Surface and body waves from hurricane Katrina observed in California

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Hurricane Katrina struck land on August 29, 2005 as one of the strongest in the United States. Continuous seismic data from a large number of stations enables us to characterize the evolution of hurricane-generated noise in detail. By beamforming noise recorded on a distributed seismic array in Southern California, we observe and track both the surface and body P-waves generated by Katrina in the 4-20 seconds period microseism band. The longer-period surface waves can be traced to the costal regions of the Gulf of Mexico, indicating that air/ocean/land coupling was a major factor in their generation. We observed P-waves that have propagated deep (1100 km) inside the Earth that exist both before and for a time-period after landfall. The source location of the P-waves can be determined by back-projection from the seismic array and the source is the shallow-water regions east of New Orleans. While both surface and P-waves are generated in shallow water they propagate with different periods, the surface wave propagates at the same period as the ocean wave and the P-wave at half the ocean wave period. These findings demonstrate that ocean microseisms can be detected at great distance and open the possibility of further use of seismic noise for studying the Earth and Earth processes, even at very low signal level.

INTRODUCTION

Significant microseismic energy propagates as surface Rayleigh waves that can be observed over long distance. In shallow water, the ocean waves interact directly with the seafloor and thus energy can be transferred to the Earth. While the precise mechanisms for the energy transfer between ocean waves and seismic waves are not known it is expected that shoaling and breaking waves are the main causes.

Ocean waves propagate much slower than seismic waves (typical ocean wave speed is from 20-40 m/s while seismic wave speed is 3000-11000 m/s). Thus, with distant seismic sensors, it is possible to obtain a clear observation of the ocean state at that time. We were not able to observe Katrina on time series from a single geophone in California, but using an array we are able to beamform and localize the coupling much more precisely than with single sensors.

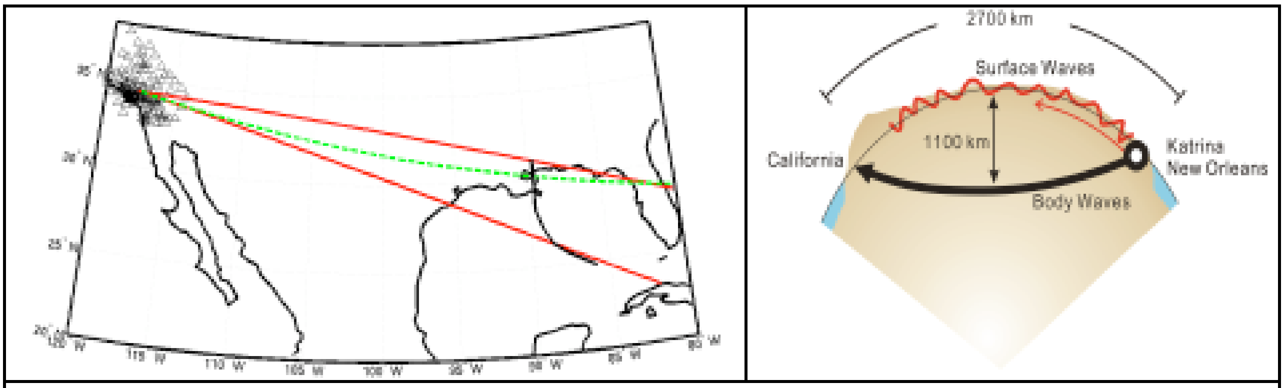

Fig1 *Paths from the seismic array in California (triangles) to the source region. A 90^o and 100^o bearing (red) from seismic array (triangles) for the surface waves and a 100^o bearing for the P-wave (green) as well as the track of Katrina (black) are indicated.) b) Schematic of the travel paths of observed wave types.*

SEISMIC BEAMFORMING

Using data from 150 seismic stations in Southern California (in effect a large-scale array), we formed beams and determined the azimuth and slowness of the waves crossing the array as a function of frequency with more detail than previously. The array geometry and representative azimuths from the array for the surface wave (great circle path 90^o and 100^o) and the P-wave (direct path 100^o) are shown in Figure 1.

For each frequency analyzed, we searched for the combination of phase slowness and azimuth that gave the best fit to the data. For example, at a period of 14 s (Fig. 2a) we find a wave having phase slowness of 0.30 s/km (velocity of 3.3 km/s) coming from 98^o corresponding to a possible location of just south of New Orleans. This phase slowness corresponds to a surface wave. The body P-wave is observed at smaller periods, e.g., 5 s (Fig. 2b), also coming from 98^o and with a horizontal phase slowness 0.085 s/km (speed of 11.7 km/s). The P-wave arrives from a narrower set of azimuths than the surface wave. Fig. 3a illustrates the propagation paths of the two observed seismic waves. Using traveltime tables, which show distance as a function of apparent velocity or traveltime for a P-wave, we can estimate the distance to the source of the P-wave. Combining the estimated range of distances with the range of propagation angles, we map the loci of possible P-wave source locations, Fig. 3b, which clearly shows the origin as being in the region of hurricane Katrina. The P-wave penetrates deep into the Earth and has a turning point at a depth of about 1100 km.

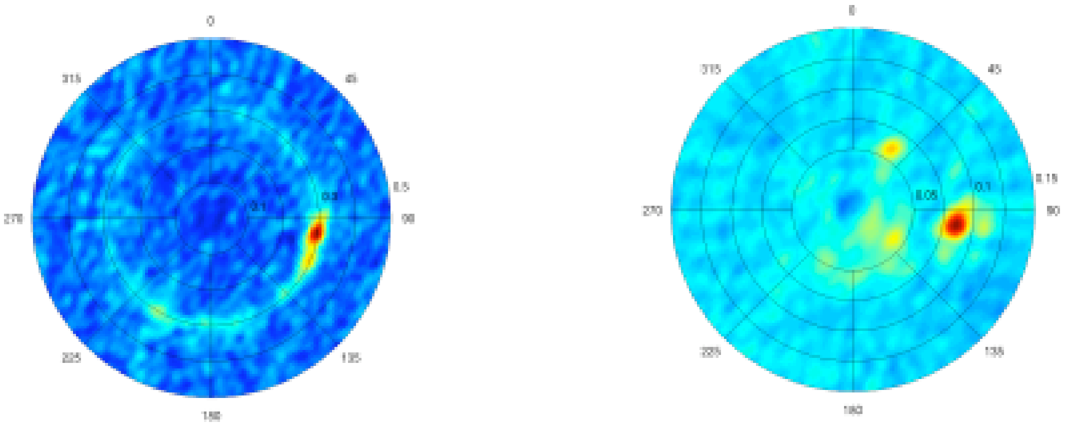

Figure 2: Beamforming and source region. a) Azimuth-slowness map (dB) of the 14-s period surface wave on 29 Aug. Direction and slowness of highest-amplitude waves are shown in red. Phase slowness is from 0 to 0.5 s/km and increases with radial distance from the center of the plot. b) Azimuth-slowness map of the 5-s period body P-wave on 29 Aug. Note the radial slowness axis is from 0-0.15 s/km.

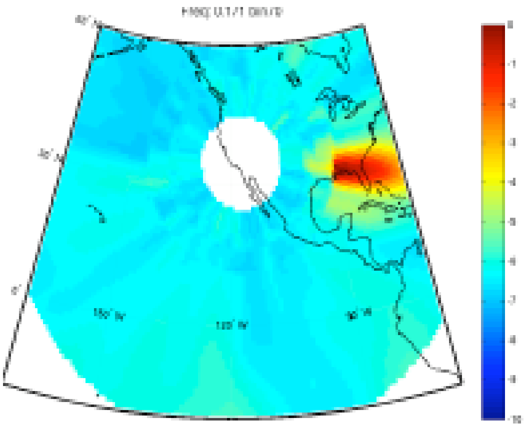

Figure 3: Propagation path and source region. Source region of P-waves obtained by back-propagating using slowness and azimuth obtained from beamforming in Figure 2b.

CONCLUSIONS

The analysis indicates that both surface and P-waves are generated in shallow water likely due to shoaling or breaking waves. However, their generation mechanism is different since they are radiating at different periods (surface wave at the ocean wave period and P-wave at half the period). With the increased hurricane activity in the Gulf of Mexico, there is considerable interest in deploying more sensors (seismic, ocean acoustic, or infrasound) to better understand hurricanes. Seismic arrays are also being deployed in for example USArray programs. With these dense sensor arrays, it will be possible to observe storms at lower signal levels, track more precisely the noise sources, and thus obtain better understanding of microseisms and their generation mechanisms.