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2aAO6. Characterization of thermohaline staircases in the Tyrrhenian Sea using stochastic heterogeneity mapping

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Processed multi-channel seismic (MCS) data acquired in the Tyrrhenian Sea in April-May 2010 provide images of oceanic thermohaline staircases. Using Stochastic Heterogeneity Mapping we characterize spatial reflector variations. This method is based on the band-limited von Kármán function. For scale sizes smaller than the correlation length, the von Kármán model describes a power law (fractal) process. We are most interested in the extraction of the exponent in the power law (The Hurst exponent) because it allows us to characterize the richness of scales present in the data set. Lower Hurst exponents represent a richer range of wavenumbers and therefore correspond to a broader range of heterogeneity in the observed seismic reflection events. The Hurst exponent is related to the fractal dimension and to the slope in the Garrett-Munk wavenumber spectrum. We interpret a richer range of heterogeneity as indicative of a greater degree of turbulent mixing. Data are presented alongside benchmark calibrations of synthetic seismic data generated from random fractal surfaces. We observe an oscillation in the Hurst exponent spectra as a function of frequency that is interpreted to represent a preferential coupling of energy across different spatial scales.

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Circulation in the Tyrrhenian Sea

The Tyrrhenian Sea is a deep, semi-enclosed basin in the larger Mediterranean Sea (Figure 1). It is located between the Apennine Peninsula and the islands of Corsica, Sardinia and Sicily. Three water masses are identified: 0-200 m, Modified Atlantic Water (MAW - water which originates at the Strait of Gibraltar); 200-700 m, Levantine Intermediate Water (LIW - originating in the Eastern Mediterranean); and from 700-sea floor (up to 3600 m), Tyrrhenian Deep Water (TDW) [Astraldi and Gasparini, 1994]. The TDW is formed as a consequence of the mixing of Western Mediterranean Deep Water (WMDW) and LIW [Budillon et al., 2009].

The TDW is the focus of our study because it contains thermohaline staircases, which are regular, well-defined step-like variations in vertical profiles of temperature and salinity. Staircases occur where variations in vertical temperature and salinity gradients share the same sign, increase with depth and nearly compensate with density [Kelley, 1984]. In the ocean they are thought to result from double diffusion processes driven by the two order of magnitude difference between the diffusivities of heat and salt [Schmitt, et al., 1987]. Staircases are believed to have an anomalously weak internal wave-induced turbulence, making them suitable for the estimation of a lower limit of turbulent disturbance detectable by multi-channel seismic (MCS) methods. They have been detected before using MCS (e.g. Buffett et al., [2009], Biescas et al., [2010], Fer et al., [2010]).

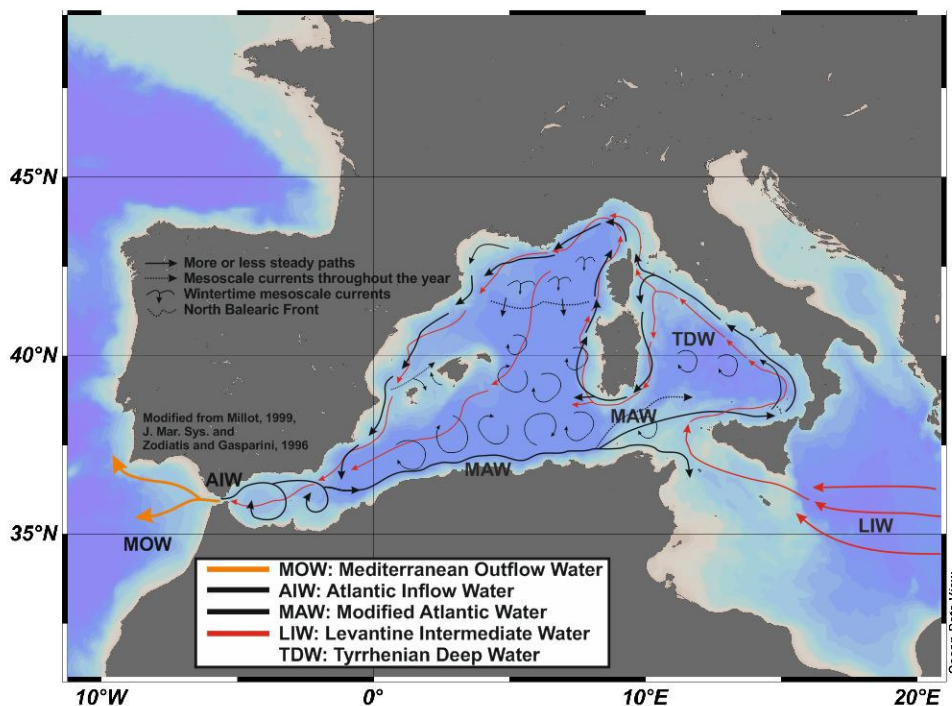


FIGURE 1.

Circulation in the Western Mediterranean Sea. Modified after Millot [1999] and Zodiatis and Gasparini [1996]. Mediterranean Water which flows into the Atlantic Ocean is replaced by Atlantic Water which resides in the upper 200 m of the water column. As it travels east it is modified by the properties of the Mediterranean Sea. It circulates cyclonically around the Tyrrhenian Sea near the surface. Similarly, Levantine Intermediate Water also circulates cyclonically around the Tyrrhenian Sea but at depths between 200 and 700 m. Both water masses have a flux into the deepest parts of the basin where the thermohaline staircases are observed.

Seismic Data Acquisition and Processing

The seismic data were acquired in April and May, 2010 in the Tyrrhenian Sea as part of the MEDOC (MEDiterranean OCCidental) project. MCS acquisition uses a repetitive impulsive source and a streamer (a towed cable filled with hydrophones) to measure the intensity of reflections from both oceanic thermohaline finestructure

and the solid Earth (see Ruddick et al. [2009] for a concise description). Acquisition parameters are summarized in Table 1. The acquisition of MCS data for ocean research is known as seismic oceanography, first reported in detail by Holbrook et al. [2003].

Optimal geometry information from ship navigation coordinates and acquisition configuration was applied to the seismic data using a back-projection algorithm. Attenuation of the direct wave (energy which travels directly from source to receiver without reflecting) was completed using a trace mix over a sliding window after a linear moveout correction followed by adaptive subtraction. Seismic data were frequency filtered, corrected for normal moveout using sound speeds derived from expendable bathythermographs (XBTs), stacked and migrated (see Yilmaz [2001] for a detailed description of seismic data processing). The migrated sections were inverted for Hurst exponent using Stochastic Heterogeneity Mapping.

TABLE 1. Seismic data acquisition parameters for the MEDOC cruise carried out in April and May, 2010.

Energy Source	Instrumentation	Cable Configuration
Total volume: 49.8 L	Format: SEG-D	Number of groups: 276
Nominal source depth: 10 m	Sample rate: 2ms	Streamer length: 3450 m
Shot point interval: 50 m	Record length: 18 sec	Group interval: 12.5
Peak Energy: 60 Hz	Filter: OUT-90/100 Hz	Nominal cable depth: 10 m
		Near offset: 120 m
		CMP spacing: 6.25 m

The Stochastic Model

In this study we follow the methodology outlined in Buffett et al. [2010], as detailed below. The 1-D von Kármán model we use is described by two principal parameters: the correlation length, of which we only consider the horizontal component (a_x), which is the upper limit for the horizontal scale invariance in heterogeneity [Carpentier, 2007] and the Hurst exponent (ν), a measure of surface roughness or, the richness of the range of scales in the power law distribution (having a value between 0 and 1). We normalize the distribution with unit variance. The exponent (ν) relates to the fractal dimension (D) by $D = E + 1 - \nu$, where E is the Euclidean dimension. For scales longer than the correlation length, the von Kármán model represents uncorrelated processes such as white noise [Hurich and Kocurko, 2000].

The structure of the impedance field, and hence its autocorrelation function follow the defined power spectrum. We choose a von Kármán stochastic distribution because it adequately describes a band-limited power law process. The analytic radial 2-D von Kármán power spectrum is given as

$$\frac{4\pi\nu a_x a_z}{(1+k^2)^{\nu+1}} \quad (1)$$

[Carpentier, 2007], where ν is the Hurst exponent, a_x and a_z are the horizontal and vertical correlation lengths, respectively and k is a weighted radial wavenumber given by

$$k = \sqrt{k_x^2 a_x^2 + k_z^2 a_z^2} \quad (2)$$

The 2D autocorrelation function expressed in the spatial domain is

$$C(r) = \frac{G_\nu(r)}{G_\nu(0)} \quad (3)$$

[Goff and Jordan, 1988], where $G_\nu(r) = r^\nu K_\nu(r)$ with $K_\nu(r)$ being the second modified Bessel function of fractional order, and r the weighted radial autocorrelation lag, written as, $\sqrt{\frac{x^2}{a_x^2} + \frac{z^2}{a_z^2}}$. Carpentier [2007] defines $G_\nu(0)$ as $G_\nu(0) = 2^{\nu-1}(\nu-1)!$.

For power law (fractal) scaling, the power spectrum is proportional to frequency (hence, wavenumber) and to the Hurst exponent by

$$S(f) \propto \omega^{-\alpha} \quad (4)$$

where ω is frequency and α is the slope. This is related to ν [Gang et al., 2009] as

$$\nu = \frac{(\alpha-1)}{2} \quad (5)$$

After seismic data processing, we apply Stochastic Heterogeneity Mapping [Buffett et al., 2010] based on the band-limited von Kármán function to stacked, post-stack time-migrated seismic data to invert for stochastic parameters such as the Hurst exponent (a measure of reflection interface roughness) and correlation length (scale length). Lower Hurst exponents represent a richer range of wavenumbers and therefore correspond to a broader range of heterogeneity in reflection events. We interpret a broader range of heterogeneity as indicative of a greater degree of turbulence because the consequence of turbulent mixing is to redistribute larger structures over ranges of smaller scales in accordance with the second law of thermodynamics.

Results

To verify the robustness of the Stochastic Heterogeneity Mapping code we generated a random fractal surface with a correlation length of 1000 m and a Garrett-Munk slope of -1.6 ($\nu=0.3$) by customizing a freely available MATLAB program [Hobbs, 2012] from which we then created a 2D seismic section of 4000 traces using the same number of vertical samples as the real data. For this we used the Phase Screen algorithm (Wild et al., [2000]; White and Hobbs, [2007]). To this noise-free synthetic seismic data we added random noise with a signal-to-noise ratio of 10 to decrease edge effects. The synthetic data were then inverted for ν using the Stochastic Heterogeneity Mapping code. Figure 2 shows a heterogeneity map overlain on the synthetic seismic data. The inversion returned a nominal Hurst exponent of 0.3 for the reflector and values near zero for the random noise found elsewhere, as expected.

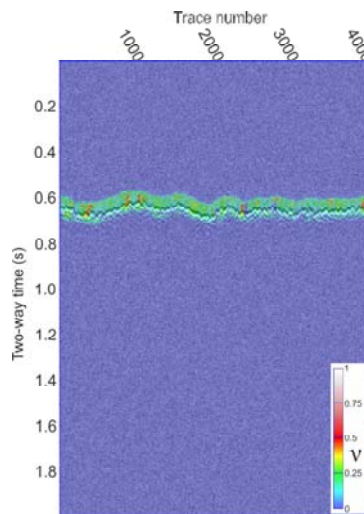


FIGURE 2. Benchmark calibration performed on synthetic seismic data that was generated from a random fractal surface with a 1000 m correlation length and a Hurst exponent of 0.3. Vertical axis is two-way travel time equivalent in seconds for the synthetic seismic data and the horizontal axis is trace number. The Stochastic Heterogeneity Mapping method nominally returns a favorable value of the Hurst exponent (ν) near 0.3.

After verifying that the Stochastic Heterogeneity Mapping code returns expected values for ν , we proceeded to test it on real data of thermohaline staircases in the Tyrrhenian Sea. The data set we used was a post-stack time-migrated seismic section acquired during the MEDOC cruise and processed as outlined above. In Figure 3 we present the results from tests with constrained frequency bands to observe whether there is any variation in Hurst exponent as a function of frequency. The frequency increment is approximately one octave per panel. We find that for some areas of the seismic data (namely, for the depths corresponding to the thermohaline staircases - approximately 700-1300 m) there is a noticeable oscillation in Hurst exponent as a function of frequency band and hence, as a function of wavenumber. That is, for the lowest frequency band (Figure 3, Panel 1) Hurst exponents are categorically the lowest (near zero), while adjacent regions are higher (about 0.25), with some values as high as 0.5. For Panels 2 and 3 there is a distinct increase in the ν values. For the corresponding frequencies in Panel 4 there is a marked drop in ν .

For depths greater than the staircases the relationship is of a general decrease in ν that is inversely proportional to frequency with values of ν decreasing from about 0.25 to near 0. For the uppermost part of the ocean (approximately 0-200 m) there is an effect similar to that of the staircase region but significantly less pronounced.

Since Hurst exponent is a measure of the richness of scales (roughness) of fractal surfaces, the implication of our result is that for some wavenumbers (frequencies), there may be a corresponding preferential coupling of energies. Specifically, we see that for the lowest and highest wavenumbers (Panels 1 and 4, respectively) there is a dominance of lower Hurst exponents; lower values of ν indicating a richer range of scales of heterogeneity (i.e. more homogeneous, overall) present in the ocean. Physically, we interpret this to mean that for the wavenumbers in the regions of the staircases, there is a higher degree of mixing occurring at some length scales (as 'seen' by the corresponding frequencies) as opposed to others. Thus, for the structures imaged using frequencies between about 20-60 Hz (Panels 2 and 3) there are higher values of ν over the broader, more coherent stratification that could represent more dynamic stability at the scale lengths detectable by those corresponding frequency bands.

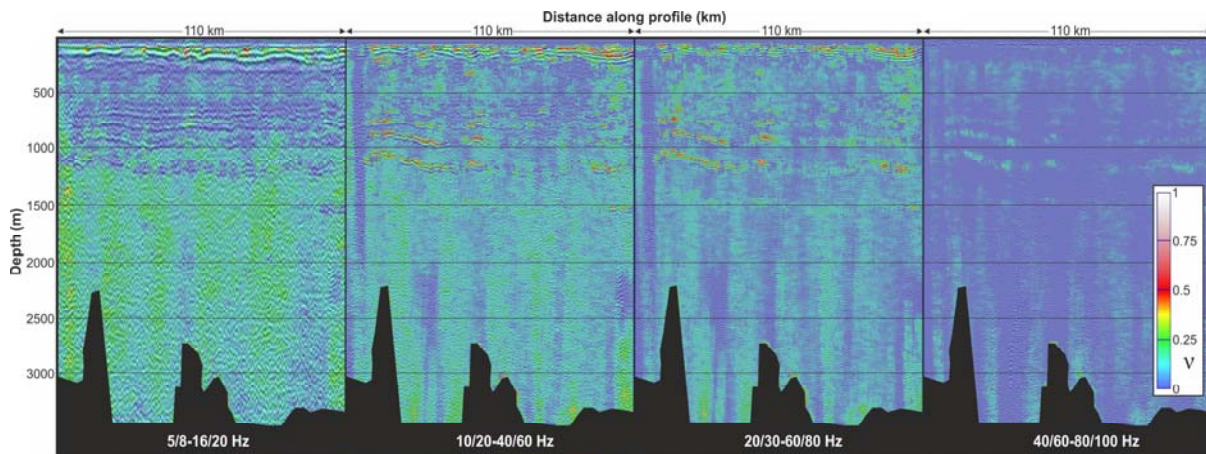


FIGURE 3. The variation of Hurst exponent (ν) as a function of frequency (color map) for thermohaline staircases overlain on greyscale seismic data. Frequency increment is approximately one octave per panel. At staircase depths (~700-1300 m) there is a characteristic increase in Hurst exponent in the frequency bands corresponding to the second and third panels. At still higher frequencies the Hurst exponent decreases again. This is not evident at other depths, where the Hurst exponent decreases along with increasing frequency. Vertical axis is water depth (calculated using the measured two-way travel time and an average speed of sound in water of 1500 m/s). Horizontal axis is the distance along the profile. Black areas correspond to the sea floor.

Conclusions

In this study we presented seismic images of distinct thermohaline staircases in the Tyrrhenian Sea. We inverted the seismic data using Stochastic Heterogeneity Mapping to extract its Hurst exponent spectra, which was then super-imposed over the greyscale seismic data to visualize its correspondence to seismic reflectivity. For calibration, we generated synthetic seismic data from a random fractal surface generator using a chosen Hurst exponent (0.3) and correlation length (1000 m), which are reported to be in the range found to correspond to typical open ocean wavenumbers in the Garrett-Munk spectra for ocean internal waves. We found that the Stochastic Heterogeneity Mapping code returned favorable values of the Hurst exponent.

By filtering the seismic data into specific frequency bands and inverting each for Hurst exponent, we observe a preferential adherence of it to specific frequencies (wavenumbers) for some areas of the seismic image. Particularly, for the depths corresponding to the thermohaline staircases (approximately 700 to 1300 m) there is an increase, then decrease in Hurst exponent values toward higher frequencies. For other depths of the ocean this trend is either not nearly as predominant (upper 200 m) or non-existent (1300 m to sea floor).

Physically, our explanation for this effect is that there is preferential coupling of energies at specific wavenumbers that seem to be less prone to mixing. That is, at the lowest and highest wavenumbers (frequency panels 1 and 4) we see low Hurst exponents, indicating that the ocean in these regions is more homogeneous at these scales, perhaps due to turbulent mixing. Conversely, for the central wavenumbers there are higher than average Hurst exponents, indicating more lateral coherence that may be a result of higher dynamic stability.

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