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Health Effects of Mercury in the Environment

Introduction:

The element mercury occurs naturally in the environment but human activities, primarily the burning of fossil fuels, has increased the amount of mercury to which people are exposed. Mercury builds up in fish and marine mammals that eat prey contaminated with mercury. Thus, people who eat large amounts of fish from mercury-contaminated waters can be exposed to unsafe levels of mercury. In high doses mercury is very toxic and can cause immediate illness, and at low doses — the doses people might get from a diet of contaminated fish — the health effects of mercury exposure are more subtle; for instance, developmental deficits in the children of exposed mothers are known to occur.

In December 1997 EPA released a report to Congress evaluating emissions of mercury to the environment in the U.S. and the health effects of those emissions. The full eight volume technical report can be found on the EPA website at http://www.epa.gov/ttnuatw1/112hmerc/merc.html. Also in December 1997 Egeland and Middaugh[1] published a policy paper in *Science* magazine disagreeing with EPA's standards and arguing that the health benefits of eating fish ought to be considered as balancing to a certain extent, the risk associated with eating mercury-contaminated fish.

CONTENTS:

We spoke with Rita Schoeny, one of the authors of the EPA report, about mercury in the environment and how EPA evaluated the risk it poses to human health. Dr. Schoeny received a Ph.D. in microbiology from the University of Cincinnati Medical Center.

ER: Dr. Schoeny, what is your position with EPA?

RS: I have been working for EPA for eleven years in human health risk assessment. I am the Associate Director of the Health and Environmental Criteria Division in the Office of Water. When I was working on the Mercury Study Report to Congress, I was in a different position in the Office of Research and Development. My title changed a few times; most of the time I was a senior scientist at the National Center for Environmental Assessment in Cincinnati. The person who is now in charge of the mercury business and who took the mercury study to completion is Katy Mahaffey Ph.D. who is at the NCEA in Washington DC.

ER: Where is mercury in the environment?

RS: Any place you look for mercury you are going to find it. There are no pristine environments; you can find it in the Antarctic, you can find it thousands of miles from any identifiable source. When mercury is released it can be swept up into the atmosphere and it can circle the globe and stay in circulation for a long time, a year or two years. Mercury that is released in the U.S. can wind up anywhere on Earth; mercury that is released in the Amazon can wind up anywhere on Earth. It will travel west because that is the direction of prevailing winds, but you cannot specifically peg any particular molecule of mercury to a particular source.

ER: Where does it come from?

RS: There are so called natural sources and there are also anthropogenic or human sources. Natural sources include volcanic activity and volatilization from soils and waters.

Some of the mercury in soils and waters is there naturally, but it can also come from human processes. For example, mercury that has been released to the air by coal burning can be redeposited to Earth; then it can be re-vaporized. A common scenario is mercury being released from the smoke stack of a coal burning utility boiler; most of it will be bound to particles and will deposit pretty close to the source. Some of the mercury will be released as vapor and that will go into the global circulation directly. Or rain can wash the mercury contaminated dirt into a water body from which it can be re-emitted to the air or it can be deposited in the sediments.

The U.S. releases 144 metric tons — 158 English tons — into the air per year; and the U.S. is not close to being the biggest source. About 87 percent of the U.S. releases comes from combustion point sources; 10 percent comes from manufacturing point sources; 2 percent is from diffuse area sources; and 1 percent is from miscellaneous sources. Most of the mercury emitted in the U.S. comes from combustion, 80 percent of which you can peg to just four sources: coal fired utility boilers are the biggest source, followed by municipal waste combustion, industrial boilers, and then medical waste incineration.

Mercury is a trace contaminant in coal and that is how it is released; we burn the coal and the mercury goes up the stack. Mercury from municipal and medical waste incineration is decreasing because of pollution prevention and control devices. Coal fired utility boilers are a little more problematic because the mercury emissions from them are harder to control.

This is the picture for the U.S. emissions; other countries are very different. A big source, for example, in South America is small gold mining operations. On a recent trip to India I saw mercury used in cosmetics and herbal medicines. So it is going to be somewhat different country by country. For our report to Congress our major focus was looking at the U.S.

At least in the developed countries, the major route of mercury exposure for humans is through the consumption of contaminated fish.

ER: How much of the total mercury pollution does the U.S. contribute?

RS: We estimate the U.S. is responsible for 3 percent of the worldwide mercury emissions. We do dump a fair amount of mercury, but we are not the worst. It is difficult to get data from other than the developed countries, and no one has done the same kind of meticulous inventory of emissions that we have done for the U.S.

ER: How are people exposed to mercury?

RS: At least in the developed countries, the major route of exposure for humans is through the consumption of contaminated fish. Mercury accumulates in fresh water and marine food webs. In the U.S. there is very little occupational exposure left.

Everyone wants to know if it is safe to eat fish; that is the crux of much of the current discussion on mercury. And the answer is if you eat a lot of fish and it is contaminated with mercury, then no, it is not safe. And this gets us into the question: How much mercury can you be exposed to and not have any expectation of harm? The way we evaluate that is with a risk estimate number called a reference dose or RfD. The definition of a reference dose is the amount of a material that you can consume over a lifetime on a daily basis without expectation of adverse effect. Our definition of a reference dose includes sensitive subpopulations. We try to calculate a risk estimate that we think is going to be the amount a sensitive group of people can consume on a daily basis for a lifetime. For mercury one of the known sensitive subpopulations is the developing fetus, and we based our reference dose on effects observed in children who were exposed *in utero*; that is, in the womb.

ER: Middaugh said there was no observed health effect due to RdD levels of mercury exposure in several scientific studies.

RS: Yes, and some of the authors of those papers have complained that their papers were misrepresented. Pal

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Weihe who was one of the co-authors of the Grandjean et al 1994 study, the Faroe Islands study, wrote a letter to *Science* in this regard; US EPA wrote a response, as have a number of scientists. The Faroes study definitely shows effects of mercury in children exposed in the womb at less than 10 parts per million mercury in maternal hair. And our reference dose is based on a benchmark dose of 11 parts per million mercury in maternal hair. That is what we estimated to be a no-effect level, but the authors of the Faroes Island study say they think there are effects at that level. The pilot or cross-sectional study in the Seychelles, noted effects in that population. They are not overwhelming effects; these children are not falling ill. There are effects measured in tests given to subsets of the Seychellois children associated with increasing maternal hair mercury.

By the time you compare the levels of methylmercury in water with the levels in a predatory fish like a pike or bass... you can see a million-fold accumulation.

ER: What is the connection between mercury in maternal hair and the kid's exposure to mercury?

RS: One of the ways that humans eliminate mercury from the body is in hair. While this is not a major pathway for excretion, it provides a biomarker of exposure. Since hair grows at a relatively steady rate, about 1 centimeter per month, it is possible to segment hair, analyze it for mercury and determine when exposure took place. This is what was done by Marsh and co-workers in their study of mercury effects on Iraqi children; they were able to make a reasonable assessment of which women were exposed during pregnancy. Maternal hair mercury has recently been confirmed in the Seychelles study as a good predictor of infant blood and brain mercury.

ER: How did EPA arrive at the reference dose?

RS: The effects on which we based our reference dose were not as subtle as those measured in either the Seychelles or the Faroe Islands studies. The health effects we used were in a population that was exposed in Iraq to rather high doses of mercury over a short time where people ate bread made from methylmercury treated grain. The effects in adults ranged from numbness in hands and feet and around the mouth, to convulsions and death. After the exposure stopped, there were effects noted in children born to women who had eaten the contaminated bread. Some of these mothers were themselves affected, and some were asymptomatic. We based our reference dose on clinically observed effects: kids that walked late, talked late, had scores that were below a certain level on a battery of tests, kids that were having convulsions. We applied some mathematical models to extrapolate down to a lower bound on a level which we estimated would produce effects in 10 percent of the population. We are using this as an estimate of a no-effect level, and that comes out to be 11 parts per million mercury in the mother's hair.

ER: Your reference dose may be a little too high according to these other researchers.

RS: We have had opinions on both sides. We have had people saying that our reference dose is way too low, we are being too conservative. We have people on the other hand saying we are not being conservative enough — take a look at the Faroes data, take a look at some of the other data from the Amazon and so on. Our report gives summaries of all the published data on mercury effects.

ER: Does mercury build up in the body like PCBs or lead?

RS: Mercury bioaccumulation is not exactly like PCBs, and it is different from lead as well. Humans exposed to lead store the lead in their bones and that is not the case with mercury. Bioaccumulation of mercury is different from PCBs also. You can find PCBs in fish, but if you skin the fish you lose the PCBs because they are associated with fat, and the fatty tissue in a fish is largely in the skin. Unfortunately the mercury is all in the muscle tissue of fish, which is what most people eat. Mercury stays with the meat, and that is how it gets accumulated in food webs.

Methylmercury is taken up by the creatures that are living in contaminated sediments; when those animals are eaten by bigger animals, very little of the mercury is excreted and it is incorporated into the bigger fish's meat. As bigger fish eat smaller creatures they consume all the mercury that is in that creature, and it stays with the fish that is doing the eating. There is very little mercury in the small creatures, but there is a big bioaccumulation between small fish and big fish. By the time you compare the levels of methylmercury in water with the levels of methylmercury in a predatory fish like a pike, bass, the kind of thing people fish for, you can see a million-fold accumulation.

ER: How does the reference dose relate to how much you can be exposed to before you become ill?

RS: When we calculated the benchmark dose we were trying to come up with a reasonable estimate from the Marsh et al data of a no-observed-adverse-effect level, or NOAEL. A standard reference dose is based on a NOAEL from human or animal studies. Once we calculated the benchmark dose which was in parts per million mercury in maternal hair, we had to convert that into an estimated amount of ingested mercury that would result in an 11 parts per million hair mercury level. So we applied an equation that takes into account such things as the ratio of hair mercury to blood mercury, the elimination time of mercury, the body weight of the people, the blood volume. There has been a lot of discussion about the numerical values that one could put for each of those parameters in the equation and we describe all that in the report. There is uncertainty in all of those parameters, but two in particular: one is the hair to blood mercury ratio, and the other is the time it takes to eliminate mercury from the body.

We estimated the amount of mercury consumed on a daily basis to result in 11 parts per million mercury in hair to be one microgram of mercury per kilogram of body weight per day, which is not a large amount. We then applied a ten-fold uncertainty factor to cover a number of different uncertainties. It is a policy of EPA to apply a three-fold factor for the lack of a two generation reproductive assay; that is, we don't know whether mercury would cause reproductive deficits at a lower dose than it causes clinical effects in some of the kids, so we are hedging our bets. We don't have data on the long term effects of exposure to mercury *in utero*. Are the clinical deficits that were noted in children reversible, or do they get worse with time? Another area this ten-fold uncertainty factor covers is the variability in the human population in terms of elimination of mercury from the body, and the hair to blood ratio. None of the studies that have been published to date give us the information that we need in those areas.

Any place you look for mercury you are going to find it. There are no pristine environments; you can find it in the Antarctic...

There are people who disagree with us on this, and in our report we addressed these other points of view; for instance, that our uncertainty factor is too conservative, or that our uncertainty factor is not conservative enough. The Agency for Toxic Substances and Disease Registry for example has a proposed a minimal risk level — an estimate not very different from our reference dose. They have proposed to use some data from a recently published Seychelles study and to apply no uncertainty factor at all. We disagree with that approach. We feel that the areas of uncertainty listed above are not addressed by published data or available analysis of data.

ER: Yet both agencies came up with estimates of safe levels of mercury that are in the same ballpark.

RS: Oh yes. What this whole business is saying to me is that we are homing in I think, on what the risk level is, or at least what the real acceptable level of mercury is.

ER: Middaugh said you are being too conservative, that you have to balance the good health effects of eating fish against the risks of consuming small amounts of mercury.

RS: On the other hand we don't want to withhold information from the public that allows people to make an informed choice. We would be remiss if we didn't give the public all the information that is available to us, and our best estimate of safe levels. Also, there are segments of the population who are not really in a position to make choices. If fish is your only protein source, you are going to eat fish. Nonetheless I think we should let people know what some of the attendant risks may be.

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Environmental Review

Volume 5 Number 6
June 1998

Ranking Threats to U.S. Agriculture

Introduction:

Some environmental problems are bigger threats to human welfare than others. The security of our food supply should be a higher priority than beachfront property values, but how do we decide what the most important environmental problems are? In *Frontiers of Sustainablity*[1], Paul Faeth ranks the threats to U.S. agricultural sustainability as greater or smaller based on the geographic scale of threats, the current trend of threats, and the uncertainty inherent in some threats. In his analysis soil erosion, often thought to be a major threat to agricultural sustainability, is a small threat because it can be corrected at the local level using well understood techniques at acceptable costs. Nutrient runoff and pesticide pollution pose potentially significant and largely unknown threats to human health and are therefore classified as medium threats to sustainability. Wetland losses through conversion to farm land have declined in recent years and is classified as a small sustainability threat. The author argues that declining farm numbers and farmland loss poses no threat to agricultural sustainability; while it is a serious social problem, it does not threaten our ability to produce food. Water supply is considered a small threat to sustainability because such a large volume of water is used inefficiently on low value crops that conservation and removal of subsidies would have little effect on total crop production. Agricultural germplasm loss — the loss of wild plants — is a major threat to U.S. agricultural sustainability. Repeated major crop losses to disease and pests have shown that modern agriculture is vulnerable to genetic losses. Extinction of wild stocks irretrievably closes off future opportunities not only for crop improvements but also the development of genetic responses to emerging pest and climate threats.

The World Resources Institute is an independent center for policy research and technical assistance on global environment and development issues[2]. Paul Faeth is the director of the economics program at World Resources Institute. His undergraduate degree is in agricultural engineering from the University of Florida and his masters degree is in resource policy from Dartmouth College. We spoke with him about his work evaluating the threats to American agriculture.

> **...we're using millions of tons of fertilizers on farms in the Mississippi watershed... And now we have a 7,000 square-mile dead zone in the Gulf of Mexico.**

ER: Paul, you wrote that what will be considered sustainable fifty years from now may be different from today's concerns, just as today's issues differ from the Dust Bowl.

PF: Sustainability is not really a goal, it's more a path, and we are discovering problems that we didn't think about before. Today we are thinking about climate and biological diversity and El Niño. During the Dust Bowl, people weren't thinking about global climate change, they were thinking about the local climate and the failure to manage in the face of long term drought. Sustainability is a moving target but it is important to figure out what are the most important issues and not get stuck in the issues of six decades ago.

ER: What is the difference between strong and weak sustainability?

PF: Basically strong sustainability means the maintenance of all forms of capital, while weak sustainability means the maintenance of the total value of all capital and that particular forms don't matter. I think there is a consensus that capital stocks need to be maintained. But capital in what form? Traditionally economists believed that capital is fungible, that it

Environmental Review

Volume 5 Number 6
June 1998

is all interchangeable. My opinion is that some stocks are not fungible and some are, and the trick is knowing where you can find substitutes that are economically feasible. If it's too expensive to substitute for something, it's not truly fungible. I heard someone one time saying that there's no sustainability problem because even if we erode all the soil, we can always use hydroponics to grow food. It's a ridiculous suggestion; there are 400 million acres of agricultural land in the United States and we're not going to do 400 million acres worth of hydroponics. So we do need to maintain agricultural land; we do need to maintain basic productivity; we do need some certain stocks and we do need water, for example, and we have to have energy. It doesn't have to necessarily be fossil energy. We can power tractors using electricity from solar energy as well, or from biofuels or diesel fuel, so there are substitutabilities in many different areas.

But in genetic stocks of crop plants there are no substitutes; that's an area where I think we need strong sustainability. If we lose a gene that gives plants resistance to a certain type of disease, it is lost forever. And while there are often chemical treatments for plant diseases, they are expensive to make and to use and to control. Genetic diversity of crop plants is one where we want strong sustainability because loss of biodiversity is permanent, and it's difficult to imagine substitutes that will be effective.

This is happening right now in the West where there's a wheat rust coming up from Mexico. *[Rusts are fungal diseases of plants. Ed.]* Plant breeders have had to sort through 30,000 different varieties of wheat to find one that was resistant to this particular rust. It was not a particularly good variety of wheat: it had no apparent value from a yield point of view, it looked crummy and the grain was not very good, but it had resistance to this rust. And now they are breeding it into our conventional varieties to give them disease resistance. So we need to maintain these so-called useless plants just in case they have a trait we may need in the future.

> **We won't fix declining farm numbers or declining rural population by giving more subsidies to agriculture, we need to fix it by investing in education and in infrastructure in rural America.**

ER: Another measure of sustainability is that pollution should not exceed the environment's ability to absorb it. It seems like we're bumping up against that limit.

PF: We are in many ways. One of the ways we are exceeding nature's assimilative capacity in agriculture is in nutrients in the soil, crop fertilizers. Waterways have some ability to use nutrients that are disposed in them, nutrients have always come off the land. But before Western civilization came to North America, there wasn't a problem with lack of oxygen in the waters of the Gulf of Mexico. The fisheries in the Gulf in fact require that some nutrients run off the land and get down to the Gulf. It's necessary for the functioning of the ecosystem to have some nutrients going into waterways. But now we're using millions of tons of fertilizer on farms in the Mississippi watershed; overusing nitrogen by one-third and phosphorus probably by two-thirds. Two-thirds of the phosphorus that is applied doesn't get taken up by the crop, so two-thirds is available in some way to be released into the environment.

ER: So our farmers are fertilizing the Gulf of Mexico?

PF: Yes. And now we have a 7,000 square-mile dead zone in the Gulf. Clearly the ability of that ecosystem to absorb the level of fertilizers that we're putting into it has been exceeded.

Another way we are exceeding nature's ability to absorb our wastes is showing up in the climate. We're putting greenhouse gases into the atmosphere, and the oceans and other ecosystems can absorb only a certain amount of that carbon. We have gone beyond the threshold at which the ecosystems in the ocean can absorb the carbon dioxide we are pumping into the atmosphere, so climate is expected to change. And climate change will affect agricultural production in ways we cannot predict.

ER: Many people will be surprised at your assessment of soil erosion as a small threat.

PF: We've spent the last sixty years trying to deal with soil erosion. Using the data from the National Resources Inventory from 1982 to 1992, soil erosion is down by about one-third. Many people in the U.S. have long considered soil loss our most serious sustainability problem, but we're getting a pretty good handle on it, so now I believe it is less serious. Until very recently we were spending about 1.8 billion dollars a year on the Conservation Reserve Program. We have spent a lot of money on soil erosion and water quality issues. And for the first time, in 1997 there was more land planted using conservation tillage techniques than conventional tillage techniques.

ER: You think of it more as a local area problem.

PF: Yes, soil erosion is controlled locally. A farmer can fix it without anybody else's help, change a piece of equipment and reduce his soil erosion by 90 percent. It's well within the control of an individual person on their fields. If a farmer is using a mold board plow and then switches to no-till, 90 percent is the usual reduction in soil erosion; that's a big decrease simply by going from one practice that's well understood to something else that's well understood.

ER: With no-till the farmer is chemically plowing using herbicides, instead of mechanically plowing.

PF: Yes, but the numbers that I've seen suggest that the overall herbicide use remains about the same whether the farmer is doing one kind of weed control or the other. The use of herbicides is a contentious issue, and it would be nice if we could avoid using chemicals and releasing chemicals into the environment altogether, but I personally think that it's a reasonable tradeoff. Herbicides are generally on the lower end of the harm continuum.

We did a study at WRI a couple years ago for the 1996 farm bill where we looked at organic methods of farm production compared to conventional methods of farm production. We looked at a whole range of alternatives from mold board plows and using lots of chemicals, to organic. When farmers go completely organic they can't do no-till and often have to plow a lot, so they can't get to the reductions of runoff like no-till. At least in the practices that we were able to identify and compare, my take on it is that a little bit of herbicide is a reasonable tradeoff if used responsibly by the operator to attain the water quality gains that you see from no-till. It's not perfect and it would be great if we didn't have to use them, but I think it's a reasonable tradeoff.

We're getting wetland loss under control, at least in agricultural areas. We are still losing wetlands and the trend's still going the wrong way, but at least it has slowed down, and in some areas we are figuring out how to reconstruct wetlands. So I think those are also relatively small sustainability threats.

There's so much we don't understand about climate, and the potential for impact is so big, that I think you can't label it anything but a large problem.

ER: We're still losing wetlands to urban development.

PF: Yes. It's mostly from urban uses now. Also in that category of smaller threat is declining farm numbers. A lot of the sustainable agriculture community considers farm loss a sustainability issue, but I see the decline as more of a quality of life issue. The reason I say that is that declining farm numbers is a much broader social problem and it's unfair to put farm loss at the feet of agriculture alone. There are many social forces at work that are pulling people off the farm: where people want to live, the pull of jobs in other sectors of society, the way we support or don't support rural areas. We don't put the money into infrastructure and schools that we should, and those are significant contributors to the loss of farms. From a strictly production point of view, it doesn't matter. You can produce a lot of food with many small farms or a few big farms. We may have social objectives and have notions about what we want rural America to look like, but those are quality of life issues as opposed to sustainability issues. We have myths about how rural America is supposed to look that are significantly different from the reality of it. If we're worried about, and I think appropriately worried about declining rural population numbers, not just declining farm numbers, we won't fix it by giving more subsidies to agriculture, we need to fix it by investing in education and in infrastructure in rural America.

The rural areas that are doing relatively better are ones that are not dependent on extractive sectors like mining and agriculture, but that are dependent more upon industry and more upon recreation. I agree that the decline of rural America is a problem, but it's not a sustainability issue for agriculture.

ER: What do you consider medium-sized problems?

PF: Nutrient runoff and pesticide pollution are two medium-sized problems. Those are larger in scale and we are dealing with things as big as the Mississippi basin. When we are talking about the hypoxia problem in the Gulf of Mexico, a big proportion of that pollution comes from the upper Mississippi.

Water quality in general I think is a medium sustainability problem for us. I think it's probably the most serious near-term issue for agriculture, aside from germplasm loss. And it's the issue that people pay the most attention to and that has been costing us the most money. Since the Clean Water Act was initiated we have spent about $115 billion on point source control, and water quality has gotten somewhat better. But agriculture is now responsible for about 60 percent of the load now and it hasn't really been addressed very effectively.

WRI is just finishing up a study on nutrient trading. We're looking in three watersheds in the upper Midwest at water quality and loads of phosphorus into waterways and how to control the loads to an ecologically manageable level. You can hit the point sources harder with traditional regulation, and that's the least cost-effective answer. You can give agricultural best management practices, and that's almost as cost- ineffective as point source regulations. The government encourages farmers to sign up, but they don't worry about what performance they get for it. Or you can do something else. We're looking at nutrient trading, where you have an emissions limit and then you allow people who have expensive costs of remediation to purchase their reductions from people who have lower costs. Everyone has to meet their limit but it can be done through the purchase of credits generated by someone who does more than they have to. On the non-point source side, reductions could be made by using conservation subsidy dollars to purchase credits from farmers.

Water quality in general I think, is a medium sustainability problem. It's probably the most serious near term issue for agriculture, aside from germplasm loss.

ER: How does that work?

PF: Well, basically you could have a pool of credit that farmers could generate from conservation practices and make available for sale, like a market. And you have certain rules to assure that the credits are real. Whoever has the cheapest reductions, that is where the money goes. You want to pay for the biggest improvements on those farms that are close to the water and not relatively ineffective practices that are far away from the water and don't have much impact on water quality. Basically trading is a mechanism for performance-based purchases to find the cheapest cost of remediation.

ER: This is similar to the credit trading in the Clean Air Act.

PF: That's right, it's a much more effective way of fixing problems than command and control or subsidies. It is still a form of regulation, but a flexible one.

ER: Many people are outraged when they hear that people are being paid to pollute.

PF: I hear that argument about the morality of trading. Someone described this to me and their reply was, Well, do you take your own trash to the dump or do you bury it in your back yard? And I said, Well, no. Of course I don't bury my trash in my back yard. Well, then you've traded. Someone else is dealing with your problem for you and you give them money to do it. Of course we all do that. I don't deal with my own sewage, I pay the city to deal with it. If it's moral for households to have a cost-effective approach where communities deal with these kinds of pollution issues, then it's just as moral for industries to do this in the same way. It's not immoral to be cost effective, but it is immoral to avoid the consequences of your actions.

ER: I've heard people express concerns that we're mining the aquifers and depleting them. What's your take on that in the United States or worldwide?

PF: It is true. There's no doubt about it. But I rated that a small sustainability threat only because it would be easy to fix if we stopped subsidizing water. Irrigation water use in general would not be a problem if we didn't subsidize it. In places like India, groundwater is being depleted because electricity is so heavily subsidized for them and service is so poor that farmers have to get all they can when they can. If the subsidies were eliminated and the funds used to improve service, the problem would be eased enormously.

In the U.S. the problem is not tied to input but output subsidies. We used to offer high prices for crops like wheat that encourage farmers to grow it in arid areas. This may decline with the move to market prices. Some fossil water is not renewable and there is nothing to do but use it wisely.

I want to stress though, that there are problems of a much bigger scope. The time frame for fixing them is longer, the scale is bigger, and some of the uncertainties are greater. We don't understand for example, the immunotoxic effects of pesticides, and that's a worry. If it turns out that these are causing immunotoxic problems in humans or wildlife, it means that we're going to have to figure something out to replace those chemicals. Those I classify as medium threats. And again, we know a fair amount about how to fix some of those problems: we can manage our fertilizers better, we can use integrated pest management and manage pesticides better.

ER: What's in your big problem category?

PF: In the large problem category the two I've identified are germplasm loss and climate change. Climate change obviously is global and could work itself out in different ways with some big surprises. When we think of climate we tend to assume that it will be a nice smooth transition to some new steady state; and that may not be the way it's going to happen, so there's a potential for big surprises. There's so much we don't understand about climate, and the potential for impact is so big, that I think you can't label it anything but a large problem.

> In the large problem category the two I have identified are germplasm loss and climate change.

Now some people say we'll be able to adapt, and we certainly will, but we don't know what it's going to cost and we don't know what we will be adapting to. If it is a new steady state where it is only twice pre-industrial levels of greenhouse gasses, and we got there in a nice smooth pattern and it gets a few degrees warmer, U.S. agriculture could adapt fairly easily to that. But remember it takes ten years to breed new crop varieties. Agriculture in under developed countries will have a much harder time.

Agricultural germplasm loss is also international in scope. Our crop germplasm derives from all over the world; there are only a few crops that originated within North America. The centers of origin for most of our important crops are outside the U.S., and many of these areas are threatened.

The center of origin for maize is Central America, and in many of the wild areas in which the maize progenitors grew, the habitat is being destroyed. Of the increases in agricultural productivity, something between one-half and two-thirds of that have come from breeding and genetic improvement. We need to continue to increase yields and productivity for a growing world population. We don't know the genes that are out there and we don't know what we're going to need next, so we had better protect as much as we can. We can't say what the value of germplasm is, but once it is gone it is too late, and it isn't all that expensive to protect.

ER: Stopping habitat loss in the developing world is not going to be easy.

PF: Let me qualify that last statement. It's relatively cheap to have seed banks and collections. And we're not doing a good enough job just in that very basic thing, we're spending something like $30 million a year on our seed collection in the United States, and that's way too little to protect it. We're not growing out the seeds and they're losing viability.

Stopping habitat loss is another matter. At the least though, we should support efforts to protect what are called biodiversity hot spots in conjunction with less developed countries.

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2 **WRI's website is http://www.wri.org**

Volume 5 Number 6
June 1998

What Are the Facts About Climate Change?

Introduction:

In a policy article for *Science* magazine[1], Jerry Mahlman wrote "... the state of the science of greenhouse warming is often warped in differing ways by people ... with widely varying sociopolitical agendas and biases." and "...such distortions grossly exaggerate the public's sense of controversy about the value of the scientific knowledge base...".

He describes the scientific consensus about greenhouse warming and climate change as a series of facts, virtually certain projections, very probable projections, and probable projections. Virtually certain facts are that greenhouse gases in our atmosphere are increasing because of human activities and these gases act directly to heat the planet. Virtually certain projections, those that have a greater than 99 out of 100 chance of being true include, stratospheric cooling and more water vapor in the air closer to the planet's surface. Very probable predictions have a greater than 9 out of 10 chance of being true and include a 1.5 to 4.5 degree Celsius global warming by the year 2100; substantial sea level rise; and an increase in global mean precipitation.

We spoke with Dr. Mahlman about his work as an "honest broker" in the policy debates about global warming and climate change.

ER: Dr. Mahlman, what is your scientific background?

JM: My Ph.D. was from Colorado State University in atmospheric science, and I started my career on the faculty of the Naval Postgraduate School in Monterey, California. In 1970, I came to my current affiliation with the Geophysical Fluid Dynamics Laboratory — GFDL — National Oceanic and Atmospheric Administration. I was a research scientist working on a number of climate, ozone, and atmospheric chemistry problems. My approach was to use and develop mathematical models of the atmosphere to address some of the key scientific questions. In 1984, I became the director of GFDL. I have been broadly involved with the science, and its implication, of the ozone depletion issue. For multiple reasons, I got entrained into the climate change problem over the last ten years. I occupy the niche of being a person in the middle of the fight between the right wing and the left wing, trying to describe the science of the problem, independent of policy-driven agendas.

> **... the amount of greenhouse gases that we emit into the atmosphere is a social choice with winners and losers, not a scientific problem.**

ER: You wrote that people with different political agendas are exaggerating the controversy about climate change.

JM: The left wing is saying that the science is in on climate change; we know it well enough and we have to mitigate now. The right wing is saying the science is a bunch of garbage or the effect is too small to be of concern, so don't do anything. These differing positions have produced an amplified sense of uncertainty about the science. My own approach is to try to be as honest as possible about what we know and what we don't know. I am concerned that these values-driven debates still being featured in the media are undermining the public's sense of what the science is telling us. By exaggerating the sense of scientific controversy, at least in the U.S. it effectively gives an artificial sense of differences about the reliability of the science.

This may help to explain why Europe is willing to make large commitments to mitigation of carbon dioxide emissions, while here in the U.S., there appears to be no way that Congress is going to ratify the Kyoto agreement in its current form. These very different policy attitudes seem to be based upon acceptance of a pretty confident science in Europe, but perceptions of a shaky science in the U.S., at least in the minds of many people who are making policy decisions. However, the reality remains that science is just the science, and we scientists in the U.S. and Europe pretty much agree on what we know and what we don't know. The actual scientific consensus is international, not regional.

Many arguments that you hear about climate change start with a political position, and with the "science" being lined up to buttress that position. When I say my opinions are policy independent, I am saying that when I talk about what we know and what we don't know, I know of no policy motive behind my statements. They are simply my best estimates; I don't know if they are high or low. The left wing can say that climate change could be twice as bad as I am saying, while the right wing can say that I am exaggerating the most likely climate change. I am left wondering how people seem to know that the consensus among climate scientists is so systematically far off on either the high side or the low side.

ER: What do you mean that the climate model uncertainly is distinct from the social uncertainty?

JM: Assume for the moment that we can agree to work with a specific scenario of the added greenhouse gases and sulfate aerosols over the next century. Suppose that we scientists could provide a perfect prediction of how these added substances would actually change the climate. How would the planet's social systems respond to this information? With considerable uncertainty and controversy, I would predict. This is because the amount of greenhouse gases that we actually emit into the atmosphere is a social choice with winners and losers, not a scientific problem.

For example, suppose that we begin to learn that our best estimates are low on the amount of climate change we would get for a particular amount of added carbon dioxide. Confronted with the new information that the climate models have been on the low side, we would surely re-ignite spirited debates on the painful social choices that would achieve a sharp reduction in the use of fossil fuels. Suppose, however, that our best calculations of global warming have been found to be too high by a factor of two. Then the social pressure to make such politically difficult decisions would be reduced substantially. Thus, social uncertainty would not disappear even if scientific uncertainty were to become very small, a prospect I don't see happening anytime soon. We will be arguing on the specifics of what to do about this problem for a long time.

ER: What is the role of the Intergovernmental Panel on Climate Change?

We are currently releasing roughly 6 billion tons of carbon dioxide a year from the burning of fossil fuels, and then another 1.5 billion tons from deforestation.

JM: Many people have pet arguments about climate change, and many times those arguments are unconstrained by quantitative thinking. IPCC, because it is grounded in refereed scientific publications, has attempted to find the broad-based scientific consensus on what we know and what we do not know about climate change. In my view, if people have contrarian ideas about the science of climate change, then they should explain why they disagree with the science-based IPCC assessments. Both right-of-center people and left-of-center people have made arguments that are scientifically bewildering to me. If they disagree with IPCC, they should explain why.

ER: The news media seems to sense that climate change is an important story, but they don't do a good job of explaining it.

JM: The tendency of the press has been to ferret out controversy more than to educate. Until recently, the press has been running to virtually anybody who has something extreme to say, presumably because controversy sells newspapers and increases ratings. I don't think the press has a liberal bias or a conservative bias. I think they have a sexy news bias.

Incidentally, this controversy has produced a peculiar inversion: the usual way science works has been turned upside down. In science the burden of proof usually is on the person who thinks that the mainstream argument is not correct; if someone has an alternative hypothesis, it should be at least testable. But in the IPCC process, the right wing has been so vociferous that the scientific establishment has felt obliged to respond to every statement or claim that is coming from that end of the spectrum. In the previous IPCC reports, essentially the entire list of the right wing's arguments have been carefully analyzed and rebutted, even though many of those arguments have never appeared in the refereed scientific literature. I thus say congratulations to the counter attackers of the right wing because they have successfully managed to flip the paradigm of science backwards. It now seems to be the burden of the scientific mainstream to evaluate all assertions, whether or not they show any evidence of scientific merit.

ER: In your *Science* article you list the virtually certain facts we know about climate change. The first fact is that greenhouse gases are increasing because of human activities.

JM: The ever-increasing amounts of carbon dioxide in the atmosphere are essentially coming from fossil sources of carbon. We extract coal, gas, and oil, and we burn it. Of the other greenhouse gases, methane, nitrous oxide, and some chlorofluorocarbons are increasing. There is not any doubt about the chlorofluorocarbon increase being from human activities because it is a human-made molecule and there are no natural sources. Methane continues to increase, and we are pretty sure it has a strong anthropogenic component. The source of the methane is burn off from natural gas, agricultural practices, rice paddies, and enteric fermentation in large animals. The increasing nitrous oxide is thought to be mainly due to use of nitrogen-based fertilizers.

ER: And we are virtually certain that these trace gases in the atmosphere trap heat?

JM: Yes. We can measure this trapping in the lab. We can measure it from space. One of the peculiarities of our planet is that nitrogen and oxygen, that compose 99 percent of the atmosphere, are diatomic molecules and they are essentially transparent to the infrared spectrum of light. It is these other trace gases that determine the trapping of heat on the planet. The planet is about thirty-three degrees Celsius warmer than it would have been had there not been water vapor, carbon dioxide, nitrous oxide, and methane in the atmosphere.

The simple truth is that if you add heat-absorbing greenhouse gases to Earth's atmosphere — which is nearly transparent in the solar radiation wavelengths — sunlight gets a nearly free ticket in, is absorbed at the Earth's surface, and is largely trapped when it tries to return to space in the form of infrared radiation — heat. It is not controversial that added greenhouse gases are producing a heating of the planet of about two watts per meter squared, about halfway to what we would expect if we double the atmospheric carbon dioxide by 2050. So the added greenhouse gases are acting to heat up the planet by putting an additional thin blanket around it.

ER: How would you describe greenhouse forcing for a non-scientist?

JM: Suppose you are sleeping in your bed on a cold night and you find yourself slightly too warm, but comfortable. Now you add a thin blanket; if you are at that warm edge, you can quickly feel the uncomfortable difference the added blanket makes. The balance between the heat your body is producing under the blankets and the loss to the cooler room has been changed by reducing the heat loss; you got too warm by reducing your loss of heat.

Another way of thinking about it is by appealing to your everyday observations of the weather and the temperature. Suppose you go outside and look up at the sky at ten o'clock on a cloudy June night. Is the temperature going to drop sharply overnight? Probably not. You know already that cloudy nights tend to prevent strong overnight cooling. Now suppose it is clear, dry, and the stars appear distinct. You know that the morning temperature will be considerably colder after such a clear night. The reason for the difference is that the clouds provide an efficient trapping of heat. The Earth tries to radiate this heat out to space, but the clouds absorb it and radiate it back like a blanket. People who live where there is a lot of variability in the humidity will notice that on clear nights that are very humid, it doesn't cool off much; on a clear and dry night, the temperature drops markedly. All these are greenhouse heat trapping effects, or lack thereof.

ER: Why are we so focused on carbon dioxide?

JM: Carbon dioxide is the dominant greenhouse gas that humans are venting to the atmosphere. We are currently releasing roughly 6 billion tons of carbon dioxide a year from the burning of fossil fuels, and then another 1.5 billion tons or so from deforestation. The good news is that this is producing a rather modest atmospheric carbon dioxide increase of about one-half percent per year. The bad news is that it is projected to go up one-half percent every year, inexorably, for a long time. Right now there is major economic and social pressure to increase the burning of fossil fuels because they are cheap, and because the developing countries want a bigger piece of the economic action. The problem is that the molecules of carbon dioxide that you added to the atmosphere by driving to work this morning have an apparent lifetime in the atmosphere of about seventy-five years. Now, imagine if we get to high carbon dioxide levels and we get a climate warming that we don't like, a renewed action to reduce fossil fuel burning sharply wouldn't produce an atmospheric carbon dioxide drop to pre-industrial levels any time soon. In fact, it could be well longer than a one-century wait.

ER: We are virtually certain that particles added to the atmosphere actually cause some cooling effect. This is a relatively new understanding about the role of sulfates isn't it?

JM: Yes. The sulfate particles, the same pollutants that bring us acid rain, have the ability to reflect solar radiation. If you add sulfate particles to the atmosphere, they reflect sunlight and produce a cooling effect.

ER: So the sunlight doesn't get to the Earth's surface in the first place?

JM: That's right. The sulfate particles increase the effective cloudiness of the planet, acting to reject some of the sunlight that is coming in.

ER: The right wing leapt upon the sulfate cooling effect, and said that IPCC didn't get its facts right, and maybe even covered up this cooling offset effect.

JM: That was a truly bogus assertion. This is not a question of scientific infallibility; it is a question of scientific correctability. If there had been a coverup where IPCC had found that the aerosol effect is more important than we previously thought, but decided to not tell anybody, then anyone would have a good reason to start yelling and screaming. That is not what happened. Once the scientific community began to see this sulfate aerosol effect is big enough to make a difference, we added to our calculations.

ER: We are virtually certain that the surface temperature has increased about one-half degree Celsius over the past century?

JM: That's right. We are virtually certain of that one-half degree, plus or minus two-tenths of a degree Celsius; the plus or minus two-tenths gives us a generous margin to cover for all of the possible problems with the measurements. This increase provides an example of how both the left wing and the right wing can misuse variability in the same way that uncertainty can be misused. The right wingers have said that this one-half degree increase in average global temperature could all be explained by natural variability and thus there may be no greenhouse warming effect at all. However, a person at the other end of the spectrum might easily have said that human-caused warming could have been one degree, but we may have had one-half degree of natural cooling that offset it. Therefore, the human-caused global warming part could actually be twice that one-half degree! Neither statement, however, would have any demonstrated factual basis. Both ends of the political spectrum can thus work natural variability to their political advantage. Unfortunately, the natural variability effect is like uncertainty. It just is; it doesn't have a preferred algebraic sign.

Many people have pet arguments about climate change, and many times those arguments are unconstrained by quantitative thinking.

ER: We are virtually certain water vapor will increase in the lower troposphere?

JM: Yes, the air holds more water vapor when it is warm than it does when it is cold; arguments to the contrary are highly dubious. If this were not found to be the case, it would be a stunning surprise. I don't expect that surprise to occur.

ER: Why should we be concerned about the amount of water vapor in the air?

JM: We should be concerned because the calculations of the temperature changes due to global warming calculate a positive feedback for water vapor. As you warm up the planet, you evaporate more water and the air can hold more water before it rains out. Another way of saying it, if the air now holds more water because it is warmed, then for the same storm circulation you get proportionally more rain. Also, if the atmosphere is wetter with more water molecules in the air, the added greenhouse blanketing effect more than doubles the original warming effect directly due to the added greenhouse gases. Water vapor is thus a potent greenhouse player in its role as a feedback gas.

ER: Your computer models of climate agree pretty well with historical records when you run them forward from the middle of the 19th century. Why is that important?

JM: If we are projecting what the climate will be for a given greenhouse gas scenario fifty or one hundred years from now, are we perfect because nobody can judge whether we are right or wrong? Of course not. The warming over the past century provides an important check of the credibility of the models. Is this observed warming consistent with theory? It turns out that the models do rather well when the observed greenhouse gas and sulfate particle increases are added to the calculation. However, the remaining uncertainties due to the unknown contributions of natural variability, and of the magnitude of the sulfate cooling effect, will leave room for the rather generous error bars we use in projections of future climate warming.

ER: Could climate warming be due to the sun putting out more heat?

JM: In part it could. The solar variability argument is rather interesting. The solar physicists have determined that over the past century the total solar heating of the Earth could have increased by as much as 0.3 watts per meter squared. But the straightforward infrared effect, that we can measure accurately as being real, is two watts per meter squared. The solar advocates are thus making a fascinating statement. They implicitly argue that the climate system is extremely insensitive to large changes in infrared forcing, i.e., greenhouse effects; at the same time the climate is assumed to be extraordinarily sensitive to much smaller changes in solar forcing. This argument requires what I call a double miracle because we have no evidence that the system is either highly sensitive to small changes in solar radiative energy, or that it is insensitive to much larger changes in heat trapping. There is nothing in the refereed literature about either of these mechanisms being present in our climate system, let alone both of them operating simultaneously.

I am still estimating a greater than 90 percent probability that the observed warming over the past century is largely due to human influences, mainly because of the conspicuous lack of credible alternative hypothesis, including this solar one.

... the sea level rise we have seen over the last century is explained mainly by the thermal expansion of sea water.

ER: The models predict global increase in average temperature that is linear with the logarithm of carbon dioxide concentration. That sounds like good news.

JM: It is good news. It says the climate system can be resistant to large carbon dioxide changes. It takes twice as much carbon dioxide added between a doubling and quadrupling of carbon dioxide to produce the same added warming as between pre-industrial and doubled carbon dioxide. The climate change is thus somewhat buffered as the carbon dioxide levels become large.

ER: By the year 2100 the global mean surface temperature would be 1.5 to 5 degrees Celsius higher?

JM: This rather broad range includes a still-generous scientific uncertainty, as well as an uncertain carbon dioxide future that will likely range somewhere between doubled and tripled carbon dioxide levels by the year 2100. The current social trajectory, without major mitigation of carbon dioxide emissions, is for the atmosphere to reach tripled carbon dioxide levels by the year 2100. However, with focus, it is feasible that we could hold to doubled carbon dioxide levels by 2100.

ER: People think that melting glaciers are causing sea level rise, but that isn't why it is happening.

JM: Melting glaciers is a potential mechanism that is lurking, but the sea level rise we have seen over the last century is explained mainly by the thermal expansion of sea water. As water gets warmer, it gets less dense and therefore occupies more volume. Our calculations show that for doubled carbon dioxide over 500 years, we get about a meter of sea level rise due just to this thermal expansion of sea water effect. Measurements do show that many lower latitude mountain glaciers have melted noticeably over the past century. If Greenland's ice were to begin to melt, the sea level rise could proceed much faster than that due to the thermal expansion effect. Our confidence in projecting Greenland ice melting rates remains quite low.

ER: We are virtually certain that we will see an increase in average global

Table of Contents: *Environmental Review* Volume Four

January - December (1997)

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precipitation of roughly 2 percent for each degree of warming?

JM: Yes. This is a direct consequence of the strong expectation that the atmospheric water vapor content will increase in accordance with the known laws of thermodynamics. The same weather system now would have more moisture available to remove in a storm system. Notice that this is for the global average precipitation. How this would play out in a particular region is much more uncertain.

ER: What is the connection between big tropical storms and climate change?

JM: The tropical storms question is tricky. Such storms don't happen very often and there are many places where they don't occur at all. Tropical storm formation requires rather rare circulation events. We have no good evidence on how those circumstances will change in a warming climate. We do know empirically and theoretically that hurricanes are energized by warm water. It is thus reasonable to think that if the oceans warm up, then hurricanes will become more intense. But most hurricanes go through a period of struggle that determines how intense they are going to be. Most of them die out before they reach their full potential: they run into cold water, they run into mountains, or they encounter unfavorable weather situations. Those tropical systems that do hang around long enough tend to crank up to near their full potential intensity. Our calculations suggest that in a greenhouse warmed Earth, the hurricanes that last long enough will likely become more intense. We still are unsure whether more or less of them will form in this warm climate.

NEXT MONTH

ELLIOT NORSE ON MARINE CONSERVATION BIOLOGY

PAUL BROCKERHOFF ON THE POVERTY OF CITIES IN THE DEVELOPING WORLD

Literature Cited:

[1] **J.D. Mahlman. Uncertainties in Projections of Human-Caused Climate Warming 1997 Science 278: 1416-1417**

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Seattle Washington 98115-6653