Geophysical Statistics Program at the National Center for Atmospheric Research
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1 Overview

The Geophysical Statistics Project (GSP) at the National Center for Atmospheric Research (NCAR) has been a successful model for making contributions to atmospheric and oceanographic science through the development and application of new statistical methodology. This has been achieved through supporting a critical mass of statistics visitors at NCAR, through the training of young researchers and close collaboration with resident NCAR geophysical scientists.

The long term impact on statistics has been substantial, not only contributing a large body of published research, but also through an extended network of university researchers who have participated in GSP as visitors and postdoctoral fellows. GSP's impact on geophysical researchers has been through *statistics by example*. Successful collaboration among NCAR scientists has provided case studies where new statistical methods have tackled problems and questions that otherwise would not be attempted.

2 Project Results

This project, *Collaboration between statistical and atmospheric sciences on modeling the climate system*, assembled a team of statistical scientists at the National Center for Atmospheric Research [1] (NCAR) in order to promote interaction among the geophysical and statistical research communities.

The overarching goals of the project were:

- initiating interdisciplinary research between statistics and the geophysical sciences
- postdoctoral training of Ph.D. statisticians
- outreach to the statistics community through colloquia and a short-term visitor program.

In the following sections, we address how these individual goals have been met.

2.1 Scientific accomplishments

Because of the emphasis on collaborative research, GSP scientific results have appeared in leading statistical journals, as well as in geophysical and environmental statistics publications. A noteworthy feature of this research is that the majority of publications are co-authored by both geophysical and statistical scientists. A centerpiece of this project is the volume, *Studies in the Atmospheric Sciences* [7] that consists of contributed chapters by statisticians and NCAR scientists highlighting new statistical methods with substantive applications in the geosciences.

[1] Base-funded by the Division of Atmospheric Sciences, National Sciences Foundation and operated by the University Corporation for Atmospheric Research a consortium of more than 50 U.S. and Canadian Universities.

In order to report in a succinct manner this wide range of research, project publications have been organized into several broad categories.

This outline is complemented by more detailed highlights of some key scientific contributions.

Statistical methodology and theory

Modeling spatial and spatio-temporal processes [12], [8], [10], [15], [17], [32], [33], [34], [41], [44], [45], [58], [59], [61], [40]
Linear and nonlinear time series analysis [2], [4], [5], [14]
Applications of Bayesian methodology [3], [57], [60] [50] [47], [48]
Spatial sampling and design [6], [42]
Analysis of functional data [35], [36]

Geophysical science topics

Geophysical time series and spectral analysis [16], [23], [25], [19], [20], [21], [22], [26], [27], [28], [30], [37],[52], [53], [55], [56]
Geophysical data fields [1], [11], [18], [29], [54], [38], [39]
Climate change detection [24] , [9]

Research highlights

Some recent GSP research accomplishments help to emphasize the substantial collaboration among the postdoctoral fellows/visiting scientists and resident NCAR scientists. These highlights are meant to be illustrative, as they constitute a subset of the GSP research activities.

Blending of ocean wind fields Satellite-derived wind estimates have high spatial resolution, but are limited in global coverage; in contrast, operational analyses provide complete global wind fields, but are of low spatial resolution. The goal is to blend these data in a manner that incorporates the space-time dynamics inherent in the surface wind field. No complete, high-resolution wind observations exist over the world's oceans, and such datasets are critical to improving our understanding of tropical disturbances, as well as for driving ocean circulation models. To blend the wind information from various scales, Bayesian hierarchical models have been developed that preserve the spatial and temporal dependencies in wind fields. The hierarchical model has been successfully implemented in a Markov chain Monte Carlo framework via a Gibbs sampler. [61], [11]

Detection and attribution of climate change This work has focused on predicting climate change due to human-induced increases in greenhouse gases, aerosol concentrations, and impacts of other activities of man on the climate system. The statistical challenge lies in detecting a climate change signal in climate observations over time and attributing this potential signal to particular anthropogenic forcings. Using a Bayesian formulation, detection and attribution methodologies in the meteorological literature can be interpreted from a statistical viewpoint. This characterization of the global warming problem is new and has shed light on the advantages and short-comings of the techniques presently implemented by climate modelers [24]. [9]

Dynamical models and parameterizations for cloud cover Clouds play a fundamental role in controlling the amount of solar and infrared radiation available to the climate system. Most clouds are smaller in area than a typical grid resolution of climate models, so a parameterization of cloud effects is necessary. Cloud cover is viewed as a spatial and temporal process where cloud cover at the current time is a nonlinear function of cloud cover in nearby locations at previous times and measures of convective activity. An autoregressive, neural network representation provides a flexible form for handling the complicated dynamical relationships for this process. This approach has been successfully applied to the infrared cloud cover measurements from the Tropical Ocean and Global Atmosphere (TOGA) program and the Coupled Ocean-Atmosphere Response Experiment (COARE). [1]

Data assimilation and adaptive observations

Informally, data assimilation refers to combining information on the state of the atmosphere with observations to give an improved estimate of the state and lies at the heart of operational weather forecasting. This process is fundamentally grounded ed in Bayesian statistics and research has been pursued on extensions to non Gaussian observations (such as precipitation) [13], [47] and to ensemble techniques [48].

This research builds a framework to study the design of observation networks and data collection to maximize their benefit. For example, in many field experiments there is a need to *target* measurements of the atmosphere in order to maximize the amount of information that is available. The Fronts Atlantic Storm Track Experiment (FASTEX) has been used as an example and as a test bed for guidance in this research. In this study, the issue is to choose aircraft flight paths and the location of dropsondes in a way so as to improve the information on the genesis and evolution of storms. Statistical designs for targeted observations compare favorably to various heuristic approaches that have been proposed in the meteorological community. [6]

Temporal trends in the vertical profile of stratospheric ozone To quantify long-term trends in stratospheric ozone due to anthropogenic activities, it is important to understand the long-term variability in ozone due to other natural forcings, such as the quasi-biennial oscillation.This study involves an investigation of how the vertical stratospheric ozone profile at mid-latitudes depends on the season and other atmospheric phenomena. Research included the development of techniques for modeling and obtaining variability estimates of curves (e.g., vertical profiles) based on observations that are irregularly sampled in space and time. [35]

Spatial inference for massive datasets A grand challenge across the geosciences is to extend spatial statistics from the moderate size datasets considered in the statistics literature to the massive and substantive records assembled to study the atmosphere and ocean. One breakthrough is the modeling of the spatial structure directly using an expansion of the fields in terms of a sequence of basis functions. This is in contrast to starting with the covariance function of the field. This simple change of emphasis has resulted in a computational strategy that exploits iterative solution methods for the large, sparse linear systems. [43]

Aerosol effects on temperature This problem involves an attempt to correct for systematic biases in tropospheric temperature data. A linear model with autoregressive errors of order one was fitted to temperature data derived from Microwave Sounding Units (MSUs) on polar orbiting satellites. The change of satellites was modeled as a step function, and the model indicates that there is systematic change from the overall mean during the time periods of interest. [16]

Statistical models for numerical model output The size and complexity of output produced by state of the art numerical models requires statistical descriptions in order to understand the overall behavior of a physical model and to represent aggregate features of the model in a succinct form. One project has been to summarize experiments from a cloud resolving model. Extreme value statistics are used to model maximum vertical velocity [38] and multiresolution methods have been designed to extract features representing the organization of convection [39]. This work has also motivated more theoretical work on multiresolution (wavelet) analysis for non Gaussian fields. [40] On a much larger spatial scale statistical methods have been used to summarize the dynamical properties from a long integration of the Community Climate model. [49]

Inference for Geophysical spatial processes Many geophysical are characterized by non Gaussian distributed and are observed at irregular locations. The development of local variograms has been applied to characterize the spatial correlation in ocean color data and precipitation fields. In the case of ocean color, a proxy for phytoplankton, the statistical analysis for the North Atlantic has suggested spatial dynamics that is consistent with other theories of ocean circulation. The modeling of monthly precipitation fields for North America has lead to the ability to generate statistical ensembles that can then be used as the input fields for ecological. The variability in output from the ecological models due to the ensemble of meteorological inputs is a rigorous way to propagate the uncertainty in the observational data to the model results.

2.2 Postdoctoral training

The highest priority of the project has been to recruit and train new recipients of Ph.D.'s in statistics and probability. A list of the GSP postdoctoral fellows appears below, including degree granting institution, tenure at NCAR, and present affiliation. Despite postdoctoral opportunities in statistics being a rather new phenomenon, we have been able to attract high quality individuals from nationally ranked programs in statistics. In fact, two GSP fellows (Levine and Fuentes) chose to delay their entry into tenure track, faculty positions to first visit GSP. Also noteworthy has been the successful placement of the majority of GSP fellows in tenure-track university positions or in other research environments (the second line in the list below indicates the fellow's subsequent position).

Postdoctoral fellows

Barbara Bailey Biomathematics, North Carolina State Univ., 1996; GSP, 3/96-7/98
Assistant Professor, Dept. of Statistics, Univ. of Illinois, 8/98.

Steve Cherry Statistics, Montana State Univ., 1994; GSP, 1994-1995
Assistant Professor, Dept. of Mathematics, Montana Tech, 1997-

Toshio Mike Chin Electrical Engineering, Massachusetts Inst.Tech., 1992; GSP*, 1/94-12/96
Staff Scientist, Jet Propulsion Laboratory, Cal. Inst. of Tech. 1998-

Montserrat Fuentes Statistics, Univ. of Chicago, 1998; GSP, 9/98-12/1998
Assistant Professor, Dept. of Statistics, North Carolina State Univ., 1/99 -

Richard Levine Statistics, Cornell Univ., 1996; GSP, 1/97-9/97
Assistant Professor, Division of Statistics, University of California at Davis, 9/97-

Zhan-Qian (John) Lu Statistics, Univ. of North Carolina, 1994; GSP, 7/95-7/97
Statistical Sciences, Seattle, WA.

Wendy Meiring, Statistics, Univ. of Washington, 1995, GSP, 1/96-8/98
Assistant Professor, Univ. of California at Santa Barbara, 9/98-

Philippe Naveau , Statistics, Colorado State Univ., 1998; GSP, 7/98-

J. Andrew Royle Statistics, North Carolina State Univ., 1996; GSP*, 3/96-8/98
Biological Statistician [2], U.S. Fish and Wildlife Service, 8/98

Gary Sneddon Statistics, Dalhousie Univ., 1997, GSP, 10/97-

Claudia Tebaldi Statistics, Duke Univ., 1997; GSP, 11/97-

Christopher Wikle Statistics and Atmospheric Science, Iowa State Univ., 1996; GSP* 7/96-8/98
Assistant Professor, Dept. of Statistics, Univ. of Missouri, 8/98-

(In the listing given above GSP* indicates cosponsorship by another group within NCAR.)

2.3 Colloquia

The colloquia sponsored by this project provide graduate students, primarily in statistics and related fields, with an overview of outstanding problems in geophysical sciences, as well as of more specialized topics in statistics of relevance to applications in the geophysical sciences. One of the goals is to influence the research of graduate students so that they will be better qualified for postdoctoral appointments in GSP. They also provide a rare opportunity for extensive interaction between geophysical and statistical scientists. The first colloquium, *Applications of Statistics to Modeling the Earth's Climate System,* was held 6-19 July 1994. It was attended by 27 graduate students and 5

[2]Research applying spatial and space/time methods to habitat modeling, including the dependence of specific habitats on climatic variation.

recent Ph.D.'s in statistics or geophysical sciences. The lecturers included 19 visitors, mostly senior statisticians from the university community, as well as 9 prominent NCAR scientists. The lecture notes appeared in a NCAR Technical Note [31]. Several of the subsequent GSP postdoctoral fellows attended this colloquium (i.e., Chin, Meiring, Sneddon, and Wikle).

A second colloquium on *Statistics for Understanding the Atmosphere and Ocean* was 18-24 July 1998. More than 25 graduate students, primarily in statistics, were supported. The workshop will be lectures by scientists from most of the NCAR divisions (12), as well as by distinguished visiting researchers, from both the statistical and geophysical sciences communities (8).

A NCAR Technical Note, originally prepared in conjunction with the first colloquium, introduces students and scientists from other disciplines to atmospheric and oceanographic data. The demand for this report has been so high that now it is available as an updated, interactive document. [46]

2.4 Visiting scientists in statistics at NCAR

To foster connections with the university statistics community, GSP also maintains a shorter-term visitor program. The senior visitors are chosen with the postdoctoral fellows in mind, as they often serve as additional mentors. A number of statistics graduate students have also visited GSP in conjunction with their thesis research or as interns.

Senior faculty visitors James Berger (Duke Univ.), Mark Berliner (Ohio State Univ.), [3] Merlise Clyde (Duke Univ.), Dennis Cox (Rice Univ.) Noel Cressie (Iowa State Univ.), Arthur Dempster (Harvard Univ.), William Dunsmuir (Univ. New South Wales), Trevor Hastie (Stanford Univ.), Karen Kafadar (Univ. Colorado, Denver), Douglas Nychka (North Carolina State Univ.), David Ruppert (Cornell Univ.), Richard Smith (Univ. of North Carolina), Michael Stein (Univ. of Chicago), Richard Tweedie (Colorado State Univ.), and Mike West (Duke Univ.).

Junior faculty visitors Robert Lund (Univ. of Georgia) and Jean Opsomer (Iowa State Univ.).

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