Lecture #13: Background

Though the title of the course is "Acoustical Oceanography," we've spent precious little time on the ocean per-se (for good reasons, but …). So in this lecture we'll try to correct that.

The first part of the lecture is a quick glance at physical oceanography (PO). (Apologies to biological, geological and chemical oceanography – they get treated a bit better in the usual course). More specifically, we'll look at the geophysical fluid dynamics (GFD) of some of the oceanography that we commonly encounter in acoustics transmissions.

At the risk of really incredible triviality, I would stress that PO and GFD are huge fields on their own, and that this "tip of the iceberg" lecture just notes some PO/GFD that intersects easily with the acoustics world. I would heartily recommend any ocean acoustician to get at least a beginning graduate level knowledge of physical, biological, geological and chemical oceanography to be able to characterize the ocean medium you are working in! For PO/GFD, I would recommend "Intro to GFD," 2nd edition, by Cushman-Roisin and Beckers as a great beginning. It contains both basic theory and computation (sound familiar?), and also has some very nice historical/current biographies of its more notable practitioners. (Personal prejudice – learn the history of your technical field as well!). If you read this book, or 1-2 of the many other good PO/GFD books out there, you will both learn how the ocean drives acoustics and also get a glimpse of a beautiful technical area.

One more note before starting; this lecture is based on notes from Prof. Rich Pawlowicz, a former MIT/WHOI Joint Program student who wanted to "give a lecture" while he was an advanced graduate student. Rich is now a full professor at U. British Columbia in oceanography.

Physical oceanography texts generally start with the equation of state for seawater density, which is the most important variable in PO. This density varies only a few parts per thousand from 1 gm/cc, which immediately has an acoustics consequence: for the purpose of ρc acoustic impedance, the seawater density is one!! The variations in seawater density that drive much oceanography are exactly zilch for acoustics. This means acoustics can't directly comment (via simple inverses for ρ) on the all-important density. But all is not lost. As we saw one on day one, acoustics is quite sensitive to the ocean temperature field, which in our age where climate warming studies are important, is not a bad thing! Acoustics measures current and vorticity well also, as we'll discuss later. And even ocean density can sometimes be indirectly inferred, if one includes ocean dynamics information into the inverses.

After looking at the density equation of state, we next look at "potential temperature θ and "adjusted" density σ_θ, which we need to sort out "pure" temperature and density effects, and not a mixture of them.

Trying to show ocean dynamics in a few pages is perhaps as futile as trying to cover scattering in a few pages - but again, we only try to give the flavor and provide a few useful nuggets.

Ocean dynamics equations ultimately derive from the nonlinear Navier Stokes (NS) equations (F=ma for geophysical fluids, cast in various forms) and conservation laws. A standard form seen is the conservation of momentum equation, shown in the notes. Each of the five terms in the equation has a wealth of detail in it. The first term, the material (total) derivative, makes the equation nonlinear, and this immediately makes the NS equations challenging. The next term, the Coriolis, puts us in a rotating system – thus the "geophysical" in GFD. The pressure gradient effect is how the ocean internal density differences make themselves felt. The gravity provides both the force to increase the ocean pressure with depth, and the restoring force for ocean waves (surface and internal). The F term at far right includes the very important wind forcing of the oceans circulation. A lot of stuff in a few terms.

Various approximations used on these terms are discussed next – they are explained reasonably in the notes, I think, so I won't belabor them here.

As an example of how one would set up a "model ocean," the quasi-geostrophic (QG) equations are shown in x, y, z component form. These are the above momentum equation sans the nonlinear advection term. (Always make life simple, yes!?).

Pieces of these QG equations can be isolated, but the dominant piece is the "geostrophic motion" shown in the notes, where the pressure gradient balances the Coriolis force. A page or two follows these equations explaining how one can get data for using the geostrophic equations, and also what the pitfalls are. GFD guru Joe Pedlosky has stated that if you could only know one fact from GFD, geostrophy might be the most important one!

Another simple piece of the QG equation is the "inertial motions" part. Basically, sudden events like storms make the water circulate in wide horizontal circles. Acoustically this is not a big effect (why?!)

The geostrophic solution (ignoring ocean surface slope effects) is driven by the heat and salt distribution of the ocean interior and is part of the "thermohaline circulation." But there is another large component of the ocean's circulation – the wind driven part (the "innocuous" F term in the QG equation). As a prelude to looking at this, we quickly look at vorticity (the curl of the current field, or how the fluid rotates), which has both a planetary (Coriolis) part and also a "local circulation" part, called "relative vorticity." Rather cooly, acoustics can measure vorticity rather well!

Three names loom very large in explaining how the wind pushes the water around in ocean basins: Sverdrup, Stommel, and Munk. Let's start with the theory due to the theory's grand-daddy, Harold Sverdrup. A simple set of equations is shown in the notes in which we add surface wind stress (τ_x, τ_y) to the geostrophic equations. We then vertically integrate these, invoke continuity, and take the curl – again, simple enough! The pressure terms cancel, and we get rid of one more pesky term by noting that $f_{coriolis} = f(y)$. Doing these straightforward manipulations, we get an amazingly compact result: The meridional transport equals the curl of the wind stress!! Add continuity to this, and we can get M_x, M_y, the total transport! So, given where you're working at in latitude (the f and β) and a map of the winds that you can numerically take the curl of, you have an ocean circulation model! Wow! I show a wind map from an experiment we did many moons ago (1988) in the Greenland Sea gyre to illustrate maps of wind stress circulation/curl! (In this era of looking at satellite pictures of weather circulations on the nightly news, this data being routine is no surprise.)

But, what does this model have to do with acoustics and acoustical oceanography? Well, at this level of simplification, not a lot. But Sverdrup's work was a big step historically in a century long march towards the ocean numerical models we have today, which address the full NS equations. Ocean acoustics forward models (and inverses) interact directly with these amazing descendants of Sverdrup's model, and so we can explore both forward and inverse acoustics in the context of a "full ocean." (CAVEAT EMPTOR: No ocean model incorporates all space and time scales – yet!). If time had allowed, I would have had a guest lecture or two on the acoustics/PO model intersection, which is a very active topic these days.

The last topic in this brief oceanography review is internal gravity waves. These waves are as ubiquitous in the ocean as surface gravity waves, and are an important effect on acoustics. (They usually are a "noisy background nuisance," but not always!).

The basic "environmental variable" for internal waves is the buoyancy frequency, .. described simply in the notes. A deep sea profile of it is shown in an attached figure. (I work more in shallow water, where the profile is much simpler!). A derivation (a page or two long) is mentioned for the horizontal wave propagation and vertical mode equation for the internal waves – it is not hard, and worth looking up and working through. Very interestingly, the resultion mode equation for the vertical displacement is very similar to our acoustic mode equation and is solved with the same methods. This wavy displacement of the fluid displaces the temperature/soundspeed field, and this is what makes internal waves acoustically important! (And remember the intertial waves? No vertical displacement!).

The second half of Lecture 13 is the PowerPoint presentation I gave at AGU Ocean Sciences and at the Acoustical Society of America meeting a few years ago as part of the "Walter Munk Award" ceremonies. (Before going further, I regard being paid to do science and working with great colleagues to be the highest awards one gets during a career. But, if I got any "formal award," I'm honored it was this one.)

The PowerPoint slides here are pretty self-explanatory, so let me just throw in some overview and then a few details.

In overview, I simply ask "what are the good science application questions" up front. It all starts from there! There are plenty of good questions in PO, GG & BIO to look at, and also acoustics! (I look at both the forward and inverse problem in this talk). I will just mention that three of the problems I am currently researching are part of this "Christmas Shpping List" I detailed as the first part of the talk. They are: 1) incorporating nonlinear internal waves into large scale coastal oceanography models, and then looking numerical at 3-D acoustics propagation through this PO model, with data comparisons to follow; 2) looking at acoustics in canyons and on the continental slope (very 3-D propagation); and 3) tracking, imaging, and measuring marine life (fish size through whale size) using arrays, AUV's and acoustics. These are only a subset of the overall list of questions I posed, which is in turn not complete in any sense.

The second half of the lecture is: given some good science/application question, what do I do that's sensible to measure what's needed to answer it? As a seemingly arbitrary example, I posed mapping the "ocean fields" (e.g. T, S, P, V) over a 50km x 50 km patch of coastal ocean. I then listed as many of the major measurement technologies as I could and put in numbers for a "bake off." I'll let you look at the answers, and perhaps refine my estimates if you wish. But one thing emerges that might seem counter to the theme of this course – acoustics didn't win this "bake off!" While acoustics can be a "winner" in other scenarios, it did not break the tape first here! The moral overall is to do an "antenna array design" with as many good options as you can, and at the far end, you will hopefully have an efficient, accurate, and cost effective means of making your measurement. (And also keep an eye on new technologies!).

In passing, the "just for grins" arbitrary example I chose to illustrate the measurement back off may not be as funny or arbitrary as it seems. A number of recent measurements would suggest that the Mid Atlantic Bight waters (the coastal waters off the Northeastern USA) are warming, perhaps due to climate change. This can drastically affect fisheries, hurricane paths and intensities, and other important things. Sooo – maybe we do want to measure temperature over a large patch of coastal ocean with good resolution! Based on the lecture and your own experience, what would you do???

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