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Workshop on Mapping and Geostatistical Methods
for Fisheries Stock Assessment
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May, 2005
Foreword

In accordance with its mandate to disseminate information on fisheries research to the scientific community, the Scientific Council of NAFO publishes the *Journal of Northwest Atlantic Fishery Science*, which contains peer-reviewed primary papers and notes on original research, and *NAFO Scientific Council Studies*, which contains review papers of topical interest and importance. Each year since 1981, the Scientific Council has held at least one Special Session on a topic of particular interest, and many of the contributions to those sessions have been published in either of these NAFO publications. For September 2003, the Scientific Council initiated its Special Session titled *Workshop on Mapping and Geostatistical Methods for Fisheries Stock Assessment*, as a specific topic of interest to the Scientific Council. The Council invited David Kulka (Canada) and Lisa Hendrickson (USA) to design and convene the workshop. It was suggested that the focus should be to provide a basic understanding of the geostatistical concepts and methods and tools that could be used by the Scientific Council in the context of stock assessments.

During 10–12 September 2003, the Scientific Council held the Special Session in conjunction with the Annual Meeting of NAFO, at the Holiday Inn in Dartmouth, Nova Scotia, Canada. David Kulka (Canada) and Lisa Hendrickson (USA) were conveners, and Nicholas Bez (France), Reiner Schlitzer (EU – Germany), Jerry Black (Canada) and Mark Simpson (Canada) were invited instructors.

At its meeting of 15–19 September 2003, the Council noted the success of the Workshop and that the complete report will be published as SCS Doc 03/22. During the September 2004 many scientists proposed that the report should be published in the Scientific Council Studies series, and the Council intersessionally agreed to make this Studies publication. This publication endorses the success of the workshop and the possibilities opened to apply geostatistical analyses in stock assessments.

May, 2005

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Workshop on Mapping and Geostatistical Methods for Fisheries Stock Assessment

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Mapping and Geostatistical Methods

Abstract

The NAFO Scientific Council Special Session of September 2003 was the Workshop on Mapping and Geostatistical Methods for Fisheries Stock Assessment. The objective of the workshop was to provide participants with the basic understanding of geostatistical concepts and methods, and provide tools to apply this knowledge to fisheries stock assessments. The instructors introduced freeware mapping and geostatistical software. Two sets of data were used for the lessons and demonstrations: the Canadian spring bottom trawl survey data from 1996 to 2002, and information from the yellowtail flounder commercial fishery on the Grand Bank from 1996 to 2002. The visualization, analysis and modeling of spatial data using Geographic Information Systems (GIS) were presented (e.g. Ocean Data View (ODV freeware), SPAN (Spatial Analysis System) and ACON (A CONtouring package). Surface (map) generating techniques were demonstrated using the various software packages. Geostatistical concepts and methods related to kriging, and methods for analyses using basics of the "R" software package were described.

Key words: GIS, geostatistics, kriging spatial relationships, map stock assessment, workshop

Introduction

Geographic visualization and geo-spatial analysis of fish, fishery and environmental data are increasingly more important components of fisheries research. Papers incorporating these techniques are becoming more common in the work of Scientific Council, this proliferation aided by the availability of GIS software. Such application tools provide mapping functions, and in addition, many have modelling and geostatistical functionality.

In marine environments, fish and invertebrates are not distributed at random but are organized in space. Fisheries and research data are often associated with a geo-reference, usually latitude and longitude. This organization results in the realization of a variable such as fish abundance being proximally related, i.e., geographically referenced data are spatially correlated. Classical (non-spatial) analyses used to compute confidence limits of a variable assume that error terms of samples are stochastically independent of one another. This condition is often not met with spatial data. Geostatistics were developed to deal with estimation problems in spatially-correlated data.

To address the recommendation of Scientific Council a Special Session, "Workshop on Mapping and Geostatistical Methods for Fisheries Stock Assessment", was held at the Holiday Inn in Dartmouth, Nova Scotia during 10–12 September 2003 convened by David Kulka (Canada) and Lisa Hendrickson (USA). Instructors included: Nicolas Bez (Centre de Géostatistique, Fontainebleau, France), Reiner Schlitzer (Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany), Jerry Black, Mark Simpson and David Kulka (Department of Fisheries and Oceans, Canada). There were 30 participants from Canada, Denmark (Faroe Islands and Greenland), Estonia, the European Union (France, Germany, Portugal and Spain), the Russian Federation and the United States of America. Ralph Mayo (USA), Chair of Scientific Council, opened the workshop.
Overview

L. Hendrickson presented an overview of the agenda and objectives of the workshop, including an introduction of the instructors and their technical backgrounds. The objective of the workshop was to provide participants with a basic understanding of geostatistical concepts and methods, as well as the tools to apply this knowledge to fisheries stock assessment using freeware mapping and geostatistical software. Two data sets from the Grand Banks, Canadian spring bottom trawl survey sets from 1996–2002, (hereafter referred to as the survey data) and information from the yellowtail flounder fishery (hereafter referred to as the commercial fisheries data), were used for the lessons and demonstrations.

The first day of the workshop focused on the visualization and analysis of spatial data using GIS (Geographic Information Systems) software packages. Participants viewed demonstrations of the software and completed hands-on exercises. Geostatistical concepts and methods, particularly related to kriging, were presented during the following two days. Participants learned the basics of using the "R" software package (freeware) to conduct geostatistical analyses using routines prepared by programmers at the Centre de Géostatistique as well as those developed during the workshop. The agenda, relevant literature citations and links to the software utilized in the workshop can be found in Appendix 1.

Spatial Visualization and Analysis

D. Kulka highlighted the long-standing need for geographic referencing of information and spatial visualization and analysis of fisheries resources and fisheries data. For example, the 1921 Proceedings of North American Council on Fishery Investigations (NACFI), a precursor of NAFO, highlighted "the need to represent the nature of grounds, to make evident at first sight the distinctive characters of the region in question from a sedimentary viewpoint, because in fishery matters the importance of sediments cannot be denied and to represent by conventional signs the bottom fauna; determine the location of whelk and shellfish beds that are sometimes utilized for the production of bait…". The Proceedings further indicated "maps which have been published are appreciated by the fishermen, to whom they bring much information". Geographical representation is now of even more importance to fishery scientists.

Background on the spatial structure of data was presented. Geographic features can be represented as point, vector or raster (described as area, polygon or surface) data. Points on a map represent locations for geographic entities such as sampling sites and can be used to spatially present measured variables such as average temperature or catch rate. Usually in the case of fishery analyses, the raw data are composed of points (fishing or sampling sets) with latitude and longitude as the geo-reference plus various attributes describing various biological and physical components. Vector data consist of a set of connected points (lines and arcs are synonymous in this context), normally used to represent physical geographic features. Raster data are used to represent a region enclosed within a boundary. An area or series of related areas can be used to represent such features as a stock distribution or a temperature surface. These various geographic components can be overlain in various combinations in a map composition and then analyzed to determine the relationships among layers.
Mapping Software and Techniques

Data visualization and analysis were demonstrated using various types of GIS/geostatistical software including R (freeware), Ocean Data View (freeware) and SPANS (SPatial ANalysis System). Attributes such as catch rates or environmental variables in space (referred to as Z values) may be represented in their simplest state by classified points (such as expanding symbols). For many purposes, however, surfaces (rasters covering the entire area of interest) provide added value through enhanced visualization and by facilitating further analysis of spatial relationships. Several surface generating techniques were described and demonstrated using various software packages.

ACON

ACON (A CONtouring package) freeware (Black, 2002), developed to transform and visualize survey and commercial fisheries data, was demonstrated by J. Black. The software can generate two and three-dimensional graphics and contains routines for generating maps in a number of projections. An internal scripting language (with an embedded compiler based on Extalk: Betz, 1988) is used to generate and execute virtual machine code. The language supports vector and matrix math in up to three dimensions.

Input data may be read from ASCII files, ODBC (Open Database Connectivity) data sources, or from Oracle SQL (Structured Query Language) databases. Output may be generated in graphics windows, as output files (e.g. PNG, Illustrator, PDF, PostScript, JPEG, SVG), or as movies in AVI or QuickTime formats. The world vector coastline is provided as a Regionally Accessible Nested Global Shoreline structure at five levels of resolution (e.g. 0.1, 0.2, 1.0, 5.0 and 25 km). Bathymetry polygons are provided for the east coast of Canada, as well as for the NAFO convention area.

The transformation and visualization of point patterns to surface distributions was demonstrated with ACON using Voronoi polygons and Delaunay triangulation tessellation methods. Voronoi polygons are generated from the circumcenters of natural neighbour circles formed between adjacent sampling points. Each Voronoi polygon edge is a perpendicular bisector of the matching Delaunay triangle (Fig. 1).

Delaunay triangles sub-divide the data region into triangles that are as equilateral as possible. Voronoi polygons are unique, as are Delaunay triangles except in the case of regularly gridded data. The relationship between Delaunay triangles and Voronoi polygons for the survey data was demonstrated (Fig. 2).

The pros and cons of interpolation methods for shaded surface contour generation such as moving averages, inverse distance weighting and Voronoi analysis were presented. For example, the moving average method does not account for either the distance between neighbouring samples or between the samples and the target. In other words, all samples in a particular neighbourhood receive the same weight. With respect to a Voronoi analysis, all of the weight assigned to a particular data point is placed on its single-most, proximate neighbour. As a result, the spatial arrangement of the resulting Voronoi diagram is more
a reflection of the location of the sampling stations rather than the values of the data at those stations. In addition, the limits of border samples may be questionable. The inverse distance weighting method assumes that the weighting factor is a function of the distances between data points and the target within a particular neighbourhood.

As an example of how custom output can be produced, script was used to generate a number of presentation graphics. The script demonstrated scaled symbol output of the number of Atlantic cod caught per std. (standard) tow (0.8 naut. miles) from the survey and surface contouring using inverse distance weighted gradient interpolation of the bottom temperature measured at each station (Fig. 3). Bathymetry contours were rendered as shaded contours and then overlaid with the observed bottom temperature as a shaded surface. Bathymetry contour lines were drawn over each surface to allow the user to infer the bottom topography in the region where the bathymetry contours were obscured by the bottom temperature surface. The inverse distance weighted gradient surface interpolation produces a shaded surface visually similar to potential mapping, in this case where the sampling density is high and a corresponding small-scale map is used. In this example both the bottom temperature observations and cod catch were aggregated to simple mean values per 15-minute square of longitude and latitude. The shaded coastline which overlays the bottom temperature surface was generated from the world vector shoreline stored in the RANGS file format. The cod catches were plotted using a constant log ratio scaling (Bertin, 1981) and rendered so that secant symbols remain distinct through ordered rendering white "halos" surrounding each symbol.

The script also demonstrated scaled symbol output of the catch of yellowtail flounder per std. tow using a similar graphic style (Fig. 4). This graphic was demonstrated through interactive browsing of the data set with Data_Dialog windows (Fig. 4). Using this technique the data set was browsed interactively, by selection of the survey year, species of interest and sampling metric (number or weight caught). The map included a Variogram (as an annotation) that was automatically calculated for the selected catch.

The plotting of multiple species on a single map using scaled symbol pie charts was demonstrated using the survey data to identify the co-location of cod and yellowtail flounder by-catch in the American plaice fishery (Fig. 5). This technique generates a synoptic view of the overall distributions of cod and yellowtail, as well species-specific and combined abundance patterns. Alternative choices of data aggregation generate different levels of detail in the spatial distribution plot. Thus, there is a trade off between a synoptic view and more precise location detail at the expense of increased information complexity.

The use of ACON as an interactive web mapping tool was also demonstrated. The web site:

http://gmbis.marinebiodiversity.ca/

utilizes ACON as a CGI (Common Gateway Interface) program that allows the user to interactively generate maps of data from the Gulf of Maine groundfish surveys and the Atlantic Reference Centre (ARC) specimen collection. The aim of the Gulf of Maine
Fig. 1. Delaunay triangles (grey) and the matching Voronoi polygons (black) with 2 circumscribing circles.

Fig. 2. Relationship between Delaunay triangles and Voronoi polygons based on analysis of data from the survey of the Grand Banks. Left panel shows the Delaunay triangles formed from the 519 sets in the 1996 survey and the right panel shows the matching Voronoi polygons.
Fig. 3. Scaled symbol output (black dots) showing the distribution of Atlantic cod (number per tow) from 1996 to 2002 overlain on a surface contour of bottom temperature created using inverse distance weighted gradient interpolation of bottom temperature measurements.
Biogeographic Information System project (GMBIS) is to develop, test and demonstrate data dissemination and visualization tools involving overlaying numerous environmental and ecosystem data layers in the Gulf of Maine region. The project explores how GIS and Internet technologies can be used to access databases and display their products in addressing specific questions relating to the biogeography and status of marine populations.

As part of this web site, the browsing of the "Electronic Atlas of Specimens from the Atlantic Reference Centre of the Huntsman Marine Science Centre" was presented (Fig. 6). On this web page, 124 000 specimens from the Reference Centre can be browsed at the Order, Family, or Genus level, providing a synopsis of the principal species in a specific mapped region.

A significant feature of the GMBIS web site is a "Map your own Data" web page, in which users can map their own data by uploading to the web site ASCII data files containing data fields such as longitude, latitude and mapping variables. Scientists wanting to visualize their own data without investing in their own GIS technology, are able to generate their own maps of the NAFO region by uploading their own data to this site. A variety of output formats are provided.

**SPANS**

D. Kulka illustrated some of the capabilities of the SPANS GIS/geostatistical software using import and export routines that are compatible with other GIS and graphics software. Although not freeware, SPANS contains point to surface functions including potential mapping routines plus overlay modeling capabilities that are particularly well-suited for fisheries data analysis. Various point to surface results were reviewed including point aggregation, Voronoi, Contour (TIN) and Potential Map (Fig. 7). Refer to Anon (1999) for further details on the application of each of the techniques.

The advantages and shortcomings of each technique were discussed. The potential map has a number of advantages over interpolation methods. It does not extrapolate beyond the influence of the point data upon which it is based (as is the case for the Voronoi and Contour (TIN) surfaces) and contains an array of functions that allow the user to control the output.

Potential mapping (Fig. 7D) is most appropriate for interval or ratio point data that represent a non-continuous variable, typified by a high degree of variance and contagious distribution, such as fish and fishery distribution data. Potential mapping converts point data, such as fishing sets, to a surface representative of a selected mapping variable or attribute (Z-value). Functions include: density of points (number of sets per km²), weighted average of an attribute such as catch rate or environmental variables, the standard error of the mean plus other measures of variance. Potential mapping uses: (a) an averaging technique; (b) does not create new values outside the range of the input data; and (c) does not extrapolate beyond the influence of the original data. The model for weighted values of Z is defined by the equation in Fig. 8.
The potential mapping derivative function generates a surface by applying a sampling radius to each point in the data layer (Fig. 9, left panel).

This process is performed on all of the points and effectively creates a very large number of crescents or circle fragments. The values of the crescents are assigned to an underlying grid. No output values are calculated for areas lying outside of any sampling radii.

When creating a surface, the user can control the effect of distance on the resulting output values by specifying: a) the size of the sampling radius and b) the rate of decay to decrease the influence of points further from the center. A classification scheme is applied to the output. Each area has a unique value assigned to the underlying grid and these entities can then be classified by the user into a continuous surface that describes an attribute (such as a catch rate or an environmental variable).

Practical applications of this method were presented using the results from previous studies. For example, the density function was used to create a series of annual maps depicting intensity of trawling, as represented as percent of area trawled (Fig. 10). This yielded a spatial depiction of where trawling effects would be greatest.

To illustrate how a point-to-surface overlay can be used to solve a practical fisheries problem, the trawling intensity surface was overlain on data points reflecting the distribution of juvenile cod. This approach effectively illustrates that there is minimal overlap between the distribution of 0–3 year-old cod and moderate to heavily trawled areas (Fig. 11). Thus, fishery managers can conclude that trawling did not significantly affect abundance of juveniles.

To further demonstrate the analytical capabilities of the software, survey catches of American plaice, yellowtail flounder and cod were overlain on a temperature surface created by potential mapping (Fig. 12). An advantage of this approach is that multiple data sources can be analyzed together in a spatial environment.

A third example demonstrated how potential mapping can be used to estimate biomass and abundance using either survey or commercial fisheries data (Kulka and Pitcher 1998). Potential mapping was used to post-stratify thorny skate survey data, strata based on the distribution of the species (rather than depth). Areal expansion was then applied within the density strata created by potential mapping (Table 1). Because the strata covered the distribution of the species, density strata were created with more stations per stratum (than in the original survey design). Both survey and commercial fisheries data can be analysed in this manner.

**Ocean Data View**

R. Schlitzer demonstrated the capabilities of Ocean Data View (ODV). This freeware, available on the Internet at http://www.awi-bremerhaven.de/GEO/ODV/, was designed for interactive exploration and graphical display of multi-parameter profile or sequence
Fig. 4. Enlarged Variogram (of the plot located to right of map), generated through the Data_Dialog window for the bottom temperature survey. Catches of yellowtail flounder (number per tow) are overlaid as scaled symbols.

Fig. 5. Map of cod and yellowtail flounder by-catch, denoted by scaled symbol pie charts, in the American plaice fishery. The coloured surfaces represent bottom temperatures created using inverse distance weighting of bottom temperature measurements.
Fig. 6. (Upper panel) GMBIS selection page for interactive mapping of specimens from the Atlantic Reference Centre of the Huntsman Marine Science Centre. (Lower panel) GMBIS web page for the interactive electronic atlas showing output map.
Fig. 7. An example of the same survey data displayed as (A) point aggregation; (B) Voronoi polygons; (C) Contour (TIN) and (D) a potential map derived from point data indicating survey catches (kg per tow) of American plaice on the Grand Banks.

![Diagram of mapping methods]

\[
\text{Weighted Average of Z-values} = \frac{\sum (f_i w(d) z_i)}{\sum (f_i w(d))}
\]

where 
- \( z \) = Z-value
- \( i \) = each point at the centre of the sampling radii that overlap the quad cell
- \( f \) = frequency
- \( w(d) \) = distance weighting

Demonstration of the classified results of the Weighted Average of Z-values surface model using a linear decay of 0.5.

Fig. 8. Potential mapping model for the weighted value of Z (attribute associated with a geo-reference) (from Anon, 1999).
Fig. 9. Creation of a potential map from points using a circle of influence (left panel after Anon, 1999). The right panel shows: 1) the data points; 2) the resulting crescents, each with a unique value, formed by the overlap of circles; and 3) the user-classified surface derived from the crescent values.

Fig. 10. Maps of trawling intensity in the Canadian Atlantic in 1980 and 1998, created using the density function of potential mapping in SPANS (after Kulka and Pitcher, MS 2001).
TABLE 1. Calculation of thorny skate biomass based on density classes (strata) created using potential mapping (refer to Kulka and Pitcher 2001 for details).

<table>
<thead>
<tr>
<th>Density class</th>
<th>Set count</th>
<th>Div. 3LNOP area</th>
<th>Mean (kg per tow)</th>
<th>Biomass (kg)</th>
<th>Biomass (tons)</th>
<th>Stn. Dev.</th>
</tr>
</thead>
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<tr>
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<td>21</td>
<td>25 051</td>
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<td>21 762 527</td>
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<td>10.36</td>
<td>128 759 791</td>
<td>128 760</td>
<td>9.00</td>
</tr>
</tbody>
</table>

Data. The software can be run on PCs under Windows and Linux, on Macintosh under OS X and on UNIX workstations under SUN Solaris, SGI IRIX and IBM AIX. The software includes coastline and topographic data as well as various databases for a large number of topographic features (gazetteers). Although originally developed for analysis of oceanographic data, the software can model output from other disciplines such as fisheries science. The data format is designed for both compact storage and direct access and can support the construction of very large datasets. ODV allows the display of point data as either coloured circles or numeric values. In addition, variable-resolution gridding algorithms permit colour shading and contouring of gridded fields along sections and three-dimensional surfaces. A large number of derived variables can be selected, calculated and displayed on-line.

**Operational Modes**

ODV can operate in five different modes (MAP, STATION, SCATTER, SECTION and SURFACE), thereby providing different analysis methods and display types used in the scientific community. MAP mode produces high quality station or cruise maps of specific regions or of the entire globe. ODV allows a choice between five map projections and provides bathymetry and land topography information, as well as the boundaries of rivers, lakes, sea-ice extent and national borders. This information is available at different levels of resolution and can be used to compose various types of context maps. Specific stations can be highlighted and annotated. Maps can be produced as GIF, EMF, or PostScript files.
STATION mode (and all of the following modes) provides a station map and one or more data plot windows. This mode is appropriate for producing \(X/Y\) property/property plots for one or more selected stations or profiles and for studying differences between stations. The stations to be plotted can be selected using different methods, with the simplest method being to click on a station with the mouse. In SCATTER mode, data from all stations on the map are displayed in the data plots. This provides an overview of all data from a given region, cruise, or station subset and is particularly useful for data quality checking. SCATTER mode (and all of the following modes) supports \(Z\) variables in addition to \(X\) and \(Y\) variables. The value of a \(Z\) variable at a given \(X/Y\) point is displayed as either the actual numerical value or by value-dependent colour-coding. Plots with \(Z\)-variables (similar to SECTION and SURFACE plots described below) can be displayed in two ways: 1) as coloured circles at the \(X/Y\) locations or 2) as continuous, gridded fields estimated on the basis of the observed data. Gridded fields (see below for a description of the gridding algorithms) can be colour-shaded and/or contoured.

SECTION mode also supports \(Z\) variables on data plots and allows all plot types of the SCATTER mode, but the set of stations is restricted to a section band usually following given cruise tracks. Section bands can be defined arbitrarily and their width can be adjusted to properly select a set of stations. SECTION mode is appropriate for presenting property distributions and property/property plots for all stations along entire cruises and to calculate and investigate geostrophic velocities perpendicular to the cross-section of a cruise track.

SURFACE mode allows the specification of surfaces in three-dimensional space, defined as points of constant value for a given variable. For example, depth, density, or temperature surfaces can be displayed and overlain on property distributions of other variables. Figure 13 shows an example of SURFACE plots produced from groundfish survey catches of American plaice in the Grand Banks region.

**Gridding Algorithms**

In addition to displaying data points as numerical values or coloured circles, ODV can produce colour-shaded and/or contoured, gridded property distributions (Fig. 13). For the gridding process, ODV has two built-in gridding algorithms: *Quick Gridding* and *VG Gridding*. *Quick Gridding* is a fast method suitable for cases with good data coverage and yields results in a matter of seconds, even for large datasets having several hundred thousand points. The underlying algorithm is a weighted-average scheme with separate user-supplied averaging length scales in \(X\) and \(Y\) directions. To achieve fast performance, the data are tile-sorted prior to the averaging process and then for the estimation at a given \(X/Y\) position, only data values within a small neighborhood of the point are used in the averaging process.
For poor or heterogeneous data coverage, *VG Gridding* is preferred over the *Quick Gridding* method. In contrast to *Quick Gridding*, which uses an equidistant, rectangular grid for the estimation, *VG Gridding* analyzes the distribution of the data points and constructs a variable-resolution, rectangular grid, where grid spacing along the $X$ and $Y$ axes vary according to data density. High resolution (small grid spacing) is provided in regions with good data coverage, whereas in areas of sparse sampling the grid is coarse and resolution is limited. For typical hydrographic sections, this procedure leads to higher spatial resolution in the upper water column and in boundary current regions (data coverage is usually very good in these areas) as compared to the deep, open ocean regions.

After construction of the grid, the property under consideration (e.g., temperature, salinity) is estimated at every grid point by applying a weighted-average scheme using data values from the grid point neighborhood. Weights decrease with increasing distance from the grid point and user-specified length scales in $X$ and $Y$ directions are applied. Averaging length scales are proportional to the grid spacing. For example, in areas of higher grid-resolution such as the upper water column and boundary currents, smaller averaging length-scales are used automatically. This overall approach allows the resolution of small-scale features in areas of dense data coverage and provides smooth and stable fields in areas with sparse data coverage. Once a property field has been estimated, the results are passed to shading and contouring routines and output as a screen display or printable file.

**Generalized Additive Models**

Modelling of the spatial distribution of fish populations using non-parametric Generalized Additive Models (GAMs) was presented by M. Simpson. It was noted that while trend surface analysis could be used to model the spatial distribution of catches, higher-order polynomial regressions provide poor fits along the edge of the spatial distribution and only capture global patterns of the distribution. In contrast, GAMs extend the range of Generalized Linear Models by allowing non-parametric smoothers. Using GAMs, spatial trends in catch in relation to environmental variables can be investigated with R software.

Two smoothing functions are available in R: *s* (cubic B-spline) and *lo* (loess). Either can be used alone, or mixed with parametric functions. GAMs permit specification of the error distribution (such as binomial, gamma or Poisson). The latter type of error distribution is appropriate for survey data (Swartzman *et al.* 1992; O’Brien and Rago 1996). The model is fitted by iteratively smoothing partial residuals. The syntax involved in running the GAM in S-plus was followed in the presentation.

A step-wise GAM that modelled yellowtail flounder survey catches (kg per tow) was used to determine the best fit using the Akaike Information Criterion (AIC) test statistic. The
lowest AIC statistic gives the best combination of parameters for inclusion in the final model. To define the test criteria, the GAM equation was specified as:

\[
\text{gameq} < \text{formula(yelnum} \sim s(\text{DEPTH}) + s(\text{BTEMP}) + \text{LAT} + \text{LONG})
\]

where yellowtail flounder catch (yelnum) was modelled as a function of depth, bottom temperature, latitude and longitude. The step-wise criteria, in which the form of the smoother (i.e., lo or s) is specified in a scope list for each environmental variable, was defined as follows:

\[
\begin{align*}
''\text{DEPTH}'' &= \sim 1 + \text{DEPTH} + \text{lo}(\text{DEPTH}) + s(\text{DEPTH}), \\
''\text{BTEMP}'' &= \sim 1 + \text{BTEMP} + \text{lo}(\text{BTEMP}) + s(\text{BTEMP}),
\end{align*}
\]

The step-wise routine generated an AIC statistic for each iteration to evaluate the model.

Start:  \(\text{yelnum} \sim s(\text{DEPTH}) + s(\text{BTEMP}) + \text{LAT} + \text{LONG}; \ \text{AIC} = 13960.87\)
Trial:  \(\text{yelnum} \sim \text{lo}(\text{DEPTH}) + s(\text{BTEMP}) + \text{LAT} + \text{LONG}; \ \text{AIC} = 15791.23\)
Trial:  \(\text{yelnum} \sim s(\text{DEPTH}) + \text{lo}(\text{BTEMP}) + \text{LAT} + \text{LONG}; \ \text{AIC} = 14469.87\)
Trial:  \(\text{yelnum} \sim s(\text{DEPTH}) + s(\text{BTEMP}) + 1 + \text{LONG}; \ \text{AIC} = 14729.04\)
Trial:  \(\text{yelnum} \sim s(\text{DEPTH}) + s(\text{BTEMP}) + \text{LAT} + 1; \ \text{AIC} = 16656.19\)

An evaluation of the model results demonstrated that the cubic B-spline smoother provided the best fit. Following model verification, the GAM produced a plot of the interpolated values in the survey area by using the commands:

\[
yellowtailGAM<-\text{gam(gameq,family }= \text{poisson,data }= \text{yellowtail)} \\
i<-\text{interp(LONG,LAT,yellowtailGAM$fitted)} \\
\text{image(i,xlab }= \text{"Longitude",ylab }= \text{"Latitude",xlim }= \text{c(-55,-47))} \\
\text{contour(i,add }= \text{T,levels }= \text{15)} \\
zcat<-\text{(yellowtailGAM$fitted)}
\]

The commands shown above will produce a plot of the fitted output from the GAM that can then be annotated with additional commands to specify the title, legend, coast, depth contours and NAFO Division boundaries (Fig. 14).

To evaluate the model, a model summary can be produced by issuing the commands \textit{summary(yellowtailGAM)} to display the Deviance Residuals:

Null Deviance: 86140.62 on 503 degrees of freedom
Residual Deviance: 13938.91 on 493.022 degrees of freedom
Number of Local Scoring Iterations: 6
Fig. 11. Average number per tow (top), percent of total abundance (middle) and percent occurrence (bottom) of 0 to 3 year-old cod in non-trawled to highly-trawled areas.

Fig. 12. Relationships between American plaice, cod and yellowtail flounder densities (number per tow) and bottom temperatures derived by a point (species density) to surface (temperature) overlay.
Fig. 13. Distribution of American plaice based on 1997-99 survey catches (kg per tow) in the Grand Banks region as examples of ODV map displays. The black dots represent the positions of the original data.

Fig. 14. Map of yellowtail flounder distribution on the Grand Banks based on spring survey data fit using a GAM.
from which a Pseudo-R² (O'Brien and Rago, 1996) can be calculated using the formula (1-residual deviance/Null deviance). In this example, the Pseudo-R² is 0.8381 and provides an indication of model fit.

GAMs, in contrast to some analytical procedures, do not make *a priori* assumptions about underlying data relationships. As a result, the data drive the fit of the model. The GAM also permits the user to visualize the additive contribution of each variable to the respective response using smoothed functions (Fig. 15).

GAMs are a powerful exploratory tool for detecting simple and complex relationships in survey distributions. Unlike tessellation methods (in which exterior polygons/triangles are undefined and no variance is associated with the interpolated points) or trend surface analyses (which only show global scale trends and have difficulty fitting the surface near edge of the distribution), GAMs are best suited to handle the nonlinear relationships between fishery catch distributions and environmental variables (e.g., depth, temperature, sediment type and salinity).

**Solving a Fisheries-related Question**

Practical examples of how spatial analysis can be used to solve a fisheries question were demonstrated in ODV, R, ACON and SPANS using the Grand Banks data. The objective of the analysis was to define the geographic overlap in the distributions of American plaice and yellowtail flounder on the Grand Banks.

**Ocean Data View**

ODV was used to generate the distribution maps for the two species based on the multi-year Grand Banks survey dataset (Fig. 16a and b).

American plaice is highest abundance in a northwest-southeastward band on the southern Grand Banks, whereas yellowtail flounder is most abundant in a north-south ellipse, situated eastward of the American plaice aggregation. There is clearly some overlap of the two species. However, precise location and extent of the overlap is difficult to determine from Figure 16 alone.

For a quantitative treatment of the problem, the American plaice and yellowtail flounder data were plotted against one another (Fig. 17a), with the data points in the overlap range (simultaneous high yield for both species; marked by a red polygon in Fig. 17a) highlighted in green. When the overlapping data are plotted in a map (Fig. 17b), the green points form a well-defined area in the southern Grand Banks region. Note that the definition and highlighting of overlap points were implemented using ODV's Patch derived variables. Refinements illustrating the degree of overlap are possible by specifying more than one patch.

**R-Geostatistics**

R-geostatistical routines were applied to quantify the spatial overlap between yellowtail flounder and American plaice. Following the protocols of Bez and Rivoirard (2000), each
species was represented by an ellipse whose focus was centered at the center of mass of the population. The inertia of the mass of fish around their central location, i.e. the fish dispersal, can be decomposed into the directions in which fish are most and least dispersed, which results in defining a fish distribution as an ellipse. The surfaces of the ellipses are equal to the equivalent surface (Bez and Rivoirard, 2001) of each population (Fig. 18). The spatial overlap between the ellipses of the two species can be quantified by a Global Index of Collocation which ranges from 0 when the overlap is null to 1 for complete overlap. In the present case, the overlap is moderate (Fig 18a) as annual GIC values are between 0.5 and 0.7 (Fig. 18b). The spatial overlap between the two species increased during the 1996–2002 period (Fig. 18b).

ACON

A geo-referenced pie chart graphic of the co-occurrence of yellowtail flounder and American plaice was generated to define the distribution, co-occurrence and relative abundance of the two species (Fig. 19). In this example, aggregation by 10-minute square provided fine scale structure along the shelf edge, in areas of high sampling intensity. However, the method does not produce global estimates for the frequency, magnitude, or variance of co-occurrence. Bottom temperature observations are contoured, as temperature is considered a continuous variable for which interpolation between adjacent observations produces a reasonable representation. However, the spatial extent of contour interpolation was constrained because the Delaunay triangulated bottom temperature data in the upper right corner of the map extended the interpolation beyond an acceptable (arbitrary) sampling distance. As a result, a "hole" appears in the contour surface.

SPANS

Matrix modeling was applied to spatially define the overlap of the distributions of the two flatfish species on the Grand Banks. Potential maps of American plaice and yellowtail flounder were first created from the survey data (kg per tow) and then overlaid using a matrix model to produce a matrix of zeros where columns defined yellowtail density and rows defined American plaice density. The matrix was then revised using a numerical classification scheme based on the degree of spatial overlap between the two species (table in Fig. 20) and a map produced illustrating the distributional overlap between the two flatfishes (map in Fig. 20).

Utilization of Geostatistics for Mapping

N. Bez presented a lecture on the utilization of geostatistics for mapping. Additional lectures on geostatistical concepts and methods were followed by hands-on exercises using Grand Banks survey and fisheries data.

History, theory and concepts

An overview was presented on the origin of geostatistical techniques in the mining industry to solve the problem of systematic over-estimation of gold reserves. The use of geostatistical tools in fisheries has gradually increased since Laurec (1977) first used geostatistics to estimate
Fig. 15. Scatterplot smooths and partial fits, with 95% confidence limits (dashed lines), of depth (top left), bottom temperature (top right), latitude (bottom left) and longitude (bottom right) for a Generalized Additive Model (GAM) of yellowtail flounder spring survey catches (kg per tow) on the Grand Banks.

Fig. 16. Distribution of (a) American plaice and (b) yellowtail flounder in the Grand Banks region for the eight-year period, 1996–2003.
Fig. 17 (a) Plot of American plaice and yellowtail flounder abundance data indicating the region of geographic overlap of the two species (red polygon and green data points); and (b) map of the Grand Banks region showing the geographical distribution of the overlapping points.

Fig. 18 Spatial overlap between yellowtail flounder (black ellipses) and American plaice (red ellipses) in the 1996–2002 DFO spring Grand Banks bottom trawl surveys. (a) Summary spatial distributions using centers of mass and inertia. (b) Evolution of the Global Index of Collocation (GIC) with time.
fishing power. Thereafter, Conan (1985), Laloé (1985) and Gohin (1985) utilized geostatistics to analyze fisheries data. Since 1985, fisheries applications of geostatistical methods have primarily focused on analyzing acoustics data, in part, because these methods were recommended for use by a 1991 ICES acoustic survey data workshop (ICES, 1993).

**Consideration of the spatial aspects of fish distributions**

The classical method of estimating the precision of spatial estimates is to compute the estimation variance by using the formula:

\[
\sigma^2_E = \frac{s^2}{N}
\]

where \(N\) represents the number of samples, \(s^2\) represents the experimental variance of the data and \(\sigma^2_E\) represents the estimation variance. However, the equation is based on the assumption that the number of samples can be considered as \(N\) outcomes of \(N\) variables that are independent and identically distributed in space (spatial homogeneity of the distribution). Independence can be attained in practice only if samples are located at random or if the underlying fish distribution has no spatial structure, and this is seldom the case.

Whether the objective of a survey is to target a particular population or to sample the distribution of multiple species, the area of occupancy of a given species is often bounded by stations with no catch of that species. The zero catches represent valuable information as they provide insight as to whether the area of occupancy of the target species has been adequately sampled. However, for the very same reason, zero catches also affect the classic tools used to analyze survey data such as histograms, means, variances and regressions. Alternative analytic approaches are available that are robust with respect to zero catches (e.g. transitive geostatistics) or which delineate the distributional area of a species by statistically describing the habitat characteristics intrinsic to that species. This latter approach, intrinsic geostatistics, consists of the use of variograms and the production of kriging maps.

**Identification of spatial structure using variograms and kriging**

The variogram is a tool used for describing the spatial structure of a variable. The variogram is a representation of the decomposition of the overall variance into distance classes. The variogram allows for the determination of the spatial scales (small or large-scale) most responsible for the overall variance. An example of a one-dimensional variogram was presented and participants computed the variogram by hand, to better understand the application of the algorithm. The estimation of two-dimensional (bi-directional) variograms was also discussed. Experimental variograms are sensitive to: distance lag, field size and shape, outliers and their location in the field and the homogeneity of the population.

The effects of adjusting the distance and direction lags on the variogram were noted. The possible use of tolerance values in cases where samples are not regularly spaced was discussed and the avoidance of overlapping distance and direction classes was recommended to avert double counting.
An example was presented, based on piezometric levels of an aquifer at various geological depths, to illustrate the interpretation of experimental variograms. The example demonstrated that the evolution of the experimental variogram is associated with the evolution from a pure nugget effect to a strong, small-scale spatial structure.

The variogram allows for the computation of the estimation variance. Thus, variogram models must be chosen that preclude negative variance estimates. Possible functions for use in fitting an experimental variogram were presented. Fitting rules available in the software include manual, semi-automatic and completely automatic. The selection of a variogram model should be based on: a) the spatial distribution of the sample data; b) any biological knowledge of small-scale spatial structure; and c) the level of measurement error associated with the sampling gear.

The variogram model is used in kriging. Kriging allows for estimation of the density at an unknown point and minimizes the estimation variance by using an algorithm that defines the weights to apply to sample data when interpolating between known points. The mathematical basis of kriging was explained and the impact of model parameters (type of model, range, or sill) on kriging outputs was demonstrated using various examples.

**Methods for summarizing spatial distributions**

In some cases, particularly when there are a large number of surveys or number of species, spatial distributions may be summarized using quick and more robust tools. For example, the center of mass and the inertia of sample values can be used to represent the mean location of a population and its dispersal about this mean. As in PCA analysis, the inertia can be decomposed into the directions in which fish are most and least dispersed, thereby defining the fish distribution as an ellipse.

**Other geostatistical methods**

Geostatistical methods other than kriging were briefly covered. Particular attention was focused on the difference between local estimation (i.e., a kriging map) and global estimation (i.e. the estimation of fish densities over a given stratum, multiple strata, or a given area). In the case of a stratified, random survey, a kriging map can be used to estimate the biomass within a stratum by summing the kriging values estimated at all grid nodes within that particular stratum multiplied by the area of a grid cell. However, a global estimation variance for each stratum must be computed using a different procedure (Rivoirard et al., 2000) and a weighted average computed by summing the stratum variances across all strata.

Multivariate geostatistics and the use of cross variograms for co-kriging was covered briefly, as were issues relating to species-specific survey designs and the impact of the size of the area swept by the trawl.

**Geostatistical analyses of Grand Banks data sets**

Geostatistical analyses incorporating data sets from the Grand Banks were conducted using R software (freeware) and geostatistical routines developed by the Centre de Géostatistique. This allowed the participants to use and test the geostatistical tools presented.
In the case of multi-species surveys, geostatistical models will typically be species and year-specific, but this depends on the objective of the analysis. No two Grand Banks species have the same spatial distribution patterns, so due to time limitations, analyses were focused on yellowtail flounder.

The spatial structure of yellowtail flounder was related to several environmental variables, such as depth and bottom temperature, and biological variables such as Greenland halibut. The potential use of CPUE data to describe the spatial structure of species was also examined.

**Yellowtail flounder**

Yellowtail flounder were concentrated in the southern portion of the Grand Banks during 1996–2002 (Fig. 21).

Figures 22–24 illustrate the steps in preparing a kriging map of yellowtail flounder abundance using the spring 2000 survey data ($N = 101$ stations). The selection of a particular area of occupancy affects the variance level and relative shape of the variogram (Fig. 22). As is often the case with fisheries data, the spatial structure of yellowtail flounder during spring 2000 exhibited a strong random component (nugget effect). The nugget effect quantifies the amount of spatial structure that is unknown and attributable to inter-sample distance (the average distance between nearest neighbors) and measurement error. In the yellowtail flounder example, the nugget effect represents half of the overall variability. The rest of the variability is explained by a spatial structure with a range of 80 nautical miles, implying that fish densities at stations greater than 80 naut. miles apart are not correlated.

After a model was fitted to the experimental variogram (Fig. 23), a kriging map and a kriging variance map (Fig. 24) were prepared. The raw values for yellowtail flounder abundance were superimposed on both maps to check the accuracy of the interpolations.

**Depth**

An experimental variogram for depth (i.e., a variable with an *a priori* strong spatial structure) was compared with that for yellowtail flounder. The depth variogram is more stable (Fig. 25) than that obtained for yellowtail flounder. Nevertheless, the depth variogram displays some nugget effect, indicating that either depth is not accurately measured or that depth can change quite quickly with respect to the inter-sample distance.

**Greenland halibut**

Trawl surveys show that Greenland halibut are distributed along the shelf edge (Fig. 26). This spatial characteristic must be taken into account in a spatial interpolation. Therefore, a transformation was conducted of the sampling coordinates into a reference system having an axis across the shelf edge and another one along the shelf edge (Fig. 26). Using the new reference system, a complete geostatistical analysis was undertaken in which a variogram and kriging map were produced. The kriging results were then back-transformed into a geographical reference system (Fig. 27).
CPUE

The potential use of CPUE (catch per unit effort) data to describe the spatial structure of yellowtail flounder was also assessed. Given the very dense concentration of CPUE data points in space and time, a short distance lag was used (0.5 naut. miles). To avoid comparing CPUE data collected too far apart in time, a time lag was also used. Nonetheless, the CPUE variogram displays a high level of local heterogeneity (the nugget effect accounts for half of the variability), although a spatial structure of several nautical miles is apparent (Fig. 28).
Fig. 19. ACON generated map of yellowtail flounder and American plaice abundance and distribution patterns on the Grand Banks, denoted by scaled symbol pie charts. Colored surfaces represent bottom temperature created using inverse distance weighted gradient interpolation of bottom temperature measurements.

<table>
<thead>
<tr>
<th>Plaice kg per tow</th>
<th>Yellowtail kg per tow</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0-15</td>
<td>0 1 1 1 1</td>
</tr>
<tr>
<td>15-75</td>
<td>0 1 2 2 3</td>
</tr>
<tr>
<td>75-200</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>200+</td>
<td>0 1 3 4 5</td>
</tr>
</tbody>
</table>

Fig. 20. Matrix overlay analysis of American plaice and yellowtail flounder. The table above the map shows the matrix used to reclassify the overlay of the potential maps of the two species. The map resulting from the matrix overlay shows the degree of overlap between the two flatfishes (1 - no overlap, 5 greatest overlap). The areas of overlap can then be compared to the fishing grounds (red lines overlaying the area).
Fig. 21. Yellowtail flounder distribution (number per tow) based on the Canadian spring bottom trawl surveys conducted on the Grand Banks during 1996–2002 and the habitat polygon utilized in a kriging analysis. The diameter of the red circles increases with flounder density and the black crosses represent stations where no yellowtails were caught.

Fig. 22. Experimental variograms, presented in raw (top) and normalized variance scales (bottom), of yellowtail flounder abundance (number per tow) on the Grand Banks as reflected in the 2000 spring bottom trawl survey. Variograms are presented with (black line) and without (red line) the inclusion of stations with no yellowtail flounder catch and which lie beyond the boundary of the habitat polygon (see Fig. 21).
Fig. 23. An experimental variogram (left), computed for all directions and variogram model (red line) for yellowtail flounder abundance (number per tow) on the Grand Banks based on data from the 2000 spring Canadian bottom trawl survey. The variogram and model are based on the habitat area delineated in Fig. 21. A kriging map (right) based on the variogram model is shown with iso-density contours (highest densities are shown in red) with the 200 m and 400 m isobaths depicted in green.

Fig. 24. Kriging map (left) showing the estimated distribution of yellowtail flounder on the Grand Banks, including the raw data points and the associated kriging variance map (right). The highest densities and variance values are shown in red and the 200 m and 400 m isobaths are shown in green.
Fig. 25. Variogram (upper panel), computed for all directions, of depths (m) sampled during the 1996–2002 Canadian spring bottom trawl surveys of the Grand Banks. The variogram model (red line) is superimposed on the experimental variogram. The kriging map of depth (with a unique neighborhood) is shown at 50-m depth contour intervals (lower panel).
Fig. 26. Spatial distribution of Greenland halibut during 1996–2002 Canadian spring bottom trawl surveys. Red circles increase in size with increasing halibut density and black crosses indicate stations with no halibut catch. The polygon indicates the selected area of occupancy (left) and the location of the selected points within this area are shown across (x axis, in naut. miles) the shelf edge and along (y axis, in naut. miles) the shelf edge (right).
Fig. 27. Variogram (left) of Greenland halibut density along the shelf edge of the Grand Banks as reflected in the 1996–2002 Canadian spring bottom trawl surveys. The variogram model (red line) is superimposed on the experimental variogram. A kriging map (with a unique neighborhood) illustrates Greenland halibut density in relation to the 200 m and 400 m isobaths (right).

Fig. 28. Variogram of yellowtail flounder weekly CPUE on the Grand Banks during 2000, based on a distance lag of 0.5 naut. miles. The variogram model (red line) is superimposed on the experimental variogram.
Conclusions

The impetus for the September 2003 workshop was the lack of familiarity with the geostatistical analyses evinced by many Scientific Council members presented at the June 2001 Scientific Council meeting (GAM and kriging results in Walsh et al. 2001). As a result of this workshop, the participants felt they had developed a better understanding of basic geostatistical concepts and methods, particularly kriging. In addition, the workshop provided members with software tools and hands-on exercises that could be applied in the future to geo-referenced data from the NAFO region.

Participants discussed how they might apply the knowledge gained at the workshop. A recommendation was made to investigate efficient ways of incorporating mapping and geostatistical analyses into NAFO stock assessments, possibly by accessing these tools via an internet site, such as the GMBIS web site, which already provides a mechanism for mapping user-defined geo-referenced data. However, it was also noted that the time commitment and programming knowledge required for this task represent potential obstacles to implementation. Multiple participants expressed positive feedback about the workshop, particularly with respect to covering such a complex topic, in a short time span, in an understandable way, and with the use of NAFO data sets. Participants also noted that they felt that the knowledge gained at the workshop would now allow them to apply geostatistical analyses in their NAFO stock assessments.

Acknowledgements

The Scientific Council would like to thank the NAFO Contracting Parties for funding the geostatistics expert, Nicolas Bez, who served as the principal workshop instructor. The Council also thanks Canada and the EU for funding the travel costs of the other instructors; David Kulka, Jerry Black and Mark Simpson (Canada) and Reiner Schlitzer (EU, Germany). The quality of the workshop was greatly enhanced by the presence of these instructors. The Council is grateful to Canada for providing two information technology experts (Pete Rioux and Todd Janes) and a wireless LAN system that greatly improved the efficiency of the workshop. We deeply appreciated the assistance from Johanne Fischer (NAFO Executive Secretary) and the NAFO staff for their assistance with the organization of workshop logistics and hospitality. Thanks also go to Fred Serchuk for his helpful comments and technical editing.

References

BEZ, N. and J. RIVOIRARD. 2001. Transitive geostatistics to characterise spatial aggregations with diffuse
Appendix 1. Workshop Agenda

Day 1

0800–0900 Establish LAN connections and download software

0900–0930 **Introduction**
Workshop Objectives, Agenda and Introduction of Instructors (D. Kulka/L. Hendrickson)

0930–1000 **Overview**
Workshop overview and brief history of geostatistics use in fisheries stock assessment (N. Bez)
- Data visualization (mapping techniques)
- Interpolation techniques – Point to Surface Transformation (i.e. Contouring, Voronoi, Potential Mapping, Kriging)
- Overlay modeling
- Geostatistics

**Data Visualization**

1000–1015 **Overview of mapping** (D. Kulka)
The value of visualization of biological and environmental data in the marine context will be reviewed. Spatial data structure will be described and illustrated.

1015–1035 **Break**

1035–1200 **Use of ACON software** (G. Black)
Participants will use ACON software (freeware) to map and analyze survey data. Transformation and visualization of point patterns to surface distributions will be examined. Tesselation methods such as plotting Voronoi polygons and the use of Delaunay triangulation will be described.

1200–1330 **Lunch**

1330–1430 **SPANS software demonstration** (D. Kulka)
Key functions in SPANS (Spatial Analysis System), a GIS, will be demonstrated. Potential mapping, a point to surface transformation will be demonstrated. Potential mapping provides an optimal interpolated estimate for locations that were not sampled. The resulting classified surface (raster) facilitates analyses not possible with the original point data.

1430–1500 **Generalized Additive Models** (M. Simpson)

1500–1520 **Break**

1520–1830 **Use of Ocean Data View software** (R. Schlitzer)
Participants will use Ocean Data View software to map and analyze NAFO survey data. This exercise will involve exploration and visualization of oceanographic and other geo-referenced profile or sequence data.
Day 2

Geostatistics

0830–1030 **Surface Overlay and Data Modelling** (D. Kulka)
Demonstration of overlaying surfaces and modeling to examine spatial relationships or to calculate spatial statistics. Examples will include species co-occurrence, habitat preferences and biomass calculations using NAFO data.

1030–1050 **Break**

1050–1200 **Why should we use geostatistics?** (N. Bez)
- Sampling Theory (Cochran, 1977) is based on the assumption that the sample values can be modeled as independent and identically distributed random variables. Each of these concepts will be discussed. When this framework is not consistent with the characteristics of either the sampling or the data, one alternative method is to use geostatistics.
- Modeling and use the use of autocorrelation present in the sample values of a given variable. Kriging will be presented as a method to allow weighting of the data according to a) spatial structure, b) relative location in space and c) position relative to the point or the polygon to be estimated.
- Analysis of spatially-correlated (multivariate geostatistics).

1200–1330 **Lunch**

1330–1530 **The variogram** (N. Bez)
- Background on variance
- Decomposition of the variance into distance bins
- Random functions
- Variogram definition
- Estimation of the variogram in practice
- Models
- Properties
- Interpretation of the spatial structure

1530–1550 **Break**

1550–1730 **Estimation and interpretation of experimental variograms** (N. Bez)
- Exercises using R (freeware version of Splus) and geostatistical routines.

Day 3

0830–1030 **The variogram, continued** (N. Bez)
- The variogram as a tool to compute variances
- Nugget effect and the reduction of variance
- Cases where statistics is relevant (pure nugget effects)
- Weighted variograms
Kriging

- Principles
- Equations
- Kriging properties
- Illustrations
- Difference between the variable and its kriging
- Kriging weights
- Local estimation as opposed to global estimations

1030–1050  *Break*

1050–1200  **Kriging exercises** (N. Bez)

Objectives include modeling the variograms and using them for kriging. Changes in the output maps by varying the variogram parameters will be examined.

1200–1330  *Lunch*

1330–1530  **Elements of the transitive geostatistical approach** (N. Bez)

- Center of Gravity and Inertia to summarize survey maps and to describe a series of survey data.
- Elements of global estimation (estimation variances, survey design, etc.)
- Presentation of alternative software (EVA, Isatis)

1530–1550  *Break*

1550–1700  **Wrap-up discussion**
Workshop Participants

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Information for Preparing Manuscripts for NAFO Scientific Publications

Introduction

The manuscript should be in English. The sequence of the material should be: title page, Abstract, text including Introduction, Materials and Methods, Results, Discussion and Acknowledgements and References. Number all pages, including the title page, consecutively with arabic numbers in the center of the top margin. There is usually no page limitation or page charge for accepted publications.

Content of Manuscript

Title page

This page should contain the title, followed by the name(s) and address(es) of the author(s) including professional affiliation, and any related footnotes. The title should be limited to what is documented in the manuscript and be as concise as possible. Where necessary the scientific names of species should be included.

Abstract

An informative abstract must be provided, which does not exceed one double-spaced page or about 250 words, the ultimate length being dependent on the size of the manuscript. The abstract should concisely indicate the content and emphasis of the paper. It should begin with the main conclusion from the study and be supported by statements of relevant findings. The scientific names of species where necessary should be included here. It is important that the abstract accurately reflect the contents of the paper because it is often separated from the main body of the paper by abstracting and indexing services.

Text

In general, the text should be organized into Introduction, Materials and Methods, Results, Discussion, Acknowledgements and References. Authors should be guided by the organization of papers that have been published in the NAFO Journal or Studies and by such authorities as the Council of Biological Editors Style Manual (CBE, 9650 Rockville Pike, Bethesda, MD 20814, USA).

The Introduction should be limited to the purpose and rationale of the study. The article should begin with a clear description of the subject (include where necessary the scientific names of species), stating the hypothesis and/or defining the problem(s) the research was designed to solve. Define the time of the study, along with literature review and other information limited to what is relevant to the problem.

The Materials and Methods should provide the framework for obtaining answers to the problems which concern the purpose of the study. Describe in sufficient detail the materials and methods used so as to enable other scientists to evaluate the work or replicate the work.

The Results should answer the questions evolving from the purpose of the study in a comprehensive manner in an orderly and coherent sequence, with illustrative tables and figures. Ensure only relevant information is presented to substantiate the findings. Avoid any confusion between facts and inferences and the restatement of table and figure captions in the text.

The Discussion should give the main contributions from the study, with appropriate interpretation of the results focusing on the problem or hypothesis. Compare with those of other authors. Speculation should be limited to what can be supported with reasonable evidence. In the case of short papers, it may be useful to combine Results and Discussion to avoid repetition.

The Acknowledgements should be limited to the names of individuals who provided significant scientific and technical support, including reviews, during the preparation of the manuscript, and the names of agencies which provided financial support.

The References represents the list of references cited in the text listed alphabetically. Good judgment should be used in the selection of references, which should be restricted largely to significant published literature. Unpublished data and documents, manuscripts in preparation, and manuscripts awaiting acceptance to other journals may be noted in the text as unpublished data or personal communications, with full contact addresses.

Literature references cited in the text must be by author's surname and year of publication, e.g. (Collins, 1960). The surnames of two authors may be used in a citation, but, for more than two authors the citation should be (Collins et al., 1960). The citation of mimeographed manuscript reports and meeting documents should contain the abbreviation "MS", e.g. (Collins et al., MS 1960). All papers referred to in the text must be cited in the References alphabetically by the first author's surname and initials, followed by the initials and surnames of other authors, year of publication, full title of the paper, name of the periodical, volume and/or number, and range of pages. Abbreviations of periodicals should, if possible, follow the "World List of Aquatic Sciences and Fisheries Serials Titles", published periodically by FAO (Food and Agriculture Organization of the United Nations). References to monographs should, in addition to the author(s), year and title, contain the name and place of the publisher and the number of pages in the volume. Reference to a paper in a book containing a collection of papers should also contain the page range of the paper, name(s) of editor(s), and actual title of the book. The accuracy of all references and their correspondence with text citations is the responsibility of the author.

Comments on Tables and Figures

All Tables and Figures must be mentioned or discussed in the text. Tables and Figures must be numbered consecutively in arabic numerals, which correspond with the order of presentation in the text. The required position of the Tables and Figures in the text should be indicated in the left margin of the relevant page. Place the originals of Tables and Figures after the list of references.
Tables. Note a well-constructed Table can eliminate elaborate text descriptions. Each Table should be carefully constructed to be easily read and understood. Each column and row must be concisely headed, ensuring relevant units of the values are given (usually within parentheses). Each Table should have a complete but concise descriptive heading, and should be on a separate sheet.

Figures. Note any reference to geographic areas relevant to the study should be shown in a Figure (or map) form giving coordinates. These and illustrations and photographs can eliminate elaborate text descriptions.

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When preparing figures, consideration should be given to details such as shading and lettering with respect to the effects of reduction in size to a page width (e.g. lettering should not be overbearing or too small). If oversized figures are necessary, only good quality page-size photocopies should be submitted. If the paper contains photographs, ensure they have good contrast whether they are in colour or black and white.

Mathematical equations and formulae must be accurately stated, with clear definitions of the various letters and symbols. If logarithmic expressions are used, the type of function (e.g. log, ln, log_{10} or log_{e}) must be clearly indicated.

Manuscript Submission

NOTE: The following are the two major NAFO scientific publications, while the Scientific Council Research Documents (SCR Doc.) and Summary Document (SCS Doc.) are series that are submitted for meeting considerations.

The NAFO Secretariat now prefers to receive manuscript submissions, for any of the above publications in a computer electronic form.

The manuscript submissions may be done by e-mail (with a hard copy and diskette also forwarded by mail), or by mail (one hard copy and diskette). All texts, Tables and Figures should be formatted using Word or WordPerfect (Word is preferred), with each Table and Figure saved in a separate file (eps preferably), tiff, pct, jpg, bmp or gif.

Please note: In view of the considerable costs involved in colour printing, the NAFO Secretariat will be printing figures not requiring full colour in grayscale unless colour contributes to the content of the figure.

The Secretariat may request alternative formats as publication technologies develop.

Journal of Northwest Atlantic Fishery Science

The Journal provides a forum for the primary publication of original research papers. While it is intended to be regional in scope, papers of general applicability and methodology, irrespective of region, may be considered. Both practical and theoretical papers are eligible. Space is also provided for notes, letters to the editor and notices.

Such manuscripts are considered for publication with the understanding that the content is unpublished and is not being submitted elsewhere for publication. Each manuscript is assigned to an Associate Editor of the Journals Editorial Board, for scientific editing. Papers are normally sent by the Associate Editors to two referees for appraisal regarding its suitability as a primary article.

NAFO Scientific Council Studies

The Studies publishes papers which are of topical interest and importance to the current and future activities of the Scientific Council, but which are not considered to be sufficiently high quality to meet the standards for primary publication in the Journal. Such papers have usually been presented as research documents at Scientific Council meetings and nominated for publication by the Standing Committee on Publications. These manuscripts are not normally refereed but undergo critical scrutiny by the Studies editor and by an expert familiar with the subject matter selected from the Journal editorial board.

Manuscripts (one hard copy and one copy saved on a computer diskette) being submitted should be addressed to:

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Scientific Publications of the Northwest Atlantic Fisheries Organization

Journal of Northwest Atlantic Fishery Science

The Journal provides an international forum for the primary publication of original research papers on fisheries science in the Northwest Atlantic, with emphasis on environmental, biological, ecological and fishery aspects of the living marine resources and ecosystems. (Scientific publications during ICNAF times during 1949–79 are available at the Secretariat).

Vol. 6, No. 1, 2 – Miscellaneous papers, (17), June and December 1985, 179 pp.
Vol. 9 – Miscellaneous papers, (13), September and December 1989, 159 pp.
Vol. 27 – Symposium papers (22) (1 Note), Pandalid Shrimp Fisheries – Science and Management at the Millennium, December 2000, 289 pp.
Vol. 35 – Symposium papers (43), Elasmobranch Fisheries: Managing for Sustainable Use and Biodiversity Conservation, April, 2005, 544 pp.
NAFO Scientific Council Studies

This publication includes papers of topical interest and importance to the current and future activities of the Scientific Council.


NAFO Scientific Council Studies (Continued)

No. 3  –  Miscellaneous papers, (8), April 1982, 82 pp.
No. 6  –  Miscellaneous papers, (9), December 1983, 104 pp.
No. 7  –  Miscellaneous papers, (9), August 1984, 98 pp.
No. 8  –  Miscellaneous papers, (12), April 1985, 96 pp.
No. 9  –  Special Session papers, (17), on *Squids*, November 1985, 180 pp.
No. 11 –  Miscellaneous papers, (11), March 1987, 127 pp.
No. 12 –  Miscellaneous papers, (8), March 1988, 90 pp.
No. 18 –  Symposium papers, (18), on *Changes in Abundance and Biology of Cod Stocks and Their Possible Causes*, July 1993, 110 pp.
No. 19 –  Miscellaneous papers, (8), October 1993, 98 pp.
No. 20 –  Miscellaneous papers, (7), February 1994, 114 pp.
No. 22 –  Miscellaneous papers, (6), May 1995, 95 pp.
No. 23 –  Miscellaneous papers, (5), September 1995, 95 pp.
No. 27 –  Miscellaneous papers, (5), (1 Note), December 1996, 81 pp.
No. 28 –  Special Session papers, (6), on *Assessment of Groundfish Stocks Based on Bottom Trawl Survey Results*, December 1996, 105 pp.
No. 32 –  Miscellaneous papers, (8), April 1999, 133 pp.

NAFO Scientific Council Reports

This publication contains reports of Scientific Council Meetings held through each year since NAFO replaced ICNAF. (The comparable publication during ICNAF was called the Redbook).

NAFO Scientific Council Reports (Continued)

(Supplement)

NAFO Statistical Bulletin

This publication replaced ICNAF Statistical Bulletin which terminated with Vol. 28 (revised). The volume numbering continues the series as the NAFO Statistical Bulletin.

Inventory of Sampling Data

This publication replaced *ICNAF Inventory of Sampling Data 1967–1978* which was completed in 1986.


NAFO Index of Meeting Documents

This publication contains lists of all documents along with a subject and author index of the NAFO Scientific Council documents issued during 5-year periods.

- 1979–84 – Index of Meeting Documents, Published March 1985, 146 pp.