Working Paper

THE DESIGN OF INTEGRATED MONITORING SYSTEMS TO PROVIDE EARLY INDICATIONS OF ENVIRONMENTAL/ECOLOGICAL CHANGES

R.E. Munn

October, 1985
WP-85-71

Presented at the International Symposium on Integrated Global Monitoring of the State of the Biosphere, October 14-18, 1985, Tashkent, USSR

International Institute for Applied Systems Analysis
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FOREWORD

<u>Environmental monitoring</u> is one of the cross-project themes in the newly restructured Environment Program at IIASA. It is therefore appropriate that a manuscript on "The design of integrated monitoring systems to provide early indications of environmental/ecological changes", should be circulated as an IIASA Working Paper.

The paper was presented at Tashkent, USSR in October 1985 at the Third International Symposium on Integrated Global Monitoring of the State of the Biosphere. It will ultimately be published in the Proceedings.

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ABSTRACT

One of the important goals of the next two decades is to achieve and maintain ecologically sustainable development of the biosphere. However, the management of ecological systems is rather difficult, largely because of uncertainties in long-term predictions of environmental and ecological behaviour. Thus, one of the objectives for integrated monitoring should be to provide early indications of impending changes so that mitigative actions can be taken.

Also it may be important to be able to estimate in advance the detectability of the environmental changes that would ensue if a particular management strategy (e.g., a 30% reduction in sulphur emissions) were to be adopted. Monitoring systems have not traditionally been set up for these purposes.

This paper includes a discussion of the factors to be considered in the design of early-warning monitoring systems, and gives some examples. One approach that appears to be particularly promising is that of identifying, quantifying and monitoring the stresses, feedbacks and component lags in the environmental-ecological system being studied.

CONTENTS

THE DESIGN OF INTEGRATED MONITORING SYSTEMS TO PROVIDE EARLY INDICATIONS OF ENVIRONMENTAL/ECOLOGICAL CHANGES

R.E. MUNN

1. INTRODUCTION

One of the objectives for integrated monitoring should be to provide early indications of impending changes in the environment or in the biosphere. These changes are often difficult to detect, at least in their early stages, because of large natural variability in the element or process being monitored. Two classes of applications can be envisaged:

1. Detection of changes which may become irreversible (for all practical purposes). There are two sub-categories in this class:

   a) changes that are expected, but with uncertainty as to magnitude and time of occurrence, e.g., CO_2 greenhouse climate warming and stratospheric ozone depletion;

   b) changes that are completely unexpected, e.g., forest dieback in Europe, which was not forecasted by anyone 15 years ago.

2. Detection of simulated changes, i.e., determination of the length of time required to demonstrate the efficacy of some proposed management strategy. For example, if it were planned to reduce sulphur emissions from a smelter by 30% say, how many months of wet deposition measurements from the surrounding network of stations would be needed in order to detect the change with 95% confidence?

Although the early detection of discontinuities and jumps is issue-specific in many cases, there are nevertheless some general principles that can be listed. One of these is that the monitoring should be undertaken within the framework of integrated monitoring (Izrael, 1980 and 1983). When based on an interconnected picture of the environment and the biosphere (through the notion of biogeochemical cycling of trace substances, for example), the monitoring system is likely to be much more responsive to detecting surprises than if it consisted of several disconnected components (an air monitoring network; a water quality network, etc.).

2. TREND DETECTION

There are five approaches that might help in getting an early indication of a trend or imminent step-change in the behaviour of an environmental/ecological system:

1. Historical reconstructions;
2. Biological indicators;
3. The mapping of signal-to-noise fields;
4. Identificiation and quantification of stresses, feedback mechanisms and component lags;
5. Creative scenario writing.

These approaches will be discussed below in general terms. Then some practical examples will be given in Sections 3 and 4.

2.1 Historical Reconstructions

There are many examples of environmental issues that arose too quickly for appropriate monitoring systems to be put in place. This has made it impossible to determine pre-disturbance "baseline" conditions. Particularly in the case of ecological monitoring, five to ten years of records may be required in order to determine the natural variability of the system. In retrospect, for example, how could we have had the foresight to monitor the European forests in the 1960s, or the exposures of mine workers to asbestos and fluorospar in the 1940s? In some cases, of course, a monitoring network had been operating for a decade or more before the "disturbance" was noticed. However, the network had usually been established for other reasons and was inappropriate for trend detection. For example, the world stratospheric ozone network was developed in the 1920s and 1930s to get synoptic pictures of the ozone field; the resolution was too coarse to detect ozone depletion by chlorofluorocarbons when that issue arose in the 1970s. The same remarks apply to the Swedish wet deposition network organized by Rossby about 1950 for the purpose of tracing the synoptic motions of air masses. Again the time and space scales of the network made it difficult to detect trends when the acid rain problem arose in the 1960s (Munn and Rodhe, 1971).

It would be useful to undertake a comprehensive review of an historically documented list of surprises in the environmental and ecological fields. Of particular interest would be a study of reasons why the surprises had not been expected.

2.2 Biological Indicators

There has been a long search for biological species that provide first indications of ecosystem damage by pollutants. It has been found, for example, that tree ring widths begin to decrease up to 20 years before there are visible signs of forest dieback.

In the context of early detection of the effects of water pollution on biota, Cairns and Schalie (1980) have produced a useful overview of aquatic indicators. They first make the point that biological indicators are indeed important in that they integrate the effects of various stresses operating on the system; information on pollution concentrations alone is a poor indicator of potential impact, toxicity being a complex function of water hardness, dissolved oxygen concentration, pH, temperature and the concentrations of other pollutants in the water. However, Cairns and Schalie go on to state that no single biological indicator has yet been found that will provide all the information necessary to interpret the behavior of an ecological system. They suggest that an array of indicators be identified.

Some of the desirable properties of an early warning biological indicator have been listed by Regier and Whillans (1980, personal communication):

1. ubiquitous natural distribution, e.g., of the indicator organism or chemical substance;

2. hypersensitive to stress;

3. not an essential community component;

4. does not die-out easily or disappear entirely as stress accumulates, rather it has response tiers;

5. has mobile and immobile facets of behaviour; for example, it regularly contacts the stressor, but can demonstrate avoidance if it prefers;

6. in the case of contaminants it stores chemicals at a faster rate than other organisms;

7. easy to collect and assay;

8. population not harmed by sampling for assay purposes.

After reviewing this list, Regier and Whillans come to the same conclusion as Cairns and Schalie (1980), viz., that a composite set of complementary indicators will be necessary.

One of the problems is that biological indicators are usually subjected to multiple stresses. A way of eliminating this difficulty is to examine the stresses one at a time. For example, a single plant species could be grown outdoors in a well-fertilized, well-watered soil. Alternatively, the species could be grown in a controlled chamber such as an ecostat, microcosm or phytotron. This approach is very useful (UNEP, 1980) although synergistic effects may then be missed. The technique should not be excluded in future research programs in which several approaches are tested.

Most of the work on biological early-warning indicators of change has been narrowly focussed on pollution toxicity. There are, however, many other kinds of stresses acting on ecosystems. Some of the factors that need to be considered in designing a monitoring system include weather (heat, cold, drought, flood, etc.), insect pests, forest fires, anthropogenic factors (overgrazing of pasture, deforestation, etc.), invasions of competing species, etc. An integrated biological early-warning monitoring system should therefore be broadly based to include measurements of these other factors.

2.3 The Mapping of Signal-to-Noise Fields*

The relative ease with which a trend can be detected depends on:

- -- the size of the trend;
- -- the variance of the time series;
- -- the shape of the trend line (a jagged trend line will be difficult to detect);
- -- the spatial coherence of the trend;
- -- the occurrence of trends in several related indicators;
- -- the degree to which the observed patterns can be explained from models.

The first two factors can be combined into a signal-to-noise ratio (S/N), which can be used to select from several stations/indicators, those locations/indicators best suited for trend detection.

If values of S/N are assumed to be normally distributed, then according to Klein (1982) and WCP (1982, pg. 17):

- -- S/N ÷ 1 occurs by chance 32% of the time;
- -- S/N ÷ 2 occurs by chance 5% of the time;
- -- S/N ÷ 3 occurs by chance less than 1% of the time.

This provides a way of assessing the statistical significance of computed values of S/N.

The noise component N is computed as the root-mean-square variability of historical data sets or of model predictions, a correction being made for the autocorrelation existing between succesive members of the time series (due to trend, for example). A way of removing autocorrelation has been described by Madden and Ramanathan (1980). Based on a spectral analysis of monthly mean temperatures, the variance of the data set is calculated as a function of frequency. Then the estimated noise N is given as twice the expected standard deviation for various averaging times.

The signal S is estimated from model predictions or from qualitatively derived scenarios. (If a range of possible scenarios leads to rather similar selections of preferred locations/indicators, there will be greater confidence in the results.)

*This subsection is derived from Munn (1984a).

The most widely quoted study of signal-to-noise ratios is that of Wigley and Jones (1981), who studied the early detection of CO_2 greenhouse warming. They used:

a) the numerical simulation of Manabe and Stouffer (1980) to estimate signal in monthly mean temperature (see Figure 1);

b) temperature variance computed from the years 1941-80 to estimate noise.

The results are given in Figure 2 as a function of latitude and month. Values of S/N generally greater than 10 and in some cases greater than 40 in this Figure are unlikely to have occurred by chance, according to the criteria listed earlier in this subsection. Figure 2 suggests that a CO_2-induced steady-state effect would be detected first in mid-latitudes in summer. This is in contrast with a strategy based on the behaviour of S as predicted by Manabe and Stouffer (1980) that warming would be greatest in high latitudes in autumn and winter. (See Figure 1.) Although the predicted warming is not so great in summer, this factor is compensated by a decreased variance at that time of year.

Studies such as that by Wigley and Jones (1981) help in identifying areas of the globe where key indicator stations should be located--but with three provisos:

-- model predictions are rather uncertain;

-- estimates of N obtained from historical time series may not be representative of future values;

-- transitory responses to climate warming may be different than final steady-state conditions.

2.4 Identification and Quantification of Stresses, Feedbacks and Component Lags

Izrael and Munn (1985) have recently suggested that the health of geophysical, ecological and socioeconomic systems is maintained as a balance amongst various positive and negative feedback mechanisms. If a new stress is imposed, the system may remain in equilibrium through changes in the strengths of the feedbacks. In this context, conventional monitoring may be very ineffective in detecting change. Sometimes too, a system under stress may appear to remain in a steady state due to the existence of lags in one or more of its components. For example, the large heat capacity of the oceans would dampen the immediate change to be expected in world air temperature if some external heating function were imposed. Ultimately of course, an equilibrium condition is reached. Another well-known example is the pH of a lake, which may remain relatively constant for some length of time, even when the water body is under stress from sulphate deposition. The appropriate indicator in this case is buffering capacity, which will reveal whether the pH of the lake will suddenly shift to a lower value.

These ideas will be elaborated in Section 3.4 below.

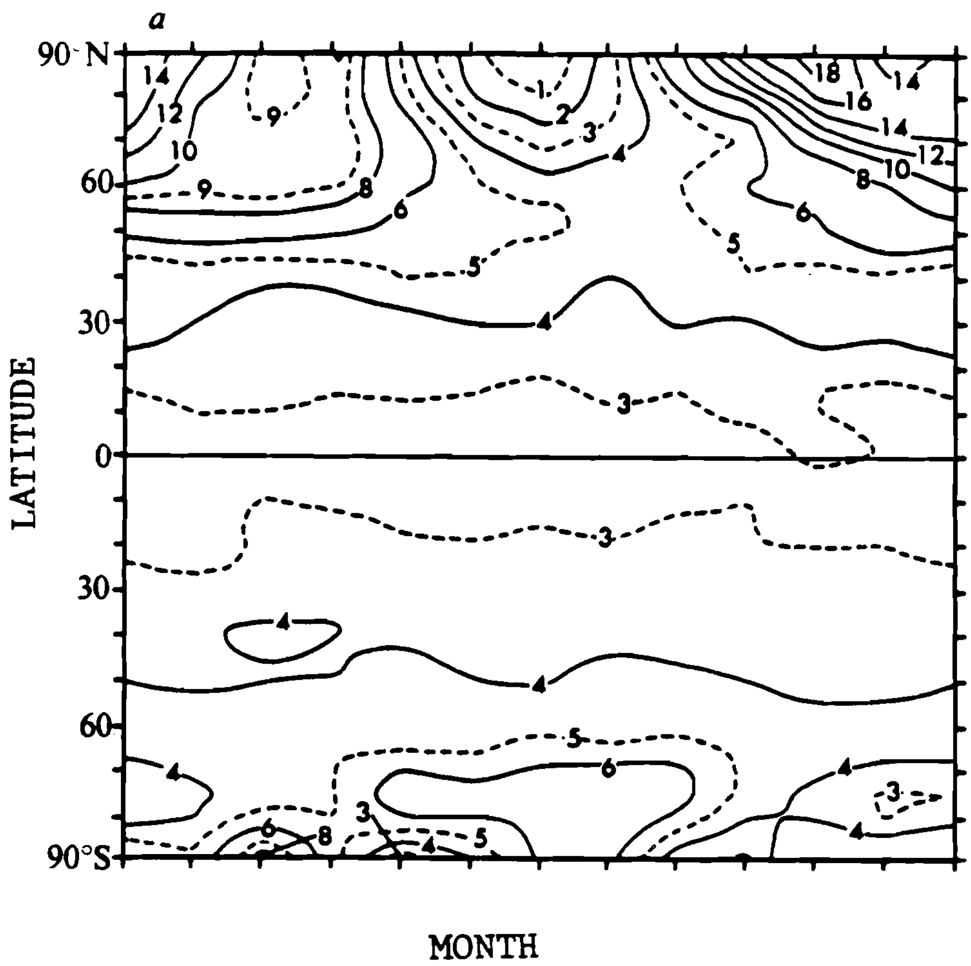

Fig. 1: Latitude-time distribution of zonal mean difference in surface air (70 m altitude) temperature (K) between present and quadrupled CO_2 experiments. (Manabe and Stouffer, 1980. A CO_2-climate sensitivity study with a mathematical model of the global climate. Reprinted by permission from Nature, Vol. 282, pp. 491-493. Copyright, (c) 1979, Macmillan Journals Ltd.)

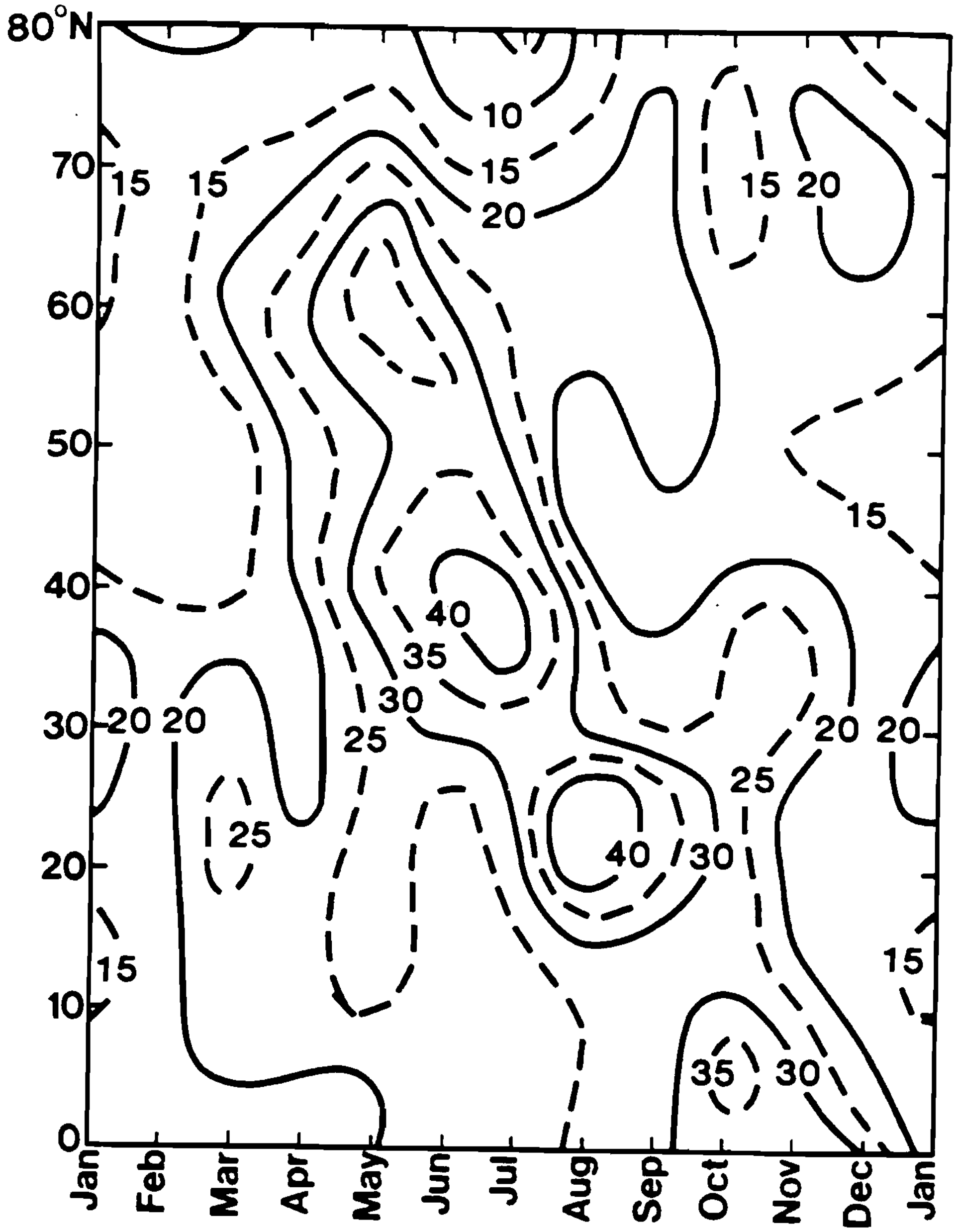

Fig. 2: Signal-to-noise ratio for predicted CO_2 induced changes in surface-air temperature as a function of latitude and month. The signal is based on the numerical modeling results of Manabe and Stouffer (1980). The noise has been calculated from grid-point surface temperature data. The value for month j at latitude L is the areally weighted average of grid points at L-5, L and L+5, and the noise level is proportional to the standard deviation of month-j values over the period 1941 to 1980, corrected for autocorrelation effects. (Wigley and Jones, 1981). Reprinted by permission from Nature, Vol. 292, No. 5820, pp. 205-208, Copyright (c) 1981, Macmillan Journals Ltd.

2.5 Creative Scenario Writing

It is difficult to peer into the future. However, a group of "wise men" can sometimes "brainstorm" to produce a meaningful list of surprises that might happen in the next several decades. Although the probability of occurrence of any particular scenario might be very low, the group might perhaps be able to design a monitoring system that would keep the various outcomes in mind. Particularly if the design of the monitoring system were developed within an overall conceptual framework, this strategy might be successful.

As an example, F. Roots (1985, personal communication) has suggested some potential surprises that might occur in polar regions. These are given in Table 1, together with an indication (far-right column) of whether the surprises could be detected.

3. AN EXAMPLE: THE EARLY DETECTION OF CLIMATE WARMING

3.1 Introduction

The global climate system will be used to illustrate some of the ideas introduced in Section 2. The atmosphere-ocean system is certainly complex, containing many feedbacks and lags; furthermore the space and time variabilities are very large. Thus the early detection of climate change is a real challenge.

3.2 Signal-to-Noise Ratios

The use of signal-to-noise ratios has already been discussed with respect to the global surface temperature field (see Section 2.3). Examination of the isopleths in Figure 2 suggests that climate warming would be detected first in mid-latitudes in summer. As emphasized by Schneider (1984), however, the isopleths of signal shown in Figure 1 are based on an equilibrium climate model, which could give results quite different from those of a transient model. It seems likely that during the transient phase, the air over continents would warm more quickly than air over oceans because of the great thermal inertia of the latter. This would change the character of monsoons, and possibly reduce the intensity of storm activity along the east coasts of North America and Asia in autumn and winter (Munn, 1984a). The isopleths in Figure 2 must therefore be applied with a measure of skepticism but as a first guess, warming might become apparent first in the central parts of continents, in mid-latitudes in summer.

3.3 Conventional Methods

Clearly greenhouse warming will be easier to detect if the measurements are homogeneous with respect to instrumentation and observing procedures and representative of global conditions, i.e., free of local influences such as urbanization and deforestation. In the case of first- and second-order weather observing stations, for example, a useful first step would be to identify the subset of stations which have not undergone significant land-use changes in the last 30 years or so, and which are not likely to undergo such changes in the next 30 years. The number of such stations will be small. In the arctic a complicating factor is the recent increase in haziness, particularly in late winter and spring. Because this could have an effect on surface temperature, only summer and autumn data should be used there for trend detection.

Surface temperature is only one of a series of meteorological elements that could be examined for early signs of climate change. Table 2 (WCP, 1982) gives a list of possible indicators, including the rationale for each. For example, greenhouse warming in the troposphere will be accompanied by greenhouse cooling in the stratosphere. Here it should be mentioned that rawinsonde temperature measurements will be noisy due to instrument error, and due to the stratospheric ozone spring warming phenonmenon; nevertheless, it might be useful to compute signal-to-noise maps of stratospheric thicknesses of representative pressure layers.

Referring back to Table 2, Klein (1982) suggests the following additional indicators:

-- upward infrared radiation at the top of the atmosphere

-- downward infrared radiation at the surface of the earth

As the concentrations of greenhouse gases increase, the upward infrared radiation at the top of the atmosphere should decrease and the downward infrared radiation at the surface should increase. Of course, the former quantity is very difficult to measure with sufficient accuracy while the latter has such a high variance that trends might be almost impossible to detect.

3.4 Identification of Stresses, Feedbacks and Lags

3.4.1 General

The stress causing climate warming is the increasing concentration of greenhouse gases in the atmosphere. The lags are the high heat capacity of the oceans and the large amount of latent heat required to melt the world's glaciers, or to create new ones. The feedbacks are as follows (Hansen et al., 1984; Robock, 1985; Dickinson, 1986):

-- ice-snow albedo (positive feedback)

a) For a Cooling Earth

The larger the area covered by snow and ice, the larger the amount of solar radiation reflected back to space and the lower the surface temperature (further increasing the area covered by snow and ice). A related positive feedback is cloudiness, which decreases as oceanic surfaces become ice-covered.

Table 1: Potential areas of surprise or discontinuity in Polar Regions (F. Roots, 1985, personal communication)

Subject Area	Reversible?	Warning that change could be detected?
1. Meso-scale climate flop* because of albedo change when ice/snow cover deteriorates beyond a given (unknown)change. At what degree of regional or patchy albedo change does the positive feedback break down?	Not likely	Modelling of energy feedback might give critical point
2. Change in Chukchi Sea circulation and stability due to ice damming of Bering Strait Exchange of North Pacific and Chukchi waters is important for Beaufort Sea stability and climate of the region - and thus for the terrestrial environment. At present water depths, a good ice jam could alter this.	Don't know	Not likely
3. Epidemic of vectorborne diseases/parasites in arctic ecosystems because phases held dormant in frozen ground could be released all once by anomalous thaw.... Vector diseases in arctic areas have had little attention, but some (e.g. Nèvè) feel that the amount of dormant disease held in cold storage is vastly under-estimated.	Recover, years to decades	Monitoring of accumulation of dormant vectors
4. Flop of tundra and taiga habitats to desert-like conditions from over-grazing, (abetted by human constraints on migratory animals (caribou) or hunting of competitors or predators (which control lemming, hare), or by human-caused effects on vegetation (patterns of susceptibility or adaptability of tundra plant communities to LRIAP very poorly known).	Recovery or flip-back* likely very slow	Habitat productivity; acid rain susceptibility; monitoring of residual buffering capacity

Subject Area	Reversible?	Warning that change could be detected?
5. Climate and sea ice changes over Arctic Ocean area because of variations in exchange through Fram Strait Strait Fram Strait is the "control valve" for export of energy and cold mass (ice) from the Arctic to lower latitudes, but its variations back up through all the arctic.	Probably irregular, sudden changes at intervals	Not known, but probably susceptible to monitoring when process known
6. Sudden changes of world sea level, due to natural and/or anthropological causes. Melting or major surge of the big icecaps. Catastrophic melt might cause important change in half a century	Geological time scale	Volume changes in Antarctic and Greenland icecaps give the most sensitive largescale integrated climate change signal available. Can be monitored by satellite
7. "Catastrophic" release of icebergs to Labrador Sea or break up of Ward Hunt Ice-Shelf; surges of large Antarctic Glaciers or ice shelves.	Centuries to Thousands of Years	Don't know
8. Rapid movement of tree-line or change of ecosystem as increasing patchiness of habitats destroys critical masses for seeding diversity, or breaks food chains; alternatively, as habitats coalesce and create totally new environment. The more we learn, the more erratic and less gradual these changes seem to be.	Not for centuries	Yes, by monitoring when criteria are known
9. Step-like changes of ecosystem or physiographic instabilities, caused by aggrading or degrading permafrost.	Decades?	Don't know

*
"Environmental flop" is used for a sudden or non-gradual change to a new quasi-stable condition. "Flip" is a bounce-back or oscillation between two conditions.

Table 2: Measurements needed for early identification of climate change, as suggested by the World Climate Programme (WCP, 1982)

Measurement	Status of Method
a. Surface air temperature from land station network and free air temperatures from radiosonde (rawin) station network.	Routine by World Weather Watch network.
b. Sea surface temperature and surface air temperature over the oceans.	Routine, but data collection and dissemination require improvement, especially air temperatures.
c. Global concentration of carbon dioxide.	Routine; continuous sampling at a few stations.
d. Global concentrations of other minor trace gases (O_3 CFMs, CH_4, H_2O, etc.)	Continuing special efforts; direct sampling and spectral absorption.
e. Concentration and distribution of stratospheric aerosols, especially following large volcanic eruptions.	Continuing special efforts; aircraft, surface-based lidar, satellites.
f. Atmospheric turbidity distribution.	Routine; actinometric network needs to be extended to tropics and southern hemisphere and complemented with meteorological data.
g. Total solar flux at the top of the atmosphere combined with continued ground-based observations of solar phenomena, e.g., sunspots, solar flares, solar diameter.	Special effort required from satellites for solar flux measurements to fraction of 1%.

b) For a Warming Earth

As snow and ice melt, the amount of absorbed solar radiation increases. Also cloudiness increases as oceanic surfaces become ice-free.

-- Water Vapour (positive feedback)

As the atmosphere warms, the concentration of water vapour increases, increasing the greenhouse effect.

-- Cloudiness

A change in cloudiness affects the planetary albedo and the degree of trapping of infrared radiation. Dickinson (1986) is of the opinion that even the sign of this feedback is uncertain.

-- Land Albedo (small positive feedback)

Desertification and deforestation could lead to positive feedbacks with respect to the global albedo but the net effect is likely to be small (Dickinson, 1986).

-- Internal Readjustments Within the General Circulation of the Atmosphere-Ocean System (positive or negative feedbacks)

A number of mechanisms have been suggested that could produce positive feedbacks, e.g., longitudinal shifts in the areas of tropical cloudiness (Hartmann, 1984), and changes in the rate of production of deep water in the north Atlantic (Broecker et al., 1985). In this latter case, it is postulated that a buildup of atmospheric CO_2 would lead to polar warming, lowering the deep sea ventilation rate, increasing PCO_2 in surface oceanic waters, and reducing the fluxes of CO_2 from the atmosphere to the ocean. This would accelerate the rate of increase of atmospheric CO_2. On the other hand, the atmosphere contains negative feedbacks, e.g., the meridional fluxes of sensible and latent heat which appear to have a strong stabilizing effect on climate (Stone, 1984).

3.4.2 Early-Warning Monitoring Strategies

In the case of a complex system such as global climate, the design criteria for an early-warning system based on the "feedback" approach should be built around explicit hypotheses about climate. Two such hypotheses will be considered here.

Hypothesis 1: The climate system is warming due to increasing concentrations of greenhouse gases. However, the warming is somewhat lagged by the world oceans and to a much lesser extent by the world glaciers.

Hansen et al. (1984) estimate that the global mean surface air temperature lags the temperature to be expected from current concentrations of greenhouse gases by 1C. As these concentrations increase, a widening gap can be expected between current and equilibrium climate.

The simplest global climate model (the energy balance model) is based on the assumption that at the outer edge of the atmosphere, the total absorbed solar radiation is equal to the total outgoing infrared radiation, i.e.,

$$(1 - A)\ Q(SW) = Q(LW) \tag{1}$$

where A is albedo and Q(SW), Q(LW) are the total downward short-wave and upward long-wave radiation. Q(SW) can be calculated from astronomical considerations. Equation 1 is of course a steady-state assumption, and a widening gap between the left- and right-hand sides, or a decrease in both terms, would indicate that an internal readjustment within the climate system was taking place.

Based on these considerations, the following elements of a climate monitoring system are recommended in principle:

-- global albedo at the top of the atmosphere (this quantity can be measured with sufficient accuracy) (5-year average is currently 0.3 + 0.005 with no indication of a trend)

-- total upward long-wave radiation at the top of the atmosphere (this quantity cannot yet be measured with sufficient accuracy). (The RMS deviation is too large to detect trends; see Gruber and Krueger (1984), for example.)

-- total area of snow and ice (to examine the postive feedbacks resulting from changes in the snow-ice albedo)

-- changes in land albedo (to examine the feedbacks resulting from desertification and deforestation)

-- changes in world cloudiness (this quantity may be difficult to measure with sufficient accuracy)

Most of these measurements would need to be annual averages; Equation 1 would not be expected to apply on a single day.

<u>Hypothesis 2:</u> The climate system has more than one stable mode. Greenhouse warming may lead to a sudden shift to a new mode.

Beginning with the work of Lorenz (1968), there has been considerable discussion of the possibility that nonlinearities in the climate system could lead to multiple equilibria. One trivial example (Dickinson, 1986) is the case in which the net downward shortwave radiation is reduced to 0.9 (say) of its current value for a sufficiently long time; if that unlikely event were to occur, the earth would become ice-covered and would remain so even if the net flux were to increase again.

Current general circulation models do not permit study of multiple modes. However, the conceptual ideas of Broeker and colleagues (Broeker and Takahashi, 1984; Broeker et al., 1985) are relevant in the context of designing early warning monitoring systems. The theory is that there are sharp transitions in the rate of production of deep water in the North Atlantic. This leads to transitions in the associated deep-ocean salinity distribution, and the partial pressure of CO2 in surface waters. If one accepts this theory, then the following quantities should in principle be monitored:

-- the ventilation rates of the deep ocean in the North Atlantic;

-- the associated salinity distributions in the deep oceans, particularly in the North Atlantic;

-- globally-averaged PCO2 in surface oceanic waters.

These are of course difficult measurements to make, but at the very least, regular observations of salinity and other tracers (e.g., radioisotopes) shoud be made in the deep waters of the North Atlantic.

3.5 Summary

In the foregoing subsection, several approaches have been discussed in an attempt to identify a small set of indicators of climate warming. The best strategy is to use an integrated approach, which should in principle include trend analyses of:

-- Seasonal and annual mean temperatures obtained from a subset of first- and second-order weather observing stations, carefully screened with respect to homogeneity and representativeness. From this subset, special attention should be given to summer observations from stations in the interior of continents in midlatitudes.

-- Seasonal and annual mean thicknesses of designated pressure layers in the stratosphere.

-- Downward infrared radiation at the surface of the earth.

-- Global albedo and outgoing long-wave radiation at the top of the atmosphere (to check Equation 1).

-- Total area of snow and ice.

-- Land albedo.

-- Global cloudiness.

-- PCO2 of the oceanic surface mixed layer.

-- The salinity distribution of the deep waters of the north Atlantic.

This set of indicators should be reviewed periodically in the light of the most recent observational data and relevant research results. It should also be noted that some of these measurements cannot yet be made with sufficient accuracy to permit trend detection. However, this deficiency should help decide priorities with respect to the improvement of current monitoring systems. There is also a need to agree on international protocols on how to calculate the noise in time series of a variety of meteorological elements. As pointed out by Wigley et al. (1985), short-, medium- and long-term climate variabilities tend to run together, so that some arbitrary conventions need to be adopted with respect to computing noise.

4. AN EXAMPLE: THE DESIGN OF A WET DEPOSITION NETWORK TO DETECT CHANGES IN AIR POLLUTION EMISSIONS

Policy-makers sometimes ask whether the beneficial effects of a proposed management strategy would be detected quickly. This question was considered at a recent workshop in the context of the detection of changes in acidic deposition, due to a scheduled reduction in emissions from a cluster of power stations or a single smelter 500-1000 km distant. The following recommendations were made (Munn, 1984b):

-- Of the several chemical constituents of precipitation, some will be affected by proposed emission control strategies, others will not. It is therefore recommended that trend detection studies be conducted on a suite of substances.

-- For locations far from sources, daily measurements of gases and of various substances in total suspended particulate samples may provide better indicators of trend than do the wet deposition values, which are much fewer in number.

-- Substantial gains in the ability to detect a change in regional emissions may be obtained by including information derived from meteorological models.

-- For a given set of wet deposition monitoring stations, the signal-to-noise ratio method could yield valuable information on sampling locations most likely to provide an early indication of change. The signal could be obtained from wet deposition trajectory analyses. (In this application, the problem of a transitional state does not arise.) The noise may be calculated from historical time series.

-- As mentioned above, the signal is obtained from areally-averaged model predictions whereas the noise is derived from point observations. In order to ensure comparable space scales, it is necessary to transform the observations into spatially-averaged values before computing noise.

5. CONCLUSION

The paper has dealt with the question of designing monitoring systems to provide early indications of environmental/ecological changes. Some of the changes will be unexpected, and existing monitoring systems may be inadequate. The methods that should be used include:

-- studies of historical surprises

-- biological early indicators

-- the mapping of signal-to-noise fields

-- identification and quantification of stresses, feedbacks and lags

-- creative scenario writing.

The best strategy is to take an integrated approach in which all of the methods are used. In this connection, the idea of fingerprinting (MacCracken and Moses, 1982) conveys the spirit of good design of a monitoring system, in which one searches for "correlated patterns of changes, not just change in one isolated parameter." For example, if stratospheric cooling were detected at the same time as tropospheric warming, the case for a greenhouse effect would be considerably strengthened.

As a final example, Crutzen (1985, personal communication) has suggested that the chemical state of the atmosphere is critically dependent on the concentration of the OH radical, which is almost impossible to monitor at current levels in the atmosphere. Although this makes the task of designing a global air chemistry network very difficult indeed, it does help to set priorities for research in the fields of instrument design and modelling.

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