

Effects of changing spatial scale on acoustic observations of patchiness in the Gulf Stream

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Abstract

We examine the influence of spatial scale on studies of nektonic patchiness at the north edge of the Gulf Stream by altering the grain size of acoustic cross sections and applying a patch-finding algorithm. From original 'pictures' of 180 pixels deep by 540–1260 pixels long, we averaged depth and length, to give 9 scales ranging from fine grain (1 m vertical \times 25 m horizontal sized pixels) to coarse grain (12 m \times 300 m sized pixels). Measures of overall echo intensity within patches were the most predictable and showed little change with scale. Measures of variability of the echo within patches showed simple negative trends with scale and were best measured at fine spatial scales. Patch size and shape related variables have a more complex relationship with scale with differences between day and night transects more pronounced at intermediate scales. This suggests behavioral patch forming mechanisms within the nekton occur at a specific grain size (4 m vertical \times 100 m horizontal) within the Gulf Stream front.

1. Introduction

Many questions in ecology require the analysis of diverse ecosystems. These include studies of biotic characteristics along latitudinal, climatic, edaphic, or biotic gradients (Sheldon *et al.* 1972; Brown and Maurer 1989; Stevens 1989). Such analysis make use of 'natural' experiments, to address underlying features or 'emergent properties' of the ecosystem. These studies make use of data not otherwise obtainable through experimental or manipulative research. However in all such system level comparisons the spatial and temporal scale of observation is critical to the phenomenon in question (Turner *et al.* 1989; Magnuson *et al.* 1991).

Choice of system scale is also critical to any attempt to extend observations beyond our observation set (Turner *et al.* 1989). A recent example of extending system observations to higher spatial and temporal scales are models of global climate change (Ramanathan 1988). Interaction of their component parts at large scales require that the modeling of small spatial and short temporal scales are realistic. Such scaling may not be appropriate (Stouffer *et al.* 1989) and requires the construction of more complex global models (Slingo 1990).

Pelagic ecosystems are unique in that physiological and ecological parameters are closely coupled to spatial and temporal physical scales (Steele 1989). Thus, our interest in spatial pattern in pelagic

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ecosystems stems from the paradigm that studies of pattern will lead to an understanding of the generative mechanism or parameters behind the pattern (Margalef 1985). We seek the dynamical mechanisms generating spatial pattern among the nekton, the large, economically important end of the food chain.

However, in aquatic ecology comparative studies of spatial pattern are limited by the choice of sampling gear. In the past, the grain size chosen for a particular research question was constrained by the physical limits of sampling programs (Downing *et al.* 1987; Herman and Platt 1980) and our inability to directly perceive the system. Pelagic systems are remotely sampled with nets, pumps, cameras or sonar leading to a plethora of data dependent on sample type and spatial arrangement. Unlike terrestrial systems direct observations are limited to SCUBA and submersibles. For these reasons, comparative studies of spatial pattern in pelagic systems are rare.

An understanding of the role of spatial and temporal extent on the nature of pelagic systems are somewhat better understood than changes in grain. Extent has been examined non-quantitatively as the general study of spatial and temporal variability over the oceans through time (Stommel 1963; Steele 1978, 1989). Grain size has only recently been studied comprehensively (Schneider 1989; Rose and Leggett 1990).

In oceanography there is considerable interest in biological patchiness. Many pelagic animals are now recognized to operate in an environment dominated by high spatial variability in food and resources (Scavia *et al.* 1984; McClathie 1986; Price 1989; Rose and Leggett 1990). Spatial variability is easily measured at a variety of scales through frequency analysis (Platt and Denman 1975). However, there is also a need to identify an individual patch and examine its internal structure and spatial relationship with other patches (Nero and Magnuson 1989; Nero *et al.* 1990). Terrestrial systems often have obvious edges and definitions of patchiness can be non-arbitrary. The organisms can often be considered acting on a two dimensional surface (Fahrig and Merriam 1985). Yet, in the open ocean, the definition of a patch edge becomes complex and must be made arbitrarily (Nero and

Magnuson 1989). Such definitions are additionally complex because oceans are three dimensional. A large extent can only be viewed from a vertical perspective (Platt and Sathyendranath 1988). Fine scale internal features are at best, viewed from cross sections through the three dimensional structure (Magnuson *et al.* 1991; Nero *et al.* 1990).

Herein, we use sonar to make scale-related observations of nekton within the ocean-day and ocean-night pelagic environment within the Gulf Stream. We quantify intense patch features and determine whether the characteristics of day and night patches are dependent on our scaling of the grain size of observations. This study will facilitate the use of sonar to make additional comparisons between disparate pelagic environments such as lakes and oceans and aid in the design and interpretation of bioacoustic assessments of fish and invertebrates.

2. Methods

2.1. Site description

Sonar images were collected from: 1) the near surface waters (0–200 m depth) of the Gulf Stream 115 km ENE of Cape Hatteras North Carolina from August 6 to 11, 1985 (Fig. 1). Each sonar image was taken along an approximate 30 km length transect along a line 135° from true north at 35°57'N, 74°44'W. This was specifically chosen to bisect the Gulf Stream perpendicular to its mean current direction. Ocean depths ranged from approximately 400 m in the northwest to 2000 m in the southeast. Transect durations were 2–6 h with 4 taken during day and 6 at night. The thermal front marking the shoreward edge of the Gulf Stream was determined from expendable bathythermographs (XBTs).

2.2. Sonar method

We used a Simrad EY-M sonar which transmitted a 70 kHz ping for a duration of 0.6 ms. This frequency best reflects from targets greater than 2 cm in length. The sonar operated at 1 ping/s. However,

because of processing limits, only echo voltages from every third ping were squared and integrated in real-time over contiguous 1 m depths to 200 m using a programmable echo processor (Powell and Stanton 1983). The short ping duration allows vertical resolution of targets that are at least 0.44 m apart, well below the resolution limit of our echo processor. We took an average of every four consecutive pings to provide an approximate 25 m horizontal grain size of the integrated echo ($\langle E \rangle$). To provide data free of interference from the ships hull and wave induced air bubbles we use data beginning below the upper 8 m of the recorded acoustic data. Details on our data acquisition and sonar-related corrections are described elsewhere (Clay and Medwin 1977; Nero *et al.* 1990).

2.3. Scaling through changes in grain

We simulate changes in grain size by averaging blocks of a number of $\langle E \rangle$ values ($n \times n$) in the vertical and horizontal direction and assigning them to a new image of simulated $\langle E \rangle$ values (where $n =$ scale). This has the effect of creating data which would result had the sonar and our post processing and analysis system viewed a larger portion of the ocean during each ping. We scaled grain over 1 through 6, 9, 10 and 12, all even divisors of 180, the number closest to 192 m, the useful vertical extent of our data.

2.4. Filter for defining patches

Patches were defined as where $\langle E \rangle$ of a single element is greater than the adjusted average background $\langle E \rangle$ of surrounding elements (Nero and Magnuson 1989). The average background $\langle E \rangle$ is determined within the bounds of a smoothing window of height \times width ($h \times w$) with its resultant value adjusted by a threshold increment (k). This algorithm functions as a high pass filter, allowing the identification of patches exhibiting spatial extent smaller than that of the smoothing window. Edge simplification routines were applied to reduce the excessive reticularity of patches (Nero and

Magnuson 1989). For all scales, we use a window of $h = 13 \times w = 55$ elements and a threshold of $k = 1.4$. Both appropriate for studies of fine-scale patchiness within the Gulf Stream (Nero and Magnuson 1989).

2.5. Patch measures

Measures of patch characteristics are adapted from Nero and Magnuson (1989). Statistics using location and size are measured in units of element sides. Angle to a nearest neighbor is the absolute angle above or below the horizontal axis expressed in radians with the distance to the neighbor measured on this angle from patch center to center. We measured patch dispersion (r_a) using the measure described by Clark and Evans (1954) where for one transect:

$$r_a = Nd \sqrt{2\rho}$$

Nd is the average distance between neighboring patches and ρ is patch density (number per transect area). We expect values of 0 at maximum aggregation, 1 for a random distribution and 2.15 at minimum aggregation. External height and width are a patch's largest dimensions regardless of intervening edges while internal height and width are a patch's largest dimensions found without crossing an edge. The fractal of perimeter on area is determined from the edge to area relationship of each patch, and is a measure of shape complexity with values of 1 representing square outline shapes and 2 denoting the most complex outline shapes (Turner 1987). This fractal measure is biased by the effect of our edge simplification routines. Internal features of (E) within each patch are measured in arbitrary A/D converter units and include the mean, peak, variance and coefficient of variance and two distribution statistics: skewness and kurtosis (Zar 1984). Roughness and associated coefficients (normalized to the mean), is determined in both horizontal and vertical directions. The conversion from our arbitrary units to volume scattering strength is: $S_v \equiv 10 \log_{10} \langle E \rangle - 101.6$ (dB) (Nero and Magnuson 1989).

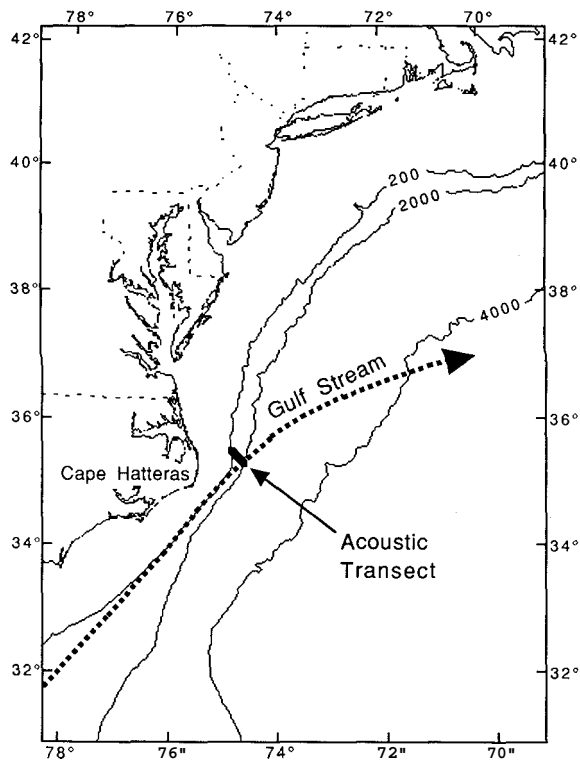


Fig. 1. Location of the study site in relation to Cape Hatteras and the Gulf Stream. Depth contours in meters.

For variables measured on individual patches, differences between night and day at one particular scale were examined by pooling the patches from all night transects and from all day transects and then testing for similarity in the two samples using the Wilcoxon rank-sum Test, (Conover 1971). For sample sizes greater than 1000 we randomly choose a subsample of 1000 patches. For transect-wide measures we used the Wilcoxon rank-sum test with 4 day transects and 6 night transects representing 4 and 6 samples respectively. Because we made 189 comparisons the Bonferroni criterion suggests our significance levels should be adjusted to $0.05/189$. However, this approach is highly conservative. Instead we indicate when $P \leq 0.05$ for individual tests and look for overall trends across scale. General trends were examined using Kendall's test (Conover 1971) for median values of each variable over the 9 scales (again, $P \leq 0.05$).

3. Results

The patch-identification algorithm provides an overall visual impression of the effect of increasing scale on patchiness and patch occurrence as shown in Fig. 2. We provide an example day (Aug. 8, 1985) and night (Aug. 11, 1985) echogram along with three scales; the smallest (scale 1); an intermediate (scale 6); and the largest (scale 12). We hypothesize that at the smallest scale the multitude of patches are associated with social or feeding aggregations (Fig. 2, panel B). At an intermediate scale, patches are associated with the Gulf Stream front, with a major concentration of biota at the sharp thermal and salinity gradient between the slope water on the left and the Gulf Stream on the right (Fig. 2, panel C). At the largest scale, a few large patches of organisms were apparent, one where isotherms approach the surface, and the other in the Gulf Stream (Fig. 2, panel D). Our quantitative measurement of these patch features allows us to more rigorously interpret these results. However, our simulation of changing grain without a concomitant change in extant resulted in a precipitous decline in the number of patches between scales 1 and 2 (Fig. 3). As a result, caution must be used in interpreting differences at these small scales.

Our three relational variables, distance between neighbors, angle between neighbors and the index of dispersion, each showed a change with increasing scale and a difference between night and day. Distance between neighboring patches, although highly variable, increased from 7–8 elements at scale 1, to 12–13 elements at scale 12 (Fig. 3). This distance was greater during night than day at scales 3 through 5. With increasing scale and a concomitant decrease in the number of patches the angle between neighboring patches showed a decline from 0.7 radians at scale 1 to 0.3 radians at scale 12 (Fig. 3). This change was caused by fewer patches being found immediately above or below their neighbors but rather in a more horizontal direction. The spatial dispersion of patches (r_a) within each transect showed a positive trend with scale ($P \leq 0.05$) (Fig. 3). It was initially low (1.1) at scale 1, indicating a random pattern and increased at scale 12 (1.7) indicating a more uniform pattern. Although r_a was

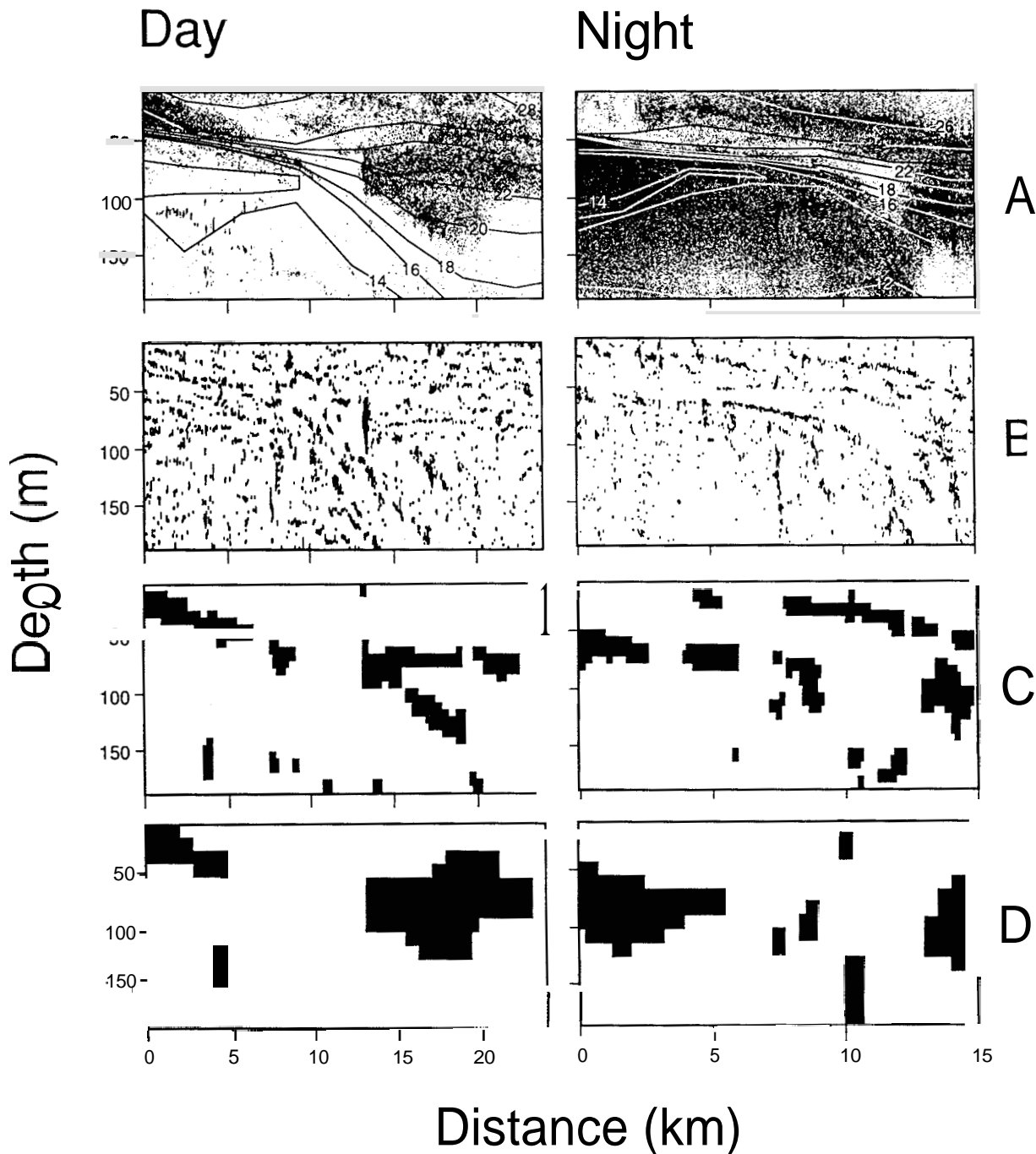


Fig. 2. A depiction of the original integrated echo data and patch locations for three scales for an example day and night transect from the Gulf Stream near Cape Hatteras North Carolina. Panel: **A**, original data; **B**, scale 1; **C**, scale 6; **D**, scale 12. Each panel is a cross section as seen by an observer looking towards the northeast, with the coast on the left and the Gulf Stream on the right.

in general higher for day than night, only at the first three scales (1, 2, and 3) were large differences observed ($P \leq 0.05$), indicating that for small scales,

day patches were more uniformly distributed than night.

Measures of patch size and shape all show depen-

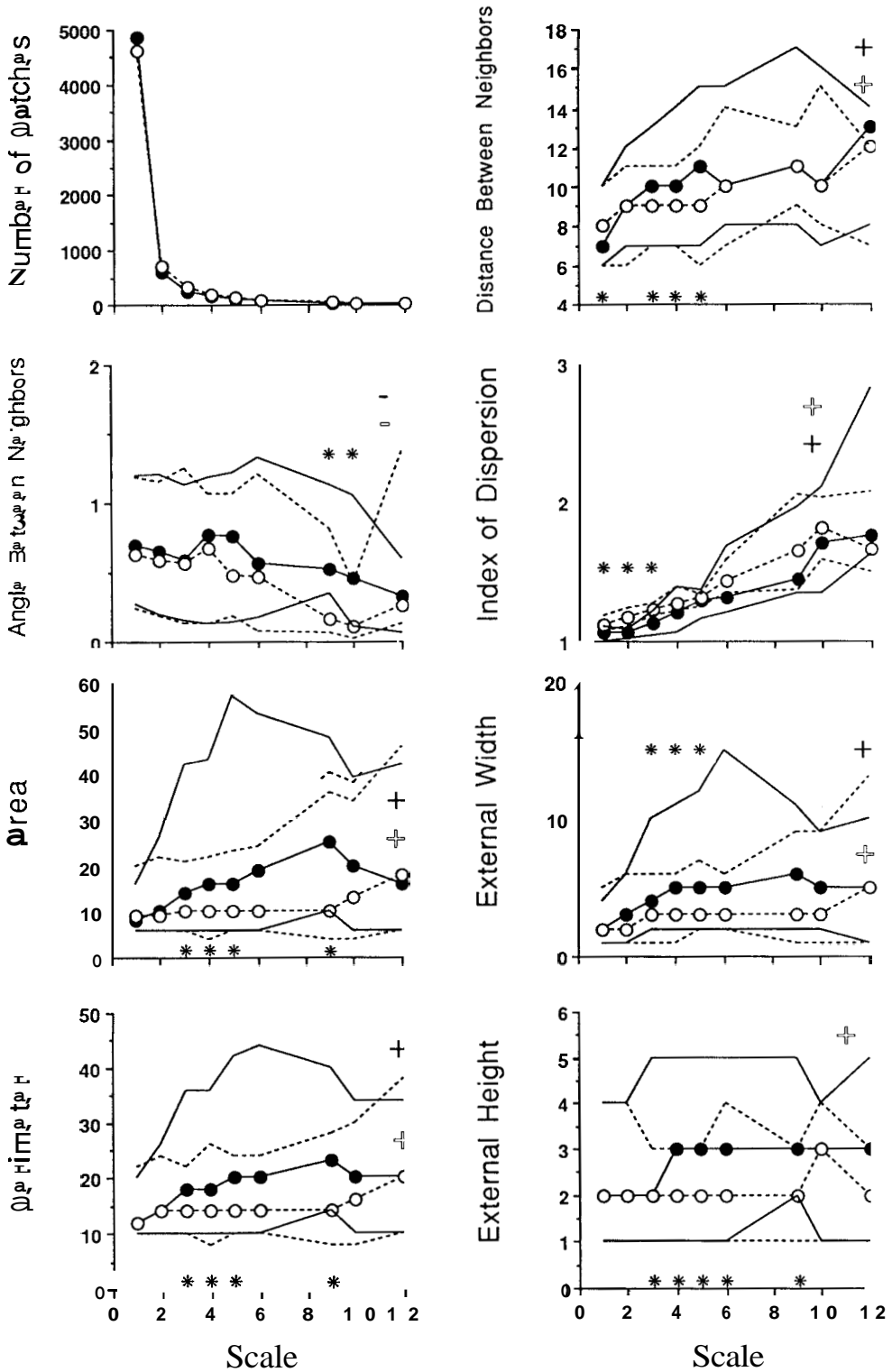


Fig. 3. Echo statistics and patch variables in relation to changing spatial scale. Day: ---O---, Night: —●—, with first and third quartiles indicated by lines above and below each set of data. '*' indicate where $P \leq 0.05$ for a difference between day and night (rank sum test), + and - symbols indicate where $P \leq 0.05$ for a trend with scale (Kendall's test for trend) with open symbols for day, solid symbols for night. Scales 1 through 12 represent data averaged to form pixels of 1×25 to 12×300 respectively (units are m vertical \times m horizontal).

dencies on scale and differences between night and day. Patch size as measured by area, external sizes and perimeter length, all increase with increasing scale (Fig. 3) (Internal sizes are not presented because they are nearly identical to external sizes). At intermediate scales (3 through 6) night patches are larger than day patches for all these measures ($P \leq 0.05$ to $P \leq 0.0002$). However, at large and small scales differences between night and day are not evident (Fig. 3). These overall trends in patch shape are only partially reflected in the fractal dimension, D , which shows a slight day – night difference at the intermediate scale of 6 but no differences at all other scales nor a trend from the smallest to largest scales ($D = 1.06$ to 1.15 respectively, Fig. 4). These differences in patch size and shape would have remained unobserved had only the smallest or largest scales been examined.

Measures of $\langle E \rangle$ strength changed in a simple manner over all scales. The background, mean and peak $\langle E \rangle$ all show a positive trend with scale with a gradual increase in mean $\langle E \rangle$ strength at larger scales (Fig. 4, only the mean $\langle E \rangle$ is shown). This suggests that at a large scale, the few remaining patches represent the largest and most intense regions (Fig. 2), while small patches from outlying low intensity regions become excluded at the large scales. This effect appears to be more pronounced at night than day (Fig. 4), suggesting that at day over the entire scene organisms are grouped in more well defined patches than at night. For all three measures of $\langle E \rangle$ strength, the $\langle E \rangle$ of night patches was significantly greater than day (4–7 X), corroborating the presence of a large abundance of organisms which have migrated up into this region at night (Cole *et al.* 1970; Boyd *et al.* 1986; Nash *et al.* 1989). This day-night difference is evident at all scales.

Measures of variability of $\langle E \rangle$ (variance and horizontal and vertical roughness) within a patch all show that night variability was 20 to 40 X greater than day (Fig. 4). However interpretation is difficult because of potential correlation of the variance with the mean $\langle E \rangle$ and a greater mean $\langle E \rangle$ at night. A better alternative is to examine the standardized variance (coefficient of variance). For all three coefficients (of variance and roughness), day

patches contain more inherently variable echoes than night patches (Fig. 4). Apparently, within patches day animals exhibit a more aggregated fine-scale distribution pattern than night animals (Nero *et al.* 1990). These variability measures also are related poorly to scale (Fig. 4), but do show more consistent day-night differences at smaller scales. This may be a spatial statistical effect. Presumably as the echo data from larger regions are averaged to create the large scales, variability of the echoes are gradually reduced and become a less reliable measure of echo variability at a scale appropriate to individual animals and school sizes.

Skewness and kurtosis are essentially higher order measures of echo characteristics. They both show day and night differences at small scales but lose their ability to accurately depict echo characteristics at large scales (Fig. 4). Presumably as more echoes are averaged fine grain characteristics are lost. At small scales, day patches are more positively skewed than night patches indicating that within a day patch there is a greater occurrence of single isolated echoes. Such a pattern suggests that by day, patches contain a few large solitary animals or small animals in tight clumps (Nero *et al.* 1990).

4. Discussion

4.1. Methodological

To what extent is this analysis dependent on the particular patch finding algorithm? It is completely dependent. We recognize that the algorithm is just one way of perceiving the world, with biases and constraints peculiar to this method. Although our choice of window size (13 X 55 elements) and threshold (1.4 X) are arbitrary, they can be reproduced and have the advantage of providing a consistent perception of patch-like features over disparate systems. Nero and Magnuson (1989) examined a number of choices of window size and threshold and determined that those we use here are best for perceiving small scale (meters to kilometers) features within acoustic transects.

We choose to change scale by altering the vertical and horizontal grain of our data. Alternatively we

could have changed the horizontal or vertical components separately. Such a manipulation would be useful if not necessary where the horizontal or vertical extent of the data is too small to allow simulated changes in grain in one dimension. An example would be in lakes where the vertical extent of the data often can be less than 25 m.

Some of our observations of scale related effects may be an artifact of the simulated scale change or interaction of the simulated scale with our patch algorithm rather than due to a natural scale related phenomena. A preliminary randomization we attempted of an array of acoustic data to build an artificial field of patches proved computationally intractable. Instead, we attempt to determine which trends are likely biological in origin, and which appear due to either physical phenomena or the scaling procedure. Our most important observations are of those variables which show a differential effect between night and day. Such differences are not likely artifacts of the method but rather are biological in origin.

In our analysis changes in patch characteristics attributed to changing spatial scale, also may be an artifact of changing map size, and the proportion, of the map occupied. Because we are simulating changes in grain by averaging adjacent pixels, map size is inversely proportional to scale. Some of our measures of patch characteristics may be influenced by decreasing map size rather than scale. A plot of the probability of a pixel being occupied, p (calculated as occupied pixels/total pixels) against map size, m (total pixels^{1/2}), suggests an inverse relationship between m and p for our data. The highest probability of a pixel being occupied (p) occurred for the smallest maps ($p = 0.19$). Low probabilities ($p = 0.10$) occurred at intermediate and larger map sizes. Based on neutral models of landscape pattern, measures of cluster (patch) number, size, and shape are all sensitive to changes in m and p (Gardner *et al.* 1987). The greatest change in pattern and increased error of estimation occurs at values of p at or above the critical probability ($p_c = 0.59$, that at which clusters span the entire map), presumably because of increased effects of map edges (Gardner *et al.* 1987). In our analysis the choice of a high threshold increment, k , results in values of p suffi-

ciently small (0.1–0.2) that patches rarely span the entire map (Fig. 2) and we avoid edge induced effects. However, our estimates of shape are not free from bias introduced by the rectangular nature of the small patches (Fig. 2 and Gardner *et al.* 1987) and our best estimate of fractal dimension (D) may be provided by the single largest patch present in a particular transect. Overall, we believe our biological interpretation of the influence of scale change on our observations within the ocean are biased little by these inadvertent changes in map size and proportion of the map occupied.

4.2. Biological interpretation

We view the ocean analogously to a terrestrial 'landscape' in which the abundance of animals are distributed within a dynamic physical and chemical environment (Magnuson *et al.* 1991). In the ocean this environment consists of physical-chemical dynamics which include: water motion; salinity and temperature induced density gradients; and the combined light and nutrient gradients. All of which influence primary production and the ultimate food resources of the nekton. In both terrestrial and aquatic systems the physical and biological processes interact to shape and form the landscape (Powell 1989; Mazumder *et al.* 1990). At the Gulf Stream front we have viewed only one component of the landscape, the free swimming large bodied (> 2 cm) nekton. However, their distribution, abundance and patchiness, will reflect to some extent the underlying mechanisms generating their distribution, be it physical water motion or active behavior in locating resources and selecting habitats.

We view the patches at changing spatial scales as components of what can be considered a 'spatial hierarchy' (O'Neill *et al.* 1986). Small sub-patches which occur at the finer grain sizes are components of a low hierarchical level. These smallest patches can be conceptualized as members of the larger intermediate sized patches which occur at intermediate grain sizes and represent an intermediate hierarchical level. Finally the largest patches are composed of regions of high densities of the subsets of smaller patches and represent the largest hierarchi-

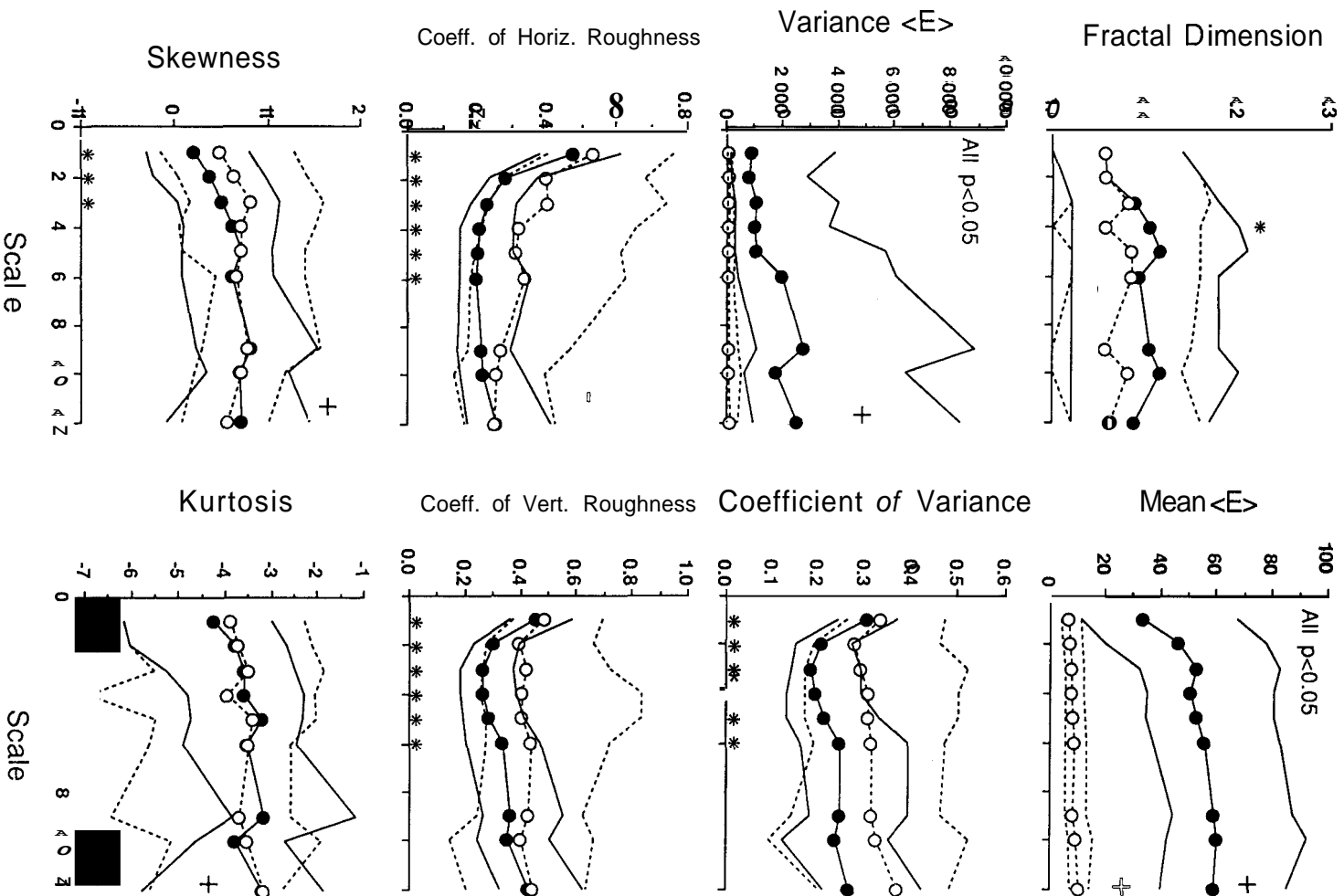


Fig. 4. Symbols and notation as in Fig. 3.

cal level. We hypothesize this hierarchy of patches represents a gradient of functional types, with small fine-grain patches representing shoals and schools of feeding assemblages of like species (Nero *et al.* 1990), intermediate grain patches representing organisms with similar preferences such as light and temperature (Nash *et al.* 1989), and finally, the largest grain patches represent overall faunistic and physical-oceanographic differences between the Slope Water side (Fig. 2, left) and Gulf Stream side (Fig. 2, right) of the front.

These scale related changes in patch characteristics are reflected in measures of patch size, shape and internal structure. We see an increase in the distance between patches, their dispersion and overall size. These changes reflect the incorporation of many small patches into a few large isolated patches. Because patch size and shape are measured in units of pixels, slightly larger or similar patch sizes at large scales, actually reflect an increase in the real size of patches at the large scales.

Coefficients of variability all show a 'U' shaped curve across scale. At small scales these coefficients of variability are high, indicating high local roughness at this fine grain. For intermediate size patches these coefficients are lower reflecting the influence of averaging regions with a similar roughness. As larger regions are included these coefficients increase. A possible explanation is that as more distant regions are averaged and included as a single patch, more dissimilar animals become included. This is corroborated in our studies of the front where we demonstrate that at the fine-scale, nearby patches contain like features but more distant patches contain dissimilar features (Nero *et al.* 1990).

Interestingly, our measures of variance and coefficients of variance from within a patch are different from measures of variability of the entire acoustic transect. Variance spectra for acoustic transects collected off Newport Oregon, show that over scales of 40 m to 500 m variance components steadily increase by two orders of magnitude (Greenlaw and Pearcy 1985). Our variance measures from within patches show only a 3 times increase in variance over scales of 55 m to 660 m (Fig. 4). Thus, the variance of entire acoustic transects

appears to increase much more quickly at large scales than that measured from within patches. This supports our conclusion that internal structure of patches is more similar across a transect than the distribution of patches per se.

Differences between patch characteristics between day and night can be used to elucidate scale-related biological phenomena, because of the extensive information on diurnal vertical migrations in the sea (Kampa 1976; Boyd *et al.* 1986). We emphasize the importance of scale on observations of animal behavior and orientation within the front. At all scales we observed an increase in integrated echo ($\langle E \rangle$) at night, reflecting an influx of vertical migrants into the upper ocean (< 200 m) and a decrease in coefficients of variability and skewness suggesting that the animals present at night have a more even distribution pattern at fine scales (Nero *et al.* 1990) or perhaps 'fill' more of the space at these higher densities. Greenlaw and Pearcy (1985) made similar observations based on higher levels of variance spectra during day in comparison to night for scattering profiles off Newport, Oregon. These observations suggest that at night the vertically migrating fish and invertebrates are distributing themselves evenly within the water in pursuit of smaller evenly dispersed zooplankton prey. Those fishes and invertebrates not migrating presumably remain during the day in small compact schools or swarms but would appear to be more dispersed at night or 'hidden' by the nocturnal migrants. The swarms or schools during day could contribute to high variability of reflected echoes depending on the species composition and the exact animal-animal spacing. Such night dispersed-day compressed spatial patterns have been observed for freshwater (Rudstam and Trapp 1987) and marine fishes (Munk *et al.* 1989).

Our observation of reduced echo variability at night could also be due to changes in fish orientation. However, photographs of herring schools show that they are more randomly oriented at night than day (Buerkle 1983) suggesting our observation of reduced echo variability at night is not likely a result of fish orientation.

Also interesting are day-night differences in patch size and shape that are only apparent at inter-

mediate scales. These measures suggest that although night animals are more evenly distributed, at a grain size of (4 m X 100 m), the patches they occur in have a greater size and shape complexity than day patches. This may be attributed to either 1: a greater dependence of the daytime, non-migratory organisms on the physical structure of the water therefore resulting in simpler shape complexity than night; and 2: during day the nekton show strong orientation behavior to group (species) into specific schools and shoals with reduced size and simple outline shapes. Overall, at night fine scale behavioral constraints are relaxed, the animals disperse outwards from visually maintained aggregations, and larger, more complex patch shapes result at this scale. These phenomena are less evident at smaller or larger scales.

4.3. General oceanographic interpretation

Many oceanographic studies address the question of spatial scale (see reviews by Steel 1989 and Powell 1989), however, few studies address mechanisms using quantitative measures taken at the space-time scale of predator-prey interactions and behavior (Schneider 1989; Rose and Legett 1990). For dependencies of biological phenomena on scale to be incorporated into the paradigms of dynamic models in oceanography, we first need measures of the scale dependencies of various phenomena. Quantitative treatment of scale related phenomena will allow their extrapolation and prediction in more general studies (Gardner *et al.* 1989). Our study revealed three general types of scale dependencies of patch characteristics which fall into the four groups proposed by Gardner *et al.* (1989). Group (1): those variables which are unaffected by changes in scale. In our study they would include those of overall intensity. They show little change and are always significantly different between night and day. Group (2+3): those with simple linear correlations with scale, such as measures of $\langle E \rangle$ variability, roughness and associated coefficients of variability. All show less significant day-night differences at increasing scale. Finally, group (4): variables which are scale variant but without a sim-

ple linear correlation. They are most difficult to deal with and cannot be predicted across scales. They show no difference at small, and large scales, but some dependency at intermediate scales.

Specifically these are size and shape. Gardner *et al.* (1989) suggests that such complex scale transformations may represent a shift to a higher hierarchical level. In our study this transition may represent the scale where patch forming mechanisms related to the physical oceanographic features become more dominant than those related to behavioral interactions among and within species (Fig. 2, panel D).

Our two dimensional vertically oriented view of a three-dimensional structure provides a number of insights not available from a 2-D surface view. Most notable are differences between the vertical and horizontal. Vertical measures of patch size show greater day-night differences over a wider scale range than do horizontal measures suggesting that changes in patch shape are greater in the vertical than horizontal components. This is presumably because of the greater current velocities in the horizontal than vertical direction and subsequent dispersal of diurnally migrating organisms in the horizontal direction (Blaxter 1975). Coefficients of horizontal and vertical roughness indicate that at increasing scales horizontal roughness is reduced while vertical roughness remains high suggesting that at large scales horizontal features become repetitive or similar while vertical features remain distinct and unique. This suggests that in general for pelagic ecosystems, biological structure is more distinct or heterogeneous in the vertical than horizontal direction.

Our two dimensional view can also be expanded to a limited 3 dimensional view. Nero *et al.* (1990) speculate on the 3 dimensional size of patches within the Gulf Stream based on the temporal sequence of our acoustic cross sections. At large scales, the along stream patch dimensions are 7 times longer (35 km) than the cross stream dimensions (5 km). Such stretching of patches along the axis of the current are similar to the observations of Mackas (1984) for the shelf and slope waters off Vancouver Island.

One application of these results is to the design of

fisheries assessment technology and procedures. Patch (or school) detection, measurement, and classification routines (Rose and Leggett 1988; Nero and Magnuson 1989) are all dependent on choice of scale. For studies of acoustically measured patchiness, we recommend the use of a fine grained scale for mean $\langle E \rangle$ and measures of its variability and skewness. If we seek to detect behavioral phenomena related to movements of the nekton, shape related parameters should be made using a grain size of approximately 4 m vertical and 100 m horizontal. In comparisons of disparate aquatic environments, we should ensure that our interpretation takes into account the spatial scale used.

For general comparisons of patch related characteristics between diverse aquatic systems, variables such as mean (E) could easily be made with a simple linear adjustment for different scales. Likewise, measures of variability could be translated between scales (Turner *et al.* 1989). The scale dependency of our spatial measures are complex and would need to be incorporated into the design of comparative studies. Finally, some of our observed trends with scale may be artifacts of the scaling procedure. They will need to be investigated further and used judiciously in comparisons with similar measures in other studies.

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