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Data for coastal GIS: issues and implications for management

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ABSTRACT: Geographic information systems can provide easy access to large quantities of geographically-referenced data for monitoring, planning and environmental decision support for coastal applications. The dynamic and variable nature of the coastal ocean environment gives rise to data issues different than those associated with land-based GIS. This paper investigates, in particular, the use of different data, including those produced by numerical simulations or ocean models, for coastal management and is illustrated with examples from a Baltic Sea GIS implementation. Implications for the use of these data in environmental management are discussed.

Introduction

The coastal zone is defined as the boundary between land and ocean, extending from the continental shelf break landwards to the coastal plains (IGBP 1990). Although this highly dynamic area only covers about 8 percent of the world's surface, it contributes 25 percent of the global biological production. More than 50 percent of the global population live within 60 km of the water's edge and more than 90 percent of the world's marine fish catch come from this area. A myriad of coastal ecosystems inhabit the coastal zone including swamp, salt marsh, estuary, lagoon, intertidal, inshore, dunes, and offshore islands; all are interrelated and vital to coastal fish and wildlife. And although external to coastal ecosystems, outputs (e.g., nutrient pollution), from upland terrestrial systems such as urban and agricultural complexes, also flow through the coastal zone and must also be included. However, while the components of the coastal zone can be identified, processes and properties within each ecosystem and, in particular, the relationships and feedbacks among component parts are not always well-known.

Environmental managers and planners need to have access to a diverse range of high quality data relating to the aforementioned components in order to inventory, monitor, and ultimately make decisions about phenomena occurring within and across the coastal zone. These data must include both the marine and terrestrial environments and cover economic and social statistics as well as physical and biological parameters. And all of the data must be geographically referenced.

The success of geographic information systems (GIS) in the management and analysis of land-based data is well-established (Maguire et al. 1991). While routinely used for tasks such as utilities management, land use planning and habitat (or Gap) analyses, the use of GIS has been developed to a lesser extent for the marine environment. And although the number of applications developed for coastal zone planning and monitoring is on the rise, there is still relatively little focus on the features and, in particular, the processes of the coastal ocean.

Factors contributing to this lack of development include the relative sparseness of marine data and the difficulty with which data of different formats are integrated within commercial GIS. In addition, ocean data sets (when available) tend to be very large and require specialised data processing routines including 3D graphics and animation (Dimmestøl and Lucas 1992; Galagan and Howlett 1994; Hamre 1992; Jacob 1995; Keller et al. 1991; Li and Saxena 1993; Mason et al. 1994; Wright 1995).

However, without data about marine processes, the role of GIS as a tool for environmental management and decision-support in the coastal zone is limited. If reliable coastal ocean data can be made more accessible and usable by incorporating them within existing GIS tools, decision-makers will be better able to incorporate process-oriented information in their tasks.

This paper addresses the issues surrounding the integration of ocean data, in particular output from numerical simulations, within a coastal GIS application for the Baltic Sea. It is not intended as a blueprint for other implementations since some of the concerns are software-dependent and will disappear or become less significant with later upgrades. The focus is on finding a suitable balance among the nature of reality, the data used to describe reality and the manner in which it is used.

The nature of coastal ocean data

There are many differences between land-based features and coastal ocean features. Most coastal ocean phenomena are four-dimensional; they have a length, width, depth and time component. Phenomena such as temperature, salinity and currents are continuous in space where every location by definition has a single value of a given attribute, and continuous in time where every time-step has a single value. And these values vary constantly. Many phenomena are difficult to observe or quantify by visual inspection; they have too small a signal over too large an area (e.g. sea surface elevation), simply too small (e.g. plankton), too deep (e.g. subsurface canyons) or invisible (e.g. chemical parameters). And there are relatively few fixed, discrete or long-term features. These characteristics give ocean data a level of complexity that rarely exists in land-based data.

Ocean data are typically four-dimensional. They are sparse, and not distributed uniformly in space and time. High quality, detailed data with repetitive sampling are found only in a few areas, the sites of major research initiatives. Where data are available, they may be aliased or undersampled vis-à-vis the needs of scientists. Woods (1995) estimates that it would require some trillion four-byte words to describe the diurnal and seasonal variation of the chemical, physical, and biological variables in a column of water (1 × 1 m surface area × 1 km depth) and describe the growth and behaviour of plankton within that column. He further estimates that elaborate joint international research projects collect less than one millionth of the data required by biological oceanographers. While the needs of biological oceanographers may be too specialised in the context of this paper, it does illustrate both the potential quantity of data required and the lack of it.

There are a wide variety of data sources for ocean data, each providing a different combination of space-time measurements in different formats. Instruments such as current meters gather information on current velocity at a single x,y,z location through a variable time period (t). Several current meters may be strung together on a single mooring to provide multiple z data. Satellite images provide synoptic data over a large area and may offer repeat coverage, but do not penetrate the water's surface (many x,y, many t, single z value). And different satellites have different swath-widths, pixel resolutions, and repeat cycles. Features such as ice edges change seasonally and may be derived from an ensemble or long-term climatology of individual edge positions. Because no single instrument can provide simultaneous x, y, z, t measures over sufficient area, large research programs depend upon synoptic sampling with multiple sensors. These different data are then processed individually and in combination.

While combining data from different sources can be, in itself, technically challenging, the multitude of source data also contributes to a confusion of scales. For example, the spatial and temporal resolution provided by satellite imagery may be adequate for identifying large surface features such as gyres and eddies, but inadequate for resolving sub-meso-scale (less than 10 km in diameter) patterns and processes (such as turbulence) and subsurface phenomena. Measurements from in situ instruments can resolve sub-meso-scale processes locally, but cannot scale up to macro- or regional scale processes without a dense and widespread network of sensors. The two data sets complement one another, but when using combined data sets, care must be taken not to infer more precision than the data can support. Error associated with combined multiscalar data is difficult to quantify.

One of the advantages of GIS is that different attributes can be geo-referenced to a common coordinate grid permitting operations such as overlay. However, there are 'no street intersections' or other identifiable control points within the field of view, making co-registration between data layers or data from different time periods difficult (Lucas 1995). Even a well-defined shoreline may be unsuitable as horizontal control since its position, in fact, it varies diurnally (with the tide), seasonally (with beach summer build up/winter erosion), and annually (with beach replenishment), at least along non-rocky coasts.

The role of ocean data in coastal applications

Coastal water quality can be used as an illustration of a coastal application with management implications. In May 1988, a toxic algal bloom developed in the Kattegat moving up into the Skagerrak and northwards along the west coast of Norway over a period of 14 days, threatening both wild and caged (salmon and rainbow trout) fish stocks. Disaster was averted through real-time monitoring of environmental conditions (Pettersson et al. 1990). Sea-surface temperature derived from satellite-based AVHRR (Advanced Very High Resolution Radiometer) data was used as a surrogate to trace the location of the bloom. Coupled with known circulation patterns, scientists predicted the path of the bloom, enabling fish farm operators opportunity to move their equipment out of harm's way.

This toxic bloom was triggered by the complex interactions among the circulation patterns, vertical mixing, subsurface chemistry, and land runoff (Asknes et al. 1989). Favourable conditions included the clear weather and high water temperatures in the months preceding the bloom, coupled with high freshwater runoff during the mild winter which led to low salinities in the surface waters and increased stratification of the Baltic, Kattegat and Skagerrak. Subsurface waters, influenced by anthropogenic nutrient sources, were nitrogen-enriched, but silicate-poor. Horizontal and vertical mixing was not a continuous process, but instead dependent upon circulation patterns (which were highly variable), winds and atmospheric pressure (especially in shallow water), and freshwater input.

While it is an oversimplification of the ecology to suggest that definitive predictions can be made about the temporal and spatial distribution of similar toxic blooms, it is realistic to suggest that better access to data could provide an early warning of potential dangers. Process-oriented data with appropriate time- and length-scales incorporated into a coastal GIS, could be used to identify and locate combinations of favourable conditions. Coupled with information on economic or recreational activities (e.g., fish and shellfish beds, swimming beaches) and rare or protected habitats, environmental managers and planners will be better prepared to deal with contingency planning.

It is recognised that environmental policies need to be more closely based on high quality environmental data (Brundtland 1995). And while there appears to be the intention to include research findings in the management and decision- process, there also appears to be some difficulty in the implementation. Zylicz (1995) describes the case of ecological-economic policies, and efforts to reduce nutrient (phosphorous and nitrogen) loadings in the Baltic. Ideal target loadings were based on the ecosystem vulnerability, nutrient mixing and drainage patterns; however, when reduction programs were implemented at various levels of government, small-scale spatial or temporal patterns were rarely considered. The designated reduction was often translated into a uniform decrease, calculated as a percentage in the pollutant emission and there was no consideration of the integrative effects of the individual nutrients. Zylicz's alternate approach recognises combinations of various ecosystem components in a more direct manner, increasing both the ecological-effectiveness and cost-effectiveness of environmental programs. However, to implement such an approach, decision-makers need access to relevant reliable databases. The on-going work of GRID and others is designed to begin to address this need (BGIS 1994, Sweitzer et al. 1996).

Issues for data selection

An ideal data set is one which is spatially, temporally and categorically precise and accurate; few of these exist. While we strive to find data that represent the phenomena of interest with a minimum of distortion and ambiguity (especially in multidisciplinary applications where subdisciplines may have their own interpretation), most data are less than ideal. In assessing the appropriateness of data one must consider data collection, input, pre-processing including calibration, format conversion, and generalisation, and once in the GIS, manipulation and display. General issues associated with error and spatial data quality are described elsewhere (Goodchild and Gopal 1989; Chrisman 1991; Kemp 1993a). Beard et al. (1991) consider the issue of visualisation of data quality and Fisher (1991) identifies common spatial data sources and problems encountered during input into GIS.

Sources of ocean data can be classified into four categories based roughly on the way in which they depict the real-world situation. They are: in situ measurements, remotely-sensed data, secondary data and numerical simulations (Kalve et al. 1995). In situ measurements are generally recorded at a single point over many layers for a period of time (x,y, variable z, many t). Typical examples include current meters (single z), CTD profilers (many z), and tidal gauges (single z integrated over the water column to estimate sea surface elevation). While these data types provide detailed information, they have limited utility in GIS without (at least) spatial interpolation to generate thematic fields. These sensors, however, are generally not used in sufficient numbers to permit reliable interpolations over large areas. But they can be overlain with other data for comparison.

Remotely-sensed data are grid-based and, baring cloud cover, provide complete coverage over the study area. Raw data has little value and must first be registered to a co-ordinate grid. The required image processing is most often performed by specialists; non-specialists take the spatial accuracy on faith (Kemp 1993a). Further processing classifies the images into categories which require ground verification. (The reader is referred to Davis and Simonett 1991 for a discussion on thematic classification accuracy.)

The AVHRR image (Figure 1) has a spatial resolution of 1.1 × 1.1 km (although this is lost in the reproduction) and has been processed to show sea-surface temperature. The image shows the high degree of spatial variation in surface temperature, however this is only a single 'snapshot' and does not give any indication of the temporal scales involved.

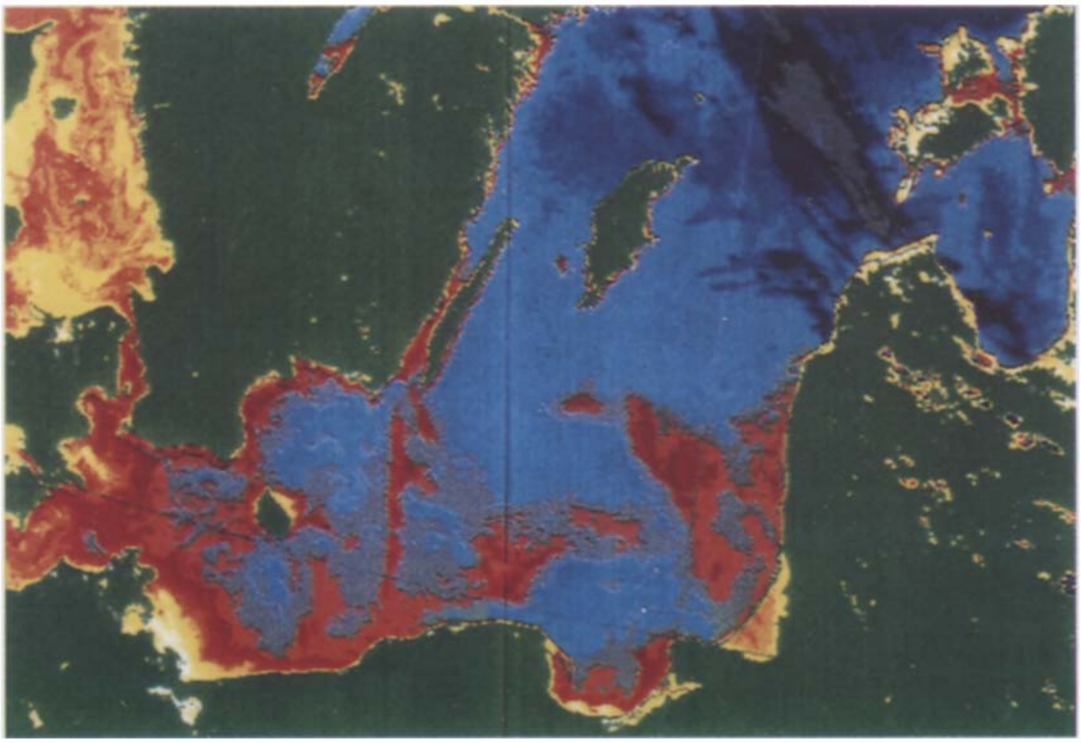


Figure 1. Spatial variability in sea surface temperature is captured by this NOAA AVHRR image from 12:20 GMT May 4, 1990. Colours are interpreted as follows: Yellow – 12 degrees C, Red – 10 degrees C, Cyan – 8 degrees C, Blue – 6 degrees C, Black – 4 degrees C, Grey – Cloud cover, Green – Land. (After Pettersson et al. 1990)

The temperatures (absolute and relative) cannot be assumed to represent anything other than the conditions existing at that particular moment. Information about seasonal temperature, rainfall, wind, mixing conditions and freshwater input are required to put the observed temperatures in context. A sequence of images would provide a temporal view of sea-surface temperatures.

Secondary data include those data sources that have been generated for other purposes and widely distributed. They offer the advantage of being readily available on the assumption that something is better than nothing. However, the disadvantage is that the data are a composite of many data sets, which are highly variable in quality and spatial-temporal resolution. To ensure fitness-for-use, it is the user's responsibility to investigate the original distribution of the data and the characteristics of the various data sources. Long-term averages or climatologies depict the mean conditions. For ocean data, these are frequently the data provided in published formats (e.g. atlases). Given the spatial and temporal variability of ocean phenomena, one needs to question the representativeness of, for example, an annual value. Does the annual value even exist at some point in time? Increasing the temporal resolution by decreasing the time-step (e.g. seasonal averages, monthly averages, daily averages), will also enhance spatial resolution. However, at the same time the associated uncertainty increases as the number of samples per location decreases. There tends to be a strong asymmetry in the seasonal sampling distribution with many fewer observations collected during the winter season for example. It is essential that the time-step be appropriate for both the variable and the context in which it is used.

Often these are derived from a variety of sources with (unknown and) variable spatial resolution; documentation is frequently unavailable or missing. Only recently have attempts been made to establish the accuracy of some commonly-used data sets (Lucas and Bivand 1994; Tveite and Langaas 1995). It is of some concern that the number of available data sets and the ease with which they can be obtained is growing as Internet access is established. The development of spatial data transfer standards and recent work in metadata should alleviate some of the difficulties in the future.

The fourth category, numerical simulations, are composed of predicted data in a matrix or grid format. These data are derived numerically where mathematical expressions represent physical processes. Other physical conditions are parameterised (e.g. air-sea drag coefficient). The model is initialised with baseline data which may be composed of in situ observations (e.g. current meter records), satellite-based fields and features (e.g. ice edge location), model-derived climatologies (e.g. circulation from the WOCE-CME), and other secondary data (e.g. shoreline, bathymetry) and driven by a forcing field (e.g. wind) over a specified time period (Lucas et al. 1994).

Unfortunately, coastal ocean models have remained in the domain of the specialist, leaving ocean data largely unknown to the GIS community. Other environmental models, such as soil erosion (Engel et al. 1993), groundwater flow (Hay et al. 1993), forest growth (Nisbet and Botkin 1993), and fish species richness (Lam 1993) have received considerable attention in the literature as they have been linked or integrated within GIS. There have been few attempts to link GIS and coastal ocean models; oil spill prediction is a notable exception to this (Reed et al. 1989). And the complexity of the modelling process inhibits adoption of ocean model data by casual users.

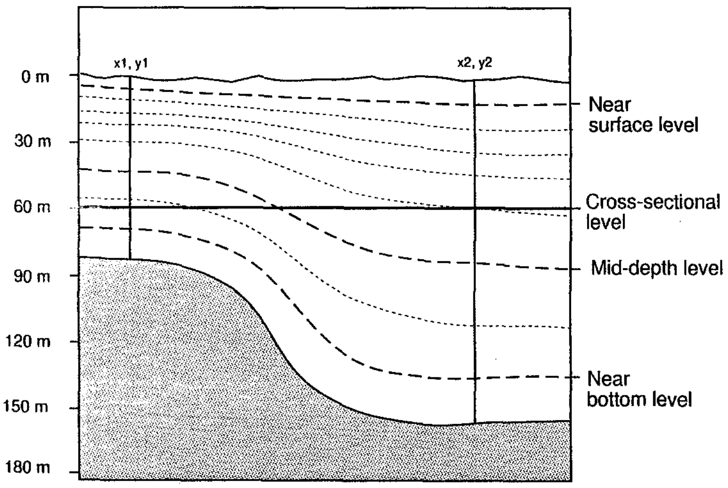
In many respects the output from simulations is similar to a suite of point sensors. However, since the intention of modelling is to produce near-continuous fields the model grid density is adequate for interpolation between points. While the input data may have varying levels of accuracy and precision, the sensitivity calculations on the model results will estimate the error associated with the model results. This is unlike a suite of current meters where each measuring device is susceptible to individual calibration and mechanical problems. However, Lam and Swayne (1993) warn that interpolated data should not be treated as real data since the question of spatial uncertainty and error is too easily forgotten. Further it must be remembered that the numerical simulation in itself is not a wholly accurate depiction of conditions at a specific place and time. Rather the model attempts to capture the relationship between variables. While a single realisation may have no mirror in reality, an ensemble should be able to replicate the time-space variability in the variables of interest. Future scenarios can be generated and by changing the forcing fields, 'what if' scenarios for extreme conditions can be explored. The simulation model also offers more control over the temporal and spatial resolution of the output data. Data can be simulated for areas devoid of other 'real' data.

The simulation model

The simulation model used in this application is the three-dimensional, sigma-co-ordinate, coastal ocean circulation model of Blumberg and Mellor (1987), also known as the Princeton Ocean Model. The specifics of this Baltic implementation are described in detail elsewhere (Aukrust 1992).

The model set-up is shown schematically in Figure 2. In this implementation, the model grid has a 5 × 5 minute resolution equal to 5 km resolution in the longitudinal direction and 10 km in the latitudinal direction across the Baltic. The vertical resolution is 14 levels. Bathymetric data was obtained on the same 5 × 5 minute grid (pers.comm. F. Wulff, University of Stockholm). The model was initialised with temperature and salinity values derived from averaged summer 1988 measurements stored in the HELCOM database. Initial surface salinity values ranged from about 3 ppt (parts per thousand) in the Gulf of Bothnia and Gulf of Finland, to about 28 ppt in the Kattegat where saline Atlantic water enters the Baltic from the North Sea. Initial data showed evidence of mixing between this denser saline water and other Baltic water at depth. The surface temperature varied between 16 and 18 degrees C. There was evidence of stratification with the lower levels having temperatures as low as 4 degrees C.

This scenario was driven by an idealised wind forcing over a 10-day period. No winds were used in Day 1 to allow the model to adjust to the initial density field. After Day 1, the wind was increased from zero to 10 m/s by the end of Day 5 and then maintained at a constant velocity until Day 10. Although these wind conditions are not realistic, they



ATTRIBUTE SCHEMA

variable	type	description
PT	CHAR	MODEL GRID POINTS
H	REAL	DEPTH (M)
TSURF	REAL	TEMPERATURE AT SURFACE (o C)
SSURF	REAL	SURFACE SALINITY (PPM)
QSURF	REAL	TURBULENT KE AT SURFACE (M2/S2)
EL	REAL	SEA SURFACE ELEVATION (M FROM DATUM)
TCROS	REAL	TEMPERATURE AT 60M (o C)
SCROS	REAL	SALINITY AT 60M (PPM)
QCROS	REAL	TURBULENT KE AT 60M (M2/S2)
WCROS	REAL	VERTICAL VELOCITY AT 60M (M/S)
TMID	REAL	TEMPERATURE AT MID-DEPTH (o C)
SMID	REAL	SALINITY AT MID-DEPTH (PPM)
WMID	REAL	VERTICAL VELOCITY AT MID-DEPTH (M/S)
TBOT	REAL	TEMPERATURE AT BOTTOM (o C)
SBOT	REAL	SALINITY AT BOTTOM (PPM)
QBOT	REAL	TURBULENT KE AT BOTTOM (M2/S2)

Figure 2. Cross-sectional view through the water at two points, (x1, y1) and (x2, y2). Only four of the fourteen levels used in the numerical model were extracted for the database. The attribute schema listing all variables is shown on the right.

did generate reasonable results verifying the validity of the model parameters and set-up. Results were viewed periodically during the model run and output every 6 hours during the 10-day simulation.

At each grid point, the following conditions were estimated for each level: temperature, salinity, turbulent kinetic energy, turbulent macro length scale, velocity components (u, v), and vertical velocity. Sea surface elevation and depth-averaged velocities were also produced.

The representation of simulation data

In a GIS, spatial data are represented as points, lines, polygons (or area features) or grid cells. Attributes or feature characteristics are assigned through a database table structure. The process of assigning the appropriate spatial representation to a feature is known as data modelling and the reader is referred to Burrough (1986) for further details on GIS data modelling. Any one feature can be modelled in a number of ways depending upon the ultimate use of the data, the GIS model used by the software, data collection and conventions (for example, the use of contours rather than a more accurate portrayal) (Goodchild 1993). However, under ideal conditions, the nature of the phenomena itself should determine the spatial representation.

Some objects (for example, most man-made features) have easily discernible boundaries and are easily represented in the GIS. Continuous spatial phenomena present a problem for data modelling. In the real world, they are independent of discretisation, but before they can be input into any of the current generation GIS, they must be artificially classified into spatial units. These units can be points, contours, grid cells, or triangles (Kemp 1993b). Through this modelling process, there will be some loss of information which should be minimised.

Modelling of the attributes follows an approach similar to that for traditional relational databases and the reader is referred to introductory literature for more information (Date 1990).

Attribute data modelling

In the first instance, simulation output was generalised to create daily averages for all attributes. This was performed out of necessity to reduce the overall size of the data files (more than 1 GB). While fine-scale temporal data was lost, the 10-day simulation was sufficient to visualise the longer temporal trends. However, the remaining 560 MB was still too much to process and maintain on-line. Rather than maintaining 14 vertical levels, only four levels were incorporated into the GIS. These levels were selected in co-ordination with both the numerical modellers who provided additional insight into the physical processes and the biologists who provided information about possible biotic conditions. Three levels were imported directly from the model; these were: the near-surface level, the near-bottom level, and the mid-depth level. These three followed the sigma surface and were therefore at various absolute depths throughout the Baltic as shown in Figure 3. Since

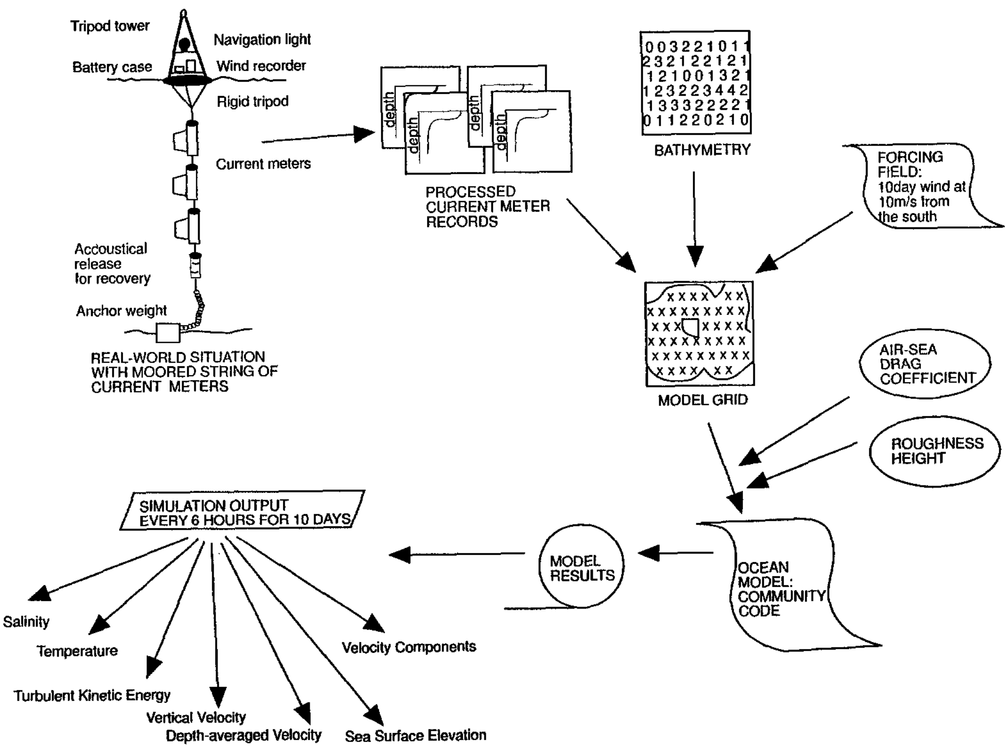


Figure 3. Data flow diagram illustrating the model development – from the collection of data to the output of simulated fields.

much of the Baltic is shallow (average depth is 51 m), it was assumed that the position of any major biotic communities in the water column would intersect with one of these levels and be captured in the data base. The fourth level is at a constant 60 metres depth and was created by interpolation of the model results. This served as a reference point between the other 'moving' data levels and allowed comparisons between sites at the same depth.

The attributes associated with each point were stored in the database internal to the commercial GIS. Since this was not a fully relational database (tables could not be linked to one another and only one table could be linked to a single map), certain restrictions were placed on the database design. On the one hand, one large table could have been created with all the data, but its size 150 attributes (15 attributes × 10 days) by 9340 grid points was awkward to manage. Individual tables for each variable on each day of the model run would have yielded many smaller, easier to manage tables, ca. 40 tables of 4 × 9340 size. Ultimately, a separate database table was assigned for each day in the model run. For each of the 10 days, fifteen attributes plus the grid point identifier were encoded for each point resulting in a table of size 16 × 9340. These attributes included bathymetry, temperature, salinity, turbulent kinetic energy and sea surface elevation. Each table was linked to a separate copy of the model grid. Velocity components were stored separately in a similar set-up.

This structure provided easy point&click querying to investigate conditions for each variable or combinations of variables on a given day. It was, though, less than optimal for querying and displaying temporal trends, since each of the 10 tables needed to be accessed. However, database access time was not a limiting factor. The most time-consuming part was manually typing the command, a bottleneck that was easily solved with a simple macro.

Spatial data modelling

The model grid and its attributes are best spatially represented by points, as this is closest to the original form of the data. And while the point-attribute combination is suitable for searching at each grid location, this form does not lend itself to either the query at random locations between grid points (solving the 'what's here?' query) or the graphic display of the data. There are a number of options which fulfil both deficiencies.

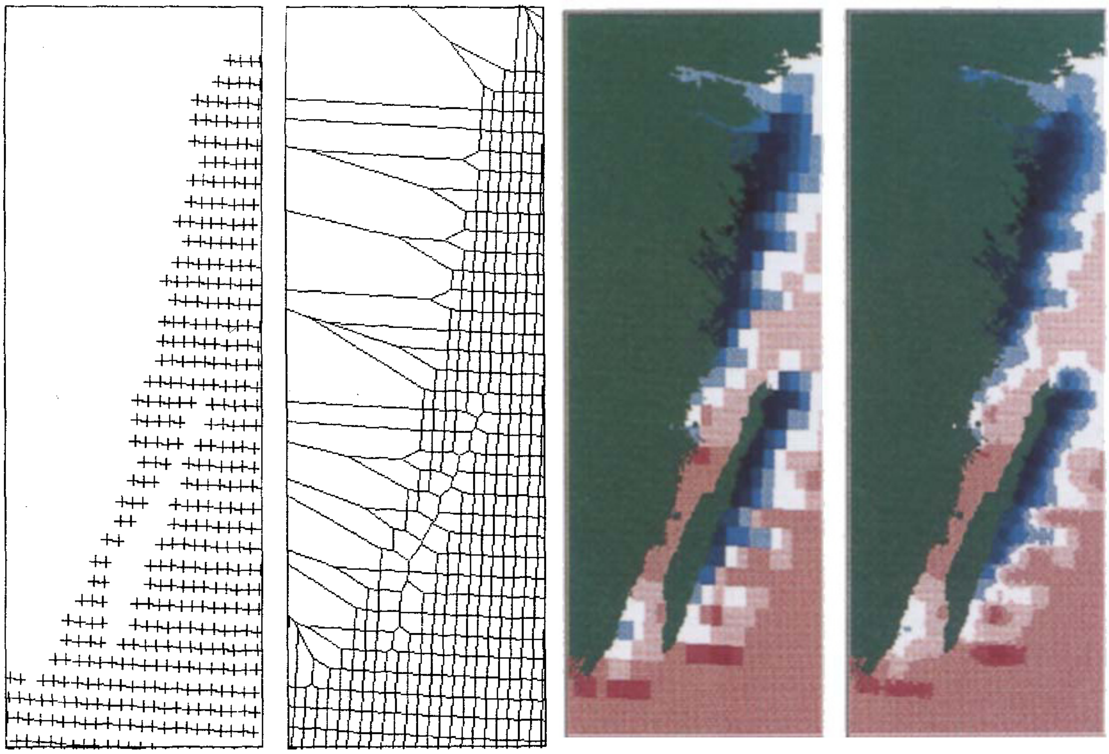
Three representations are required. Their construction is shown in Figure 4. Data needed to be converted into a continuous surface representation. In the first instance, Thiessen polygons were constructed around each point (4a and 4b), and all attributes assigned to the new spatial features. Individual or combinations of attributes could be selected, classified, coloured and displayed (Figure 4c), a process made simpler with a script. The resultant image was suitable for display at small-scale although when displayed in large scale (as in Figure 4c) individual Thiessen polygons are evident. The same initial data was interpolated onto a gridded raster image having a 500 × 500 m grid cell resolution using an inverse weighted distance function (Figure 4d). In comparing Figures 4c and 4d, the latter appears to display a more detailed structure giving the impression of higher resolution data when in fact, no additional data have been included. This impression can lead to misplaced confidence in the data, if the interpolation routine used to convert from point to continuous structure is not appropriate for the phenomena in question. Unfortunately there are rarely guidelines to assist with the selection of interpolation routines and function specifications. There is a risk of inappropriate use of the data should these seemingly detailed maps be passed along without warning. And once data are in digital map form, there seems to be an implied accuracy associated with it. Some suggestions to prevent unintentional misuse of interpolated or other processed data include: flashing warning markers 'do not use at scales less than xx', manual pages attached to the maps, and hardcoding map scale information as part of the legend.

Upon close examination of Figure 4d, artefacts generated by the interpolation routine can be seen along the class boundary. These rectangular shapes give a blocky or stepped appearance to the classification when compared to smoother contours of Figure 5d. Figure 5d begins with the same base data but uses a fifth-order polynomial spline to interpolate between points. The grid resolution is also 500 × 500m.

Results of the data modelling

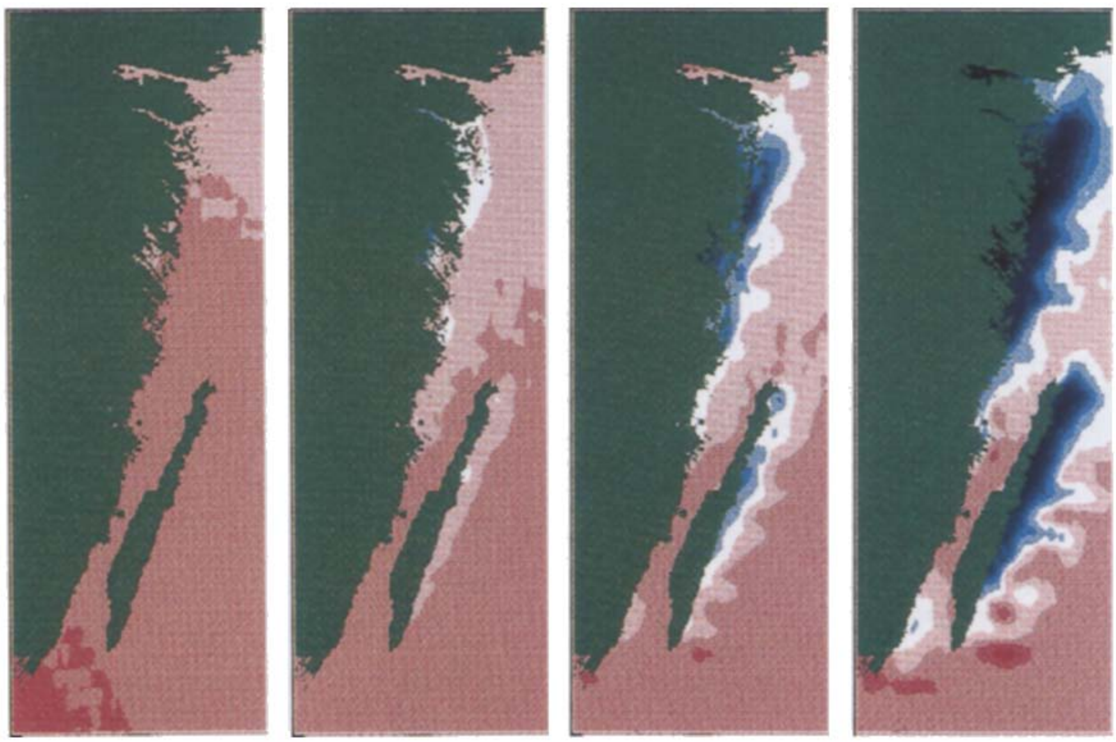
The data modelling for the simulation data was difficult. Conventional database strategies were not of much help in constructing a 4D database using 2D tables; much of the work was done by trial and error. A fully relational database would have simplified data management. While the point spatial representation was suitable for linking to the attribute tables, in practice they were difficult to use. Point maps were mostly used to generate new coverages and to convert from one spatial data representation to another. In addition, they served as explicit reminders of the spatial distribution of the original data (i.e. the model grid).

Multiple representations of the data were needed. It was easiest to integrate point maps with other data having different spatial structures (e.g. satellite images). Raster-based thematic maps (coloured from the continuous maps generated in the gridding process), were optimal for displaying individual fields. However, it was neither efficient to generate



a b c d

Figure 4. The four steps to convert point data into a continuous raster map are shown. Area is along the west coast of Sweden. There are 13 colour codes for Figures 4 and 5: Dark blue – less than 7 degrees C, White – 14 to 15 degrees C, Dark pink – 19 to 20 degrees C. (a) Numerical model grid as a point feature. Each grid point is symbolised with a cross. (b) Thiessen polygon network around the model grid. This converts the points into an areal feature. (c) Thiessen polygons are classified with surface temperature data. (d) Surface temperature is interpolated using an inverse weighted distance function. Artefacts of the interpolation routine are seen as stepped edges.



a b c d

Figure 5. Four of the 10 days from the simulation illustrate the development of upwelling. In these examples, the interpolation uses a 5th order polynomial spline. (a) Day 1: Initial conditions. (b) Day 4. (c) Day 5: Maximum wind obtained, upwelling is turned on. (d) Day 7: Enhancement of upwelling phenomenon. Compare this with 4(d).

these raster maps on the fly, nor create raster maps for every attribute at every time step. Only the surface characteristics were produced as thematic maps.

Multiple scales were also required. Depending upon the cell size selected, considerable apparent detail could be generated for the raster maps although all gridded maps began with a common data source (i.e. the model grid). With the resolution 500×500 m only about one-third of the area of the Baltic Sea could be interpolated in a single pass. Three separate maps were generated for a single theme which could be tiled together. But it has never been necessary to display the whole Baltic at this resolution as a single map. The much coarser resolution afforded by the Thiessen polygons is suitable for investigation of patterns and processes at this smaller viewing scale. The high resolution raster maps were used at larger viewing scales.

Interpretation and implications

Figure 5 shows the variation in surface temperature between Days 1 and 7. Initial conditions are seen in Day 1 (Figure 5a); there is little spatial variation in the temperature. By Day 4 (Figure 5b), 3 days into the wind spin-up, cooler temperatures are observed throughout. This tendency continues such that by the end of Day 5 (Figure 5c), distinctly cold water has appeared on the surface near the coast. This upwelling continues to develop through Day 7 as warmer surface water is blown offshore by the south wind driving a current deflected to the right (due to Coriolis), and colder bottom water moves to the surface to replace it. Upwelling zones are associated with productive fisheries elsewhere in the world. Figure 5d can also be compared to Figure 1 which shows downwelling in the same area, at a different time of year. This raises the question: would the average conditions show 'no vertical movement' for this area? Unfortunately, even though temporal data are contained in the database there are really no capabilities for animation. Separate software is required for this and could help to emphasise the dynamic nature more so than a series of 'snapshots'.

Also present in the map area is a coastal jet – a fast, narrow surface current moving northwards along the coast – triggered by the strong south wind. This persistent feature about 10 km wide does not appear on maps of generalised circulation patterns but has serious implications for coastal management (e.g. oil spill trajectories). The coastal jet can be identified through the attribute database, but its symbolisation presents a problem. Streamlines or arrows (indicating speed and direction), the conventional map representations can be created in graphics software, but are difficult to automatically generate in GIS.

While all of the 3D and temporal data can be accessed through the database and used in analyses, the GIS display capabilities are problematic for some data. Thematic maps (2D) are simple, well-understood and hence, useful for conveying static information to a non-expert audience. Processes are difficult to capture in a thematic map. However, advanced visualisation of particularly, 4D data can enhance the understanding of environmental processes, for both the scientist and the manager (Giertsen and Lucas 1994). Animation, slice and rotation functions can be used to visually inspect the data. In a GIS, draping of raster layers over, for example, bathymetry can provide limited 3D-like capabilities. Systems integrating GIS, models and advanced visualisation will certainly have a role in environmental management in the future (Lam et al. 1994).

Conclusions

The issues surrounding the use of ocean data in coastal GIS are largely related to the difficulty in capturing the spatial and temporal variability exhibited by coastal ocean phenomena. Vast quantities of data are required, but often not available and surrogate data must be used. Information about data quality, uncertainty, source and method of generation are frequently unavailable. There are further difficulties incorporating the different types of data required for coastal ocean studies into the current generation of commercial GIS.

Output data from numerical simulations were successfully used as a surrogate for conditions in the Baltic. The development of upwelling and the coastal jet were easily identified, in spite of their fine spatial scale and intermittent nature. This demonstrates the potential role that numerical simulation data can have in coastal planning where features such as these kind have long-reaching implications vis-à-vis environmental planning and decision-making.

References

Aksnes, D.L.; Aure, J.; Furnes, G.K.; Skjoldal, H.R.; Sætre, R.: Analysis of the Chrysochromulina polylepsis bloom in the Skagerrak, May 1988. IBM Bergen Scientific Center Paper 89/1. Bergen 1989.

Aukrust, T.: Adapting the three-dimensional sigma-co-ordinate model by Blumberg and Mellor to the Baltic Sea. IBM Bergen Scientific Center Paper 92/1. Bergen 1992.

Baltic GIS Working Group.: The basic geographic information of the Baltic Drainage Basin: Feasibility Study Report. Environmental Data Centre, Finland. 44p. 1994.

Beard, K.; Clapham, S.; Buttenfield, B.: Visualization of spatial data quality. NCGIA Initiative 7, NCGIA Publication 91–26, University of California, Santa Barbara 1991.

Blumberg, A.F.; Mellor, G.L.: A description of a three-dimensional coastal ocean circulation model. In: Heaps, N. (ed.) Three-dimensional coastal ocean models, Volume 4, Washington 1987.

Brundtland, G.H.: Knowledge – a sea change. Address at the conference 'Understanding earth: Retrospectives and visions', April 6, 1995, Washington, DC. 1995

Burrough, P.A.: Principles of geographical information systems for land resources assessment. Monographs on Soil and Resources Survey No. 12. Clarendon Press, Oxford 1986.

Chrisman, N.: The error component in GIS. In: Maguire, D.J., Goodchild, M.F., and Rhind, D.W.(eds.), Geographical information systems. Longman Scientific and Technical, London 1991.

Date, C.J.: Introduction to database systems. Addison-Wesley 1990.

Davis, F.W.; Simonett, D.S.: GIS and remote sensing. In: Maguire, D.J., Goodchild, M.F., and Rhind, D.W.(eds.), Geographical information systems. Longman Scientific and Technical, London 1991.

Dimmestøl, T.; Lucas, A.E.: Integrating GIS with ocean models to simulate and visualize spills. Proc. ScanGIS'92, Helsinki 1992.

Engel, B.A.; Srinivasan, R.; Rewerts, C.: A spatial decision support system for modeling and managing agricultural non-point source pollution. In: Goodchild, M.F., Parks, B.O. and Stayaert, L.T. (eds.), Environmental modelling with GIS, Oxford University Press 1993.

Fisher, P.: Spatial data sources and data problems. In: Maguire, D.J., Goodchild, M.F., and Rhind, D.W. (eds.): Geographical information systems. Longman Scientific and Technical, London 1991.

Galagan, C.; Howlett, E.: Integrating GIS and numerical models. Proc. Requirements for Integrated GIS. New Orleans. 1994.

Giertsen, C.; Lucas, A.E.: 3-D visualization for 2-D GIS: an analysis of the users' needs and a review of techniques. Computer Graphics Forum 13(3), 1–12 (1994).

Goodchild, M.F.: The state of GIS for environmental problem-solving. In: Goodchild, M.F., Parks, B.O. and Stayaert, L.T. (eds.), Environmental modelling with GIS, Oxford University Press 1993.

Goodchild, M.F.; Gopal, S. (eds.): Accuracy of spatial databases. Taylor and Francis, Basingstoke, UK. 290pp. 1989.

Hamre, T.: Integrating remote sensing, in situ and model data in a marine information system. Proc. Next Generation GIS Conference. Ås. 1993.

Hay, L.E.; Battaglin, W.A.; Parker, R.; Leavesley, G.: Modeling the effects of climate change on the water resources in the Gunnison River Basin, Colorado. In: Goodchild, M.F., Parks, B.O. and Stayaert, L.T. (eds.), Environmental modelling with GIS, Oxford University Press 1993.

IGBP: The International Geosphere-Biosphere Programme: A Study of Global Change. Chapter 4. How changes in land use affect the resources of the coastal zone and how changes in sea level and climate alter coastal ecosystems. IGBP Report No. 12. Stockholm 1990.

Jacob, A.: Development of an ice information system (IIS) to be implemented at the NERSC. Computers and Geosciences 21(8), 937–946 (1995).

Kalve, T.; Lucas, A.E.; Budgell, W.P.: Visual inspection for integration and model verification: a GIS approach. Proc. ScanGIS '95 Conference. Trondheim 1995.

Keller, C.P.; Gowan, R.F.; Dolling, A.: Marine spatio-temporal GIS. Proc. Canadian Conference on GIS. Ottawa 1991.

Kemp, K.K.: Spatial data: sources and issues. In: Goodchild, M.F.; Parks, B.O. and Stayaert, L.T. (eds.), Environmental modelling with GIS, Oxford University Press 1993a.

Kemp, K.K.: Environmental modelling with GIS: a strategy for dealing with spatial continuity. NCGIA Publication 93-3, 1993b.

Lam, D.C.L.; Swayne, D.A.: An expert system approach of integrating hydrological database, models and GIS: application of the RAISON system. In: Proceedings HydroGIS 93, pp. 23–33. IAHS Publication no. 211, Vienna 1993.

Li, R.; Saxena, N.K.: Development of an integrated marine geographic information system. Marine Geodesy 16, 293–307 (1993).

Lucas, A.E.: Reconstruction of a salt marsh in three dimensions. Proc. ScanGIS '95 Conference. Trondheim 1995.

Lucas, A.E.; Abbedissen, M.B.; Budgell, W.P.: A spatial metadata management system for ocean applications: requirements analysis. Proc. Requirements for Integrated GIS, New Orleans 1994.

Lucas, A.E.; Bivand, R.S.: Inference, data interpretation and GIS: comparative studies with a GRID data set. Conference on GIS in ecological studies and environmental management. Warsaw, Poland 1994.

Maguire, D.J.; Goodchild, M.F.; Rhind, D.W. (eds.): Geographical information systems. Longman Scientific and Technical, London 1991.

Mason, D.C.; O'Conaill, M.A.; Bell, S.B.M.: Handling four-dimensional geo-referenced data in environmental GIS. International Journal of GIS 8, 191–215 (1994).

Nisbet, R.A.; Botkin, D.B.: Integrating forest growth model with a GIS. In: Goodchild, M.F.; Parks, B.O. and Stayaert, L.T. (eds.), Environmental modelling with GIS, Oxford University Press 1993.

Pettersson, L.H.; Kloster, K.; Johannessen, O.M.: Fellesnordiske overvåknings program. NERSC Special Report No. 8. Bergen. 1990.

Reed, M.; French, D.; Grigslunsd, T.; Opaluch, J.: Overview of a natural resource damage assessment model system for coastal and marine environments. Oil and Chemical Pollution 5, 85–97 (1989).

Sweitzer, J.; Langaas, S.; Folke, C.: Land use and population density in the Baltic Sea Drainage Basin: A GIS database. Ambio (1996, in press).

Tveite, H.; Langaas, S.: Accuracy assessments of geographical line data sets, the case of the digital chart of the world. Proc. ScanGIS 95 Conference. Trondheim 1995.

Woods, J.D.: Virtual ecology. Inaugural lecture, June 14, Imperial College of Science, Technology and Medicine, University of London, London 1995.

Wright, D.J.: From pattern to process on the deep ocean floor: a geographical information system approach. Unpubl. PhD Thesis, University of California, Santa Barbara 1995.

Zylicz, T.: The ecological-economic problems of the Baltic Sea. In: Kuklinski, A. (ed.), Baltic Europe in the perspective of global change. Warsaw 1995.