How Many Water Masses Fill the Ocean?: A Spectral Unmixing Approach

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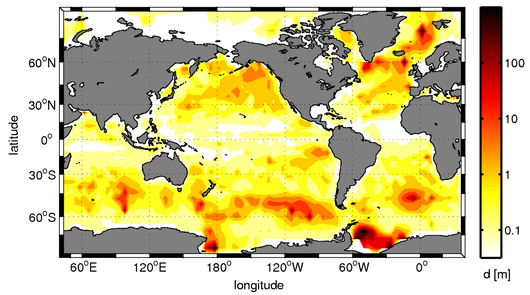
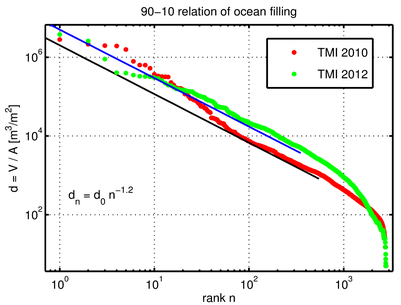
1.Background

Deep ocean property distributions are thought to be the consequence of the mixing of just a few water masses, but defining the property sets of these water masses is subjective. A natural way to track pathways in the ocean is to label waters by their surface origin[1]. With this definition, however, a few thousand surface locations significantly influence the ocean interior.



Ocean volume originating from the surface, expressed as an effective thickness, d= V/A, where the volume is divided by the surface area. Calculated by the Total Matrix Intercomparison (TMI, 2012 update) method with the WOCE global climatologies of temperature, salinity, nutrients, and oxygen.

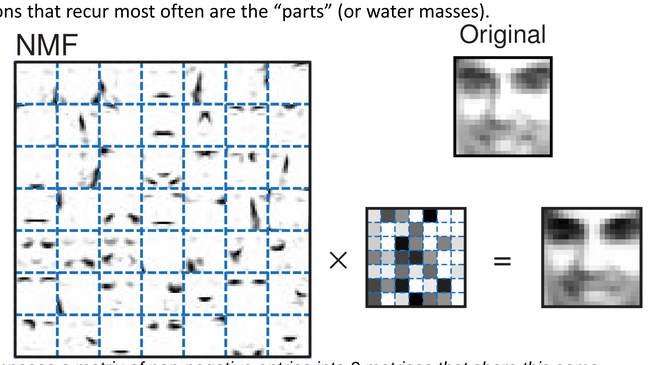


Rank-thickness diagram of the surface contributions. A shallow power law (p=-1.2) describes the influence of many surface locations and is consistent with the 2010 and 2012 versions of the TMI method[2]. 10% of the surface fills 90% of the interior, reminiscent of scaling laws found in economics, astronomy, and many other fields.

So, how many water masses fill the ocean, just a few or many thousand? (or something in between)

2. Method

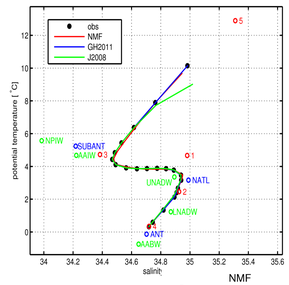
Satellite images or photographs can be spectrally unmixed into their constituent parts using a non-negative matrix factorization (NMF)[3] . Applying NMF to the ocean, each interior location has a spectrum of surface waters, and those combinations that recur most often are the "parts" (or water masses).



NMF decomposes a matrix of non-negative entries into 2 matrices that share this same property, while best reconstructing the original matrix in a Frobenius 2-norm sense.

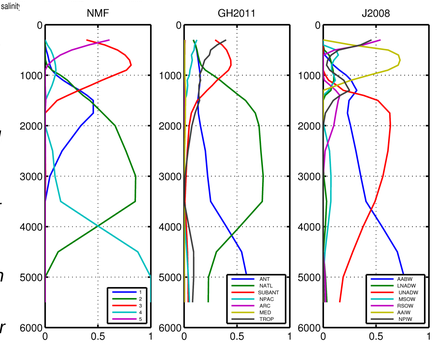
3. Test Case: S. Atlantic Profile

Does the method work with a vertical profile at 8°S, 30°W?



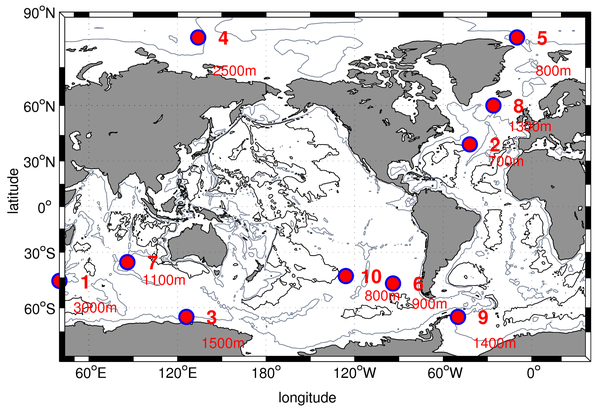
The NMF method estimates optimal surface combinations of waters that are translated into endmember values (for water masses 1-5). Compare these endmembers to those from a regional surface average method (GH2011)[2] and the traditional deep water formation sites (J2008)[4].

The vertical decomposition of the profile into water masses as defined by the 3 methods above. The NMF method uses less water masses to fit the same data, while also finding water masses that are more abundant. NMF reproduces what we expect in this test case, with some improvement over past methods.



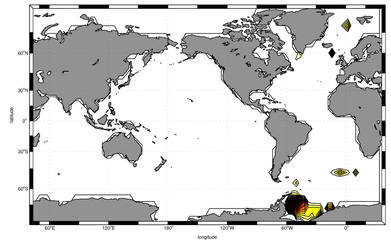
4. Optimal global water masses

NMF is implemented on the global TMI pathways matrix to determine the surface patterns of each water mass. Each surface pattern corresponds to an interior location where the water mass is pure (labelled below with water mass # and depth).

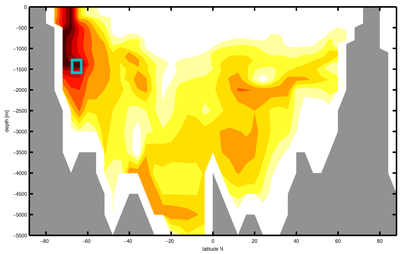


5. Pathways of a water mass

Water mass #9 is identified by the interior location with the teal box (right), or by its surface pattern (left). The adjoint transport pathways connect the two locations, where the hotter colors represent a greater fraction of water that will encounter the interior box in the future. Water mass #9 provides a rigorous definition for deep water formed in the Weddell Sea.

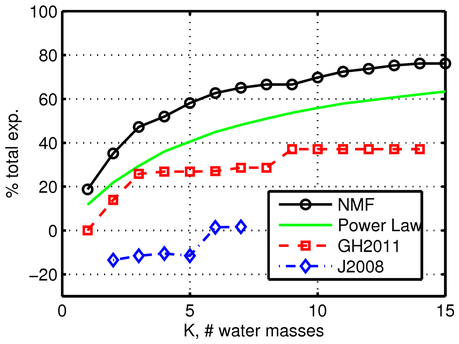


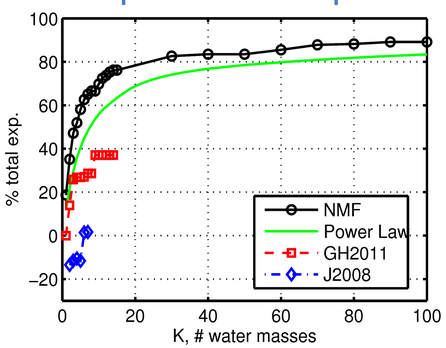
Surface origin



surface to interior path

6. How well can water masses explain ocean pathways?





100 water masses are needed to explain 90% of variability in the pathways matrix. The power law description[2] is not strictly a measure of water masses, and is an over-estimate of the number of waters needed. Other definitions of water masses can't explain the majority of ocean variability.

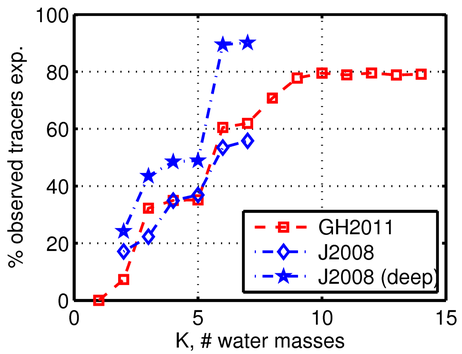
7. Conclusion

A few water masses are inadequate to describe the pathways of the interior ocean.

Traditional water-mass decompositions give a poor prediction of interior property distributions of tracers with surface expressions that are different from those in the WOCE dataset.

NMF-based water masses indicate the optimal locations to observe ocean properties in order to reconstruct global distributions of tracers that are well observed, as well as those that are not.

Using an 80% criterion consistent with the sub-thermocline ocean being 80% of the total ocean volume, about 20 water masses are needed to explain deep tracer pathways.



Modern-day datasets include only a handful of globally-observed tracers, so if the goal is to reproduce this limited data, only a handful of water masses are necessary. The lack of observational data types explains the persistence of the small water-mass picture of the world ocean, despite its lack of predictive power.

Bibliography:
1) Gebbie & Huybers, 2010, *JPO*.
2) Gebbie & Huybers, 2011, *GRL*.
3) Lee and Seung, *Nature*, 1999.
4) G.C. Johnson, 2008, *JGR*.

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