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Statistical Issues in Environmental Exposure Assessment

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Exposure assessment is the study of the frequency, duration, and magnitude of pollutant concentrations experienced by an individual or group of individuals as they go through their daily activities (Sexton and Ryan 1988). Exposures can come through various pathways but are considered to be limited to three routes: inhalation, ingestion, and dermal contact (Lioy 1990). Exposure is often the "missing link" in the chain commencing with a source of the pollutant, the movement of a pollutant through the environment, exposure, uptake and dose, and ultimately effect. In recent years, the importance of this missing link in the chain has become evident (Ott 1985).

Measurement error in exposure assessments is receiving a good deal of research interest. Instrumental and statistical methods for multimedia, multipollutant exposures studies may not exist or may be poorly developed. Hence, many pollutant exposures must be estimated using surrogates for actual exposures. Using such surrogates results in various types of measurement error that are different for different pollutants and or if the measurements are taken at different times. Such

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Inside

Water & Statistics

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Without water, life is impossible and with contaminated water, aquatic organisms and human health are threatened. No wonder the two questions most frequently asked of water agencies are: Do we have enough water? Is the water safe for drinking and swimming? Statisticians have a fundamental role to play in providing sound answers to such questions and in helping water authorities make appropriate and cost-effective decisions to protect the integrity of water resources and human and ecosystem health. The role of statisticians is defined by what they normally do: develop methods for collecting useful data and for extracting relevant information from data collections. Clearly answers to the two questions have to be based on water quantity and water quality data and if statisticians fail to be involved, others will fill the gap and take their place at a cost to our profession and to the taxpayers.

Data collected on water resources can broadly be classified into two types: routine and research data. Monitoring water levels in rivers and lakes or the bacterial densities in drinking and swimming waters provide examples of routine data collection. The aims are to estimate status, detect trends or to verify compliance with standards and regulations. Here, what is appropriate to measure is normally well accepted by most subject matter scientists and legislators. For example, E. coli is used as an indicator of fecal contamination and/or of the presence of pathogens which can cause water-borne disease. Rapid screening methods for the detection of trace metals and organics in drinking water supplies are of interest due to the persistent nature of many current contaminants of concern.

The upstream-downstream monitoring of the Niagara River

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Notes from the Field

Fish Contamination with PCBs in Lake Hartwell, SC

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1. Abstract

Fish contamination with polychlorinated biphenyls (PCBs) in Lake Hartwell, SC has been documented since 1975 in a series of studies. Even if the source is no longer discharging PCBs, their effects are ever present. The purpose of this paper is to predict PCB concentration using recent data, and model it as a function of other variables. Three species were taken to represent fish consumption in Lake Hartwell. Fish tissue samples were chemically analyzed to determine PCB concentration. Data were analyzed using SAS. From the analysis we concluded that current recommendations should be maintained and recommended continued monitoring of Lake Hartwell.

2. Introduction

The contamination was caused by the discharge of PCBs via Sangamo Electric Company's wastewater treatment plant effluent into Town Creek. The current advisory, issued by SC Department of Health and Environmental Control in 1998, recommends eating no fish from Twelve Mile Creek and the Seneca River arm of Lake Hartwell. For the remaining waters the restrictions refer to eating no hybrid and striped bass, and limiting the consumption of largemouth bass and channel catfish to one meal per month. The purpose of this study was to predict PCB concentration using recent data, and model it as a function of other variables.

3. Methods

Largemouth bass, hybrid bass, and channel catfish were selected for study because of their association with sport and/or commercial fisheries and because of their migratory and habitat selection characteristics (Gaymon, 1982). PCB analyses were conducted by the EPA between 1990-1994, and by Northeast Analysis between 1994-1997. Trend analysis is based on the total PCB concentrations found in fish tissue. Data were analyzed using SAS (SAS Institute Inc., 1989), constructing general linear models.

4. Results and Discussion

PCB concentration (parts per million, ppm) was initially modeled as a function of species, station, sex, length, weight, percentage of lipids, and the ratio of weight to length. Sex remained a non-significant predictor, and a final regression model contained only numeric variables: year, length, weight, percent lipid and weight divided by length. The highest p-value is 0.0274 (Table 1). All the variables are significantly correlated one to each other, except for year and weight ($p=0.2128$) (Table 2). Average PCB concentrations, computed over the study period for all species in the three areas surrounding the stations, revealed no obvious trend for any of the species (Table 3). However, it can be noticed that the mean PCB concentration is higher in general for the hybrid and the largemouth bass, which are predator species positioned at the end of the food chains.

5. Conclusions

The best regression model uses: year, length of fish, weight of fish, the percentage of lipids contained by fish tissue, and the ratio between weight and length. Sex is not a significant predictor. Data for other variables should be still collected to be used for other models. PCBs are significantly correlated with weight, length, percentage of lipids, and time. None of the three species is safe for consumption.

6. Recommendations

Current recommendations must be kept in effect. The monitoring should be continued to collect yearly data and extended to include data for the crappie (Pomoxis annularis) and the striped bass (Morone saxatilis).

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Newsletter

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Table I. SAS output for the final regression model

Model: MODEL3
Dependent Variable: PCBs
Analysis of Variance

Source	DF	Sum of squares	Mean square	F Value	Prob>F
Model	5	600.52971	120.10594	7.382	0.0001
Error	668	10869.06257	16.27105		
Corrected total	673	11469.59228			

Root MSE	4.03374	R-square	0.0524
Dep Mean	3.06984	Adj R-sq	0.0453
C.V.	131.39914		

Parameter Estimates

Variable	DF	Parameter estimate	Standard error	T for H0:	Prob > |T| parameter=0
INTERCEP	1	63.193295	12.58477892	5.021	0.0001
YEAR	1	-0.551747	0.13300449	-4.148	0.0001
LENGTH	1	-0.022236	0.01006014	-2.210	0.0274
WEIGHT	1	0.008840	0.00363739	2.430	0.0153
PERC_LIP	1	0.175516	0.06304173	2.784	0.0055
W_OVER_L	1	-4.050253	1.83111573	-2.212	0.0273

Table 2: Correlations

	PCBs (*)	Year (*)	Length (*)	Weight (*)
Year (*)	R=-.08, p=.007	—	—	—
Length (*)	R=.09, p=.002	R=-.08, p=.008	—	—
Weight (*)	R=.13, p=.001	R=-.04, p=.213	R=.87, p=.001	—
Lipids % (**)	R=.11, p=.003	R=.20, p=.001	R=.44, p=.001	R=.59, p=.001
* n=1177	** n=674			

Table 3: PCB concentration during mentioned period for all species in the three zones

Fish species >>		**Channel catfish (Ictalurus punctatus)**	**Hybrid bass ("Morone saxatilis X M. chrysops")**	**Largemouth bass (Micropterus salmoides)**
Zone	**Year**			
1	1990	2.09	—	9.28
SV-107 –	1991	3.24	5.64	5.99
Closest to	1992	3.28	2.42	3.69
Schlumberger	1993	3.98	2.96	3.36
SV-106 –	1994	4.88	4.24	3.95
Next point	1995	1.69	3.53	2.78
SV-532 –	1996	1.71	4.66	4.95
Highway 24	1997	1.98	3.30	4.75
2	1990	0.56	1.08	0.37
	1991	0.56	2.73	0.93
SV-535 –	1992	0.75	1.35	0.39
Below 85	1993	0.45	3.26	0.59
	1994	0.70	4.54	0.84
SV-642 –	1995	0.39	4.88	0.75
Dam	1996	1.00	3.30	1.09
	1997	0.57	1.35	0.58
3	1990	—	1.29	0.34
	1991	0.29	2.18	0.31
SV-641 –	1992	0.53	1.89	0.16
Tugaloo river	1993	0.48	3.18	0.20
	1994	0.68	5.55	0.48
	1995	0.22	2.99	0.12
	1996	0.12	2.55	0.14
	1997	0.25	2.43	0.20

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by Environment Canada is an example of routine monitoring with multiple purposes. This program has been adopted by the Canadian and US governments to: 1) estimate the yearly input and output loadings of more than 100 toxic chemical contaminants to and from the River; 2) detect and estimate the trends in the loads and concentrations; and 3) compare these trends to the targets specified in the Declaration of Intent, signed in 1987 by the two governments to reduce the toxic contaminant loadings to the River.

In such monitoring programs, statisticians can contribute to: a) the design of the program by helping in the determination of the target population and the selection of sampling schemes including locations, type of sampling (integrated, discrete), frequency of sampling etc., b) the analysis of data by accounting for various sources of variability; dealing with data problems (missing data, censoring and unequally spaced data, etc.); and c) the communication of the results of the analysis to the public and decision makers. With the need to develop Total Maximum Daily Loads (TMDLs) for water bodies in the U.S. that do not meet water quality standards, estimation of loads and efficient sample designs for point and nonpoint sources will also be needed.

Research data from limited field studies and/or controlled laboratory experiments play important roles in the development of standardized procedures for assessing and understanding the consequences of exposure to impaired waters. Hardly a week goes by without headlines in the news about chemicals and/or the appearance of exotic (non-native) species in water. Methods need to be developed to determine sources, estimate quantities, measure effects, and compare the effectiveness of competing remedial action plans. It goes without saying that these issues are fertile ground not only for the application of existing statistical methods, but more importantly as a source of statistical research problems for extending the scope of the statistical tools. For example, it is common to base chemical regulations on no-effect and aqueous environmental concentrations obtained from toxicity testing experiments. These concentrations are then combined with known facts about the chemicals and used as input to mathematical and statistical models to estimate risk to the target and non target organisms from exposure to the chemicals.

Statisticians can and should make significant contributions to these areas. Further, most of the water quality indicators that have been proposed involve the establishment of reference sites and the application of biocriteria. Selection of appropriate reference sites for comparison to impacted sites involves issues in spatial statistics, multivariate statistics (ordination methods), and logistic regression. Suitable biocriteria must be developed and tested using careful experimental designs.

With the projected increase in world population and the approximately constant total annual global renewable fresh water available, the per capita water available will decline and shortages will become even more critical in some regions of the world. According to a recent announcement by the United Nations, more than 80 countries have inadequate water supplies and almost 40 percent of the world's population must struggle to meet water needs. The misery of conflicts, wars, and waterborne diseases can be the direct result of water-shortage as it is often difficult to separate water quantity problems from water quality problems. Statistics can make significant contributions to help the world in its quest to chart a water survival strategy. Application of time series methodology for forecasting water shortages or disasters such as floods and droughts are areas where statisticians can make a difference. ENVR

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Program Spotlight

Enviornmental and Spatial Statistical Research at The Ohio State University

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The Program in Spatial Statistics and Environmental Sciences (SSES) was established in 1999 within the Department of Statistics at The Ohio State University. Two SSES projects that may be of interest to ENVR members are described below. For further information, see the Program's web site: http://www.stat.ohio-state.edu/sses

Long-Lead Prediction of Climate Phenomena Using Bayesian Hierarchical Modeling

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Climate processes exhibit substantial spatio-temporal variability that is often nonstationary, nonlinear, and dependent. Although it can be quite difficult to model such variability with traditional spatio-temporal approaches, we demonstrate that it is possible to use hierarchical, stochastic, Bayesian, spatio-temporal, mixture models. Key features of these models include substantial dimension reduction and the reliance on hidden-state dynamical processes that govern the nature of the mixture. Through the combining of substantial physical understanding and statistical modeling and learning, our procedure acquires considerable predictive skill. These models can be used to forecast the onset and/or life-cycle of climate phenomena such as El Niño. The approach accounts explicitly for uncertainty in the formulation of the model, which leads to realistic error bounds on forecasts. More generally, this methodology can be extended to model so-called teleconnections, or appreciable multivariate space-time correlations over very large geographical regions.

The application of this approach to long-lead prediction of climate phenomena is illustrated on the El Niño Southern Oscillation (ENSO) phenomenon. The interannual variation of tropical Pacific sea surface temperature (SST) is an important factor in climate variability throughout the globe. The dominant feature of this field is the episodic warming and cooling of ocean waters with periods of approximately 3-5 years, namely, the ENSO phenomenon. In recent years, long-lead predictions of tropical Pacific SSTs have improved greatly in light of better observational networks, analysis schemes, and understanding of the processes that govern the interaction of the atmosphere and ocean.

Although statistical methods for SST prediction have performed as well or better than deterministic, physically derived dynamical methods, there is often a perception in the climate community that much of the potential of statistical models has been exhausted. This is because many of the long-lead statistical prediction schemes for SSTs that have been used to date have focused on relatively simple linear models. The statistical sciences have undergone a dramatic change in recent years as computationally based nonlinear methodologies have been developed and applied in complex settings. In particular, the hierarchical Bayesian statistical paradigm has benefited from this revolution. The tropical Pacific SST prediction problem provides an exceptional context in which to demonstrate the long-lead predictive power of, and associated quantification of uncertainties possible with, hierarchical Bayesian dynamical modeling.

Fast Statistical Processing of Global Spatio-Temporal Data From Satellites

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The general statistical problem addressed in this research is that of fast, statistically optimal, spatio-temporal prediction of global processes at spatially regular locations, based on irregular data. Importantly, the predictions are needed at different spatial resolutions; thus, one of the challenges is to make the predictions and the prediction (co)variances consistent across resolutions. By combining several small regions into a larger region and several larger regions into an even larger region, and so forth, we build up a scheme for changing resolutions. Then, an acyclic directed graph can be constructed by drawing arrows from larger "parent" regions to smaller "child" regions, which provides a framework for a statistical model that is autoregressive in levels of resolution. From this model, we are able to develop a "mass-balanced," change-of-resolution Kalman filter that is statistically optimal, very fast, and consistent across changes of resolution. This approach is easily able to process large-to-massive amounts of daily data from remote-sensing instruments on satellites, such as the Total Ozone Mapping Spectrometer (TOMS), without overflow into the next day's processing time.

A key component of NASA's Earth Science Enterprise is the launching of 22 instruments and spacecraft between now and 2003. They will remotely sense

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problems lend themselves to statistical analyses. One particular form of measurement error ensues when a single cross-sectional study of exposure is used as a surrogate for a much longer exposure duration. For example, a one-day measurement of exposure used to make inferences about exposure experienced over a one-year period.

Longitudinal Measures of Population Exposure

Understanding the way exposures to pollutants change with day of week, season, or longer is of great interest to the exposure assessment community. Much of the design focus of current exposure assessment investigations is on optimizing the statistical power of the investigation constrained by available instrumentation (Buck et al. 1995, Lebowitz et al. 1995, Pellizzari et al. 1995). Studies designed to gather information on temporal variability are typically of a repeated-measures design. Our work in the National Human Exposure Assessment Survey (NHEXAS)-Maryland investigations has taken this approach by measuring approximately 80 individuals as many as six times approximately evenly spaced throughout a one-year period (Buck et al. 1997, Echols et al. 1999, MacIntosh et al. 1999a, MacIntosh et al. 1999b, Scanlon et al. 1999, MacIntosh et al. 2000, Ryan et al. 2000). I now discuss a few of the approaches our group has chosen to implement as an aid understanding temporal effects on exposure.

The central aim of our research has been to develop statistics that afford description of temporal variability in various medium-pollutant concentration combinations in our population. Two different and somewhat competitive goals are before us. The first of these is to identify population temporal variability. We ask the question: Are there statistically significant differences in the population mean throughout the year? Our main analytical approach for this question has been to use a mixed (fixed and random) effects analysis of variance model in which our fixed effects variable is sampling cycle while our random effects variable is the statistically selected individual. Because it is likely that such data for a given individual displays some autocorrelation, it is necessary to account for this phenomenon.

Such accounting is effected through the inclusion of a presumed or calculated correlation structure among the repeated-measures observations. It is expected that cycles close to one another may be more highly correlated than cycles somewhat more removed temporally. On the other hand, cycles nearly one year apart are likely to show increased correlations, as activities tend to have an annual cycle. Further, while this pattern may hold in general, the magnitude of "adjacent" correlations may be very different for various pollutants. For example, persistent, chlorinated pesticide exposure may reflect outdoor contact with contaminated yard soil and be relatively consistent during the warmer months while exposure to a topically applied herbicide may be episodic, as the compound may not persist in the environment to any degree.

To account for this type of behavior, we have made use of the SAS (SAS Institute, Cary NC) PROC MIXED software with a repeated-measures switch identifying the so-called "unstructured" covariance structure. Using this procedure, the software defines the best possible covariance structure among the various monitoring periods. This procedure is computationally difficult and requires close attention to initial starting points for the maximum likelihood estimate. Typically, we begin our studies by forcing another covariance structure, say AR(1) or compound symmetric, to obtain an initial solution and then use this solution as a starting point for the unstructured procedure.

Intraindividual Temporal Variability

While the exposure of the population is of interest, individual health outcomes may be of importance as well. While temporal variability of the population is important, differences experienced by individuals are what typically results in adverse health impacts. Our research group has made efforts to assess such variability in a concise manner using several approaches.

In the first approach, the population-mean, intra-individual or within-person coefficient of variation is computed for an exposure measure. The mean coefficient of variation for the population expresses the variability of exposure among sampling events for a typical individual compared to their annual average exposure. In the second approach, the mean correlation coefficient calculated from the correlation matrix for each exposure variable as determined by the PROC MIXED result discussed above is used to assess the variability across cycles. This is a crude measure of how much "alike" cycles are at the individual level.

Finally, the intraclass correlation coefficient of reliability was computed. This value is the ratio of between-person variance of exposure to the total variance of exposure observed in a repeated measure study as estimated by a one-way ANOVA with an exposure metric (e.g., arsenic concentration in drinking water) as the dependent variable and respondent identification number as the categorical independent variable. In this context, values for this ratio near 1 suggest that a single cross-sectional exposure measurement predict overall variability well, while values near zero suggest that intra-individual variability is large relative to population variability. As a comparison value, we generally calculate the number of repeated measures needed to ensure that intra-individual variability is no more than 20% of the total variance.

Summary Comments

Temporal studies of exposure represent a new area of exposure assessment research with many challenges. We have presented some fledgling steps in this area with the intent of stimulating interest in the environmental statistics community. We invite comments from both environmental statisticians and from the exposure assessment community as a whole.

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the earth and its atmosphere to provide a better understanding of environmental changes, producing data sets that give daily global coverage. For any given day, the data are many and spatially irregular. Recall that our goal is to predict values that are spatially regular at different resolutions; such values are essential to people making informed decisions about the environment. Specifically, they are often used as input to general circulation models (GCMs) and the like. Because data acquisition is relentless, our algorithms are designed to process the data very rapidly. Data from the TOMS instrument on the Nimbus-7 satellite, and in the future from NASA's Earth Science Enterprise instruments, provide a number of important applications. ENVR

Conference Announcement

International Meetings on Statistical Climatology

The "International Meetings on Statistical Climatology" have been organized by a group of independent climatologists and statisticians since 1979. The eighth of these meetings will be held on March 12-16, 2001 in Lueneburg, Germany; organized by the GKSS Research Centre in Geesthacht near Hamburg.

The purpose of the meetings is to bring together climatologists and statisticians, to exchange concepts and problems. Climatologists present statistical problems in climatology (including meteorology and related fields) and consider the methods that are currently used to deal with these problems. Also, techniques tailored by climatologists for the specific needs of climatology are presented. Statisticians, on the other hand, present new, state-of-the art techniques developed within mathematical statistics and other scientific fields. By discussing the needs of climatology and the possibilities offered by modern statistics, synergetic effects are obtained, advancing the methodical basis of climatology and helping statistics to focus on relevant problems.

The eighth meeting is organized into five sessions, each dealing with a challenge that climatology is presently facing: Stochastic climate models, Extreme value analysis, Statistics, Models and data assimilation, Simulation models, Decision making. Contributions unrelated to these chosen topics are welcome as well.

Further information is available at http://w3g.gkss.de/8imsc.html

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