun would affect climate involves changes in the solar constant. We estimate the effect of these changes by employing a two-dimensional energy balance climate model (EBM) first developed by North *et al.* (1983b). Many previous studies

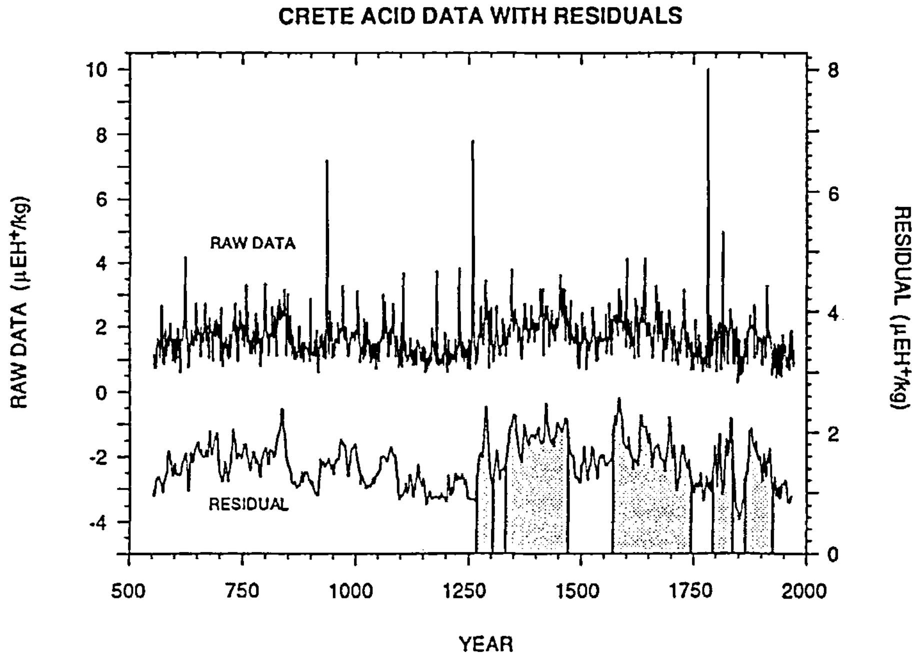

FIG. 3. Comparison of full 1400-year record of acidity with background acidity levels (5-pt. smoothing) obtained after removal of spikes. Note the nonrandom nature of the background fluctuations; shading emphasizes high levels of residual acidity during the Little Ice Age. (From Crowley *et al.*, 1993.)

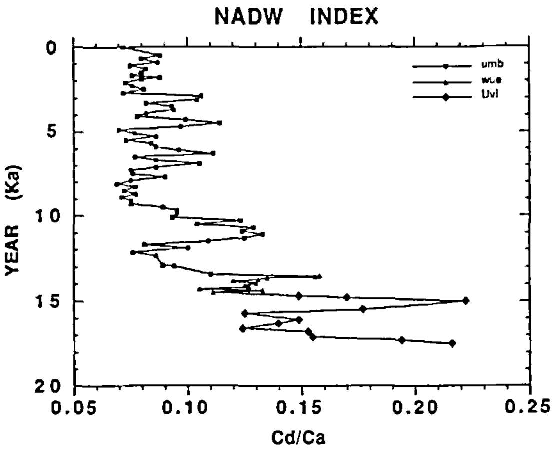

FIG. 4. Record of deep-water changes in the western North Atlantic for the last 20,000 years (from Boyle and Keigwin, 1987). Increasing cadmium/calcium ratio implies older deep water. Different symbols refer to different species analyzed. Note slight evidence for centennial-scale pulses at 3.0, 4.5, 6.3, 6.9 and 7.7 ka.

indicate that various versions of the model have sensitivities comparable to general circulation models (GCMs) and observations (Crowley *et al.*, 1991; Kim and North, 1991, 1992). We used two different versions of the model, one with a mixed layer ocean (North *et al.*, 1983b), the other with a deep-ocean coupled to a surface layer by means of an upwelling-diffusion model (Kim *et al.*, 1992). This latter model attempts to incorporate some of the longer time scales expected from modulation of surface temperature by the deep-ocean circulation.

Following the lead of North *et al.* (1983a), we illustrate the effect of solar forcing at two different periods, because the response will vary by the period — the shorter the period, the greater the land–sea contrast in response (cf. Short *et al.*, 1991). Since the transient, or kinetic, sensitivity of the model is less than the equilibrium sensitivity (see North *et al.*, 1984), the magnitude of the response will also vary inversely to the frequency of forcing.

Figure 5 illustrates the response to an 11-year period with solar constant fluctuations of 0.1%. The response is extremely small (~ 0.05°C amplitude, which is one-half the range) and peaks slightly over land. There are only minor differences between the responses in the mixed layer and upwelling-diffusive models. As the period of solar forcing increases, the kinetic sensitivity increases and the land–sea difference is smoothed out. This pattern is illustrated (Fig. 6) by examining 80-year period fluctuations (approximately the Gleissberg cycle) with a 0.5% change in the solar constant. The upwelling-diffusion model has approximately a 0.5°C temperature response that is fairly uniform globally, but with a slightly larger amplitude in the low latitude regions subject to a larger absolute reduction in forcing. The mixed layer response is similar but has an amplitude about 20% larger (result not shown). Both models show only small phase shifts (2–3 years) between forcing and response over land and a 4–7 year lag over the ocean.

Note that comparison of the modeled results with the 'observations' (Table 1) indicates some substantial differences. Not all proxy records contain solar signals and it is hard to discern any order to the geographic response as a function of frequency of forcing. This comparison suggests that the solar forcing effect, if it is real, is manifested in a more complex manner than predicted by the simple model. Because there is a geographic and frequency dependence of the system response to noise forcing (Kim and North, 1991, 1992), part of the sun–climate discrepancy may simply reflect an inadequate treatment of the climate noise problem. An explicit example includes some evidence for enhanced meridional flow patterns during the Little Ice Age (Zhu, 1973; Fritts *et al.*, 1979; Crowley, 1984). These changes could impose a large overprint on the pattern we simulate. GCM studies (cf. Rind and Overpeck, 1993) may shed more light on this problem, but the low amplitude of the forcing changes will probably require sophisticated applications of signal-to-noise detection methods (e.g. North and Kim,

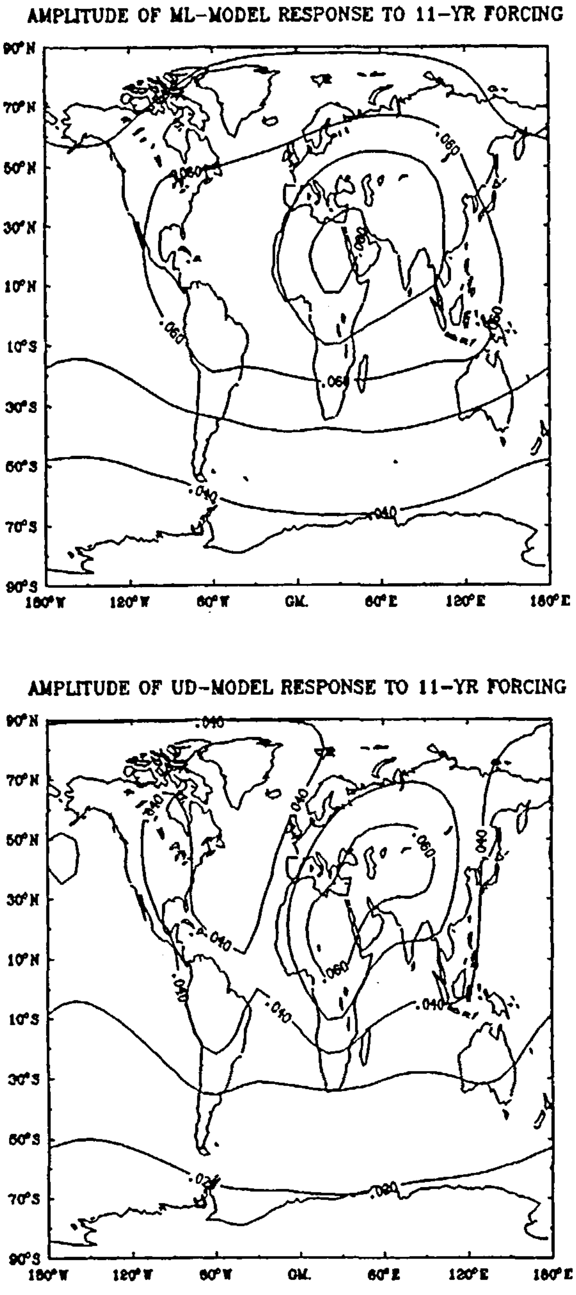

FIG. 5. Amplitude (equals one-half range) of EBM response to 11-year periodic solar forcing with an amplitude of 0.1% (top) mixed layer ocean model; (bottom) upwelling-diffusion model.

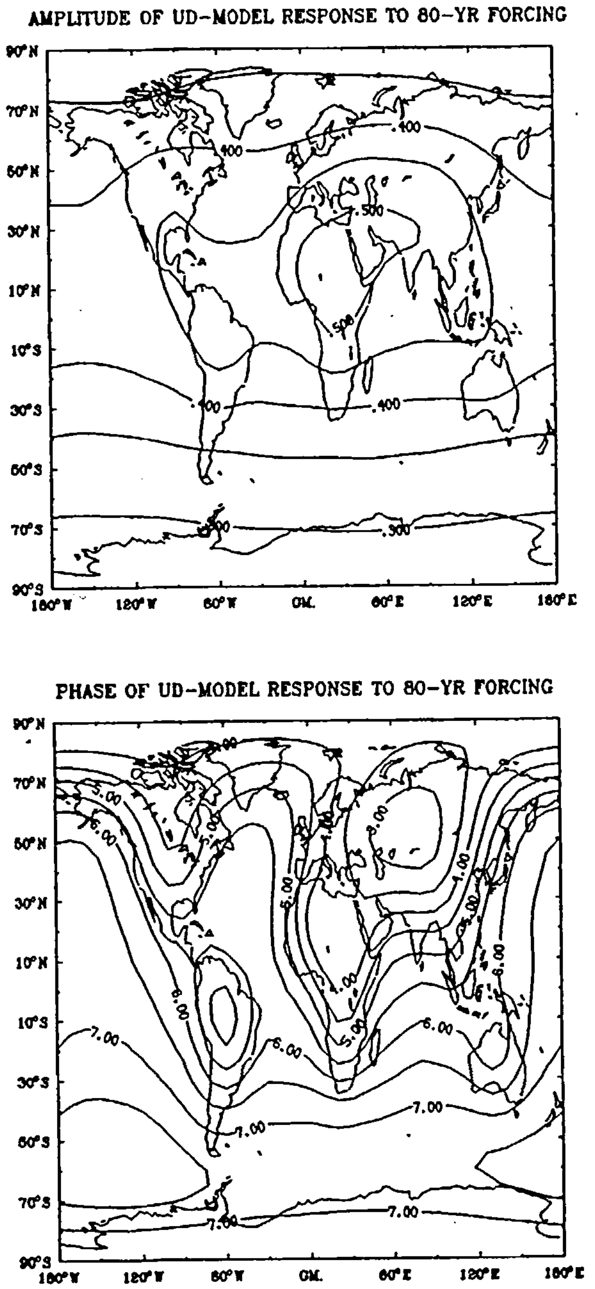

FIG. 6. Amplitude of response of upwelling-diffusion EBM to 80-year periodic solar forcing with an amplitude of 0.5%. (top) temperature; (bottom) phase in years after forcing.

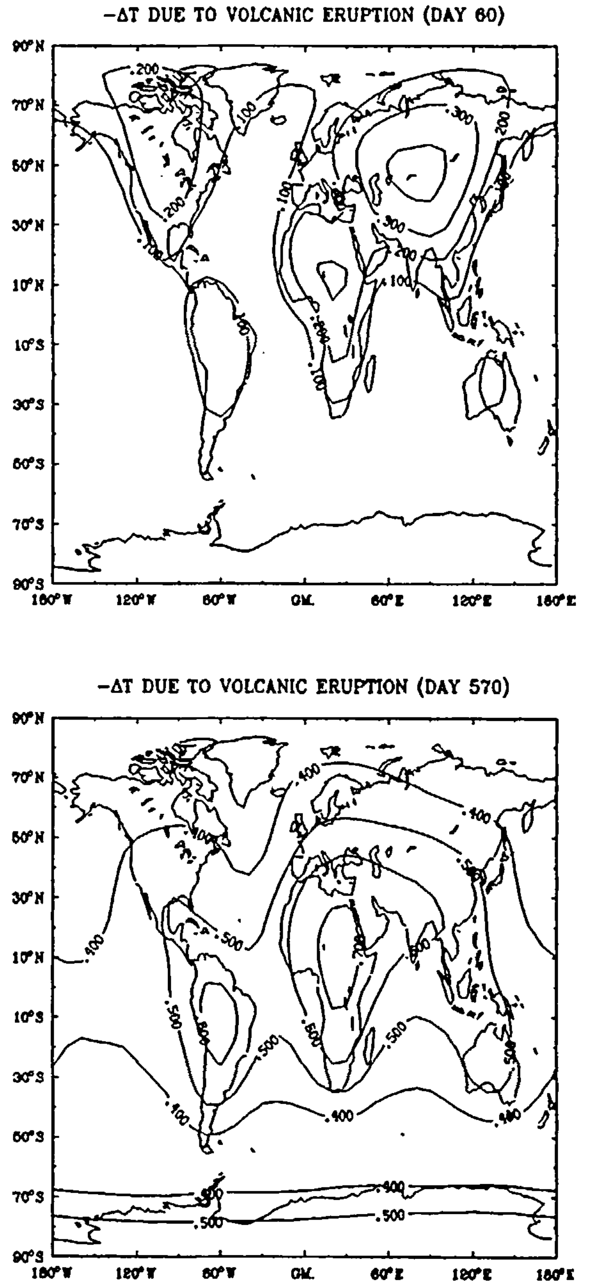

FIG. 7. Example of system response to volcanic forcing with an amplitude equivalent to a 1.0% reduction in the solar constant and eruption starting on July 1. (top) change in temperature on day 60; (b) change in temperature on day 570.

1993). It must also be born in mind that different GCMs are notorious for simulating different types of regional responses to changes in forcing. We consider the results presented herein as representing only the first step (or a baseline experiment) in the development of a strategy for objectively assessing the effects of the solar variability.

Volcanism

Although new results discussed in the prior section significantly reduce the importance of volcanism for decadal-scale climate variability, we nevertheless include some illustrations of the potential effect. We simulated the effect of a volcanic signal by making a step-function decrease in the solar constant by 1.0% on July 1, allowing the perturbation to persist for 1.5 years, and then ramping the decay back to zero. The amplitude of the perturbation is comparable to that estimated for a moderate-sized (Agung–Pinatubo) volcanic eruption (Hansen and Lacis, 1990; Hansen *et al.*, 1992). Samples of the response are illustrated in Fig. 7.

The early response (day 60) to a volcanic perturbation is primarily over land. This is in keeping with the idea that the low heat capacity of land allows for a more rapid response to a perturbation. However by day 570 (Fig. 7b) the response is over both land and ocean, with a maximum in the low latitudes again reflecting the maximum reduction in absolute insolation. The global mean cooling of 0.5°C is comparable to that estimated by Hansen *et al.* (1992) for a similar sized perturbation. These results agree well with preliminary analysis of global mean temperature differences between

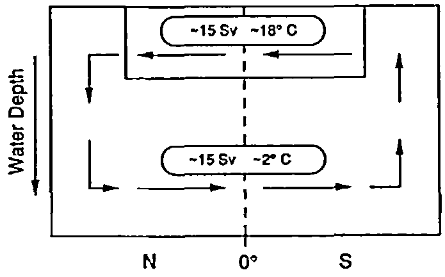

FIG. 8. Schematic explanation for hemispheric differences in temperature response due to NADW variations. Figure illustrates cross-section of transport in the western Atlantic basins. At present export of cold deep North Atlantic water across the equator requires import of warmer South Atlantic surface and near-surface waters in order to conserve volume. Shutdown of NADW shuts off import of warm water from the South Atlantic; the latter region warms accordingly. The difference in mean temperatures of these layers can explain the observed heat exchange between the North and South Atlantic (~1015W) (From Crowley,1992.)

1992 and 1991 (when Pinatubo erupted in June) that indicates a 0.6°C decrease in temperature (Kerr, 1993). Note that the equilibrium sensitivity of the EBM is only about one-half of that of the GCM used by Hansen *et al.* (1992). The comparable sensitivities of response for the two models appear to reflect the more comparable kinetic sensitivity of the two models (see discussion above).

Changes in the Thermohaline Circulation

It is our opinion that the nature of the geographic signature of changes in the ocean thermohaline circulation has not been fully appreciated. Although reductions in North Atlantic Deep Water (NADW) production are associated with decreased transport of the Gulf Stream, the far-field response is often opposite in sign. This opposition can be understood by means of the simple cartoon illustrated in Fig. 8. At present NADW transports about 15 Sv of water across the equator. In order to conserve volume, this export must be compensated by an import of an equivalent volume of water from shallower, warmer layers. The net result of this heat exchange is that the southern hemisphere exports 0.5–1.0 PW of heat to the northern hemisphere (e.g. Hastenrath, 1982; Hsiung, 1985), equivalent to 1–2% of its total energy receipt. The area-average of this export is 2–4 W/m^2 for the southern hemisphere — 50–100% of a CO$_2$-doubling signal.

The geographic signature of an equilibrium response is shown in Fig. 9, which illustrates the difference in two modes of a coupled ocean–atmosphere model run by Manabe and Stouffer (1988). Note that when NADW is on, the southern hemisphere is cooler than in the off-mode. This is precisely what would be predicted by the simple cartoon. However, the magnitude of the response is relatively small, partly because the cross-equatorial heat exchange in the GFDL (Geophysics Fluid Dynamics Laboratory) model (0.3 PW) appears to be less than occurs in the real world.

Applying the thermohaline model to the problem of decadal- to centennial-scale variability results in patterns different than the equilibrium response, because the time scale of the temperature change is less than the equilibrium time scale of the ocean. The transient nature of the geographic signature depends on the ocean model. Where the thermohaline circulation is more restricted to the North Atlantic basin, the principal response is also in that basin. Delworth *et al.* (1993) have demonstrated quite a good agreement between the GFDL GCM and observations of SST change in the North Atlantic during the 20th century.

For an ocean model that has larger levels of cross-equatorial exchange, the geographic signature of the response is somewhat different. For example, Mikolajewicz and Maier-Reimer (1990) have modeled significant changes in the Atlantic thermohaline circulation on centennial scales. Analysis of the surface heat flux changes due to these circulation changes indicates at least two modes of response (Mikolajewicz and Maier-Reimer, 1991), which are illustrated in the top panels of Figs 10 and 11 (we thank Uwe Mikolajewicz for kindly providing the heat flux product from these simulations). The EBM was then used to calculate the temperature response to these heat flux changes, in a manner similar to that done by Crowley and Kim (1992). The largest response occurs in the Antarctic Circumpolar Current

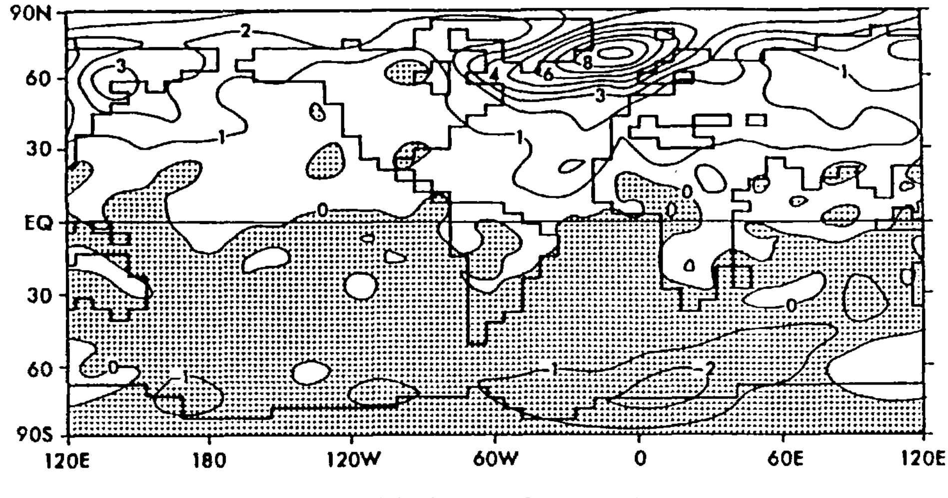

FIG. 9. Effect of increased production rates of North Atlantic Deep Water on surface temperatures, as calculated by a coupled ocean–atmosphere model. Figure illustrates the differences in temperature between a mode with active NADW and one without (positive values indicate warmer temperatures with NADW on). Shading denotes temperature decreases in the southern hemisphere. (From Manabe and Stouffer, 1988.)

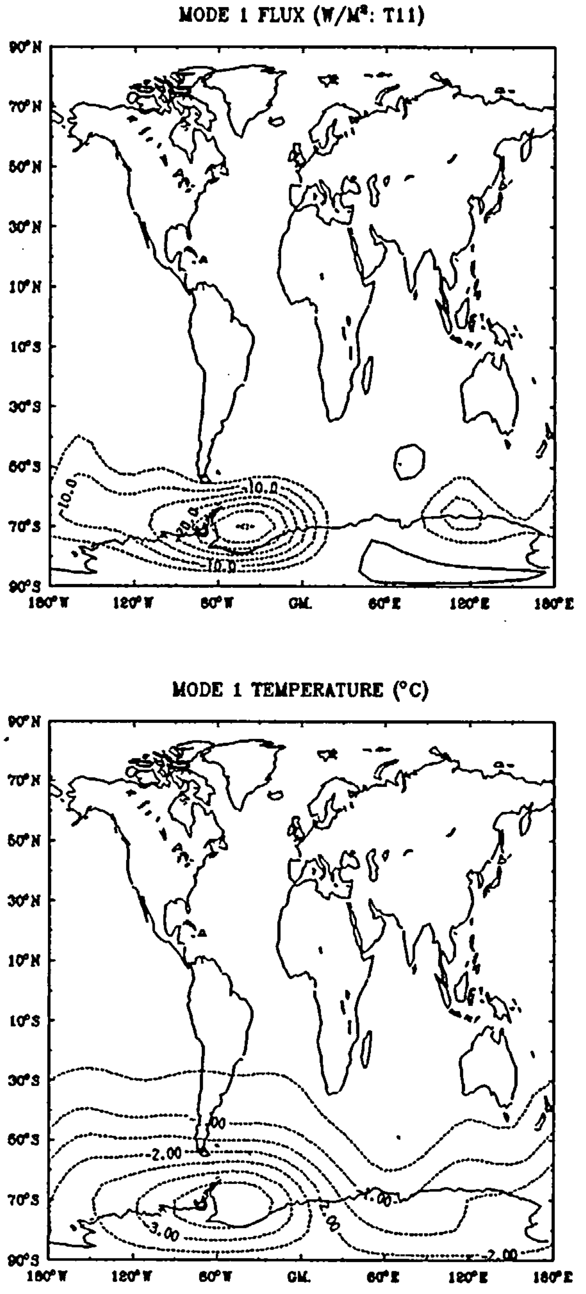

FIG. 10. Mode-1 response of an ocean GCM to white-noise freshwater variations (based on results from Mikolajewicz and Maier-Reimer, 1990). (top) changes in ocean heat flux (W/m²); (bottom) EBM temperature response to heat flux changes.

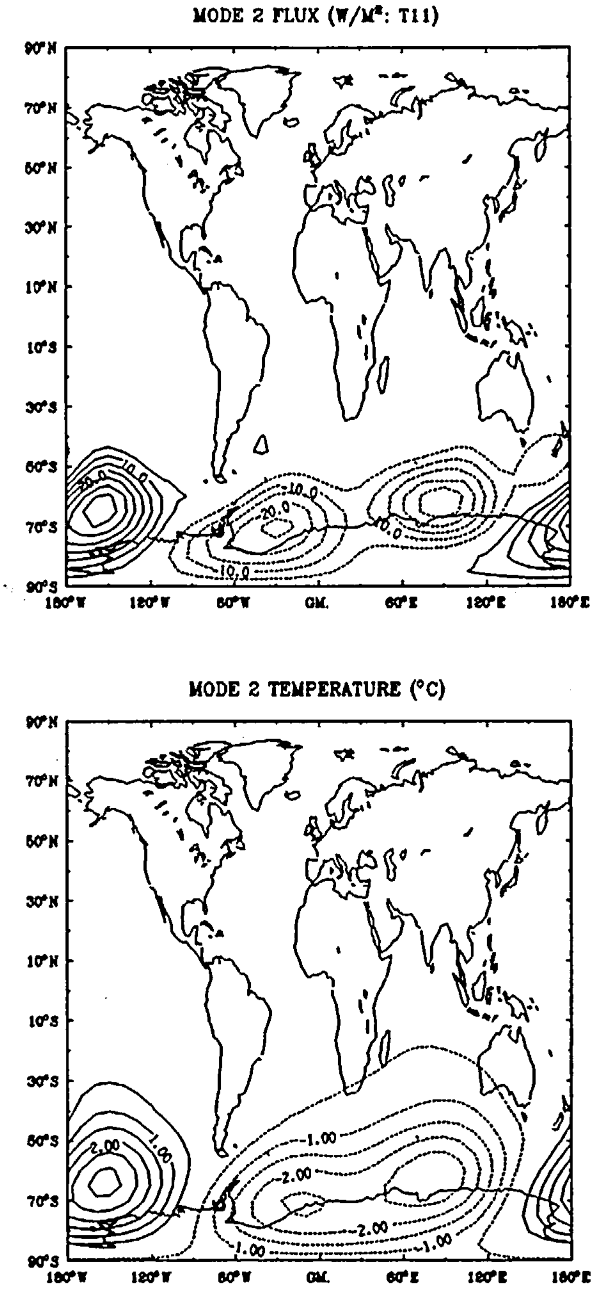

FIG. 11. Mode-2 response of an ocean GCM to white-noise freshwater variations (based on results from Mikolajewicz and Maier-Reimer, 1990). (top) changes in ocean heat flux (W/m²); (bottom) EBM temperature response to heat flux changes.

and has two modes of variability. One mode (principal oscillation pattern) had a response primarily in the Weddell Sea and is associated with temperature fluctuations of 2–3°C. The second mode is of larger geographic extent in the Atlantic–Indian sector but its amplitude is slightly smaller (Fig. 11b). There is also a response of opposite sign in the region of the Ross Sea for this mode.

There are some indications that the modeled whole-Atlantic response may be present in observations. For example, Fig. 12 illustrates time series of differences of SST between the North and South Atlantic for the 20th century (from Folland *et al.*, 1986). This pattern is consistent with that predicted from the discussion of interhemispheric heat exchange. However, the out-of-phase relationship may not be a unique reflection of this process and requires more investigation.

EXAMPLE OF A SAMPLING STRATEGY FOR PARTITIONING SYSTEM RESPONSE TO DIFFERENT MECHANISMS

To summarize, EBM simulations indicate that solar forcing should have a near-global signature, volcanism a response that is more strongly influenced by the land–sea distribution, and the 'North Atlantic seesaw' is primarily restricted to the Atlantic basin and the Southern Ocean. High-frequency weather variability can be expected to modify these patterns, perhaps quite significantly. For

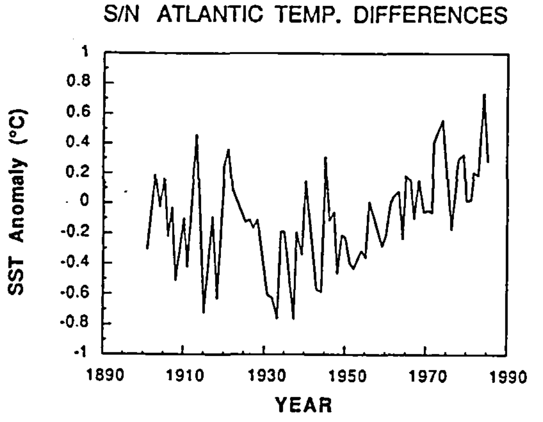

FIG. 12. Time series of differences in SST between the South and North Atlantic during the twentieth century (after Folland *et al.*, 1986). Positive values indicate that the South Atlantic is warmer than the North Atlantic. Note the decadal-scale duration of hemispheric differences, which could reflect the seesaw discussed in this paper. (From Crowley, 1992.)

example, Crowley *et al.* (1993) discuss some examples of how large volcanic eruptions of the past have different geographic signatures. However, if clusters of eruptions were important for decadal-scale climate fluctuations, we would expect that noise associated with individual events would tend to cancel out, leaving an average response not unlike the pattern we simulate.

Preliminary comparison of solar calculations with observations indicate that, if the solar influence is real, it is not being manifested in terms of simple cooling. Changes in the ocean–atmosphere system may be significantly modifying the response, and signal-to-noise considerations also have to be taken into consideration (cf. North and Kim, 1993). Despite the disagreement sometimes between simple models and observations, we nevertheless propose that climate models can be used to develop a sampling strategy to partition the effects of the different mechanisms. We suggest that a rather small number of sites from key 'centers of action' may help impose some rationale into development of a sampling strategy for detecting the origin of decadal- to centennial-scale climate variability. As an example we illustrate in Fig. 13 a sampling strategy keyed to the model results discussed herein. Some sites provide information about more than one mechanism. Note that the Pacific sites are included to provide information about the relative weighting of land vs. ocean temperature responses, and the South American and African sites are included to provide information about the global scale of temperature change during the last few hundred years.

Note that it is beyond the scope of this paper to systematically test the above strategies. In most cases

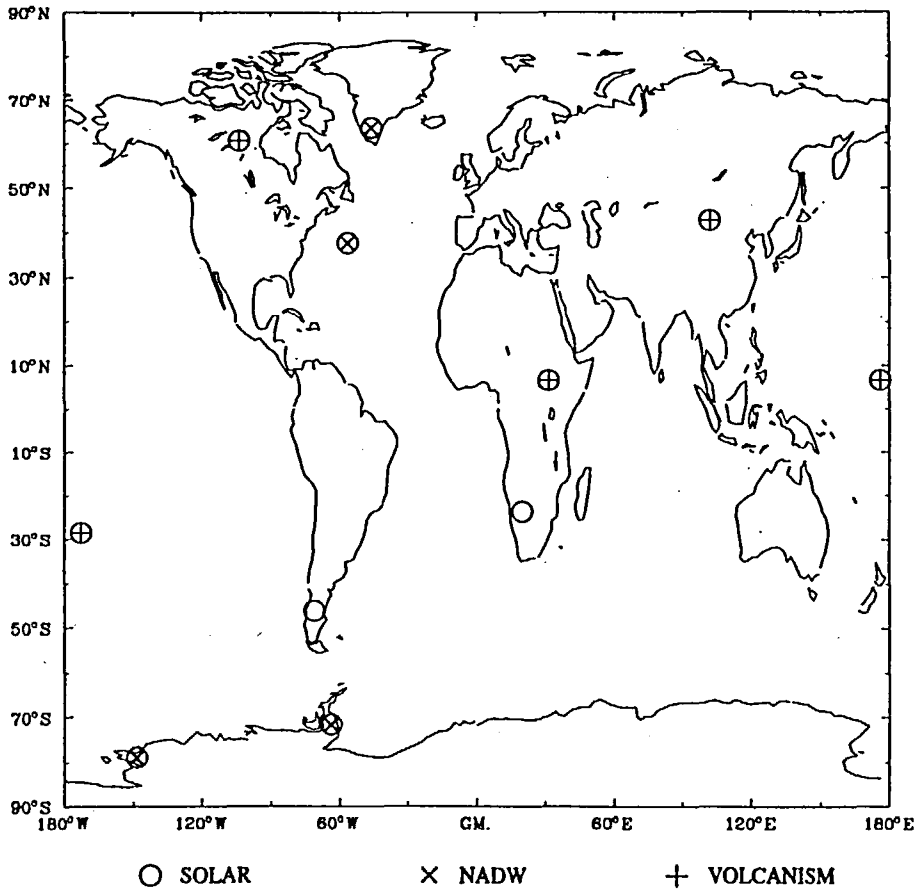

FIG. 13. 'Centers of action' of surface temperature response to different types of forcing. All regions potentially record information on solar forcing, whereas the responses to volcanism and NADW variations are more restricted. It is suggested that key samples from these regions may enable discrimination of which factors are controlling decadal–centennial-scale climate fluctuations.

information is lacking that allows for a fully satisfactory test. The sceptical reader might further note that there are a number of well-known paleoclimate sites not included in our array, that different proxy monitors are not recording the same information, and that the actual climate system response may differ from how we illustrate it. All of these critiques are valid. However, we are not implying that other sites do not provide much valuable information, and we fully recognize the problems associated with intercomparisons among different indices. GCM studies can provide additional information about other possible centers of action and modify our predictions somewhat (cf. Rind and Overpeck, 1993). Thus our proposal should be considered a starting point for analysis of paleoclimate records and not a final suggestion. Even with its limitations the strategy represents an attempt to impose some level of order on the present plethora of information flooding the field.

SUMMARY AND CONCLUSIONS

(1) Three mechanisms have been proposed to explain decadal- to centennial-scale variability. The evidence for solar variability is patchy but it seems to occur more often than would be expected by chance alone. Evidence for a volcanic influence may have been overestimated. Changes in the thermohaline circulation represent a theoretical possibility but there is at present only a very modest amount of information relevant to changes during the last 10,000 years.

(2) Each mechanism should have a different geographic signature of response. EBM studies suggest solar forcing should have a near-global scale response, with a potential amplitude on the order of 0.5°C for the 80-year solar period. That such a response does not occur in nature indicates either that solar variability is not important or that the ocean–atmosphere system is significantly modifying the solar input signal.

(3) Volcanism should be affected by both the hemisphere of the eruption and the land–sea distribution. Its response is potentially near-global, but shorter lived, and more weighted toward land than solar variability.

(4) Changes in the thermohaline circulation should primarily affect temperatures in the Atlantic sector and Southern Ocean, with changes in the northern and southern hemispheres almost out of phase.

(5) An example of a sampling strategy is proposed that focuses on a small number of sites from key centers of action identified by modeling studies.

ACKNOWLEDGEMENTS

This research was supported by NSF grant ATM-9115507. We thank G. North for discussion, U. Mikolajewicz for providing the results for Figs 10 and 11, and M. Chandler and an anonymous reviewer for their comments.

REFERENCES

Angell, J.K. (1990). Variations in global tropospheric temperature after adjustment for the El Nino influence, 1958–89. *Geophysical Research Letters*, **17**, 1093–1096.

Baliunas, S. and Jastrow, R. (1990). Evidence for long-term brightness changes of solar-type stars. *Nature*, **348**, 520–523.

Baumgartner, T.R., Soutar, A. and Ferreira-Bartrina, V. (1992). Reconstruction of the history of Pacific sardine and northern anchovy populations over the past two millennia from sediments of the Santa Barbara Basin, California. *California Cooperative Oceanic Fisheries Investigations Reports*, **33**, 24–40.

Boyle, E.A. and Keigwin, L.D. (1985/86). Comparison of Atlantic and Pacific paleochemical records for the last 215,000 years: Changes in deep ocean circulation and chemical inventories. *Earth Planetary Science Letters*, **76**, 135–150.

Boyle, E.A. and Keigwin, L.D. (1987). North Atlantic thermohaline circulation during the past 20,000 years linked to high-latitude surface temperatures. *Nature*, **330**, 35–40.

Bradley, R.S. (1988). The explosive volcanic eruption signal in northern hemisphere continental temperature records. *Climate Change*, **12**, 221–243.

Bradley, R.S. and Jones, P.D. (1992). Records of explosive volcanic eruptions over the last 500 years. *In*: Bradley, R.S. and Jones, P.D. (eds), *Climate Since A.D. 1500*, pp. 606–622. Routledge, London.

Crowley, T.J. (1984). Atmospheric circulation patterns during glacial inception: A possible candidate. *Quaternary Research*, **21**, 105–110.

Crowley, T.J. (1992). North Atlantic Deep Water cools the southern hemisphere. *Paleoceanography*, **7**, 489–497.

Crowley, T.J. and Howard, M.K. (1990). Testing the sun–climate connection with paleoclimate data. *In*: Schatten, K.H. and Arking, A. (eds), *Climate Impact of Solar Variability*, pp. 81–89. NASA Conference Publication 3086, NASA/GSFC, Greenbelt, MD.

Crowley, T.J. and Kim, K.-Y. (1992). Complementary roles of Milankovitch and North Atlantic Deep Water during late Pleistocene interglacials. *Paleoceanography*, **7**, 521–528.

Crowley, T.J. and North, G.R. (1991). *Paleoclimatology*. Oxford University Press, New York, 339 pp.

Crowley, T.J., Baum, S.K. and Hyde, W.T. (1991). Climate model comparison of Gondwanan and Laurentide glaciations. *Journal of Geophysical Research*, **96**, 9217–9226.

Crowley, T.J., Criste, T.A. and Smith, N.R. (1993). Reassessment of Crete (Greenland) ice core acidity/volcanism link to climate change. *Geophysical Research Letters*, **20**, 209–212.

Damon, P.E. and Sonett, C.P. (1991). Solar and terrestrial components of the atmospheric ^{14}C variation spectrum. *In*: Sonett, C.P., Giampapa, M.S. and Matthews, M.S. (eds), *The Sun in Time*, pp. 360–388. The University of Arizona Press, Tucson.

Delworth, T., Manabe, S. and Stouffer, R.J. (1993). Interdecadal variations of the thermohaline circulation in a coupled ocean–atmosphere model. *Journal of Climate*, **6**, 1993–2011.

Diaz, H.F. and Markgraf, V. (eds) (1992). *El Niño, Historical and Paleoclimatic Aspects of the Southern Oscillation*. Cambridge University Press, 476 pp.

Folland, C.K., Palmer, T.N. and Parker, D.E. (1986). Sahel rainfall and worldwide sea temperatures, 1901–85. *Nature*, **320**, 602–607.

Fritts, H.C., Lofgren, G.R. and Gordon, G.A. (1979). Variations in climate since 1602 as reconstructed from tree rings. *Quaternary Research*, **12**, 18–46.

Hammer, C.U., Clausen, H.B. and Dansgaard, W. (1980). Greenland ice sheet evidence of post-glacial volcanism and its climatic impact. *Nature*, **288**, 230–255.

Hansen, J., Lacis, A., Ruedy, R. and Sata, M. (1992). Potential climate impact of Mount Pinatubo eruption. *Geophysical Research Letters*, **19**, 215–218.

Hansen, J.E. and Lacis, A.A. (1990). Sun and dust versus greenhouse gases: An assessment of their relative roles in global climate change. *Nature*, **346**, 713–719.

Hasselmann, K. (1976). Stochastic climate models, Part 1: Theory. *Tellus*, **28**, 473–485.

Hastenrath, S. (1982). On meridional heat transports in the world ocean. *Journal of Physical Oceanography*, **12**, 922–927.

Hsiung, J. (1985). Estimates of global oceanic meridional heat transport. *Journal of Physical Oceanography*, **15**, 1405–1413.

Johnsen, S.J., Dansgaard, W., Clausen, H.B. and Langway, C.C. (1970). Climatic oscillations 1200–2000 A.D. *Nature*, **227**, 482–483.

Kerr, R.A. (1993). Pinatubo global cooling on target. *Science*, **259**, 594.

Kim, K.-Y. and North, G.R. (1991). Surface temperature fluctuations in a stochastic climate model. *Journal of Geophysical Research*, **96**, 18,573–18,580.

Kim, K.-Y. and North, G.R. (1992). Seasonal cycle and second-moment statistics of a simple coupled climate system. *Journal of Geophysical Research*, **97**, 20,437–20,448.

Kim, K.-Y., North, G.R. and Huang, J. (1992). On the transient response of a simple coupled climate system. *Journal of Geophysical Research*, **97**, 10,069–10,081.

Kyle, H.L., Hickey, J.R., Ardanuy, P.E., Jacobowitz, H., Arking, A., Campbell, G.G., House, F.B., Maschhoff, R., Smith, G.L., Stowe, L.L. and Vonder Haar, T. (1993). The Nimbus earth radiation budget (ERB) experiment: 1975 to 1992. *Bulletin of the American Meteorological Society*, **74**, 815–830.

LaMarche, V.C. (1974). Paleoclimatic inferences from long tree-ring records. *Science*, **183**, 1043–1048.

Lean, J., White, O.R. and Livingston, W.C. (1992). Estimating the total solar irradiance during the Maunder Minimum. Abstract: 1992 Spring Meeting, American Geophysical Union. *EOS*, **73**, 244.

Manabe, S. and Stouffer, R.J. (1988). Two stable equilibria of a coupled ocean–atmosphere model. *Journal of Climate*, **1**, 841–866.

Meko, D.M. (1992). Spectral properties of tree-ring data in the United States Southwest as related to El Niño/Southern Oscillation. *In*: Diaz, H.F. and Markgraf, V. (eds), *El Niño, Historical and Paleoclimatic Aspects of the Southern Oscillation*, pp. 227–241. Cambridge University Press, Cambridge.

Mikolajewicz, U. and Maier-Reimer, E. (1990). Internal secular variability in an ocean general circulation model. *Climate Dynamics*, **4**, 145–156.

Mikolajewicz, U. and Maier-Reimer, E. (1991). One example of a natural mode of the ocean circulation in a stochastically forced ocean general circulation model. *In*: Latif, M. (ed.), *Strategies for Future Climate Research*, pp. 287–318. Hamburg, Germany.

Mosley-Thompson, E., Thompson, L.G., Grootes, P.M. and Gundestrup, N. (1990). Little Ice Age (Neoglacial) paleoenvironmental conditions at Siple Station, Antarctica. *Annals of Glaciology*, **14**, 199–204.

North, G.R. and Kim, K.-Y. (1993). Detection of forced climate signals. Part II: Simulation results. *Journal of Climate* (*submitted*).

North, G.R., Mengel, J.G. and Short, D.A. (1983a). Climatic response to a time varying solar constant. *In*: McCormac, B.M. (ed.), *Weather and Climate Responses to Solar Variations*, pp. 243–255. Colorado Associated University Press.

North, G.R., Mengel, J.G. and Short, D.A. (1983b). Simple energy balance model resolving the seasons and the continents: Application to the astronomical theory of the ice ages. *Journal of Geophysical Research*, **88**, 6576–6586.

North, G.R., Mengel, J.G. and Short, D.A. (1984). On the transient response patterns of climate to time dependent concentrations of atmospheric CO_2. *In*: Hansen, J.E. and Takahashi, T. (eds), *Climate Processes and Climate Sensitivity*, pp. 164–170. Geophysical Monograph 29, American Geophysical Union, Washington, D.C.

Peterson, L.C., Overpeck, J.T., Kipp, N.G. and Imbrie, J. (1991). A high-resolution late Quaternary upwelling record from the anoxic Cariaco Basin, Venezuela. *Paleoceanography*, **6**, 99–119.

Porter, S.C. (1986). Pattern and forcing of northern hemisphere glacier variations during the last millennium. *Quaternary Research*, **26**, 27–48.

Rind, D. and Overpeck, J. (1993). Hypothesized causes of decade-to-century-scale climate variability: Climate model results. *Quaternary Science Reviews* (this issue).

Röthlisberger, F. (1986). *10,000 Jahre Gletschergeschichte der Erde.* Aarau, Verlag, Sauerländer.

Short, D.A., Mengel, J.G., Crowley, T.J., Hyde, W.T. and North, G.R. (1991). Filtering of Milankovitch cycles by earth's geography. *Quaternary Research*, **35**, 157–173.

Sonett, C.P. and Suess, H.E. (1984). Correlation of bristlecone pine ring widths with atmospheric ^{14}C variations: A climate-Sun relation. *Nature*, **307**, 141–143.

State Meteorological Administration (SMA) (1981). *Annals of 510 years*' Precipitation Record in China (in Chinese). The Meteorological Research Institute, Beijing.

Stuiver, M. and Quay, P.D. (1980). Changes in atmospheric carbon-14 attributed to a variable sun. *Science*, **207**, 11–19.

Stuiver, M. and Braziunas, T.F. (1989). Atmospheric ^{14}C and century-scale solar oscillations. *Nature*, **338**, 405–408.

Thompson, L.G., Mosley-Thompson, E., Dansgaard, W. and Grootes, P.M. (1986). The Little Ice Age as recorded in the stratigraphy of the tropical Quelccaya Ice Cap. *Science*, **234**, 361–364.

Wang, Y., Guangyuan, L., Zhang, X. and Li, C. (1983). The relationships between tree rings of Qilianshan juniper and climatic change and glacial activity during the past 1000 years in China. *Kexue Tongbao*, **28**, 1647–1652.

Wigley, T.M.L. and Kelly, P.M. (1990). Holocene climatic change, ^{14}C wiggles and variations in solar irradiance. *Philosophical Transactions of the Royal Society London*, **A 330**, 547–560.

Zhang, D. (1980). Winter temperature variation during the last 500 years in southern China. *Kexue Tongbao*, **25**, 497–500.

Zhang, D. (1984). Synoptic-climatic studies of dust fall in China since historic times. *Scientia Sinica (Series B)*, **27**, 825–836.

Zhu, K. (Chu, K.) (1973). A preliminary study on the climatic fluctuations during the last 5,000 years in China. *Scientia Sinica*, **16**, 226–256.