UNIVERSITAT DE BARCELONA

Seismic Oceanography

A New Tool to Characterize Physical Oceanographic Structures and Processes

Grant George Buffett

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Seismic Oceanography

A New Tool to Characterize Physical Oceanographic Structures and Processes

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PART III.

Conclusions and Future Considerations

CHAPTER 7

Conclusions

Education has failed in a very serious way to convey the most important lesson science can teach: skepticism

--David Suzuki

Seismic oceanography is quickly emerging as a viable tool of physical oceanography. Its emergence is for two particular reasons: 1) the tool has been widely used successfully by industry and academia for over 40 years, thus making it robust and therefore its development and adaption to oceanography a relatively straight-forward endeavor; and 2) the need of physical oceanographers to visualize in thermohaline finestructure on large horizontal scales what they have suspected for years but have not been able to produce, simply for lack of sufficient horizontal sampling. This being said, seismic oceanography is much more than just horizontal flow visualization. It has been demonstrated by various authors that real physical parameters can be acquired from the data, including but not limited to, estimates of temperature and salinity, scale lengths, turbulent dissipation parameters and dynamics. Obtaining these parameters and others will help in the understanding of the ocean circulation that is paramount to generating accurate models of climate.

The following is a summary of the main conclusions of the author's work during the completion of this thesis, contained in four published papers and the one that has been submitted to a peer-reviewed journal.

Chapter 1 - Seismic reflection along the path of the Mediterranean Undercurrent

This research was conceived in the month of April, 2007 while conducting the GO experiment in the Gulf of Cadiz. It became clear from an understanding of the Mediterranean Outflow Water and the Mediterranean Undercurrent (which is crossed at several points along its flow path by some archived seismic data from the Iberian-Atlantic Margin survey, conducted in August and September, 1993), that it should be possible to test whether the seismic data were sensitive to observing certain intrinsic properties and structural trends downstream. Four seismic lines were processed and analyzed which corresponded to different two-dimensional vertical slices of the Mediterranean Undercurrent along its flow path, moving away from its source at the Strait of Gibraltar. The main conclusions are:

- Seismic trace amplitudes can be used to analyze the structural and intrinsic property values resulting from the evolution of the Mediterranean Undercurrent from its source at the Strait of Gibraltar. Trace amplitudes dropped in proportion to temperature and salinity decreases (but, mainly in correspondence with temperature, see Figure 3.10), in agreement with other studies. In this way, trace amplitudes represent a proxy for temperature.
- Three distinct water masses were mapped: the North Atlantic Central Water (≈0-500 m), Mediterranean Water (≈ 500 m − 1500 m) and North Atlantic Deep Water (≈1500-sea floor). The MW depth for any given location is given by an increase of a factor of 5 or more of the RMS seismic amplitude relative to the surrounding water amplitudes.
- Many curious features were noted in the seismic data such as the evolution of meddies (Mediterranean water eddies - or large salt lenses) as a function of distance traveled. That is, it appears that meddies lose their internal structure as they become more well-mixed over time (Compare meddies of Appendix III, sections IAM-3 and IAM-11).
- A general decrease in consistent lateral stratification in areas of the profiles proceeding downstream is observed, within the nearest 80 km from the coast of Portugal, the region in which independent studies place the Mediterranean Undercurrent. This observation seems to indicate that stratification is slowly disturbed due to the flow of the undercurrent.

Chapter 2 - Stochastic Heterogeneity Mapping around a Mediterranean salt lens

This paper followed a statistical approach to seismic analysis. The premise behind the approach is that different types and degrees of reflectivity are amenable to different methods of seismic ensonification. Stochastic heterogeneity mapping was conceived to address the difficulty of imaging certain lithologies in the solid Earth. That is, while seismic reflection profiling works well to image horizontal or sub-horizontal sedimentary stratification, the method breaks down somewhat when crystalline rocks are the target of investigation. This is because of the different types of reflectivity due to the rocks' internal structure. Highly stratified rock layering show marked acoustic impedance boundaries that reflect specularly. However, in regimes of complex geology such as mountain thrust belts and cratonic rocks, reflectivity is diffuse. Stochastic heterogeneity mapping statistically analyzes the reflectivity field of a seismic image for the presence of heterogeneities, or anomalies in an otherwise homogeneous fabric.

The ocean is not ubiquitously and uniformly stratified. It is characterized by many zones of turbulence and mixing where strata are constantly being created and destroyed by interactions with surrounding water masses and the heat exchange between them. This fact makes physical oceanographic structures and processes ideal for testing of diffuse reflectivity patterns. From the reflectivity field of a processed seismic stacked image, two useful parameters were extracted, the Hurst number and the correlation length. To determine what processes might differ we analyzed the perimeter of a meddy into three distinct zones: its top, bottom and sides.

- Our calculations of Hurst number for the top of the meddy agreed with recent theoretical work, which used values between 0.25 and 0.5 to model internal wave surfaces based on simulating a Garrett-Munk (GM76) wavenumber spectrum of –2.
- The corresponding correlation lengths (scale lengths) mapped over the same reflectivity field however, did not fit as well to specific seismic reflectivity.
- Two possible explanations were put forward: (1) due to the fact that the stochastic parameters were derived from the reflectivity field rather than the impedance field the estimated scale lengths may be underestimated; and (2) because the meddy seismic image is a two-dimensional slice of a complex and dynamic three-dimensional object, the estimated scale lengths are likely biased toward the direction of flow.

This publication was a first step in applying a statistical, non-deterministic approach to seismic oceanography data. Follow up work using this approach is being prepared by using oceanic in situ probes (XBTs) to confirm the correlation of the stochastic parameters to the acoustic impedance field, that is to constrain the degree of correlation to the reflectivity field. These constraints could then be applied to solid earth studies, where such a sound speed function (via a well-log) is practically unattainable.

Chapter 3 - Near Real-time visualization of thermohaline finestructure

The Ocean is dynamic on times scales shorter than acquisition times. Visualization of thermohaline finestructure is an important way of understanding ocean fluid dynamics because it quantifies the movement. We present the first near real-time animation of the motion of what appear to be internal waves. Developing and testing a processing scheme to take advantage of the passage of a seismic acquisition streamer over a fixed point on the seafloor to create not just one, but a series of images, or "stacks", in order to build up a 7-frame "movie" of fluctuating thermohaline finestructure in time steps of 3.5 minutes. In this way each image shows a slightly different thermohaline finestructure allowing us to create a striking visualization of what are likely temporally oscillating internal waves.

Chapter 4 - Imaging meddy fine structure using multichannel seismic data

This paper was a short, high-impact research letter. The author's role in this paper was part of the seismic data processing, interpretation and copy editing. The work was the first to seismically image meddy finestructure both horizontally and vertically and to compare it to Turner angles, which are practical indicators that differentiate regions prone to diffusive convection (-90°< Tu <-45°) and salt finger instability (45°< Tu < 90°) from stable regions (|Tu| < 45°). The main regions within the meddy, previously detected by conventional oceanographic instruments, are clearly observed in the seismic snapshots, such as:

- The upper boundary zone, characterized by the presence of a few, strong, laterally continuous reflectors.
- The lower boundary zone, with more numerous, shorter and 3–4 times weaker reflectors distributed into a broader region.
- A very weakly reflective central core region.
- With respect to meddies, the MCS method allows the detection of these rotating highly saline lenses of Mediterranean water, while giving information about their dimensions, as well as the detailed vertical and lateral distribution and the characteristics of their finestructure.

- Results show that high-energy sources and long streamer lengths (in this case chosen to image deep crustal structures) are suitable for seismic oceanography.

Chapter 4 - Relative contribution of temperature and salinity to ocean acoustic reflectivity

The paper by Sallarès et al. [2009] calculated the degree of reflectivity that can be attributed to either temperature or salinity variations (assuming a constant increase in pressure with depth). The contribution of the author to this work was in seismic data analysis, interpretation and copy editing.

For a given depth (pressure), temperature and salinity are the contributing factors to density and sound speed, thus to acoustic impedance, and therefore, to reflection coefficient. This paper was an important contribution to seismic oceanography because it isolated the causes of ocean acoustic reflectivity, a first step in determining the physical properties of water masses directly from seismic data.

The main conclusions of this paper were:

- The principal contribution to reflection coefficient are sound speed variations, or, 90-95% contribution, whereas density only accounted for 5-10% of the reflection coefficient.
- In a similar manner, temperature accounted for approximately 80% of the contribution and salinity accounted for the remaining 20%.
- However, the partial proportion of each of temperature and salinity is spatially dependent. For example, near the top of the Mediterranean water mass, salinity accounted for up to 40% of the partial contribution, whereas at the base of the Mediterranean water, salinity only accounted for approximately 15%.
- The high variability of the partial contributions makes it virtually impossible to extract precise values of temperature and salinity from unconstrained seismic data.

- In the study region, areas dominated by a high salinity contribution were found to be prone to diffusive convection, whereas areas with a small salinity contribution are more likely prone to salt fingering processes.

These five studies illustrate the diversity of the techniques of seismic oceanography combined with historical and coincident/simultaneous oceanographic measurements. These papers, among those by other authors, form the base of an increasingly common methodology in physical oceanography. Through the author's research, significant advances have already been made in the understanding of ocean turbulence, mixing, topographic interaction, spatial scale ranges, meddies and ocean dynamics.

Outside of the obvious technical challenges that have been (and will be) faced, there has been a growing collaborative effort between the seismic and oceanographic scientific communities. This is illustrated well by the participation of seismologists in traditionally oceanographic conferences and vice-versa. However, the finest collaboration to date was seen in the 2008 European Science Foundation sponsored Seismic Oceanography Workshop (SOW) that was held in Begur, Spain and organized in part by the author among his Spanish colleagues. This workshop brought together for the first time a relatively small group of individuals from the international seismology and oceanography disciplines. In addition to the advances made at the technical sessions, strong scientific networks have been established among some of the world's best physical oceanographers and seismologists that have solidified seismic oceanography as a scientific community unto itself. Already preliminary preparations are being made for a follow-up SOW to be held in England in the summer of 2012. Many of the same groups of scientists as well as newer international groups have shown interest ensuring that seismic oceanography will remain a feasible methodology for years to come. The next chapter addresses some of the international research initiatives and challenges that are currently under development for seismic oceanography.

CHAPTER 8

Future Considerations

Learn to read. The rest will follow.

-- Patrick James Grant

Future prospects for seismic oceanography are rich in scope. New methodological and technological advances will allow more comprehensive analyses and interpretations of data. Some of the ways in which seismic oceanography may be used are:

- Improvement and customization of seismic acquisition to oceanographic environments and targets. This might involve substantial modification of the source and/or receiver arrays. For example, CHIRP-like high frequency sources or continuous signals may be useful [Ruddick et al., 2009] especially for imaging shallow water ocean events like the thermocline where there is an abundance of biological activity.
- High frequency sources may also be useful in 'seismic limnology' where studies can be performed on, for example, suspended sediment content in lakes, or salinity and temperature variations with a plethora of interpretive results. In deeper lakes, such as the Great Lakes of North America, there may not need to be substantial changes to the acquisition methodology. Indeed, seismic surveys have already been done in these regions and a preliminary investigation of these surveys for inter-lacustrine acoustic impedance reflections would be a rather simple exercise.
- Inversion of seismic data for the properties that give rise to reflectivity is an important challenge for seismic oceanography. Temperature and salinity variations are the primary reason for reflectivity, but the relative contribution of each is difficult to obtain universally in practice because they both affect density, and thus acoustic impedance, differently. However, given good constraints on salinity, temperature can be derived from seismic data. The importance of this is manifold since the remote estimation of sea temperature at depth is not possible on global, or even regional scales (modern satellite measurements can estimate sea surface temperature and, more recently salinity, but only within the first several centimeters of the surface). A temperature map of the ocean in this way would be extraordinarily important to studies of ocean circulation. Other parameters could then be estimated such as turbulent dissipation and mixing rates.

- Fluid dynamics are characterized by stochastic processes. Therefore it is valuable to analyze the ocean in this context. Stochastic Heterogeneity Mapping (Chapter 2) makes the first application of a stochastic, statistical approach to thermohaline fine structure. However, there is some uncertainty in the estimation of the Hurst number (the exponent in the power law which characterizes the range of scales that are present). This uncertainty is due to the fact that the Hurst number estimations are derived from the reflectivity field, which, while highly correlated to the impedance contrast field, is not strictly the same. A significant advance in understanding the fractal geometry of turbulent processes could be made by first creating synthetic seismic data from oceanographic probes. Since we know that the generated synthetic reflectivity series is directly related to impedance contrasts, a comparative study of Hurst number and scale length distributions in real and synthetic data would constrain the uncertainty in estimations from the reflectivity field. This would promote Stochastic Heterogeneity Mapping as a tool of seismic oceanography, permitting better estimates of fractal geometries, thus better characterizing oceanic dynamical processes. Detecting invisible fluid motions from a vessel, which is itself moving, is a non-trivial exercise. In addition to relative horizontal motions, the ship is continuously subject to the motion of surface waves, and the recording streamer is not perfectly stationary. In addition, it is unknown what are the combinations of subsurface flows; some may be along the ship's trajectory, some may be against it or at some angle to the ship. The combination of these motions may add up in various ways leading to a non-unique answer. However, further studies of the fractal geometry of isopycnal surfaces should lead to advances in understanding turbulence and mixing in a non-deterministic way. That is, given the enormous complexity of the ocean, it is perhaps pertinent to focus on general mechanisms rather than attempt to understand the workings of the ocean deterministically. One of these general mechanisms that the author would like to explore in the future is the concept of self-organized criticality (SOC) [Bak et al., 1987]. The premise of SOC is that the fractal dominated patterns in nature can be characterized by 1/f noise, particularly in complex systems. 1/f noise (a misnomer since 1/f signal is a more appropriate term for useful data) describes the occurrence of the magnitude of natural phenomena and plots as a straight line on a log vs. log plot. It has been found applicable to many different facets of nature, manifest by phenomena as diverse as population distributions, light fluctuation from quasars, highway traffic flow, earthquake and volcanic activity, economics, evolution by natural selection and the flow of a river (The British geophysicist J. Hurst–for whom the Hurst number is named – spent decades measuring the water level of the Nile and found that its fluctuations were characterized by 1/f noise). This statistical approach would be a useful extension of Stochastic Heterogeneity Mapping, which addresses the distribution of scale lengths and roughness in a heterogeneous fabric. The study of ocean turbulence, among other phenomena would benefit greatly from SOC insights into its general working mechanisms through analysis of seismic data.

- The interaction of internal waves with topography is also an interesting subject of study. Several studies have already demonstrated the validity of internal wave spectra estimations from both synthetic and real data. But, the general mechanisms which give rise to internal waves through their interaction with topography warrant further study. The Mediterranean Undercurrent provides a suitable natural experiment for this because it hugs the continental shelf of Iberia where it interacts with topography. Several high-quality databases exist in this area which would be amenable to study.
- Many oceanographers and geophysicists are interested in the first true 3D seismic oceanography study. There has been one publication by Blacic and Holbrook [2009] using a 3D dataset that measured the spatial orientation of internal waves. But, many more could be analyzed given the large quantity of 3D marine datasets available. Since 3D data sets provide data in the form of a volume, rather than a 2D slice the effect of a seismic quasi snapshot (as opposed to a static image that one would obtain of the solid Earth) would be exacerbated by the length of time required to acquire such a dataset. Nevertheless, large scale features and structures would likely remain stable over such periods and future analysis of 3D datasets would be very useful, for example to obtain an image of a meddy in true 3D.

- Ocean dynamics are probably one of the most important aspects that can come from seismic data. However, it is still in its infancy in this respect. While the immediate benefit of seismic oceanography is clearly seen through flow visualization (of meddies, fronts, thermohaline staircases, etc...), detailed estimations of dynamics, without significant constraints and assumptions, still remains elusive. One possible idea would be to modify the acquisition system to include a 'static streamer'. That is, through the deployment of a buoyed streamer and recording equipment (either 2D or a 3D grid), one could get improved estimates of dynamics by shooting seismic over the same region for an extended period of time and thus seeing the evolution of thermohaline finestructure rather than just an instantaneous snap-shot.
- Gas hydrates plumes are methane-rich plumes that emanate from the seafloor. They have been observed in several regions using traditional sonar and could be very easily identified and characterized with seismic oceanography due to the high density and temperature contrasts with the surrounding water. In this way, reserves could be located and exploited as an energy resource. In addition, important information could be obtained about how they interact with the surrounding waters.
- At this point there have been no direct studies of biology using seismic oceanography. There has been at least one study relating chlorophyll distributions to internal waves, structures that could be mapped with seismic oceanography. Indirect observation of biological activity is plausible in a number of ways. For instance, by mapping an internal wave distribution that is consistent with independent measurements of chlorophyll or by mapping the upwelling of water masses, which are known to bring nutrients and microorganisms to the surface from depth. Large cetaceans would be near the limit of detection by seismic reflection methods (≈10 m), but detection would offer little intrinsic value. However, a direct observation of microorganisms such as plankton blooms for example, would add much valuable information to the understanding of their distribution and their biological settings, as well as how they relate to factors such as temperature, salinity, mixing and topography in a physical oceanographic setting. Finally, using high-resolution seismics,

estimates of mixing rates in the photic zone would likely be of interest to marine biologists.

- Hydrothermal vents (or, 'black smokers') may be another viable future target, for, like gas hydrate plumes they would show a strong acoustic impedance signature. The temperature of these vents is about 400°C at their source at the seafloor. This should show a strong reflectivity signature. Hydrothermal vents are an interesting area of research for geophysicists, geochemists and marine biologists. Physically, because they give insights to plate tectonic activity, chemically, for their chemical signature and biologically, for the abundance of life that is sustained by them, well out of the photic zone and thus the influence of sunlight.

Seismic oceanography at the present time, while showing great potential, has met moderate skepticism. Some oceanographers, while seemingly impressed with the striking images of ocean internal structure, are still stoic with regards to its role as a tool of physical oceanography. This attitude has been likened to the reaction of some oceanographers when shown the first satellite maps of sea surface temperature. Some were contemptuous, but slowly the contempt turned to acceptance. A similar situation started (and has persisted to a certain degree) between some geology and geophysics communities. The introduction of the seismic method (single channel) to geologists in search of oil reservoirs was taken as an affront to a field dominated by geologists who were without doubt worried about the direction their profession was headed. Skepticism is healthy in science and is a good approach toward knowledge and understanding, but scientists are human, subject to the emotion of personal and professional interests. Other special interests such as those of governments or influential corporations ultimately may play a role in determining which methods are successful and which are discarded. Seismic oceanography will not redefine physical oceanography but it will add new information that physical oceanographers can avail of to test and therefore either confirm or refute their present models of large scale circulation and oceanic processes. Its main contribution to date is still its unprecedented horizontal resolution, one that is near the equivalent of deploying oceanic probes every five to ten meters. This has pushed flow visualization, previously confined to the laboratory, to new heights allowing oceanographers for the first time to actually see the high resolution horizontal continuity of isopycnals, and to thus map the ocean on a much grander scale than was previously feasible.

Finally, not only does seismic oceanography offer a new perspective for physical oceanographers through the acquisition of new data. Marine multi-channel seismic reflection profiling has been commonplace for over forty years with the objective of imaging the solid Earth, while incidentally recording the comparatively weak reflections of the ocean. Much of this data has been archived and still retains its original data integrity. Consequently, not only can seismic oceanography offer spatial parameter maps but, in comparison with archived data, temporal maps may be created to study how particular ocean circulation patterns have changed over time. In light of the seriousness and imminence of global climate change, and the significant role of the ocean in this respect, one may expect to be able to monitor climate change on decadal scales. Then perhaps, from this knowledge we can begin to contemplate our collective actions and maybe even modify our behaviors to preserve what semblance of global environmental sustainability remains.