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A Conversation with Noel Cressie

Christopher K. Wikle and Jay M. Ver Hoef

Abstract. Noel Cressie, FAA is Director of the Centre for Environmental Informatics in the National Institute for Applied Statistics Research Australia (NIASRA) and Distinguished Professor in the School of Mathematics and Applied Statistics at the University of Wollongong, Australia. He is also Adjunct Professor at the University of Missouri (USA), Affiliate of Org 398, Science Data Understanding, at NASA's Jet Propulsion Laboratory (USA), and a member of the Science Team for NASA's Orbiting Carbon Observatory-2 (OCO-2) satellite. Cressie was awarded a B.Sc. with First Class Honours in Mathematics in 1972 from the University of Western Australia, and an M.A. and Ph.D. in Statistics in 1973 and 1975, respectively, from Princeton University (USA). Two brief postdoctoral periods followed, at the Centre de Morphologie Mathématique, ENSMP, in Fontainebleau (France) from April 1975–September 1975, and at Imperial College, London (UK) from September 1975–January 1976. His past appointments have been at The Flinders University of South Australia from 1976–1983, at Iowa State University (USA) from 1983–1998, and at The Ohio State University (USA) from 1998–2012. He has authored or coauthored four books and more than 280 papers in peer-reviewed outlets, covering areas that include spatial and spatio-temporal statistics, environmental statistics, empirical-Bayesian and Bayesian methods including sequential design, goodness-of-fit, and remote sensing of the environment. Many of his papers also address important questions in the sciences. Cressie is a Fellow of the Australian Academy of Science, the American Statistical Association, the Institute of Mathematical Statistics, and the Spatial Econometrics Association, and he is an Elected Member of the International Statistical Institute. Noel Cressie's refereed, unrefereed, and other publications are available at: https://niasra.uow.edu.au/cei/people/UOW232444.html.

Key words and phrases: Bayesian statistics, geostatistics, spatial statistics, spatio-temporal models.

(The conversation between Noel Cressie, Chris Wikle, and Jay Ver Hoef took place on July 30, 2018 at the Joint Statistical Meetings in Vancouver, BC (Canada) over a three-hour period. The conversation touches on Noel's early life and training as it led to the development of his 1991 classic book and its revised edition, *Statistics for Spatial Data, rev. ed.* (Cressie, 1993), as well as his work in environmental statistics, Bayesian statistics and beyond. The interview has been edited for brevity and clarity.)

Christopher K. Wikle is Curators' Distinguished Professor and Chair, Department of Statistics, University of Missouri, Columbia, Missouri 65211, USA (e-mail: wiklec@missouri.edu) Jay M. Ver Hoef is Senior Scientist and Statistician, Marine Mammal Laboratory, Alaska Fisheries Science Center, NOAA Fisheries, 7600 Sand Point Way NE, Seattle, Washington 98115, USA (e-mail: jay.verhoef@noaa.gov).

FAA

Chris: Noel, to start things off, congratulations on your recent election to the Australian Academy of Science. What did this mean to you?

Noel: It was a singularly fabulous moment—it's an indication that the research I've been doing for over 40 years has been recognized in the science commu-

FIG. 1. *May* 2018: *Press photo*, *Australian Academy of Science lecture*.

FIG. 2. 1966: *Press photo*, *Lions Club exchange scholarship to South Australia*.

nity. I think my work has been appreciated within the statistics community, but it's special to become a Fellow of the Australian Academy (FAA), because they only elect 20 per year from all disciplines.

EARLY YEARS

Jay: I know that your parents had a strong influence in your life. How did they contribute, if at all, to developing your interest in statistics?

Noel: I would say their contribution was to give me a love of learning. Dad left school at 14 and mum at 15, during the Great Depression, and financially there was no way that they could have stayed at school. They were smart people, but not well educated, and they had three children to bring up. We all did well at school, and mum and dad helped us apply for university scholarships. So I managed to go through the education system in Western Australia (WA) for free, and then I left home at age 20. Now, regarding statistics and what influence they had on that—none. To be honest, I don't even recall mum or dad helping me with homework from school. I just always did it. But, I was a bit slack. We got a TV when I was about 11 or 12, and I kind of liked TV. My dad would remind me at about 9:00 at night that I hadn't done my homework, and I would say something like, "Alright, I've got it covered." And then I'd go and do my homework after being kicked out of the living room. I don't remember school being hard, and I remember really liking it. A number of years later, post Ph.D., I have a fond memory of my father holding a signed and bound copy of my thesis in his hand and, for about the fifth time, asking, "Noel, why don't you explain to me again what's in this? I just really want to know."

Chris: What did you like to do in your spare time?

Noel: I played a lot of sport, and I started out playing Australian Rules Football—but very quickly it was clear I had no talent at that. I did swimming—you can't live near a river without being able to swim like a fish. The Indian Ocean wasn't all that far away, so I joined a surf life saving club. I'd go there Saturday mornings and compete in sand races and swimming races out to a buoy in the ocean and back again. Then we'd go on lifesaving duty, watching out for sharks and trying to keep swimmers safe. When I was 12 or 13 years old, I started to play field hockey—we called it hockey, of course, because we had no notion of frozen ponds in WA. My father had played hockey in the army, and he encouraged my brother and me to join a team that was just starting up at the Fremantle YMCA. My parents were very big into the YMCA, and I was a leader in their youth program as well. I really liked hockey! I worked on it and became quite good at it, I think. So, I played for Fremantle YMCA and then for the Australian National University (ANU) team in Canberra just before I went to do a Ph.D. in the United States, where men's hockey is only ice hockey. Except somehow I found a men's team there and played three seasons for the North Jersey Field Hockey Club! You know, hockey took me all around the world, as did my statistics research. For example, I played for my NJ club at hockey tournaments in Toronto and Washington, DC, in a U.S. representative side in Bermuda, then in the London League during a post-doc period at Imperial College, and five seasons of A grade in Adelaide, South Australia. When I traveled to weekend

hockey tournaments, I didn't want to be a statistician on Monday. And when I was a statistician, I felt, ah, hockey, I love it, but my knees are not going to carry me through.

PRINCETON

Chris: How did you end up at Princeton for your Ph.D.?

Noel: It's interesting. I did my bachelors degree at the University of Western Australia, the only university in WA at that time. I took a lot of mathematics courses very early in my degree, and I found that I was quite good at it—I won several university prizes in mathematics. In my third year, I was learning a bit about statistics, which was taught pretty theoretically. There was a statistics associate professor in the Department of Mathematics named Don McNeil, whom I never had in class, and in 1970 he had just got a job offer from Geof Watson at Princeton University. The Statistics Department at Princeton was founded a few years earlier. John Tukey was the inaugural chair and Geof Watson was recruited as chair in 1970. So, at the end of my third year, at some party or other, Don said, "So, what are you doing next year, Noel?" I said, "Well, I'm going to do my honours year." He said, "You know, I'm going to Princeton. I think you should write to me, and I'll get you there to do a Ph.D. You don't need any money. We'll get you support."

So, in 1971 when it came time to start applying for Ph.D. scholarships, I applied formally for one at the ANU in Canberra and two or three in the U.K., and I just wrote this letter to Don McNeil at Princeton. I didn't know Princeton was Ivy League. I didn't know where it was in the U.S. and had to look it up on a map. Don replied very enthusiastically, and he mentioned John Tukey and Geof Watson in his letter—I didn't know who they were. In the meantime, I was offered Ph.D. scholarships to go to Cambridge and to Imperial College in the U.K.

I thought, okay, I've got offers from two really good places in the U.K. I only had a letter from a guy at Princeton who I didn't know very well and had talked to at a party a year before. The U.S. looked like the new world to me, and the U.K. looked like the old world, and the sort of problems that people were working on in the U.K. at the time looked more like applied-probability problems and less like statistics problems. I was really passionate about doing statistics with some sort of science application back then when it actually wasn't all that fashionable. So I chose Princeton.

Jay: Can you talk a little bit more about your time in Princeton and how it influenced your future career?

Noel: Princeton was a wonderful mix of traditional and new. In terms of the graduate program, it was really quite different from all of my experiences as a professor in the U.S. I think that if they saw that you knew your stuff, you could go through the Ph.D. program quickly. I came from Australia with very good mathematics and mathematical statistics training. So, within nine months, I had done all the Ph.D. qualifiers, and I was ready to write a thesis. I finished it in about a year and a half, so I was at Princeton for a little over two and a half years. I was 24 and very happy to have finished my Ph.D. so quickly. I was ready for research, and it was because the Statistics Department was small and fairly new that I was able to achieve that.

Chris: What sort of classes did you take?

Noel: The classes I took in those first nine months were just great. I love learning new things. Watson, Tukey, Peter Bloomfield, Gary Simon and Henry Braun taught core and special topics classes in the program, and I continued to take classes after I became a Ph.D. candidate. There was an early class that I took that was especially important to me, taught by Geof Watson. In 1972, he had just come back from a summer in Fontainebleau, France, and he was talking a lot about this guy called Georges Matheron. So, in the fall he taught a class about mathematical morphology, which was one of two areas that Matheron was developing in his center in Fontainebleau. The other area was geostatistics, but Geof didn't talk about that. He finished the course with statistics for spherical and circular data,which was fascinating because there was a huge controversy up to the 1960s about whether there was continental drift. Watson used his methodology to support what we now accept as fact, that there was. Geof was a consummate statistical scientist and an amazing writer, explaining clearly what he was doing and the intuition behind it. I think I learned from his example, and my goal is to always write in that fashion.

Jay: Did Geof Watson choose you and try to cultivate your interest in what he was doing, or do you think that you saw what he was doing and said, "That's kind of what I want to do?"

Noel: Almost immediately after arriving at Princeton I became Watson's research assistant, funded by his Office of Naval Research grant. After two or three months, he said, "You know, Matheron's got this book he's writing called *Random Sets and Integral Geometry*" (Matheron, 1975) A lot of people who work in the area know the published book, but at that time it was a

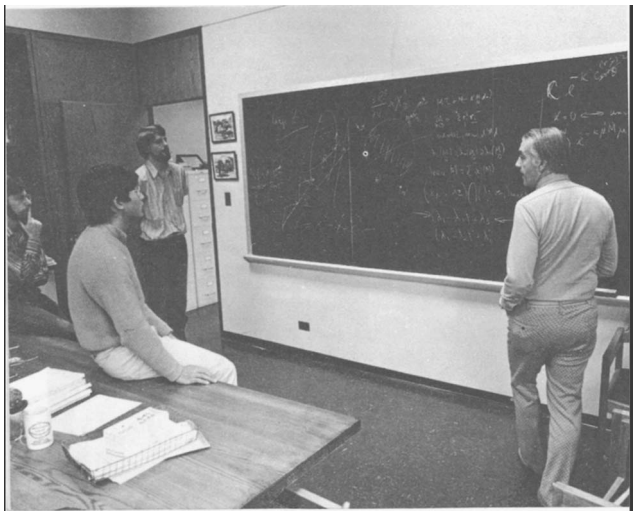

FIG. 3. 1974: *PAW Press photo, in Geof Watson's Office, Princeton University* (*Left to Right*: *Paul Velleman*, *Tony Quon*, *Noel Cressie and Geoffrey Watson*).

FIG. 4. *Circa* 1974: *Eyes on the ball, North Jersey Field Hockey Club match.*

draft in French, in a rough state and was sort of working its way into English. Geof had me co-translate it with Matheron. So, I was 21 years old, I had undergraduate-level math training from the University of Western Australia, I wasn't even halfway through the first year of my Ph.D., and I was working with Matheron on what became a famous book.

Jay: Did you have some French then already?

Noel: A little from high school. And then it became clear that Matheron was very happy that I was doing this—I made some technical corrections as well. The next year, in 1973, I went to his center in Fontainebleau for a summer program or conference and I met him, and he thanked me. He said, "We want to have you back as a visitor." The seeds were being sown to have me come to Fontainebleau as a post-doc, and so I started to take French courses at Princeton.

Chris: Did you have a lot of visitors come through Princeton?

Noel: Watson was pushing the visitor program. He had Paul Switzer there—I took a class from him about his work in image analysis and remote sensing. Julian Besag visited for a year in 1974–1975—I had no idea who he was, but we became friends quickly. We shared a love of hockey, and I introduced him to the North Jersey Field Hockey Club. I took his class on stochastic processes, and he was actually an examiner of my Ph.D. thesis.

Chris: That must have been quite the time in terms of listening to Besag because that was about when he was publishing his classic 1974 paper on Markov random fields (Besag, 1974).

Noel: I don't think it was quite out yet but he lectured on it. I don't claim to have understood everything he said, but it was stunning. It was fascinating to hear this notion of conditioning. Julian was building joint models based on univariate conditional distributions. I learned the statistics and the mathematics, but I didn't appreciate the power of what was being done and how to knit those conditional distributions together until a few years later.

Jay: It's interesting that you chummed around with him, too, playing hockey.

Noel: Within a couple of days of Julian showing up in the department, he's talking about hockey. And I say, "Hockey? You play hockey?" and he looks at me and says, "Noel? You play hockey?" I say, "Yeah, I've got a team for you." I was his best mate at that point, and he became a member of our North Jersey field hockey team.

Jay: You started out friends, and at some point you really weren't talking to each other. What was the source of the disagreement?

Noel: I think the first disagreement was with hockey! We were playing hockey, and Julian was holding himself in a particular way to stop the ball. I suggested a different way, and that was not a good move on my part. And I started to realize that there was a lot of sensitivity behind Julian. We were friends early on, and much later he started to say unkind things about what I was trying to do in spatial statistics. You see, Julian was an expert in modeling lattice data with Markov random fields, and I was pushing the geostatistics side of things. From my point of view, they were all part of spatial statistics, but Julian was a pretty hard gatekeeper for what spatial models should

look like. There was a little rapprochement in about 1990 in Seattle when we worked on a publication on spatial statistics for the National Academy of Sciences, and he asked me to write a chapter on geostatistics. Julian picked me up from the airport, and one evening we went to his houseboat and had pizza and beers. I wrote a tribute to Julian after he died, as part of a collection organized by Peter Green (see https://www.sustain.bris.ac.uk/JulianBesag/tributes/Oxford.html).

ACADEMIC CAREER PATH

Jay: You've had four major stops along your academic career, Flinders, Iowa State, Ohio State and now Wollongong. How did these jobs come about?

Noel: After Princeton, I did a post-doc in Fontainebleau, France for about five months in 1975, then I did another post-doc, or visiting lecturer actually, at Imperial College in London, where I got to know David Cox, now Sir David. But I was absolutely passionate about going back to Australia with my training. So, I applied to and got an offer from The Flinders University of South Australia (in Adelaide), to start in 1976. I didn't even interview, but I suppose that Princeton and the letters from Watson and Tukey got me the job. I really liked living in Adelaide, but I knew quite quickly this job was not for me. I was in a pure-mathematics-oriented school with only two statisticians (Professor John Darroch and me). In my years there, I developed a new Stat 101 type course, an advanced course in Robustness, and for the first time I taught courses in Design, Linear Models and Multivariate Statistics. I also developed strong collaborations with the newly created Flinders Medical Centre, and I became a biostatistician simply by solving problems with research teams at the medical center. My time at Flinders came with self-doubts that I could do research at a smaller university. But, by the time a couple of places in the U.S. started to sort of suss me out in the early 1980s, I had published about 25 papers, although none was on spatial statistics.

Chris: So, this is when you moved to Iowa State University in Ames?

Noel: Yes, Iowa State University and North Carolina State University had almost simultaneously contacted me late in 1982 about the possibility of coming. North Carolina State wanted me as a visitor, to see what I was like. But, the chair at Iowa State, Herbert A. David, was originally from Australia, and he understood both academic systems. I knew Oscar Kempthorne from a trip

FIG. 5. *Circa* 1980: *Flinders University, Eureka Stockade emblem.*

he'd made to Australia a few years earlier, and he was very supportive. So, in 1982–1983 a move was made to get me to Iowa State. I came in September 1983, as a full professor with a green card, and I stayed 15 years. I had some wonderful Ph.D. students, the two of you included, and I wrote a book on spatial statistics. So you know, Iowa State was all about growth for me. It was a really good job and provided me the flexibility to see horizons that were opening up, one at the U.S. Census Bureau doing spatial small area estimation and another in environmental statistics.

Chris: You also got involved in ecological statistics at Iowa State, right?

Noel: I knew no biology or ecology before I met Jay, and it's thanks to him that I am seen as somebody who could publish in and review for ecological journals. And the work that we did trying to understand pattern, based on Jay's field work in botany, was something that I'm very proud of. I think we had some really nice ways to quantify pattern.

Chris: You both also made some fundamental contributions to spatial statistics, specifically multivariate geostatistics.

Noel: Yes, I suggested that Jay take on multivariate geostatistics and think about what the variogram should become when you have two variables. At the time, there was a cross-variogram that Matheron had proposed to deal with multivariate geostatistics, based on a cross-product of the spatial-lagged differences of each of the two variables. It looked like the natural analog to the univariate variogram, however there was another possibility based simply on the spatial-lagged difference between the two variables. And it turns out that this simple differences cross-variogram is the right

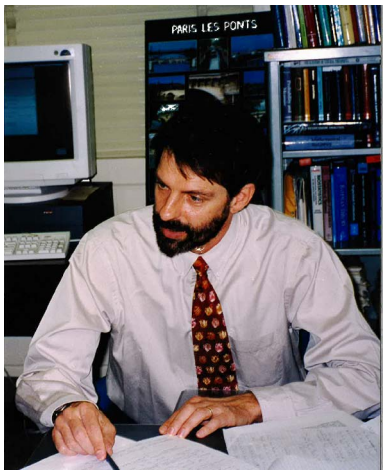

FIG. 6. 1993: *Press photo, Distinguished Professor of Liberal Arts and Sciences, Iowa State University.*

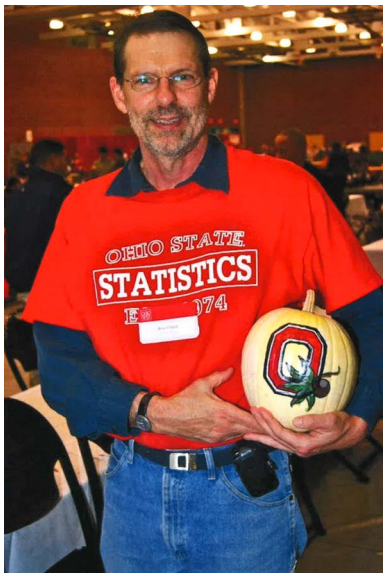

FIG. 7. *Circa* 2010: *Volunteer server at Ohio State University's Thanksgiving Dinner.*

one to use in the most general spatial setting where there is asymmetric cross-dependence. We ended up doing a pretty darn good job of showing that we would get non-optimal multivariable spatial predictions if we used the cross-product cross-variogram versus getting optimal multivariate kriging predictions using the differences cross-variogram. But we had to get it through refereeing, and while it wasn't easy we did publish it in the most appropriate place, *Mathematical Geology* (Ver Hoef and Cressie, 1993).

Jay: Can you say a bit more about your interest in environmental statistics?

Noel: It was just crying out for spatial statistics. Geostatistics was developed for mining, but mining is about taking from the environment, and environmental statistics is about stewardship of the environment. I could see that our planet is fragile, and I felt I could make a difference with some of the things I was doing in my research. I suppose that's what's driven me ever since. There was so much demand in the spatial arena for addressing environmental problems, and it became a passion to use my work to make a difference as to how we might live on this planet and how we might care for it.

Jay: How was this received at Iowa State?

Noel: I think the growth in environmental statistics was starting to influence some of the agricultural sampling work in the Survey Section on the second floor of Snedecor Hall. There were things I thought we could do together, but that wasn't welcomed, which was a pity. I was also trying to get a university-wide GIS unit established, but it required buy-in from various Deans, and that didn't happen. More growth looked to be difficult, so I started to think about finding a job elsewhere.

Chris: This was the transition to Ohio State?

Noel: Ohio State's Department of Statistics asked me come as a visitor first—Iowa State let me take leave and give a quarter-long course on spatial statistics at Ohio State. Then Tom Santner, who was chair at the time, was instrumental in getting me there. He wanted me to establish a center or a program, which I did within a month or two of arriving in late 1998. I called it the Program in Spatial Statistics and Environmental Sciences (SSES)—later I changed "Sciences" to "Statistics."

Jay: In what ways was it different at Ohio State compared to Iowa State?

Noel: At Ohio State I didn't initially have the graduate students knocking on my door like I had at Iowa State, and so it took a while to find the right Ph.D. students. I liked the department and was very active in the graduate program as well as leading environmental statistics initiatives with engineering and earth sciences. About mid-way through my time there, the department went from being in a small college of sciences to being in an amalgamated college of arts and sciences, almost half the university. And while statistics at Iowa State was seen as the jewel in the crown of their liberal arts and sciences college, statistics at Ohio State was seen as a minnow, and our high-quality research in the department wasn't valued by the college deans. There was a cohort of faculty who retired around 2010 and were not replaced, and there was even talk from our associate dean about merging statistics back into mathematics to become a school of mathematical sciences. Because of this worsening situation, I started to

look elsewhere. I understand that things have improved for statistics at Ohio State over the last few years.

Chris: So how did you end up back in Australia at Wollongong?

Noel: I had opportunities to stay in the U.S., but at that time I was 60 and the commodity I needed most was time—time to think, research and write. The University of Wollongong (UOW) offered me something I couldn't get elsewhere, which was no formal teaching commitments, and to this day I'm totally grateful for that. It has allowed me to do some things that I had wanted to do for a long time, that I really felt were needed, like statistics for remote sensing data and statistical inverse problems for big data (e.g., Cressie, 2018).

Chris: Did you find that as rewarding as you thought it would be?

Noel: Yes, but I do miss having a significant group of students involved in my research program. I hadn't fully appreciated that it'd be hard to recruit students in a small program if I'm not teaching. Still, I have supervised a couple, and I was able to appoint several research fellows at UOW, most notably one in the role of a statistical computing scientist, Andrew Zammit Mangion. Andrew has been a wonderful collaborator on projects, papers, and is a co-author with Chris and me on this latest book, *Spatio-Temporal Statistics with R* (Wikle, Zammit-Mangion and Cressie, 2019). Andrew was promoted to a permanent position at UOW, and we continue to collaborate, all of which I can gratefully attribute to the start-up package that UOW gave me.

Jay: Plus you get to live in Sydney and have a really nice lifestyle.

Noel: Wollongong is close enough to commute to from Sydney, so I chose to make my home in one of the most beautiful cities in the world with 50 miles of stunning coastline between it and Wollongong. Both of you have had the pleasure of staying with me in Sydney, tasting my cooking, doing touristy things and hanging out with me at various art museums and music performances.

ORIGINS OF THE BOOK *STATISTICS FOR SPATIAL DATA*

Chris: Can you talk about your transition into spatial statistics?

Noel: My Ph.D. with Geof Watson was not on spatial statistics, it was on goodness-of-fit on the real line and on the circle. My transition to spatial statistics was slow. In my first lecturing job, at Flinders University, I had attracted a Ph.D. student, Tim Read, who got going on a problem on goodness-of-fit for discrete multivariate data. Out of that came the class of power divergence statistics and the so-called Cressie–Read statistic with power $= 2/3$. Tim wrote such a nice thesis that we turned it into a book (Read and Cressie, 1988). I also worked with an economist at Flinders, Peter Morgan, on Bayesian sequential design, where we developed dynamic-programming solutions and ultimately wrote five or six papers together.

At Flinders, ideas were also coming to me from rereading notes I had taken in John Tukey's famous Stat 411 Princeton course. There were so many of them, particularly about robustness/resistance, so I started to do work in robustness and what Tukey called exploratory data analysis (EDA). Although many mathematical statisticians of the day viewed Tukey's approach to statistics as slightly nutty, he was a towering intellect and visitors of all statistical persuasions left Princeton changed. For example, Besag was moved to write and publish a paper about EDA in *Biometrika* several years after his visit (Besag, 1981).

Recall I went to Fontainebleau straight after my Ph.D. I was hanging out with people like André Journel, Jean Serra and Georges Matheron, learning about geostatistics and mathematical morphology. I was in the center's library a lot, reading the many reports that Matheron had written. He was a guy who didn't spend a lot of time on reviewing the literature. He basically used his mathematical skills to develop whatever was on his mind, and it was really a brilliant mind. As a consequence, his group would sometimes reinvent things and give them new, exotic names. So "variogram," "nugget effect," and "kriging" took a while to take hold in the English-speaking world. I worked on one of these with Doug Hawkins during a visit to South Africa in 1979, leading to a paper on a new variogram estimate that was resistant to outliers (Cressie and Hawkins, 1980). The classical variogram estimate is based on the average of lagged differences squared, which is highly sensitive to outliers. Our idea was to downweight them by defining a new estimate, later called the Cressie–Hawkins variogram estimate, based on the average—or the median—of the square root of the absolute differences.

This combining of my Fontainebleau and Princeton/Stat 411 experiences continued. In 1982, André Journel invited me to give a talk at a NATO advanced study institute on geostatistics at Lake Tahoe, California. I had all this stuff from Matheron. I had all this

stuff from Tukey. So, I talked about resistant ways to find and visualize outliers in geostatistical data at Lake Tahoe and then published a paper on it in the institute's proceedings. I was doing Exploratory Spatial Data Analysis or ESDA. I don't know if I invented that term—I think I did—but if someone else said they did, I'd agree with them.

Jay: How did that lead to such a comprehensive book on spatial statistics?

Noel: At this point, the book was taking shape in my mind. I had just come from hanging around with Matheron, Journel and other geostatisticians at the Lake Tahoe conference, and a week later after arriving at Iowa State my chair asked, "What would you like to teach in the spring [of 1984]?" And I said, "I'd like to do a special topics course in spatial statistics." I had no idea what I was promising.

Chris: That must have been daunting.

Noel: Well, I had Besag's notes on Markov random fields, I had Matheron's papers on geostatistics, and I had Brian Ripley's RSS read paper on point processes (Ripley, 1977). And I could see that there were new things to say beyond Ripley's 1981 book (Ripley, 1981). So, in 1984, I taught a class on statistics for spatial data.

Jay: How did the class transition into the book?

Noel: The course went well enough, so I thought there was a book there, and I had some fabulous Ph.D. students working on spatial problems—Carol Gotway, Martin Grondona and Steve Rathbun—in the early days. I think this was the first significant spatial stats group in the U.S., but I might be wrong. Later on there were other wonderful students, including you two, and younger colleagues too numerous to mention who did some stunning things in spatial statistics that made Iowa State a real force in the area. After teaching the course for the first time, it became clear to me that this was an opportunity to marry linear models and geostatistics—at that time at Iowa State, some people felt threatened by spatial statistics, believing that it was trying to replace linear models. And there was a guy in Australia, Graham Wilkinson, who was developing nearest neighbor methods and not quite seeing their relationship to spatial statistics. Nearest neighbor methods seemed spatial, but they looked different from Besag's work and different from geostatistics. So, there was all this stuff going on, it was confusing, and even after teaching the course several times I wasn't seeing the link between them.

Chris: So, what changed?

Noel: It wasn't until I was really seriously writing the book that I had an epiphany as to how they might be linked together—how they could be separate but the same. So in Chapter 1, I wrote down a general model for spatial and spatio-temporal statistics. I gave a notation for the variable Z to have a spatial index of $\mathbf{s}$ ranging over a set D and a temporal index t ranging over a set T. Then I made the set D a function of t, so in fact there could be an evolution of sets, and that's where I got random sets involved, because D could be a random set. A special case would be if Z is only ever a constant on the spatial random set D, which can be used to generate a point process. And if Z is not a constant, like the diameter at breast-height of a tree indexed by its location, you would have a marked point process. I remember being very excited about having seen the link and telling people around me about it.

Jay: Those Eureka moments are always pretty special, aren't they, when you get that flash of insight?

Noel: Yeah, at the time there were these three different approaches to spatial statistics depending on what type of data you had. Looking back, if I hadn't had that insight, the book wouldn't have have been as harmonious as I think it is, even at 900 pages.

Jay: Have you had other Eureka moments in your career?

Noel: I feel I have. You know, you work hard, you write up what you've done, and sometimes something clicks into place. Hierarchical statistical modeling fits that bill, but it was more like an evolution of moments. The approach lets you solve difficult problems with messy, missing data, something a frequentist approach struggles so hard to deal with. And you say, "No worries," because you have the notion of a latent process behind the data. What we now call the data model handles all of that messy stuff, and you can concentrate on modeling the science in the latent process.

Chris: Don't you feel that your spatial models and the way you presented them in your book was doing that, too?

Noel: No, I didn't have it. In the book, I did have the idea that you could have your cake and eat it too, that you could have fixed effects, which could be really interesting scientifically, and then you could have other stuff in the random effects that are captured through a spatial covariance model, and you could either be doing parameter estimation or you could be doing spatial prediction. In Chapter 3, I made it clear that the notion of kriging was different from generalized least squares estimation of the mean, and I was able to relate them and their measures of uncertainty. My book

has about 20 pages in Chapter 7 covering the revolutionary image-analysis work by Stu and Don Geman (Geman and Geman, 1984) and related work by Besag. I didn't see that I could have done that type of hierarchical modeling for geostatistical data and for point patterns as well.

BAYESIAN STATISTICS, EMPIRICAL AND HIERARCHICAL BAYES

Jay: We have all seen this explosion of Bayesian statistics, not only in the hierarchical models for spatial or space–time processes, but philosophically. You taught Bayesian statistics at Iowa State. Can you give us some of your thoughts on this?

Noel: Well, I was first exposed to Bayesian statistics, like most of us trained as frequentists, through a technical result. Bayes' theorem is elegant, but at first it looks a bit strange when you're switching the conditioning around. Then, as you start to think a bit deeper, it's expressing uncertainty—probability—on things that you want to find out about. And you're updating the uncertainty with data. Those ideas came through in the summer class [on Bayesian statistics] I taught at Iowa State that you mentioned. That notion that today's posterior is tomorrow's prior is a really nice way to think about how knowledge is accumulated sequentially. I have this feeling that babies are born with a fairly flat prior and, gradually, using something like Bayes' theorem they learn about how the world works.

Jay: You were trained as a frequentist, so how did you come to teach Iowa State's class in Bayesian statistics?

Noel: Actually, I had some background in empirical Bayes. In my first year at Princeton, Geof Watson gave me a manuscript that was written by Fred Lord at the Educational Testing Service (ETS), located near Princeton. I didn't know it at the time, but Lord was probably the most famous psychometrician in the country. He was having trouble publishing a non-parametric empirical Bayes predictor of an examtaker's intelligence, he had a very simple binomial model with a non-parametric underlying distribution of the probability of getting the answers right, and he had done some optimization to give a range for the probability given the data. I took a look at it, was able to improve it a bit, and then we published it. Later, I generalized the idea to other families and published the results in the *Annals of Statistics* (Cressie, 1982). It's a little paper that I'm fond of.

Jay: Didn't you have an interaction with Herbert Robbins around that time as well?

Noel: Yes, Herb Robbins is considered one of the founders of empirical Bayes. He read a draft of my paper and, during a sabbatical I took in 1980 at ETS working with Lord and Paul Holland, I asked him to come down to ETS from Columbia University to give a seminar. We never wrote a paper together, but at that time our approaches to empirical Bayes were similar.

Chris: Did you see the connection to Bayesian hierarchical modeling?

Noel: The notion of Bayesian hierarchical modeling is quite different. I have found that a number of people who were brought up Bayesians don't get the idea that there is a process model between the data model and the prior. That middle distribution is fundamental. State-space modelers know about this—they are doing what we might call empirical hierarchical modeling, where they have a measurement equation, which is a model of the data conditional on the process (and some parameters). Then they have a state equation, which is a model of the process conditional on some more parameters, and the parameters are typically estimated or specified.

Chris: There were Bayesian papers in spatial and environmental statistics, but this hierarchical notion didn't really take hold until Mark Berliner published his classic paper in 1996 (Berliner, 1996). You were an early adopter of this view.

Noel: Mark had the terminology: data model, process model, parameter model, but I don't remember using it early on. I like it and certainly use it now. My initial work was in disease mapping, where the data came from small areas with observed disease rates, and there was a hidden rate process that I wanted to make inference on. It was only later that I put priors on parameters, in a sense completing the Bayesian hierarchical model but never losing sight of the process model. It might've been you, Chris, who introduced me to Mark's paper when you went to NCAR in 1996 as a post-doc to work with him.

Chris: Yes, that's right—Mark was always generous about visitors getting involved in projects, and of course we were still working on publishing things from my dissertation. I think that's when you got involved in it, and we worked on a joint paper with Mark on hierarchical Bayesian spatio-temporal modeling.

Noel: Yes, Mark said, "Let's do something together, the three of us, on space and time." At that point, Mark didn't have much experience in spatial statistics. He was working in chaos theory and temporal-processes modeling, but he thought the way to learn about something new was to work on it with somebody. We ended

up publishing our paper in *Environmental and Ecological Statistics* (Wikle, Berliner and Cressie, 1998). Actually, I think it's a watershed paper. Although the journal is not highly visible, our paper has been cited quite a lot, and our approach was subsequently rediscovered in the simpler, spatial-only setting. Chris, you wrote most of it, and your MCMC algorithm appeared in great detail in the Appendix. Anecdotally, a lot of people based their own spatio-temporal MCMC algorithms on yours.

Chris: That started the ball rolling in using Bayesian hierarchical modeling in environmental and spatio-temporal statistics.

Noel: Yes, and it really led to our 2011 book, *Statistics for Spatio-Temporal Data* (Cressie and Wikle, 2011), which presents spatial and spatio-temporal statistics from a hierarchical perspective.

ADVICE AND FINAL THOUGHTS

Chris: How do you see the connection between spatial statistics and spatio-temporal statistics?

Noel: I look upon a spatial process as being a slice of a spatio-temporal process. So you really have to know how to look for dependence within a slice, and then you have to know how to relate dependencies between slices. I think that the notion of a field at a particular time evolving into another field at another time—these are the slices I'm talking about—is a powerful way to build a spatio-temporal statistical model. You know, we always talk about Tobler's first law of geography being at the core of spatial statistics. I think there are three further "laws" or, more correctly, guidelines for spatial statistics, ultimately leading to a guideline for spatio-temporal statistics. The first law, that nearby things tend to be more alike than things far apart, leads to the second law, which says that that spatial variability can be expressed in terms of large-scale, small-scale, and micro-scale variability, the latter being where the nugget effect is found. The third law is that the spatial variability of a spatial process is generally inversely related to the amount of aggregation associated with it. And the fourth law says that these scales of spatial variability are actually related through a temporal process that's sometimes moving at different rates, so creating a spatio-temporal process.

Jay: Statistics is a scientific field, just like any other, but it is somewhat unique in how it serves basically every other science. Do you have a philosophy of science, and do you think being a statistician makes it different from other disciplines?

Noel: I call myself a statistical scientist, and we hold to the principles of science, moving forward by establishing theory and methods that may be replaced or generalized at any time when a better approach can be demonstrated. It used to be that an experimental design course was a required part of any Statistics Ph.D. program. I suggest we return to that, not because I'm a traditionalist but because "design" gives the language and structure that science needs. It is based on our understanding and partitioning of variability in ways that get us as close as possible to "causation," which is science's holy grail. So, if we are to occupy an important place in the world of data science, it starts with our knowledge of experimental design and variability characterization. But we have much more to offer: data sets of any size inform our understanding of the world—more or less! Answers to questions asked of these data come with uncertainty, and we must definitely bring this out at every opportunity and quantify the uncertainty in scientifically meaningful ways.

Jay: Do you have any specific advice for young Ph.D. statisticians?

Noel: Yes, learn mathematics as early as possible, learn to code in a high-level language such as C or C++, become proficient in R, and be sure to take a course in design. Then follow the three Ls for the rest of your career: learn, learn, and learn—from your teaching, from your colleagues and students, and from the literature.

Chris: If you were limited to only one sentence or phrase to characterize your career, what would it be?

Noel: I was a mathematical statistician who learned to start worrying about uncertainty and love Bayes' theorem, and they all played a role in my becoming a statistical scientist.

I'd like to look forward as well, by turning something Pablo Picasso once said ("Art is a lie that makes us realize truth...") on its head. In a populist, post-truth world, science must be seen as truth that reveals the lie, and statistical science has a critical role to play here, now more than ever before.

Finally, I would like to add a post-interview *merci infiniment* for all the time you spent doing this interview and writing it up—what a great honor to be asked!

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