

Introduction to Spatial Data and Models

Sudipto Banerjee¹ and Andrew O. Finley²

¹ Department of Forestry & Department of Geography, Michigan State University, Lansing Michigan, U.S.A.

² Biostatistics, School of Public Health, University of Minnesota, Minneapolis, Minnesota, U.S.A.

March 9, 2009

1

- Researchers in diverse areas such as climatology, ecology, environmental health, and real estate marketing are increasingly faced with the task of analyzing data that are:
 - highly multivariate, with many important predictors and response variables,
 - geographically referenced, and often presented as maps, and
 - temporally correlated, as in longitudinal or other time series structures.
- ⇒ motivates **hierarchical** modeling and data analysis for complex spatial (and spatiotemporal) data sets.

2

ENAR 2009 Hierarchical Modeling and Analysis

- **point-referenced data**, where $Y(\mathbf{s})$ is a random vector at a location $\mathbf{s} \in \mathbb{R}^r$, where \mathbf{s} varies **continuously** over D , a fixed subset of \mathbb{R}^r that contains an r -dimensional rectangle of positive volume;
- **areal data**, where D is again a fixed subset (of regular or irregular shape), but now partitioned into a **finite** number of areal units with well-defined boundaries;
- **point pattern data**, where now D is itself random; its index set gives the locations of random events that are the spatial point pattern. $Y(\mathbf{s})$ itself can simply equal 1 for all $\mathbf{s} \in D$ (indicating occurrence of the event), or possibly give some additional covariate information (producing a **marked point pattern process**).

3

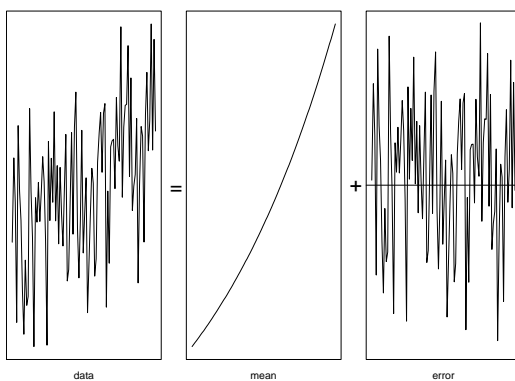
ENAR 2009 Hierarchical Modeling and Analysis

- First step in analyzing data
- First Law of Geography: Mean + Error
- Mean: first-order behavior
- Error: second-order behavior (covariance function)
- EDA tools examine both first and second order behavior
- Preliminary displays: Simple locations to surface displays

4

ENAR 2009 Hierarchical Modeling and Analysis

First Law of Geography



5

ENAR 2009 Hierarchical Modeling and Analysis

Scallops Sites



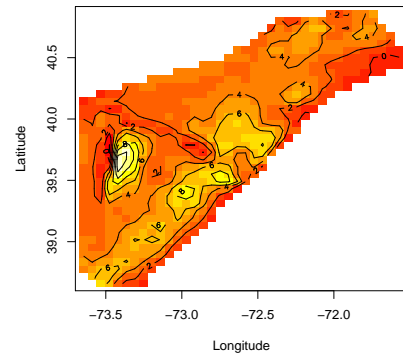
6

ENAR 2009 Hierarchical Modeling and Analysis

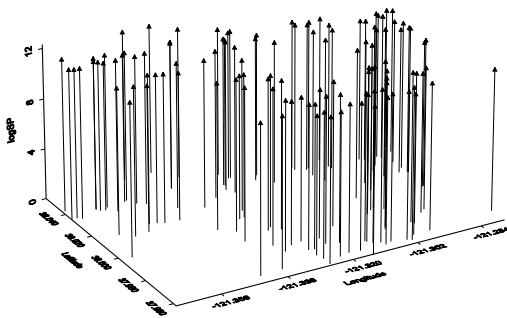
- Spatial surface observed at finite set of locations $\mathcal{S} = \{s_1, s_2, \dots, s_n\}$
- Tessellate the spatial domain (usually with data locations as vertices)
- Fit an interpolating polynomial:

$$f(\mathbf{s}) = \sum_i w_i(\mathcal{S}; \mathbf{s}) f(\mathbf{s}_i)$$

- "Interpolate" by reading off $f(\mathbf{s}_0)$.
- Issues:
 - Sensitivity to tessellations
 - Choices of multivariate interpolators
 - Numerical error analysis



Drop-line scatter plot



Surface plot

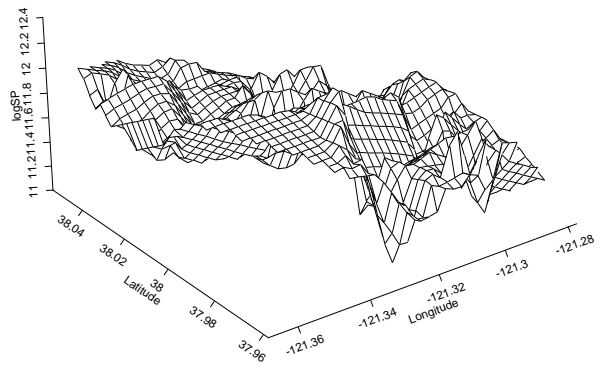
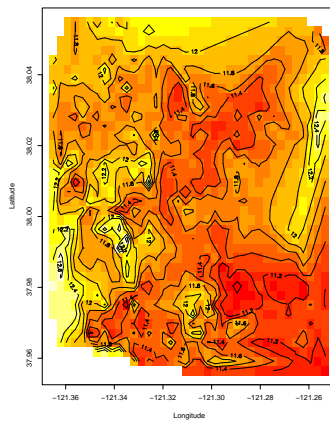
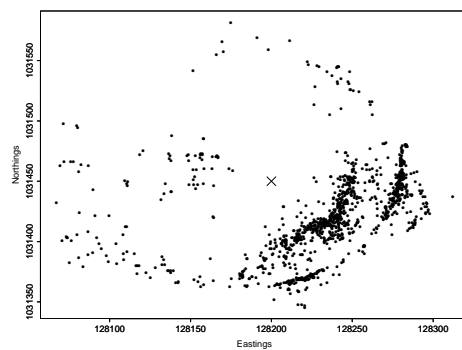


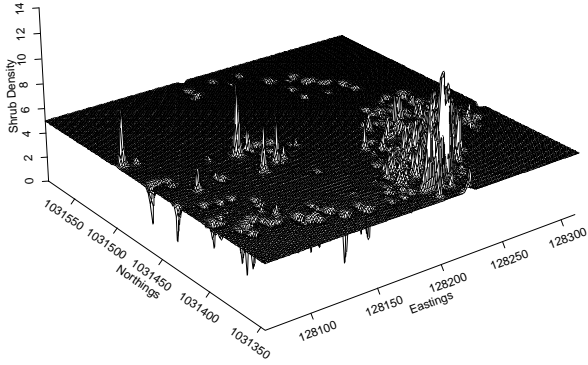
Image contour plot



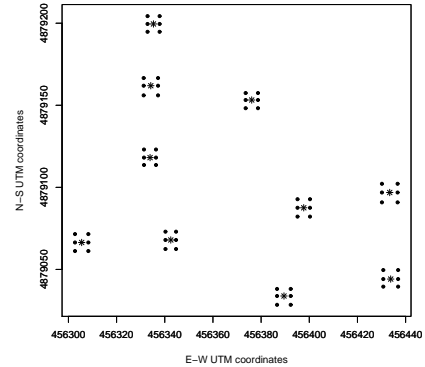
Locations form patterns



Surface features



Interesting plot arrangements



- Point-level modelling refers to modelling of spatial data collected at locations referenced by **coordinates** (e.g., lat-long, Easting-Northing).
- **Fundamental concept:** Data from a spatial process $\{Y(\mathbf{s}) : \mathbf{s} \in D\}$, where D is a fixed subset in Euclidean space.
- **Example:** $Y(\mathbf{s})$ is a **pollutant level** at site \mathbf{s}
- **Conceptually:** Pollutant level exists at all possible sites
- **Practically:** Data will be a partial realization of a spatial process – observed at $\{\mathbf{s}_1, \dots, \mathbf{s}_n\}$
- **Statistical objectives:** **Inference** about the process $Y(\mathbf{s})$; **predict** at new locations.

Suppose our spatial process has a mean, $\mu(\mathbf{s}) = E(Y(\mathbf{s}))$, and that the variance of $Y(\mathbf{s})$ exists for all $\mathbf{s} \in D$.

- **Strong stationarity:** If for any given set of sites, and any displacement \mathbf{h} , the distribution of $(Y(\mathbf{s}_1), \dots, Y(\mathbf{s}_n))$ is the same as, $(Y(\mathbf{s}_1 + \mathbf{h}), \dots, Y(\mathbf{s}_n + \mathbf{h}))$.
- **Weak stationarity:** Constant mean $\mu(\mathbf{s}) = \mu$, and $Cov(Y(\mathbf{s}), Y(\mathbf{s} + \mathbf{h})) = C(\mathbf{h})$: the covariance depends only upon the displacement (or separation) vector.
- **Strong stationarity implies weak stationarity**
- The process is **Gaussian** if $\mathbf{Y} = (Y(\mathbf{s}_1), \dots, Y(\mathbf{s}_n))$ has a **multivariate normal** distribution.
- For Gaussian processes, strong and weak stationarity are equivalent.

Variograms

- Suppose we assume $E[Y(\mathbf{s} + \mathbf{h}) - Y(\mathbf{s})] = 0$ and define
$$E[Y(\mathbf{s} + \mathbf{h}) - Y(\mathbf{s})]^2 = Var(Y(\mathbf{s} + \mathbf{h}) - Y(\mathbf{s})) = 2\gamma(\mathbf{h}) .$$

This is sensible if the left hand side depends only upon \mathbf{h} . Then we say the process is **intrinsically stationary**.

- $\gamma(\mathbf{h})$ is called the **semivariogram** and $2\gamma(\mathbf{h})$ is called the **variogram**.

Note that intrinsic stationarity defines **only** the first and second moments of the differences $Y(\mathbf{s} + \mathbf{h}) - Y(\mathbf{s})$. It says nothing about the **joint** distribution of a collection of variables $Y(\mathbf{s}_1), \dots, Y(\mathbf{s}_n)$, and thus provides **no likelihood**.

Intrinsic Stationarity and Ergodicity

- Relationship between $\gamma(\mathbf{h})$ and $C(\mathbf{h})$:

$$\begin{aligned} 2\gamma(\mathbf{h}) &= Var(Y(\mathbf{s} + \mathbf{h})) + Var(Y(\mathbf{s})) - 2Cov(Y(\mathbf{s} + \mathbf{h}), Y(\mathbf{s})) \\ &= C(\mathbf{0}) + C(\mathbf{0}) - 2C(\mathbf{h}) \\ &= 2[C(\mathbf{0}) - C(\mathbf{h})]. \end{aligned}$$

- Easy to recover γ from C . The converse needs the additional assumption of **ergodicity**: $\lim_{\|\mathbf{u}\| \rightarrow \infty} C(\mathbf{u}) = 0$.
- So $\lim_{\|\mathbf{u}\| \rightarrow \infty} \gamma(\mathbf{u}) = C(\mathbf{0})$, and we can recover C from γ as long as this limit exists.

$$C(\mathbf{h}) = \lim_{\|\mathbf{u}\| \rightarrow \infty} \gamma(\mathbf{u}) - \gamma(\mathbf{h}).$$

- When $\gamma(\mathbf{h})$ or $C(\mathbf{h})$ depends upon the separation vector only through the distance $\|\mathbf{h}\|$, we say that the process is **isotropic**. In that case, we write $\gamma(\|\mathbf{h}\|)$ or $C(\|\mathbf{h}\|)$. Otherwise we say that the process is **anisotropic**.
- If the process is **intrinsically stationary** and **isotropic**, it is also called **homogeneous**.

Isotropic processes are popular because of their **simplicity**, **interpretability**, and because a number of relatively **simple parametric forms** are available as candidates for C (and γ). Denoting $\|\mathbf{h}\|$ by t for notational simplicity, the next two tables provide a few examples...

Some common isotropic variograms

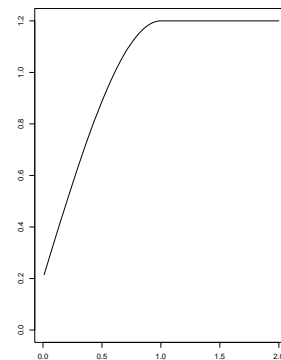
| model | Variogram, $\gamma(t)$ |
|-----------------------|--|
| Linear | $\gamma(t) = \begin{cases} \tau^2 + \sigma^2 t & \text{if } t > 0 \\ 0 & \text{otherwise} \end{cases}$ |
| Spherical | $\gamma(t) = \begin{cases} \tau^2 + \sigma^2 & \text{if } t \geq 1/\phi \\ \tau^2 + \sigma^2 [\frac{3}{2}\phi t - \frac{1}{2}(\phi t)^3] & \text{if } 0 < t \leq 1/\phi \\ 0 & \text{otherwise} \end{cases}$ |
| Exponential | $\gamma(t) = \begin{cases} \tau^2 + \sigma^2(1 - \exp(-\phi t)) & \text{if } t > 0 \\ 0 & \text{otherwise} \end{cases}$ |
| Powered exponential | $\gamma(t) = \begin{cases} \tau^2 + \sigma^2(1 - \exp(- \phi t ^p)) & \text{if } t > 0 \\ 0 & \text{otherwise} \end{cases}$ |
| Matérn at $\nu = 3/2$ | $\gamma(t) = \begin{cases} \tau^2 + \sigma^2 [1 - (1 + \phi t) e^{-\phi t}] & \text{if } t > 0 \\ 0 & \text{o/w} \end{cases}$ |

Examples: Spherical Variogram

$$\gamma(t) = \begin{cases} \tau^2 + \sigma^2 & \text{if } t \geq 1/\phi \\ \tau^2 + \sigma^2 [\frac{3}{2}\phi t - \frac{1}{2}(\phi t)^3] & \text{if } 0 < t \leq 1/\phi \\ 0 & \text{if } t = 0. \end{cases}$$

- While $\gamma(0) = 0$ by definition, $\gamma(0^+) \equiv \lim_{t \rightarrow 0^+} \gamma(t) = \tau^2$; this quantity is the **nugget**.
- $\lim_{t \rightarrow \infty} \gamma(t) = \tau^2 + \sigma^2$; this asymptotic value of the semivariogram is called the **sill**. (The sill minus the nugget, σ^2 in this case, is called the **partial sill**.)
- Finally, the value $t = 1/\phi$ at which $\gamma(t)$ first reaches its ultimate level (the sill) is called the **range**, $R \equiv 1/\phi$.

Examples: Spherical Variogram



b) spherical; a0 = 0.2, a1 = 1, R = 1

Some common isotropic covariograms

| Model | Covariance function, $C(t)$ |
|-----------------------|--|
| Linear | $C(t)$ does not exist |
| Spherical | $C(t) = \begin{cases} 0 & \text{if } t \geq 1/\phi \\ \sigma^2 [1 - \frac{3}{2}\phi t + \frac{1}{2}(\phi t)^3] & \text{if } 0 < t \leq 1/\phi \\ \tau^2 + \sigma^2 & \text{otherwise} \end{cases}$ |
| Exponential | $C(t) = \begin{cases} \sigma^2 \exp(-\phi t) & \text{if } t > 0 \\ \tau^2 + \sigma^2 & \text{otherwise} \end{cases}$ |
| Powered exponential | $C(t) = \begin{cases} \sigma^2 \exp(- \phi t ^p) & \text{if } t > 0 \\ \tau^2 + \sigma^2 & \text{otherwise} \end{cases}$ |
| Matérn at $\nu = 3/2$ | $C(t) = \begin{cases} \sigma^2 (1 + \phi t) \exp(-\phi t) & \text{if } t > 0 \\ \tau^2 + \sigma^2 & \text{otherwise} \end{cases}$ |

Notes on exponential model

$$C(t) = \begin{cases} \tau^2 + \sigma^2 & \text{if } t = 0 \\ \sigma^2 \exp(-\phi t) & \text{if } t > 0 \end{cases}$$

- We define the **effective range**, t_0 , as the distance at which this correlation has dropped to only 0.05. Setting $\exp(-\phi t_0)$ equal to this value we obtain $t_0 \approx 3/\phi$, since $\log(0.05) \approx -3$.
- Finally, the form of $C(t)$ shows why the nugget τ^2 is often viewed as a **"nonspatial effect variance,"** and the partial sill (σ^2) is viewed as a **"spatial effect variance."**

The Matérn Correlation Function

- Much of statistical modelling is carried out through correlation functions rather than variograms
- The Matérn is a very versatile family:

$$C(t) = \begin{cases} \frac{\sigma^2}{2^{\nu-1}\Gamma(\nu)} (2\sqrt{\nu}t\phi)^\nu K_\nu(2\sqrt{\nu}t\phi) & \text{if } t > 0 \\ \tau^2 + \sigma^2 & \text{if } t = 0 \end{cases}$$

K_ν is the modified Bessel function of order ν (computationally tractable)

- ν is a smoothness parameter (a *fractal*) controlling process smoothness

- How do we select a variogram? Can the data really distinguish between variograms?
- Empirical Variogram:

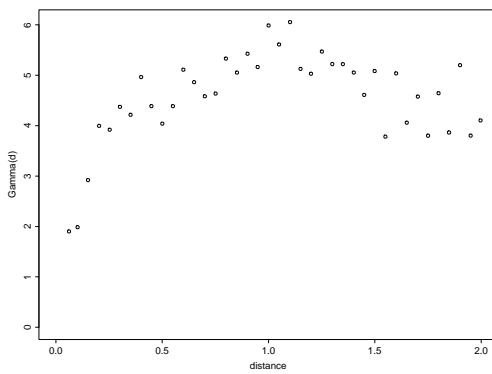
$$\gamma(t) = \frac{1}{2|N(t)|} \sum_{\mathbf{s}_i, \mathbf{s}_j \in N(t)} (Y(\mathbf{s}_i) - Y(\mathbf{s}_j))^2$$

where $N(t)$ is the number of points such that $\|\mathbf{s}_i - \mathbf{s}_j\| = t$ and $|N(t)|$ is the number of points in $N(t)$.

- Grid up the t space into intervals $I_1 = (0, t_1)$, $I_2 = (t_1, t_2)$, and so forth, up to $I_K = (t_{K-1}, t_K)$. Representing t values in each interval by its midpoint, we define:

$$N(t_k) = \{(\mathbf{s}_i, \mathbf{s}_j) : \|\mathbf{s}_i - \mathbf{s}_j\| \in I_k\}, k = 1, \dots, K.$$

Empirical variogram: scallops data



Empirical variogram: scallops data

