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Probing the sources of ambient seismic noise near the coasts of southern Italy

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[1] In this study we probe the source of ambient noise in the southern Apennines and the Calabrian Arc by cross-correlating two months of ambient seismic noise records collected during the Calabria-Apennine-Tyrrhenian/Subduction-Collision-Acretion Network (CAT/SCAN) project. Significant Rayleigh wave energy is observed on the vertical component of the noise correlation stacks and reveals multiple sources of ambient noise in southern Italy. The most dominant noise sources are found along (1) the Tyrrhenian coast of northern Calabria-southern Campania and (2) the Adriatic Sea near the Gargano Promontory. Enhanced ocean currents evident from buoy records during the study period could be responsible for the observed microseisms. We validate the source locations using earthquake records and the consistency between noise and earthquake correlation functions supports the observed dominant directions of ambient seismic noise. **Citation:** Gu, Y. J., C. Dublanko, A. Lerner-Lam, K. Brzak, and M. Steckler (2007), Probing the sources of ambient seismic noise near the coasts of southern Italy, *Geophys. Res. Lett.*, *34*, L22315, doi:10.1029/2007GL031967.

1. Introduction

[2] Coastal impact of ocean waves and the standing waves produced by nonlinear wave interactions have long been documented as potential sources of microseisms. The characteristics of these two sources are distinguishable by frequency: while the wave-coast interaction is potentially responsible for the primary microseisms at 10–20 sec [*Gutenberg*, 1951], nonlinear interaction of direct and reflected waves may produce the strongest peak in the noise spectrum near 5 sec [*Longuet-Higgins*, 1950]. Recent studies of noise correlation [e.g., *Campillo and Paul*, 2003; *Schulte-Pelkum et al.*, 2004; *Dolenc et al.*, 2005; *Shapiro and Campillo*, 2004; *Campillo et al.*, 2005; *Sabra et al.*, 2005b; *Gerstoft et al.*, 2005; *Yao et al.*, 2006; *Yang et al.*, 2007; *Bensen et al.*, 2007] presented ample evidence that links ocean waves and seismic bodysurface waves on land. By correlating seismic noise between nearby stations, the propagation properties and the dominant source(s) of seismic noise can be, at least partially, recovered through averaging [*Shapiro and Campillo*, 2004; *Paul et al.*, 2005].

[3] So far, regional noise-correlation studies often focused on well-sampled regions bounded by a single, semi-linear coastline, for example, the Gulf of California [*Schulte-Pelkum et al.*, 2004; *Shapiro et al.*, 2005; *Sabra et al.*, 2005a]. The simplicity of the source (the Pacific Ocean) and the strong directivity of ambient noise [*Schulte-Pelkum et al.*, 2004; *Dolenc et al.*, 2005] greatly reduce the number of unknown effects in the study areas. Association with a simple point or line source is far more challenging in a multiple ocean system due to the potential interference of noise signals. Surrounded by the Tyrrhenian, Ionian and Adriatic Seas – all potential sources of ambient noise, southern Italy presents a prototype for such a complex system.

[4] In this study we probe the sources of ambient seismic noise near southern Italy. The unique tectonic setting of this region directly stems from subsurface deformations in the past 30 Ma due to the rollback and fragmentation of the Western Mediterranean subduction zone [e.g., *Di Stefano et al.*, 1999; *Cimini and Gori*, 2001; *Faccenna et al.*, 2002; *Barberi et al.*, 2004]. The rich tectonic history and the complex coastal geometry offer both a challenge and a motivation for uncovering the source(s) of microseism in this general area. Fortunately, the dense seismic instrument coverage from the Calabria-Apennines-Tyrrhenian/Subduction-Collision-Accretion Network (CAT/SCAN) project, the largest temporary broadband seismic deployment in this region to date, provides an ideal platform to determine the presence and nature of dominant noise sources.

2. Data and Methods

[5] Figure 1 shows the temporary, broadband seismic stations from the CAT/SCAN project during the period of 1 August to 30 September 2004. This time window is selected to optimize the station coverage (34 stations selected) and the dominant station spacing is 40–60 km in the southern Apennines and 5–20 km in Calabria. After the preliminary processing of three-component seismic data, we resample the vertical-component seismograms at 1 sec and divide the largely continuous recordings into hourly traces. We then define a threshold magnitude (Mb, Ms or Mw) of 5 and eliminate records one hour prior to and two hours after the origin time of any $M > 5$ earthquake; earthquake "clipping" is an important procedure with or without bit normalization [e.g., *Yang et al.*, 2007; *Bensen et al.*, 2007]. An hourly correlation function is subsequently computed for each station pair using time lags t between -300 and 300 sec. By our sign convention, a peak with a negative lag between station 1 (anchor) and station 2 would indicate that the station 1 receives a propagating wave before station 2.

[6] We apply the above correlation procedure to the semi-continuous recordings and stack the normalized correlation

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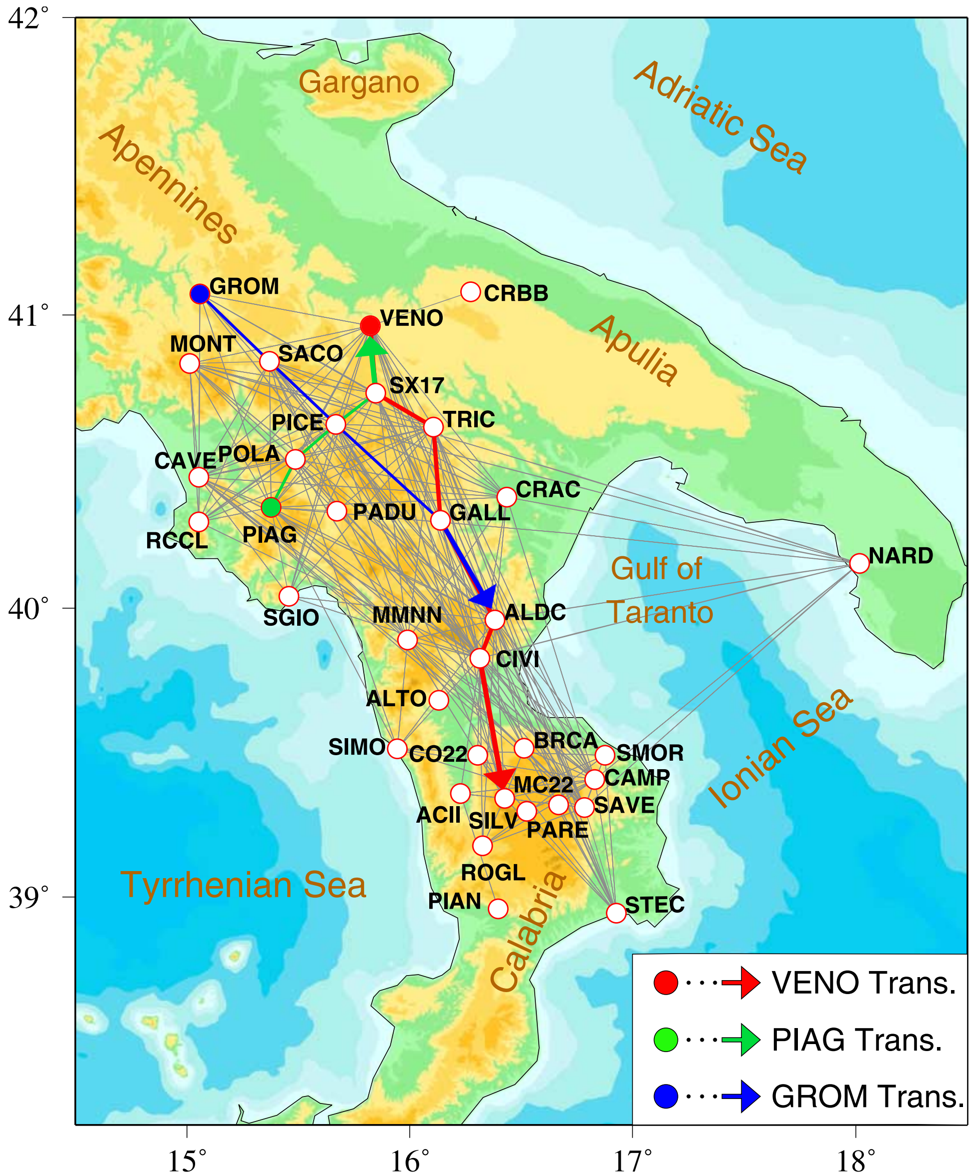

Figure 1. Station locations superimposed on the topographic map of the southern Apennines and the Calabrian Arc. The semi-linear profiles (thick lines and arrows) enable a detailed comparison of stacked correlation functions along and across the southern Apennines (see Figure 3). The thin lines connecting the stations indicate the station pairs used in producing Figure 2a that are selected based on a signal-to-noise ratio estimate.

functions for each station pair for the two months of our study period. As the final step, we fit a cubic spline envelope function to the local maxima of the correlation stacks to emphasize phase groups.

3. Noise Correlations

[7] Figure 2a shows the correlation functions computed for each station pair, without redundancy, against distance. To eliminate poor correlations associated with distant station pairs, we define a correlation window of 300 sec centering at zero lag as the proxy 'signal' window, and use the remaining 300 sec as the 'noise' window. The ratio between the average absolute correlations within these two time windows constitutes an effective signal-to-noise ratio (SNR). We restrict the frequencies to 0.03 Hz and 0.2 Hz, which encompass the typical microseisms associated with primary and, potentially, secondary ocean wave signals.

[8] The correlation peaks for all stations (randomly paired) with SNR > 7 follow a well-defined phase group, as highlighted in Figure 2a. Both symmetric and asymmetric correlation stacks are present, despite the overall symmetric appearance caused by the unknown source orientation(s) relative to the orientations of the station pairs. Anomalous correlation peaks that do not follow the moveout curve can be identified in the distance range of 35–42 km, which we associate with source complexities and/or anomalous velocity structures beneath the study region, particularly under Calabria. The SNR generally decreases with increasing distance between stations, but there is little

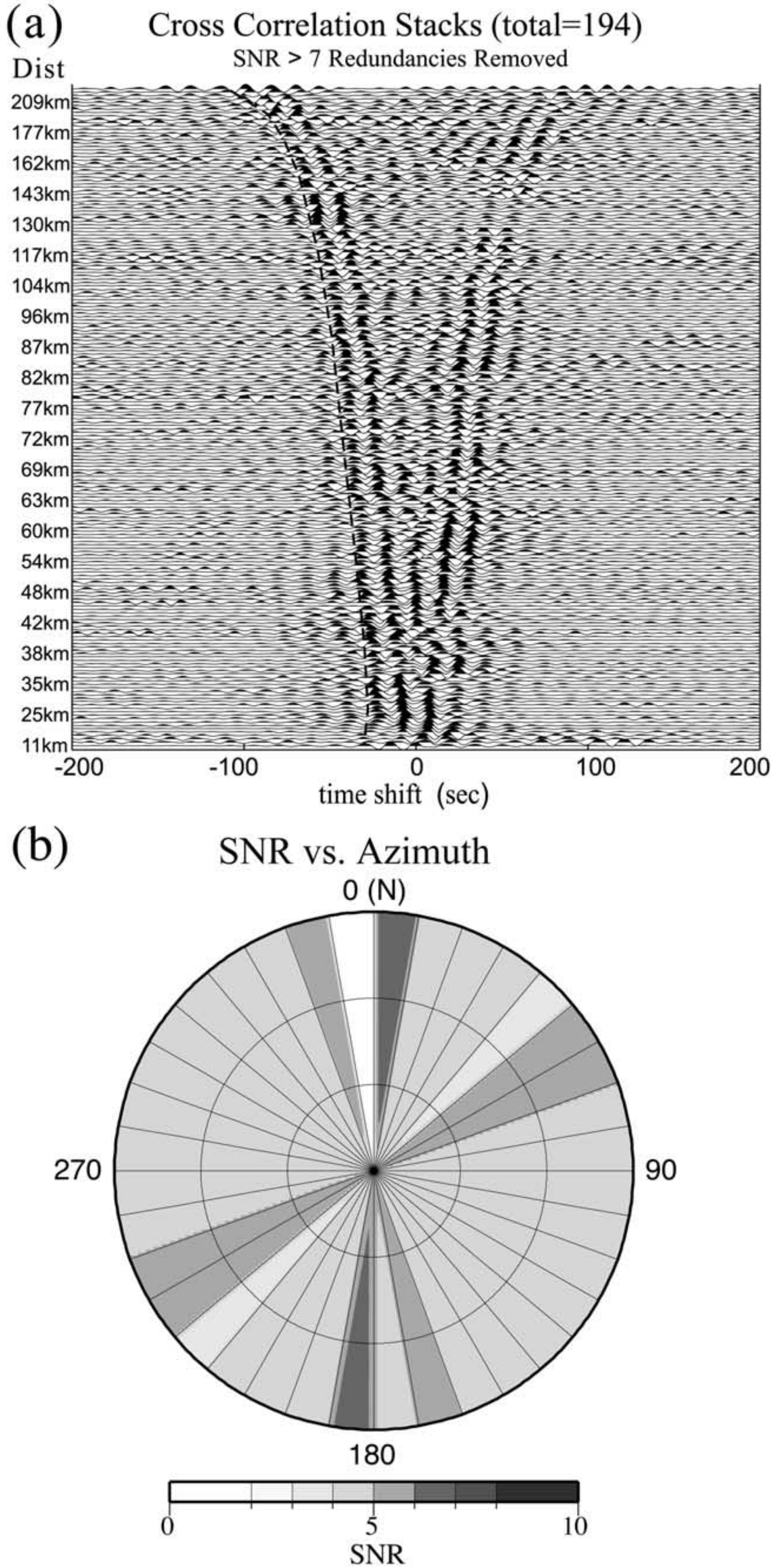

Figure 2. (a) Stacked correlation functions in the frequency range of 0.03 to 0.1 Hz using the station pairs shown in Figure 1. The dashed line marks the approximate timing of the main phase group. (b) SNR variations with the azimuths between stations. This plot shows two azimuth ranges with high SNR.

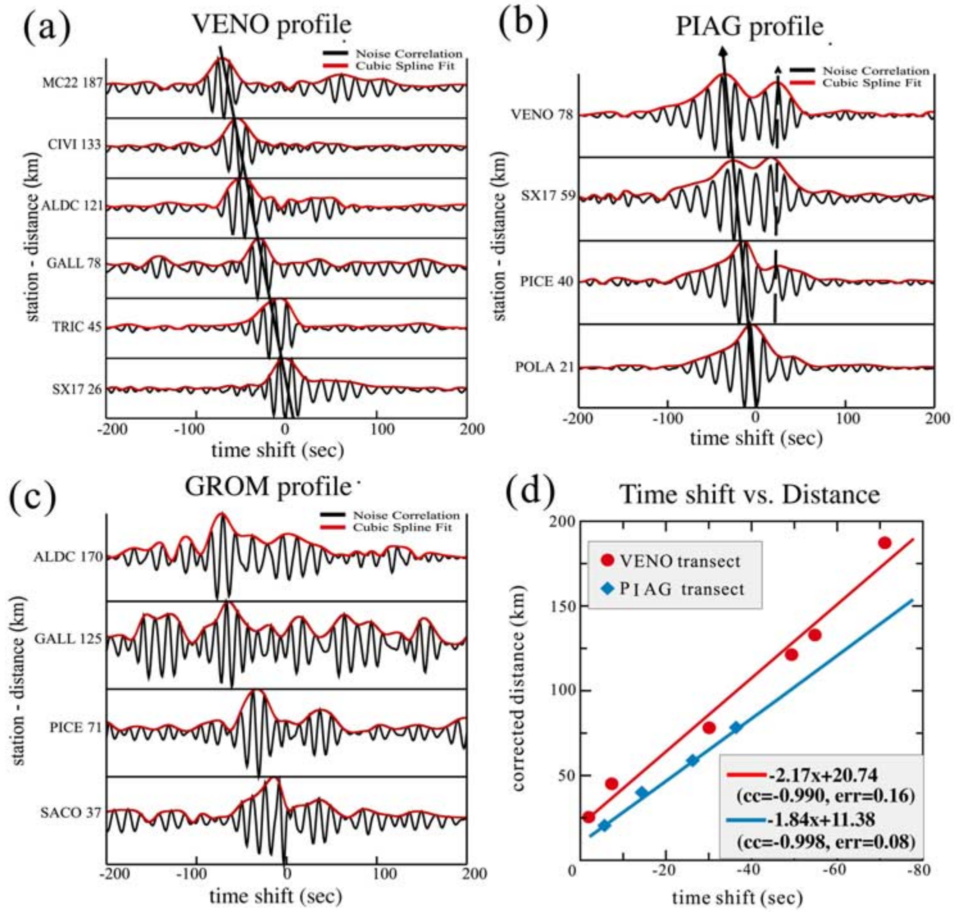

Figure 3. Correlation stacks of the (a) VENO, (b) PIAG, and (c) GROM profiles (see Figure 1) for the frequency range of 0.06–0.1 Hz. The arrows show the optimal linear fit to the correlation peak locations. (d) Plots of distance vs. correlation-peak lag time for the dominant phase groups along the VENO and PIAG profiles. The linear regression values indicate a faster average speed along the strike of the Apennines than across it. Results from 0.02–0.05 Hz and 0.1–0.2 Hz show similar overall characteristics (e.g., asymmetry, clarity) as Figures 3a and 3b, but the linear regression values are different from Figure 3d.

evidence of a statistically significant relationship, for example, an exponential decay, between SNR and distance.

[9] Figure 2b shows the average SNR of stacked correlation functions within 10-deg azimuth bins for all station pairs. The pattern exhibits cylindrical symmetry since most station pairs are considered in two opposite quadrants due to the reversal of station order of each pair. High SNR stacks are identified in the azimuth bins of 0–10° (180–190°) and 50–70° (230–250°), with the highest value exceeding 15 in the former window. On the other hand, the azimuth range of 90–150° (260–330°; see Figure 2b) and stations in Calabria (not shown) are marred by low SNR. Similar azimuth variations are observed for a larger data set covering Aug–Dec (2004), albeit with higher overall SNR.

4. Linear Profiles and Source Locations

[10] The azimuth variations of SNR highlight the critical data window for further source analysis. To narrow the search for source location(s), we select semi-linearly aligned station pairs largely contained within the two best SNR windows, anchored by stations VENO, PIAG and GROM (see Figure 1 for the selected profiles). The profile anchored by station PIAG (hereafter, the PIAG profile) is highly sensitive to potential sources originating from both the Tyrrhenian and Adriatic Seas, the GROM profile facilitates the mapping of sources along an approximate north–south orientation, and the VENO profile further refines our search from an intermediate angle where SNR is low (see Figure 2b).

[11] Cross correlations with station VENO boast the simplest result out of the three profiles (Figure 3a). The correlation functions are highly asymmetrical: the primary arrival follows a negative distance-time relationship and the correlation values generally decay with distance from SX17, the closest station to VENO. The asymmetric correlation peaks (see Figure 3a), negative time lags and linear moveouts (Figure 3d) all seem to favor a single, dominant noise source north of station VENO. Should the source be aligned with the station profile, the slope of the lag times would infer an average seismic speed of 2.17 km/sec between stations VENO and CO22.

[12] The PIAG profile begins with a clear correlation peak before 0 sec (Figure 3b) that is likely caused by strong noise energy propagating from the Tyrrhenian coast of the Italian Peninsula. As the correlation distance increases

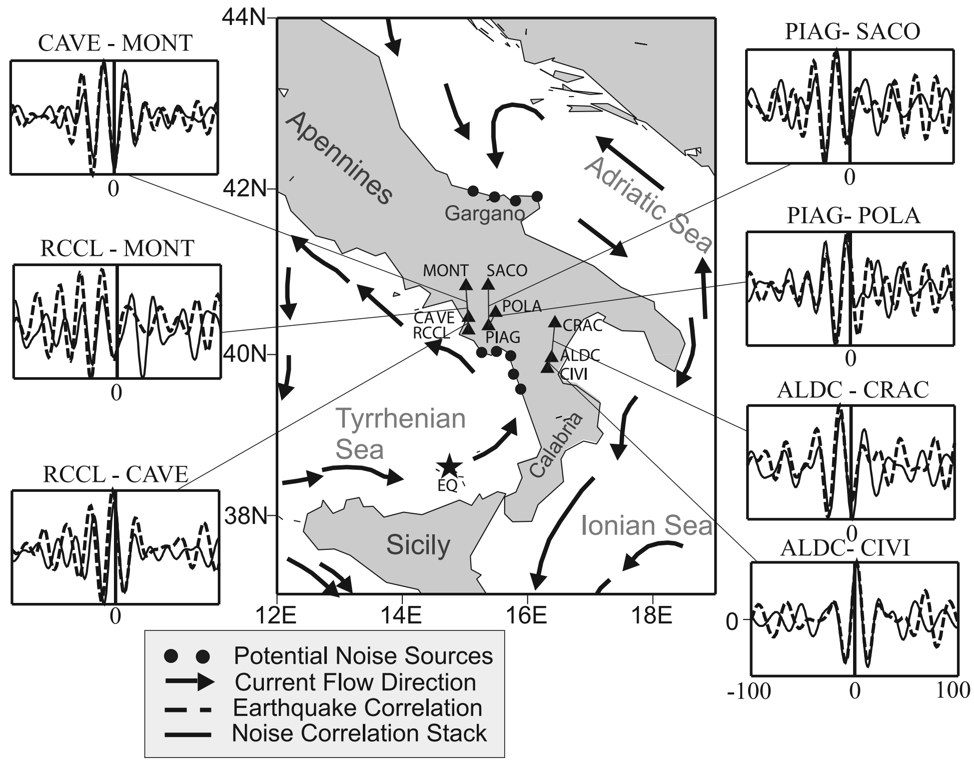

Figure 4. A comparison of noise correlation with ''earthquake correlation'', where we select an earthquake (5 May 2004) under the Tyrrhenian Sea and compute 1-hour correlation functions between stations. The solid dots denote the projected source entry points along the coastlines. The arrows show the interpreted ocean current directions based on buoy records during the same period. The locations of the hypothesized source regions coincide with regions of enhanced ocean wave activity.

toward the northeast, the peak progressively decays, as would be expected from the strong attenuation across the Apennines. The correlation functions also become more symmetrical with respect to 0-sec time shift. The isotropic nature of the correlation peaks at large distances could be caused by a competing noise source east of the profile, or by inhomogeneous distribution of random sources away from the Tyrrhenian coast [*Stehly et al.*, 2006]. The first (and more dominant) phase group exhibits a strong linear distance-time relationship (Figure 3d) with an average propagation speed of 1.84 km/s.

[13] The GROM profile is significantly noisier than the two aforementioned profiles. An asymmetric correlation peak with a negative time shift can be identified on individual correlation stacks, which may originate from a potential source approximately aligned with (and northwest of) this profile. The orientation of source location(s) cannot be confidently resolved due to the undesired SNR, however.

[14] In short, the robust, asymmetric correlation peaks exhibited by the VENO profile suggest a dominant source of ambient noise that influences the stations from the north. Furthermore, a weaker noise source may reside in the west of the PIAG profile. Extrapolations from these two profiles yield two potential source locations oriented along (1) the Adriatic Sea near the Gargano Promontory (solid circles represent entry points; Figure 4) and (2) the Tyrrhenian coast from the Gulf of Policastro to northern Calabria. The apparent velocities determined from the linear regression (2.2 km/sec) is in reasonable agreement with the reported values of 2.3–2.6 km/sec [*Yang et al.*, 2007] for the crust/upper mantle structure using noise correlations. A comparison between these two profiles suggests slightly higher crustal velocities along the strike of Apennines than in the cross-strike direction. While these velocities are only approximations due to imperfect source-profile and station-station alignment, the 3% + velocity difference between the along- and cross-strike directions is, to first order, consistent with earlier estimates from earthquake-based studies [*Di Stefano et al.*, 1999; *Cimini and Gori*, 2001].

5. Noise and Earthquake Correlations

[15] While the mechanism(s) of ambient noise generation is still in question [*Longuet-Higgins*, 1950; *Shapiro and Campillo*, 2004], the affinity of ambient seismic noise with the ocean and atmosphere have been widely suggested at microseismic ($\sim$0.2 Hz) (see review by *Weaver* [2005]) and modal [*Ekström*, 2001; *Watada et al.*, 2002; *Tanimoto*, 2005] frequencies. The asymmetry and linear distance-time relationships exhibited by the CAT/SCAN correlation peaks provide clear evidence of propagating Rayleigh waves from southern Italy. The surface wave nature of ambient noise and the source locations are further supported by a comparison of earthquake correlation functions with noise correlation stacks (Figure 4). In this comparison, we identify a subduction zone earthquake near Sicily (Mw = 5.5, 5 May 2004) and compute correlation functions between

stations for one hour of data following the earthquake origin time. The resulting unstacked correlation functions of common station pairs are highly consistent with those obtained by stacking two months of noise records during the same year; such agreement is only possible if the source region approximately overlaps with the earthquake-receiver paths. Most of the correlation peaks for the Tyrrhenian Sea earthquake arrive before 0 sec, which indicates that the hypothesized propagating Rayleigh waves originate from the southwest of the station pairs. In fact, we identify consistent earthquake correlation vs. noise stacks for ~40% of the station pairs for this earthquake, but only obtain ~7% of station pairs during a similar test using an Ionian Sea earthquake (along a northwest-south orientation; lat = 37.5N, lon = 20.2E, 31 January 2005).

[16] There appears to be a possible link between seismic noise and direction of ocean currents, as evidenced by the edited flow directions based on buoy records for the month of August 2004 (NOAA, CLS Aviso, http://www.jason.oceanobs.com). Major "hotspots" of sea-wave activity can be identified near the Gargano Promontory and the Tyrrhenian coast, where converging ocean waves and coastal geometry can cause significant changes to the main flow directions (see arrow directions, Figure 4). Enhanced sea level variations have also been reported; for example, the peak-to-peak variation along the Gargano Promontory nearly doubles the level observed in the Gulf of Taranto during the study period. While an earthquake correlation is unavailable, major reorganization of sediment pathways has been documented near Gargano Promontory in response to substantial sea level changes [*Steckler et al.*, 2007]. Considering the relatively normal ocean depths at the two proposed locations, enhanced ocean currents from nonlinear wave interaction (away from the coastlines) could contribute to microseisms at both high and low frequencies [*Stehly et al.*, 2006].

[17] Caution has to be exercised to avoid over-interpreting the stacked noise records, especially in tectonically complex regions such as the Calabrian Arc and southern Apennines. The majority of the station pairs within Calabria do not show recognizable correlation peaks that are traceable to their respective sources. We hypothesize that the coastal impact near this narrow arc region can cause significant seismic wave interference. Larger time intervals and careful source modeling may be necessary to apprehend the potential sources of ambient seismic noise beneath Calabria.

6. Conclusions

[18] In conclusion, by analyzing vertical-component, stacked correlations of noise records, we are able to identify a dominant noise source near the Gargano Promontory and a moderate source near the Tyrrhenian-Sea coast of northern Calabria-southern Campania. These sources are well constrained, though their presence may not be unique in this region. The strength and timing of the noise correlation peaks vary with both noise frequency and seismic structure surrounding the stations. In the near future, the same "noise" data set can be combined with seismic tomographic approaches [e.g., *Sabra et al.*, 2005a; *Shapiro et al.*, 2005; *Yao et al.*, 2006] to refine the existing knowledge of the seismic structure beneath the southern Apennines and Calabrian Arc. The resulting crust/mantle velocities, rather than the path-averaged velocities presented by this study, can significantly enhance the constraint on the locations and nature of ambient seismic noise near the Italian Peninsula.

[19] **Acknowledgments.** This paper benefited greatly from the scientific discussions with Mauricio Sacchi and Ahmet Okeler, as well as from two anonymous reviews. The data were archived and distributed by the IRIS data center. This research is supported by NSERC, Canadian Foundation for Innovation (CFI) and Alberta Ingenuity funds. This paper is LDEO publication 7092.

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