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Coastal typology: An integrative "neutral" technique for coastal zone characterization and analysis

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Abstract

Typology, the 'study or systematic classification of types that have characteristics or traits in common', has become a commonly used term and technique in coastal zone studies over the past two decades. At least part of this is due to adoption by the first Land–Ocean Interactions in the Coastal Zone (LOICZ) project of a typological approach as a way to understand and organize the daunting diversity of natural and human systems comprising the world coastal zone, and to the concurrent development of tools and databases to support systematic applications. This paper reviews some of the history of the term 'typology' and the concepts and techniques that it subsumes, and discusses its adoption and adaptation in coastal studies. It also addresses the continued and increasing relevance of typology to the continuation of the LOICZ project and its objectives, and outlines the opportunities and challenges involved in realizing the potentials of the approach – both within LOICZ and for the scientific and coastal zone communities in general.

Keywords: typology; classification; cluster; LOICZ; coasts; methodology

1. Background, general and specific

1.1. History of the term, definition(s), fields of origin

The term 'typology' has a long history of English usage. A survey of on-line dictionaries showed that it occurred in nearly every one, usually with only slight variations in its definitions. For example, the Encarta on-line dictionary (http://encarta.msn.com/dictionary_/typology.html) offers three common definitions – "(1) classification of types: the study or systematic classification of types; (2) language study: the study of syntactic and morphological similarities in languages without regard to their history; and (3) study of religious texts: the study of religious texts for the purpose of identifying episodes in them that appear to prophesy later events."

However, the growing use of the term (in the sense of definition (1), above) in the fields of natural and physical science has not been recognized by lexicographers; none of the on-line technical or scientific (including social science) dictionaries or glossaries surveyed contained entries. Of the 80 uses of the term found in the electronic Encyclopedia Britannica (http://www.britannica.com), almost all dealt with religion, languages or a constellation of cultural, social and political topics – very few with an explicitly geospatial and/or environmental focus.

Many of the techniques associated with what we call typology are well-established in the field of remote sensing,

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although the term 'typology' is not commonly used in that field. The techniques applied in remote sensing typically classify in parallel both remotely sensed and ground-truth data in order to deconvolve and calibrate the remotely sensed data. This creates distributed groups from the data, rather than up-scaling the original data and/or data groups into similar geospatial classes. In this paper, we confine our discussion to the up-scaling process, while noting that these other areas appear to be ripe for the exchange of ideas and techniques.

In addition to geographical or environmental applications, the recent increase in usage of the term often distinguishes itself from traditional uses by being explicitly quantitative in terms of either the development or the application of the typologies. Recent usage in the scientific literature was sampled by searching the ISI Web of Science database (titles, abstracts, and keywords in both Science and Social Science databases) with two queries aimed at coastal zone applications: "Typology and (coast* OR ocean* OR marine OR estuar*)" and " Typology and (river* OR stream OR basin OR catchment)." The search was repeated with both queries modified by inclusion of "and (cluster* OR quantitative* OR statistic*)." In the syntax of these queries, the asterisk (*) accepts any suffix to the word – for example, "ocean*" would find ocean, oceans, oceanic, oceanography, etc.

The results represent only an incomplete sample. As the database covers only journals, the search would miss any paper in which the use of typology or quantitative methods was not called out in the title, abstract, or keywords, and some of the hits have nothing to do with the applications of actual interest. However, trends are nonetheless evident. For the combined general searches (coastal plus riverine) a total of 254 unique entries were found between 1983 and 2005 (the temporal extent of the database). These are summarized and classified in Table 1. At least 50% of these publications had some relevance to the interactions of land, ocean, and humans in the coastal zone.

Beginning in the early to mid-1990s, the use of 'typology' in the natural and social science disciplines relevant to coastal zone issues began a steady increase that appears to be exponential after 1994 (Fig. 1). Indeed, a 3-year moving average increases the R^2 to 0.95, suggesting a doubling-time of 5–6 years. At the same time, there was the rather abrupt appearance of quantitative and statistical terms associated with literature discussions of typology. This terminological shift does not, of course, mean that the art and science of coastal classification began only then; Cooper and McLaughlin (1998), for example, review 14 papers on classification-based coastal risk assessment which in general did not apply the term typology to their work.

It is our contention that one of the factors in this methodological transition was the first Land–Ocean Interactions in the Coastal Zone (LOICZ-I) core project of the International Geosphere Biosphere Programme (IGBP), and that these developments – including the growing acceptance by the wider community – have the potential to play a substantial role in achieving the objectives of LOICZ-II, which is a core

Table 1
Breakdown of 254 unique citations[a] of 'typology' from Web of Science search (see Section 1.1 for details)

Year	River-Sci[b]	River-Soc Sci[b]	Coast-Sci[b]	Coast-Soc Sci[b]	Total[a]	3-year MA[c]	Quant All Coast	Quant All River	Total
1983					0				
1984			1	1	2				
1985					0	0.67			
1986					0	0.67			
1987	2				2	0.67			
1988					0	0.67			
1989		1			1	1.00			
1990	1		1		2	1.00			
1991	2				2	1.67			
1992	2	1	3	2	8	4.00			
1993	4	2	2		8	6.00			
1994	9	5	5	1	20	12.00	1	4	5
1995	5	1	1		7	11.67	1	1	2
1996	6	3	3		12	13.00	1	2	3
1997	11	3	4	1	19	12.67		3	3
1998	11	3	3	1	18	16.33		2	2
1999	6	2	8	1	17	18.00			0
2000	14	2	5	2	23	19.33	3	2	5
2001	8	2	5		15	18.33	3	4	7
2002	14	1	8	3	26	21.33	1	1	2
2003	16	3	17	6	42	27.67	4	2	6
2004	19		11	3	33	33.67		1	1
2005	16[d]		8[d]		24[d]	33.00	2[d]	5[d]	7[d]
Sum	146	29	85	21	281		16	27	43

[a] Some of the references appeared in both the Science and Social Science databases, so the sum in the table is greater than 254.
[b] Database used: Sci = Science; Soc Sci = Social Science. Search topics: River = typology + river terms; Coast = typology + coastal terms (see text for details).
[c] MA = moving average.
[d] Not a full year of references.

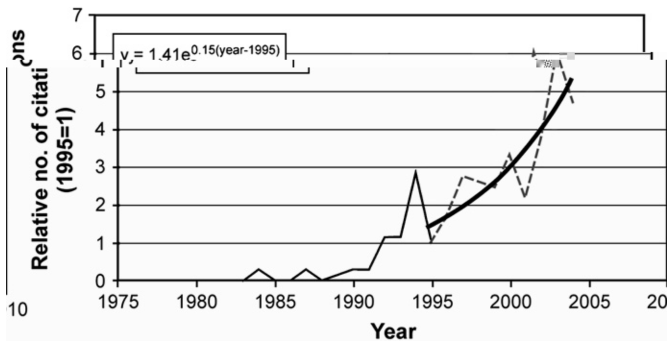

Fig. 1. Relative number of citations per year of the term ‘typology’ in the CZ literature relative to 1995, the year in which the LOICZ implementation plan was generated.

project of the International Human Dimensions Programme (IHDP) as well as of IGBP. This paper reviews some of the past and potential future developments and takes steps toward developing definitions and guidelines for at least some sorts of typological methods.

1.2. LOICZ history

1.2.1. Rationale for and evolution of the concepts and applications

As the LOICZ-I project was moving from the conceptualization to the implementation stage, it faced the daunting task of finding consistent methods that could be used to characterize the world coastal zone (CZ) and its roles in global climate dynamics and biogeochemical cycles. The CZ is, ignoring fractal issues, approximately 10^6 km long (Crossland et al., 2005, p. 3); its width depends on the nature of the question addressed. It occurs in every climate regime found near sea level, its biotic and geologic features are similarly diverse, and it is affected by the full range of geophysical and anthropogenic pressures. Moreover, in terms of available data and detailed process-based understanding, most of the CZ is essentially unknown territory, punctuated with specific locations and small regions where studies of various types have been carried out. The wide range of types of study poses a major integrative challenge, especially because of the importance of combining the social and natural sciences in considering CZ dynamics (Crossland et al., 2005, Ch 1).

Further constraints were imposed by the terms of reference under which LOICZ-I operated. To achieve its objectives, it had to engage in integrative analysis on a global scale within its 10-year lifetime (1992–2002) and its financial resources, and to produce results that were ultimately quantifiable. It was clear that global-scale multi-disciplinary process models and/or massive data collection efforts were out of the question; progress depended on finding ways to integrate, interpolate and up-scale the disparate existing data sets representing a variety of locations.

Typology was identified as the most promising approach – in this case, in the sense of developing a functional classification system for coastal regions, using objective and reasonably quantitative (probably statistical) methods, so that data available for some members or regions within a class could be adapted to develop realistic estimates for the other class members. Consistent global-scale analyses had to rely on globally available data, and initial efforts led to the development of a one-degree gridded database of public domain data sets. The final version of that data assembly is available at www.loicz.org. It quickly became apparent that this grid size was too large to capture many critical features of the coast, and work was begun on a much more ambitious half-degree data set. The results of this effort are accessible at www.kgs.ku.edu/Hexacoral, which is the result of a cooperative effort between LOICZ-I and a US National Science Foundation (NSF) bioinformatics grant (see details in Acknowledgements).

The LOICZ-I Implementation Plan (Pernetta and Milliman, 1995) was developed in 1992–1994, and outlined an extensive and detailed research and synthesis approach across spatial (local to global) and temporal (seasonal to geological) scales to determine overall changes in the global coastal zone. The plan recognized that the magnitude of such a global assessment needed to embrace wide scales of heterogeneity in physical–chemical forcing and socioeconomic drivers of change on coastal system structures and processes, and the practical constraints of “human and financial resources” to achieve the assessment goals. Thus, a key tenet of the research program was identified as the need for “…the development of an objective typology of coastal units to serve as a sampling framework and to determine the appropriate weighting for preparation of global syntheses, scenarios and models on the basis of limited spatial and temporal research data. …” (Pernetta and Milliman, 1995, p. 29).

Early coastal typology experiments within LOICZ-I used principal component analysis (PCA) to explore similarities, as it was clear that the complexity of the subject was not addressable through expert judgment approaches. Although PCA produced promising results, the efforts involved in repetitive trials and especially in displaying and mapping the results made it a slow and laborious process. One of us (BAM, a computer engineer with interests in visualization) became intrigued by the problem and embarked on the development of a tool that was eventually served to the community as Web-LOICZView (WLV – http://fangorn.colby.edu/loicz), a geospatially oriented tool for clustering and other analyses with data-manipulation capabilities and map-projected as well as linear graphical outputs (Buddemeier and Maxwell, 2001; Maxwell and Buddemeier, 2002). When linked to the half-degree database, this tool provided even inexperienced users with the ability to explore relationships through clustering and mapped visualization of the results.

Concurrently, the biogeochemical budgets team within LOICZ created standardized approaches to budgeting carbon–nitrogen–phosphorus fluxes and transformations in the coastal zone (summarized in Smith et al., 2005), designed to bring available coastal data sets into a common format and to facilitate the participation of scientists with relevant data sets. The confluence of these three components set the stage for widespread application experiments within LOICZ. It must be acknowledged that LOICZ was by no means the only player in developing and popularizing the typology approach; others, both inside and outside the IGBP organization, were also discovering the promise of the method and developing techniques and applications (e.g., Meybeck, 1993; Vörösmarty et al., 2000).

1.2.2. Implementation and dissemination

Based on the tools and data sets developed, a joint project was established between LOICZ-I, the United Nations Environment Programme (UNEP) and the Global Environment Facility (GEF). This project, oriented toward capacity and scientific infrastructure development, funded a series of workshops in developing countries that first constructed biogeochemical budgets for the regions, and then used hands-on typology workshops to explore their relationships. Final integrative activities included three regional workshops and a synthesis workshop that were documented by LOICZ reports (see Buddemeier et al., 2002a for a summary and references, and Le Tissier et al., 2006 for an overall project report).

This period of applications of the technique to the growing inventory of biogeochemical budgets was the basis for many subsequent developments. The process of guiding other professionals through the learning and application process resulted in feedback that improved documentation and training tools, which further resulted in additions and modifications to the Web-LOICZView tool, enhancing both capabilities and ease of use. It also produced a cadre of scientists and teachers familiar with the concepts and the methods, providing a basis for the further expansion and development of the use of typology in environmental characterization.

One of the key outcomes of this period was the recognition that the half-degree database was still too coarse to capture many of the natural and human system characteristics that showed promise as a basis for similarity analysis. A global data set at finer resolution, although possible for some variables in terrestrial settings, was not feasible for the strictly coastal and marine features of the environment. The approach taken was to use Geographic Information Systems (GIS) to characterize river basins at the 1-km scale, and to nest (and apportion) the resulting data within the appropriate half-degree cells. Since resources did not permit doing this on a global-scale, emphasis was placed on the catchments of the biogeochemical budget sites and the coastal regions they influenced. Although incomplete and somewhat awkward, this proved to be both effective and critical to many outcomes (McLaughlin et al., 2003; Smith et al., 2003) and was the initial step in dealing with multiple resolutions and the combination of polygon and grid data that has continued to be a focus of development.

Concurrently, other groups within the LOICZ core project adopted a more descriptive typological approach to the classification of river basin functions and futures (Crossland et al., 2005, Ch. 4). Integrating this approach with the quantitative methods inherent in cluster-based typologies will be facilitated by the fact that both groups are considering the same geographic entities (catchments) and many of the same variables. This integration can be seen as a precursor of the challenges facing LOICZ-II in the efforts to forge a greatly improved integration of environmental and social factors in the CZ.

The conclusion of the UNEP—GEF project and a summary of its products (e.g., Buddemeier et al., 2002a,b; Smith et al., 2003) coincided with the beginning of the LOICZ-I synthesis process (Crossland et al., 2005; see also the appendix to this volume, and the publication list at www.loicz.org). This marked a temporary culmination of LOICZ-driven typology efforts, with a shift to developments in other fields and programs. The lessons learned during LOICZ-I and the key developments during the period of transition from LOICZ-I to LOICZ-II are summarized in the following sections.

1.2.3. LOICZ-I products, experience, and conclusions

Inevitably, many of the procedural ‘discoveries’ made over the course of 5—6 years of active development and experimentation were never formally documented. One of the more important and generalizable consensus findings concerning typology development by clustering was that the ideal of identifying a single, all-inclusive typology that would include both the socioeconomic and environmental data for all systems and serve multiple purposes was unrealistic. The most effective approach involved multiple typologies, both as products and as steps in the development process. These both derive from and point to the following specifics.

- Typologies are most easily understood and visualized if they are based on a moderate number of clusters (e.g., $\leq$10—12) derived from a relatively small number of variables (e.g., >2—6) (Buddemeier et al., 2002a, pp. 74—76). The ‘‘garbage can’’ approach of clustering a large number of disparate variables frequently yields intuitively satisfying patterns, but it is often equivalent to a qualitative process, since the key controlling factors are difficult to identify and understand.
- If a more extensively divided classification is desired, a hierarchical approach of further clustering within individual clusters or combinations can be effective. A related technique excludes extreme values to emphasize distinctions within the range of interest — for instance, the 5—10 largest river basins (Amazon, Nile, Mississippi, etc.) have characteristics so different from the small- and medium-sized basins that directly influence most of the world’s CZ that their inclusion may overwhelm important distinctions at smaller scales.
- The number of systems used in the most intensive applications to date (LOICZ biogeochemical budgets or the NOAA estuarine eutrophication work described below) has often been too small for development of a robust typology. Using more systems is an important adjunct to using a moderate number of classes, and it might also result in greater ability to incorporate systems represented by fewer or more uncertain data. In the end, and assuming LOICZ-II continues with both budgeting and typology, this might be one of the more substantive reasons for continuing the two. In addition to filtering the data, transformation (most commonly to a log

scale) and construction of multi-variable index variables or dimensionless constants can be useful ways to increase the power of cluster analysis.

1.3. Other applications and products

Use of cluster-based typology has been spreading, both inside (e.g., GLOBEC SSC, 1999, pp.162–164; Meybeck et al., 2001, 2006) and outside the IGBP. By the end of LOICZ-I, the WLV clustering tool had acquired so many add-on capabilities (e.g., eigenvector analysis, supervised clustering, optimum cluster number prediction) that it was badly in need of recoding. Bruce Maxwell's student Casey Smith undertook the task, and produced the Deluxe Integrated System for Clustering Operations (DISCO) (http://fangorn.colby.edu/disco-devel/).

DISCO was the subject of an NSF grant (see details in Acknowledgements) to develop and extend the second-generation web-based tool for geospatial clustering, with extensions including the addition of time series clustering and analysis of multidimensional data sets. The first production version is available for use at the URL cited above; any potential user can request an account through the on-line request form, and DISCO now has accounts for over 50 users. Both WLV and DISCO are available on-line for continued use, but all new development activity is being focused on DISCO.

DISCO is now being applied because of its improved ability to display and measure cluster stability and overlap (fuzzy clustering) and to display partitioned data sets. A variety of analyses can be applied to databases or uploaded data using the web interface. Clustering is useful for a variety of tasks, including pattern classification, vector quantization, datamining and visualization. Users can choose not only the number of clusters but also which variables to use, how to weight the variables, the type of data normalization, and the clustering method. In addition to the main clustering functionalities, DISCO provides tools for estimating the natural number of clusters within a data set and for visualizing the data in a variety of ways, including comparing two clusterings of the same data using different parameters. Development work completed with NSF funding focused on giving DISCO the capability to cluster and visualize time series and similar data in a natural way. This capability is functional; users can create profile variables – data that vary with time, depth, location, or conceptual category – and group data points across the profile variable as appropriate to the task. In addition, the profile variables can be grouped with static variables at the same geographic location to provide a powerful mixture of dynamic and static information when developing classifications. For example, a user could combine elevation at a geographic location with a single profile variable that grouped the average temperature for each month of a year at that location.

The clustering tools have also inspired related technical developments (Bartley et al., 2001; see also Section 2.2 below) and have been applied to a variety of studies, including biogeography (McLaughlin et al., 2003; Cha et al., 2004), biogeochemistry (Smith et al., 2003) and hydrology (Bokuniewicz, 2001; Bokuniewicz et al., 2003). WLV has been applied to water resource data analysis in the Kansas High Plains Aquifer by researchers (Wilson et al., 2002), managers, and regulators, and to analysis of socioeconomic systems (Maxwell et al., 2002; Pryor, 2003, 2005). Other developments of particular relevance to LOICZ are the adoption of typology approaches in coastal management assessment by the National Institute of Water and Atmospheric Research (NIWA) in New Zealand, and the adoption of DISCO as the preferred tool for classifying estuarine systems by the NOAA Estuarine Eutrophication Program (NEEA), discussed further in Section 2.2. These latter applications are of particular significance because of their intended direct relevance to management of the environmental systems based on practical scientific classification embodied in the cluster typology approach. Fig. 2 illustrates some of the multiple data and output display modes of DISCO, drawn from work on the NEEA. This figure also illustrates several points made elsewhere in this paper.

2. Tools and techniques in relation to objectives

2.1. Quantitative, qualitative, objective and subjective typologies

LOICZ-II has adopted five scientific themes as its organizational framework (Kremer et al., 2005). Four of these themes are oriented toward specific families of CZ issues and one is integrative; all are inherently multi-disciplinary. In such a system, typologies can play an important role in transmitting concise, information-rich summaries or results and analyses among the various themes. The typological method, if systematically employed from the beginning, can also provide the diverse participants with a common tool and conceptual approach that will facilitate communication and synthesis. For this to succeed, however, the typologies will need to have some specific characteristics.

Multi-variable environmental classification schemes, although common and useful, have generally been ultimately qualitative products, even when based on quantitative data, and have had a significant subjective component in their "expert judgment" formulations. These characteristics are typically quite appropriate for the proximate purpose of the classification, but seriously limit their potential for extension, revision, or redirection, especially in quantitative studies. Numerous examples can be drawn from the literature on land cover, land use, climatic zones, and biotic regions. One of the most relevant to LOICZ is the global ocean "ecological geography" developed by Longhurst (2001).

Longhurst's ocean regions are based on physical and biological oceanographic data and geomorphologic characteristics, which are all quantifiable if not already quantitative. The amount and quality of data vary substantially among the regions, and expert judgment has played a substantial role in defining regions and their boundaries. The Longhurst coastal regions, however, are excessively large for most LOICZ purposes, and there is no practical way to subdivide them in an objective and globally consistent fashion while still remaining

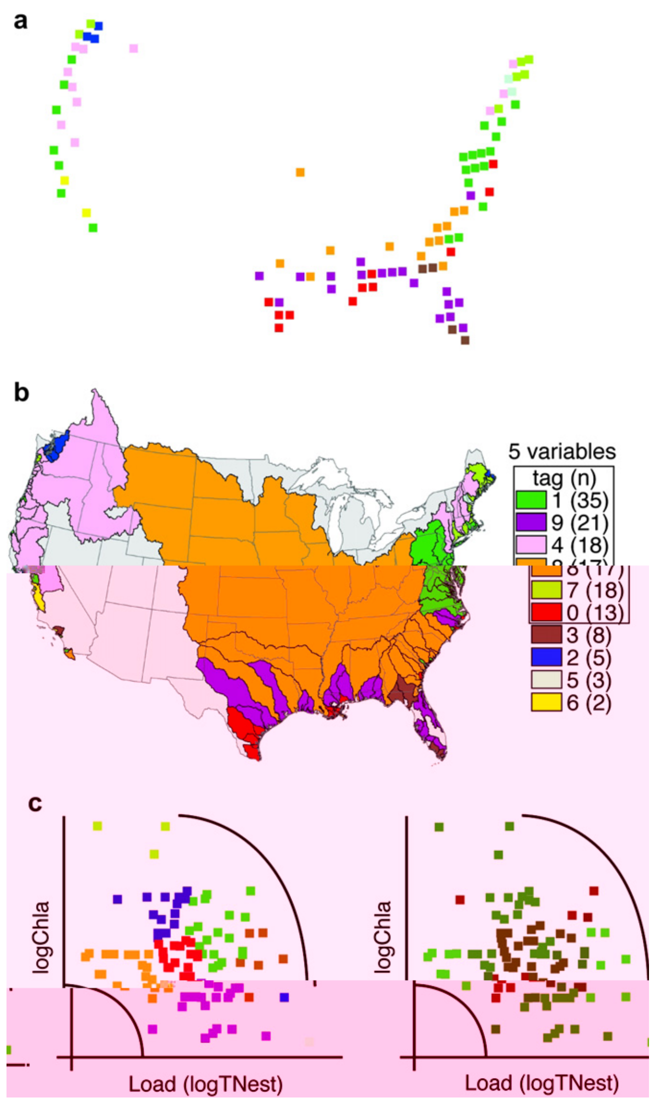

Fig. 2. (a) DISCO output, showing clusters of the drainage basins of approximately 140 US estuaries on the basis of the five variables tabulated – best estimate of depth, percent of mouth open to the ocean, tide height, mean air temperature, and the log of freshwater input. The program also returns detailed statistics on each cluster and their separations. Data and access to DISCO are available from http://geoportal.kgs.ku.edu/estuary/. (b) The results of a similar analysis with catchments mapped using GIS. Ready interconvertibility between cluster results and GIS provides for easy overlay analysis of the clusters and other data. The clusters within the box around part of the legend account for 120 of the 138 total, and are distinguished by (from the top down): medium depth, % open, temperature; low depth, medium % open, high temperature; low % open, temperature, high freshwater; high freshwater, low depth; high tide, medium % open, low temperature; and low freshwater, depth, % open. (c) From the same set of experiments, DISCO output of a linear crossplot of two variables not used in the clustering – log of estimated chlorophyll *a* concentration (a classed response variable) and log of the estimated total nitrogen concentration (a stress variable). The figure on the left plots the points with their cluster colors. The figure shows cluster stability; clear green points are consistently associated with the same cluster in multiple trials. As the points grade from green to brown, the frequency with which the point is assigned to other clusters increases.

faithful to the larger framework of functional relationships in the Longhurst system.

This dilemma arises partly from the fact that there is usually no single axis (not even one based on a complex multi-parameter index) along which the classes will have a unique and reproducible order – thus the classification does not produce a ‘continuous variable,’ which is necessary if the categories are themselves to be used as variables in clustering. In addition, the subjective decisions made in assigning boundaries and detailed class memberships are typically not reducible to a consistent set of equations, so the categories cannot be ‘recalculated’ to include additional variables.

The essentially static and irreproducible nature of qualitative and/or subjective typologies make them of limited utility in rapidly developing fields where classification needs to be reproducible and adaptable in order to be used iteratively and modified on the basis of advancing knowledge. We advocate the continued development and application of the techniques and tools inherent in WLV and DISCO, as these provide the user with not only quantitative output, but also the scope to apply judgment and calibration of results by:

- using proxy or index variables;
- including qualitative information expressed as appropriate classed variables;
- transforming or filtering variables;
- performing supervised clustering; and
- weighting the variables used.

At the same time, however, if these processes are documented, the experiment becomes reproducible and subject to reanalysis, reapplication, or modification as the circumstances may require.

2.2. Alternative and complementary techniques

A variety of tools and statistical methods have been applied to coastal classification and analysis. Some of these have been mentioned earlier in the text or are discussed in references. Here we focus on the specific approaches most relevant to geospatial clustering in the LOICZ context.

Use of GIS has become essential for any large-scale geospatially oriented scientific project, and it has been extensively used in coastal classification and analysis (Cooper and McLaughlin, 1998). It serves not only as a powerful means of analysis and display of data, but also as a data exchange and education/information tool. LOICZ-II has committed to development of a GIS data inventory, which is strongly complementary to the cluster typology approach discussed here. The ESRI family of Arc products has geo-statistical packages, including clustering, and a visualization and display capability vastly more powerful than the WLV and DISCO packages. However, ArcMap and related products are expensive and require considerable learning, effort, and computer power to use effectively, while marine data are less well represented in public domain GIS databases than are terrestrial data. We suggest that the more focused and less technically demanding geospatial clustering tools of WLV and DISCO are complementary to GIS in terms of supporting broad participation.

Internet map server (IMS) applications make it possible to dynamically create GIS maps and some analyses on remote websites. These are impressive and informative, but require significant infrastructure and resources to support and have significant speed limitations on the size of the database and complexity of the operations they can support in real time. The outputs of DISCO and WLV are compatible with GIS display (e.g., see Fig. 2b) and it would be possible to link them dynamically to an IMS display.

It is also possible to have web-based applications that use the display power of IMS but couple it to a faster and simpler analysis tool than the GIS program. One such product, developed as a partial spin-off from the LOICZ-I activities, is the KGSMapper biogeographic tool. A version of this is currently running in support of the Biogeography of the Hexacorallia site (www.kgs.ku.edu/Hexacoral) and the Ocean Biogeographic System (OBIS) portal (www.iobis.org). Another stand-alone version, with provisions for analyzing user-supplied data in conjunction with data from the environmental and biological databases, is available at (http://drysdale.kgs.ku.edu/website/Specimen_Mapper/mxmapit.cfm); it is described by Guinotte et al. (2006).

2.3. Data and databases

An important aspect of realizing the advantages of a consistent typology approach to the issues addressed by LOICZ lies in having consistent, or at least closely comparable, typology databases available to all workers. This does not mean that research teams cannot exploit unique information resources, but it does serve to ensure that major components of any typology developed will be transportable for application elsewhere – and that all will have some common ground for ultimate synthesis.

The databases developed for LOICZ-I were discussed above; a glimpse of how data for more specific and well-characterized local systems might be brought into play can be had at the NEEA support sites, where a LOICZ-style database and the DISCO clustering tool are being used to recruit the extended community into participation in the classification process (http://www.eutro.us, http://geoportal.kgs.ku.edu/estuary/). Participation and data contribution by national-scale entities such as NOAA can build regional data sets while making progress toward an upgraded, higher-resolution global database.

2.4. Community-building, collaboration, and cooperation

LOICZ-II continues a major commitment to information dissemination and capacity-building (Kremer et al., 2005, Section 4.3). The experience of LOICZ-I showed that typology-oriented workshops (both biogeochemical and river basin oriented) were an effective means of building a global cohort of scientists sharing both methodological and conceptual approaches to CZ issues. The availability of web-based tools and data sets permitted these scientists to expand and explain their activities – for example, by using typology as teaching exercises in university classes.

3. Opportunities and challenges

The use of quantitative typologies in general, and of geospatial clustering to develop them, has many advantages to offer, both overall and especially in LOICZ, where the concepts and tools have been developed and tested. There are, of course, further needs to be met and challenges to be overcome in realizing its full potential. Both are addressed briefly below.

3.1. Opportunities and advantages

3.1.1. Acceptance, users, and resources

In addition to the science and management applications discussed in Section 1.3, application of LOICZView/DISCO to coastal vulnerability to climate change (mapping and assessment) in Australia has been proposed, and CSIRO (Australia) is pursuing development of relatively high resolution data for numerous oceanographic variables that can fit the finer-scale coastal needs – these model-derived data derived from global models would be nested in a hierarchy of scales and calibrated with ground-truth from regional information.

Added to the growing use in practical applications, the extended network of users provides a strong base from which to develop further expansion of use and applications. In turn, because of the broad base of users and applications, there are available a wide range of explanations, instructions, and examples of applications that can be adapted for further extensions.

3.1.2. Unique relevance to the objectives and situation

To a much greater extent than the natural sciences, social sciences provide a mix of qualitative and quantitative data, and social science data often come at very different scales. Use of classification techniques to express qualitative data in quantified form makes it accessible for cluster analysis. Typologies developed with the clustering tools are often more achievable and capable of delivering rational and useful products than process models, especially in relation to either common conceptualizations or data at a common scale.

The heterogeneous nature of the global CZ, and the integrated multi-disciplinary objectives of LOICZ-II, suggest that the typology approach is relevant to a multiplicity of task elements in themselves, as well as in sectional or project synthesis.

3.1.3. Institutional base for carrying the work forward

LOICZ-II can be a powerful force in further developing and coordinating the applications of cluster-based coastal typologies, particularly in a setting where it can draw upon the experience and resources of other users. The continuity LOICZ provides, combined with the computer and informatics resources possessed by its long-term collaborators, the experience and the user base discussed in Section 3.1.1, sets up a nearly ideal situation for further systematic development and application of the technique to deliver innovative approaches and products necessary for the achievement of LOICZ-II goals.

3.2. Challenges

3.2.1. The multi-scale, cross-scale problem

Typologies and the clustering processes used to create them, although robust, are not immune to the problems of working at multiple spatial and temporal scales, or of mixing data sets of very different resolution. In many ways, the solution to this problem lies primarily in data processing and presentation external to the clustering process. Fortunately, this problem is receiving widespread attention, and there is reasonable hope that nested data sets with automatic scaling and multi-layer access will become available. Since DISCO has a time series analysis capability, it will have the ability to handle both observed and predicted changes in ways consistent with spatial analysis of present conditions, once appropriate data sets are available.

It has become apparent that the scale issue is easier to deal with on land than on the marine side of the CZ. On land, the spatial (and temporal) distributions of variables can be obtained down to scales that are well inside any present desire or operational requirement to classify. In comparison, while the spatial scale in the ocean can (in principle) be done more finely than at present, there is little incentive to do so from a strictly oceanographic perspective. The "open boundary" problem further complicates oceanic analysis; catchments provide a clear geomorphic definition for the landward extent of the coastal zone, but there are no comparable features on the oceanic side. For many reasons (e.g., data availability and the related issue of not being able to "see" things remotely, rapid dynamics of variation, essentially linear shape of the coastal zone) these problems are more daunting in the ocean than on land. We can hope that the proposed Australian marine data development work (Section 3.1.1) will be a major step in resolving these issues.

3.2.2. Data availability

Filling or bridging the data gaps in the CZ was a major original motivation for adopting the typology approach in LOICZ-I, and expanding the charge of LOICZ to extend further into the human dimension area only heightens the problem. Selectively developing data sets – whether by measurements, by reprocessing existing data or by developing useful proxies – will be a key to the continued extension and development of the typology approach. Fortunately, clustering can serve as a very effective diagnostic and targeting mechanism by which to decide priorities: what kind of data, how much, how good and where.

3.2.3. The communication and multi-disciplinary collaboration problem

Typology can be a tool for communication and collaboration – but an unused tool will build nothing. Initial efforts and organization will be required to develop acceptance, cooperation, and ultimately intercalibration of the process among the various themes and projects. In addition to making tools and data more user-friendly and widely available to the community, a critical function of the LOICZ governance structure will be to facilitate and advocate consistent, common use of typology methods across the project.

4. Summary and conclusions

Cluster-based quantitative typologies provide a tool that is disciplinarily "neutral" and can be used to enhance communication of data and concepts, as well as active collaboration among multiple disciplines.

The approach is particularly well suited for organizing research and analysis in the coastal zone, where complexity is high and data are often sparse.

The capability of using classified data together with other data sets offers opportunities for converting qualitative data into usable semi-quantitative data.

In building bridges between the social and the natural sciences for integrated understanding and management of the CZ, typology methodologies offer advantages not available with process modeling or analytical calculations.

If adopted and applied consistently throughout the LOICZ-II activities, cluster-based approaches can facilitate integration and synthesis both within and between science themes.

5. Recommendations

There are three key "action items" required to build on the typological accomplishments of the past and to achieve the potential of the approach.

- Continued user-oriented development and dissemination of a range of tools for data acquisition, processing, and analysis will be required to involve the multiple, diverse communities for which typology is a powerful integrative tool.
- Data (and database) access needs to be greatly expanded and simplified, and distributed databases linked and made interoperable. This must be done for the benefit of the scientists and managers in the field, not as an exercise for modelers or computer experts.
- Broad communication about typology developments and applications needs to be aggressively facilitated – meeting sessions, workshops, journal issues, and reviews targeting different disciplinary audiences are all useful means of building bridges across disciplinary boundaries and achieving the needed synergy in both methodology and the resultant science.

Taking advantage of, and constructively guiding, the rising tide of interest and application illustrated in Fig. 1 will not be without cost. Time, money, and (perhaps most challenging) some subordination of immediate short-term organizational advantage to the longer-term integrated objectives will be required. These resource investments, however, have the potential to achieve major payoffs of integration and understanding.

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References

Bartley, J.A., Buddemeier, R.W., Bennett, D.A., 2001. Coastline complexity: a parameter for functional classification of coastal environments. Journal of Sea Research 46, 87–97.

Bokuniewicz, H., 2001. Toward a coastal ground-water typology. Journal of Sea Research 46, 99–108.

Bokuniewicz, H., Buddemeier, R., Maxwell, B., Smith, C., 2003. The typological approach to submarine groundwater discharge (SGD). Biogeochemistry 66, 145–158.

Buddemeier, R.W., Maxwell, B.A., 2001. Typology – low-budget remote sensing. Global Change Newsletter No. 46, International Geosphere–Biosphere Programme, Stockholm, pp. 19–23. [Earlier version published as: Buddemeier, R.W., Maxwell, B.A., 2000, LOICZ Newsletter No. 15, pp. 1–4. Land–Ocean Interactions in the Coastal Zone, NIOZ, Texel, The Netherlands].

Buddemeier, R.W., Crossland, C.J., Maxwell, B., Smith, S.V., Swaney, D.P., Bartley, J.D., Misgna, G., Smith, C., Dupra, V.C., Marshall Crossland, J.I. (Eds.), 2002a. LOICZ/UNEP Regional Synthesis Workshops: Australasia–Asia, the Americas, Africa–Europe. Summary Report and Compendium. LOICZ Reports & Studies, No. 22. LOICZ IPO, Texel, The Netherlands, 76 pp.

Buddemeier, R.W., Smith, S.V., Swaney, D.P., Crossland, C.J., 2002b. The role of the coastal ocean in the disturbed and undisturbed nutrient and carbon cycles. In: LOICZ Reports & Studies, No. 24. LOICZ IPO, Texel, The Netherlands, 83 pp.

Cha, H.-R., Buddemeier, R.W., Fautin, D.G., Sandhei, P., 2004. Distribution of sea anemones (Cnidaria, Actiniaria) in Korea analyzed by environmental clustering. Hydrobiologia 530/531, 497–502.

Cooper, J.A.G., McLaughlin, S., 1998. Contemporary multidisciplinary approaches to coastal classification and environmental risk analysis. Journal of Coastal Research 14, 512–524.

Crossland, C.J., Kremer, H.H., Lindeboom, H.J., Marshall Crossland, J.I., Le Tissier, M.D.A. (Eds.), 2005. Coastal Fluxes in the Anthropocene. Global Change – The IGBP Series. Springer, Berlin, Heidelberg, New York, USA, 231 pp.

GLOBEC SSC, 1999. Global Ocean Ecosystem Dynamics Implementation Plan. IGBP Report 47. The International Geosphere–Biosphere Programme, Stockholm, Sweden, 207 pp.

Guinotte, J.M., Bartley, J.D., Iqbal, A., Fautin, D.G., Buddemeier, R.W., 2006. Modeling habitat distributions from organism occurrences and environmental data: case study using anemone fishes and their sea anemone hosts. Marine Ecology Progress Series 316, 269–283.

Kremer, H.H., Le Tissier, M.D.A., Burbridge, P.R., Talaue-McManus, L., Rabalais, N.N., Parslow, J., Crossland, C.J., Young, B., 2005. Land–Ocean Interactions in the Coastal Zone: Science Plan and Implementation Strategy. IGBP Report 51/ IHDP Report 18. Available from: http://www.loicz.org/public/loicz/about_us/loiczspisfinal.pdf. IGBP Secretariat, Stockholm, Sweden, 60 pp.

Le Tissier, M.D.A., Buddemeier, R.W., Parslow, J., Swaney, D.P., Crossland, C.J., Smith, S.V., Whyte, H.A.Y., Dennison, W.C., Hills, J.M., Kremer, H.H. (Eds.), 2006. The Role of the Coastal Ocean in the Disturbed and Undisturbed Nutrient and Carbon Cycles – A Management Perspective. LOICZ, Geesthacht, Germany, 39 pp.

Longhurst, A.R., 2001. Ecological Geography of the Sea. Elsevier – Academic Press, San Diego and London, USA & UK, 398 pp.

Maxwell, B.A., Buddemeier, R.W., 2002. Coastal typology development with heterogeneous data sets. Regional Environmental Change 3, 77–87.

Maxwell, B.A., Pryor, F.L., Smith, C.A., 2002. Cluster analysis in cross-cultural research. World Cultures 13, 22–38.

McLaughlin, C.J., Smith, C., Buddemeier, R.W., Bartley, J.D., Maxwell, B.A., 2003. Rivers, runoff, and reefs. Global and Planetary Change 820, 1–9.

Meybeck, M., 1993. Riverine transport of atmospheric carbon: sources, global typology and budget. Water, Air, and Soil Pollution 70, 443–463.

Meybeck, M., Green, P., Vörösmarty, C., 2001. A new typology for mountains and other relief classes: an application to global continental water resources and population distribution. Mountain Research and Development 21, 34–45.

Meybeck, M., Durr, H.H., Vörösmarty, C.J., 2006. Global coastal segmentation and its river catchment contributors: a new look at land–ocean linkage. Global Biogeochemical Cycles 20, GB1S90. doi:10.1029/2005GB002540.

Pernetta, J.C., Milliman, J.D. (Eds.), 1995. Land–Ocean Interactions in the Coastal Zone Implementation Plan. IGBP Report No. 33. IGBP, Stockholm, Sweden, 215 pp.

Pryor, F.L., 2005. Rethinking economic systems: a study of agricultural societies. Cross-Cultural Research 39, 252–292.

Pryor, F.L., 2003. Economic systems of foragers. Cross-Cultural Research 37, 393–426.

Smith, S.V., Buddemeier, R.W., Wulff, F., Swaney, D.P., 2005. C, N, P fluxes in the coastal zone. In: Crossland, C.J., Kremer, H.H., Lindeboom, H.J., Marshall Crossland, J.I., Le Tissier, M.D.A. (Eds.), Coastal Fluxes in the Anthropocene. Global Change – The IGBP Series. Springer-Verlag, Berlin, Heidelberg New York, Germany/USA, 231 pp. (Chapter 3).

Smith, S.V., Swaney, D.P., Talaue-McManus, L., Bartley, J.D., Sandhei, P.T., McLaughlin, C.J., Dupra, V.C., Crossland, C.J., Buddemeier, R.W., Maxwell, B.A., Wulff, F., 2003. Humans, hydrology, and the distribution of inorganic nutrient loading to the ocean. Bioscience 53, 235–245.

Vörösmarty, C.J., Fekete, B.M., Meybeck, M., Lammers, R.B., 2000. Geomorphometric attributes of the global system of rivers at 30-minute spatial resolution. Journal of Hydrology 237, 17–39.

Wilson, B.B., Young, D.P., Buddemeier, R.W., 2002. Exploring relationships between water table elevations, reported water use, and aquifer lifetime as parameters for consideration in aquifer subunit delineations. KGS Open-File Report 2002-25D. Available from: http://www.kgs.ku.edu/HighPlains/OHP/2002_25D.pdf. Kansas Geological Survey, Lawrence KS, USA, 28 pp.