1998

A Blueprint for Improved Global Change Monitoring of the Terrestrial Biosphere

Steven W. Running
University of Montana - Missoula

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-- Steve W. Running (swr@ntsg.umt.edu), Numerical Terradynamic Simulation Group, University of Montana

The Kyoto Earth Summit recently ended, amid substantial disagreement over current and future global change, and their significance to humankind. The core of the problem is that many global leaders are unconvinced that significant global change is now occurring. Further, there is insufficient confidence in the accuracy of global-scale computer models that project future changes to initiate the political and economic re-directions that would be required to alleviate the problem. As was first said years ago, we are conducting the first global-scale biogeochemistry experiment, the outcome of which is not known, and which could severely impact the habitability of the planet. Conversely, any meaningful reduction in fossil fuel consumption will require the redirection of trillions of dollars of the world economy. The decision to embark on a serious redirection of world energy consumption is, along with population control, possibly the most fundamental global policy of the next century.

Global climate change is to some extent the environmental equivalent of the national debt to economics. Most economists agree that a little debt is harmless, maybe in certain circumstances even helpful. But at some level, the debt becomes too high, the trajectory of additional debt too relentless, and the consensus slowly has emerged that too much national debt, in the long run, should be avoided. Ethically, we are having a party today paid for on our "national credit card," and leaving it to our children and grandchildren to pay off the resulting bills, with interest. National debt has the advantage of being easily measured, although agreement on how much is too much is more difficult. In global-change science, not only does society have no agreement of when change is too much, we do not even have a clear idea of what environmental variables can and should be measured to monitor change. Are we now building a global "environmental debt" that our descendants will have to clean up? The root of the disagreement in Kyoto was that there just was not sufficient hard-measured evidence of damaging global change to warrant the profound policy actions that would be required.

The lack of pertinent global-change data should be taken as a professional challenge to every global environmental scientist. If there is another Kyoto Earth Summit in, say, 2017, will there be an array of critical, well-replicated measurements that can definitively illustrate whether important and detrimental global change is occurring? If there is not, I submit that we as a science community will have failed in our responsibility to humanity.

The purpose of this letter is to suggest a small, critically chosen set of variables for which I feel immediate, coordinated global monitoring networks could and should be established, if we expect to be ready for the hypothetical Kyoto summit in 2017 with better answers than we can offer today. I restrict my suggestions to the terrestrial biosphere, as atmospheric and oceanic monitoring are covered elsewhere. There are wide and ongoing discussions on monitoring of climate itself, so here I am more concerned with the responses of the biosphere to changing climate. In the terrestrial sciences, I will restrict my suggestions to vegetation and hydrologic processes, and particularly to processes that have both tight connection to climatic drivers, and have high relevance to human welfare. To meet my standard as a critical and achievable monitoring variable, a methodology must be available that is either very simple and has a long history of prior measurements, or it must be a newer technology that can be calibrated, propagated widely, and have uniform, automated data processing. An appropriate methodology must have sufficient precision to clearly quantify responses to seasonal and/or interannual variability in climate if we are to expect it to have relevance for global climate-change monitoring.

The best current examples of the monitoring I am suggesting are the atmospheric CO_2 flask network begun at Mauna Loa in 1958 by C. D. Keeling and now coordinated globally by NOAA, and the global monitoring of glacierlengths reported by Oerlamans (1994). The Mauna Loa atmospheric CO_2 record is undoubtedly the most important data set in global change science today. Although it is a measure of atmospheric chemistry, the dynamics it follows are predominantly those of the land and ocean surface carbon exchanges of the biosphere, and the additional anthropogenic loading produced by humankind. The glacier-length data sets are an excellent example of a tightly climatically-influenced hydrologic measurement that is sufficiently simple that it has been recorded for over 150 years at certain locations. Imagine attempting to discuss global change without these two critical data sets for clear quantitative evidence. Yet, as we saw in Kyoto, these data alone are insufficient to trigger the massive policy shifts that would be needed if human-caused global change is imminent. Clearly, a wider array of biospheric monitors is needed.

Vegetation

We must clearly separate variables that are a first-order response to climatic forcing from variables that are contaminated by direct human disturbance unrelated to climate. Both may be meaningful measures of global change, but the former has greenhouse gas emissions as a component of causality, while the latter does not, which implies huge differences in the appropriate remediation measures.

I suggest that we need a fundamental on-going measure of the global extent of vegetation cover. This simple measure would quantify desertification and deforestation dynamics, and also track changes in natural disturbance frequency such as wildfire extent, etc. This can be a difficult variable to define with precision, as land-cover conversion from natural to agrarian uses has been part of human habitation for millennia, and does not necessarily imply a degradation of the land ecologically. In order to avoid the imprecisions of complex multiple biome land-cover classification schemes (Running et al. 1994), I suggest merely an annual global mapping of vegetated versus non-vegetated area, with a single further discrimination to forest and non-forest vegetation (which would include all grasslands and croplands). We currently estimate there are 90 million km^2 of vegetated area (Nemani and Running 1997, Waring and Running 1998), and up to 0.1 million km^2, is possible. The precision gained by these measurements, 0.1%, is much better than normal in situ process data can ever attain. This simple designation will be possible to mentor with the new Earth Observing System AM-1 satellite that will be launched in the summer of 1998. One sensor on this system, MODIS, will map global land cover annually to 1 km^2 spatial resolution, as part of a suite of remote-sensing observations of the land surface (Running et al. 1995). It is currently the intent of the Earth Observing System science community to sustain this measurement for the next 20 years, pending regular replacement of the necessary satellites.

Probably no biospheric variable has more direct relevance to humankind than net primary productivity (NPP), the growth of vegetation that provides the renewable food/forage/fiber/fuel for all human life. Recent estimates are that we co-opt 40% of global NPP for human use already (Vitousek et al. 1997). Terrestrial NPP has been measured locally for many decades as merely the annual growth of various types of vegetation, albeit with variable methodology and precision. Global NPP averages 500 gC m^{-2} yr^{-1}, with absolute measurement precision of maybe 50 gC m^{-2} yr^{-1}. Because the precision of the NPP measurement is rather low, only vegetation sampled with identical protocols at exact locations every year can provide relative measures of variability. Crop NPP is frequently changed by fertilization, irrigation, weed control, and genetic improvements, all of which are unrelated to climatic conditions. Productivity of natural vegetation such as forests more directly reflects climate, but must be corrected for reductions in productivity that occur naturally as forest stands age, called "age detrending" in dendrochronology research. A greater problem is that most forest productivity determinations measure the commercially-valuable portion of the tree only, not total productivity. It would be highly valuable to global-change research to identify stable historical records of any vegetation NPP that avoids the above confounding influences. Currently, only dendrochronology of carefully selected ancient trees in severely climate-limited growing environments have shown the methodological precision required for global-change monitoring (Jacoby et al. 1996).

Two recent technologies have the potential to provide a different measure of vegetation carbon balances from very different perspectives, but of high relevance to global-change monitoring. Recent developments in micrometeorology have produced the ability to continuously monitor the fluxes from the land surface of both CO_2 and H_2O year round (Wofsy et al. 1993). This technology measures net ecosystem exchange (NEE) of CO_2, not net biomass productivity, but has the advantage of being repeatable, independent of any particular vegetation type and being highly automated. NEE ranges 10 gC m^{-2} day^{-1} either positively or negatively, as any point in the biosphere can be either a source or sink of CO_2 under given circumstances. Measurement precision is about 5%, or 30 gC m^{-2} yr^{-1}, better than direct biomass measures. A global network of CO_2 flux towers is being planned (Baldocchi et al. 1996), and may provide the best next-generation measurement of biospheric carbon dynamics to augment the atmospheric CO_2 measurements begun by Keeling et al. (1996). The advantage of the CO_2 flux tower is that it provides a direct measure of ecosystem CO_2 balance; the liability from a global perspective is that only a small plot, < 1 km^2 is monitored. The Earth Observing System will provide a satellite-derived estimate of NPP that will cover every square kilometer of global vegetation. Although the precision of a satellite-derived estimate of NPP is lower, errors are on the order of 30%, the more-precise quantification of areal extent of productivity provided by satellites ultimately gives a more-complete analysis of biospheric activity as a whole. The logic for relating absorbed photosynthetically active radiation by vegetation to primary productivity originated with J. L. Monteith, and the application to remote sensing has been pursued by many groups (Field et al. 1995, Ruimy et al. 1994, Prince and Goward 1995). Again, it is the intent of the EOS science community that an annual estimate of global

NPP will be sustained over the next 20 years, pending regular replacement of aging satellites.

Hopefully, the combination of carefully selected direct vegetation measurements, continuous carbon flux measurements from a global network of towers, and satellite estimates of total global NPP will, in combination, allow an answer in 20 years to the question of whether biospheric productivity is changing.

Probably the most readily observable climate-controlled activity of vegetation is the onset of bud and leaf growth in the spring after winter dormancy in temperate and boreal latitudes. Simple observations of the "beginning of spring" have been recorded by naturalists for centuries, and the U.S. Dept. of Agriculture operated a formal phenology network from 1961-1980. Interannual differences for a single location have been recorded of up to 2 months from the earliest to the latest date when vegetation bud growth was initiated, and year-to-year variability is regularly 10-14 days. Vegetation canopy measurements can be expanded to define growing-season length by measuring the senescence of vegetation in autumn, but with less precision. These simple measurements could be renewed, possibly with automated digital cameras, to provide very direct evidence of any climatic warming responses by vegetation.

Once again, new technology has produced a satellite equivalent of spring bud-burst and growing season length, the weekly recording of a Normalized Difference Vegetation Index, or NDVI. Many vegetation remote-sensing scientists have studied the rapid increase in the NDVI value that can be quantified by satellite, particularly for deciduous forests, grasslands, and croplands (Schwartz 1994, Reed et al. 1994, White et al. 1997). A twelve-year record of NDVI data suggests that the spring growing season in boreal forests of Canada may begin 7-10 days earlier now than in the early 1980s (Myneni et al. 1997). EOS will provide the global 1-km data set to compute this spring onset of growth annually for the next 20 years. However, this satellite record needs a ground-monitoring network to validate the computed spring-vegetation dynamics.

Hydrology

Many global climate predictions emphasize that a large and poorly understood climate feedback may occur through the hydrologic cycle, so a clearly planned monitoring program is essential. As mentioned earlier, monitoring of glacier length is a simple repeatable hydrologic observation that has been carried out on glaciers around the world, and now provides important evidence of climatic change. The global archival and distribution of glacier data have been organized at the World Glacier Monitoring Service in Zurich, Switzerland. The compilation, error checking, archival, and distribution of comparable data sets from around the world is an important aspect of turning any array of global data into a useful global-change monitor, yet is often difficult to get funded.

River discharge is the hydrologic equivalent of NPP for vegetation. It is the most fundamental measure of water availability from a landscape for human use, and has been measured with simple continuous recording devices for over 100 years all over the world with rather high precision, on the order of 5% from the best stations (Georgakakos et al. 1995). However, both the magnitude and seasonal timing of river discharge are profoundly influenced by land-use changes in the watershed above the gauging device. Changes in vegetation cover, consumption of water for irrigation, and reservoir impoundments all cause most river gauging to be an inadequate global-change monitoring system. There exists a subset of high-mountain gauged watersheds, often in wilderness areas or national parks, that have endured no land-use changes and minimal changes in vegetative cover that could provide an excellent network of global-change monitors. These watersheds could provide both consistent monitoring of frozen/unfrozen precipitation and of annual streamflow dynamics. Their location in high, uninhabited mountain regions provides the sort of regional-scale monitor uncontaminated by local influences that was the rationale for choosing the original atmospheric CO_2 site to be at Mauna Loa.

Another readily observable and highly relevant hydrologic variable for climate-change monitoring is the seasonal extent and duration of snowpacks. Snow depth and water-equivalence surveys have been undertaken with simple hand measurements for about 50 years in many mountainous and boreal regions of the world. These simple measurements have a precision of 1 cm or better. A compilation, archive, and distribution of relevant comparable snowpack data could provide a critical climate change hydrologic monitor (Robinson et al. 1993). EOS satellites cannot estimate snow depth or water equivalence adequately, but can provide regular global monitoring of snow areal extent. The weekly satellite-derived snow extent monitoring combined with ground snowpack surveys is a critical global-change monitor that can be developed with existing systems.

A highly dynamic and easily observable hydrologic variable is lake levels, measurable to accuracies of at least 5 mm. Once again, only certain lakes whose levels have not been changed by human water-management schemes, or adjacent land-use changes could be relied upon for a global-change monitor. Again, high mountain regions may contain lakes fitting these criteria. Also, both Australia and Africa have shallow ephemeral lakes of thousands of square kilometers in desert regions that literally appear and disappear altogether in response to the regional water-balance dynamics (Graetz et al. 1992). Because the precision of measuring simple lake areal extent is often higher than water balance processes, monitoring of these ephemeral lakes may be advantageous. Identifying critical lakes, and building a network for reporting and archiving data in a comparable way would be required to make these observations useful.

Implementation Needs

Implementation needs fall into two areas. First, for variables that have a history of measurement, such as stream discharge or snow depth, an assessment of critical sites must be done, to identify only the sites best suited for global-change monitoring, those with stable, calibrated data in areas unperturbed by local influences. While we often focus on maximizing the number of global stations taking certain data, for global-change monitoring it may be better to concentrate on a smaller number of very formally organized and calibrated stations, and concentrate on temporal precision of the measurements, rather than on attempting coordination of a large number of stations. Possibly, spatial sampling should be consciously left to satellite measurements alone, which limits the variables measured but provides complete global sampling. From this subset of sites a global network can be developed with a centralized archiving and distribution facility, as was done with the World Glacier Monitoring Service. Networked computers and Internet now make global data transmission infinitely easier than a mere decade ago, and an archive center could reside in any country willing to host it.

For the new measurements suggested, such as the CO_2 flux towers, an array of global sites taking consistent calibrated measurements must be encouraged. International scientific organizations such as the International Geosphere-Biosphere Program, World Climate Research Program, Global Climate and Terrestrial Observing Systems (GCOS/GTOS) and International Association of Hydrologic Sciences are virtually the only coordinating mechanisms to develop a global network of consistent data collection. The international cooperation required is large, and organization is often slow, but no alternative exists. Satellite data are inherently globally consistent, and archive and distribution points are established by the country that launches the satellite. The Earth Observing System was designed specifically as a global-change monitoring system, so many of the data archiving and distribution requirements are part of the programmatic plan. Only when regular, precise, point measurements can be combined with satellite-derived measures of areal extent of key observable properties, extrapolated with terrestrial simulation models, can an analysis of global terrestrial change be complete.

There is a near endless list of measurements that might be taken to detect and monitor global change in the terrestrial biosphere, some done by the general public. For example, organized annual bird counts may be valuable data. However, while scientists sit in endless meetings deciding what can and should be measured, time is ticking away. I have elected to identify a short, critical list of variables that could begin right now to build a consistent record of terrestrial response to global change. Certainly, more and better ideas will arise in the future, but I feel it is imperative that we begin today to build a global monitoring system that can provide quantitative answers 20 years from now, when policy makers most assuredly will ask us again "what evidence is there of global change?" We must have more data than only air temperatures and atmospheric CO_2.

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