

Oceanographic Weather Maps: Using Oceanographic Models to Improve Seabed Mapping Planning and Acquisition

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Abstract

In a world of high precision sensors, one of the few remaining challenges in multibeam echosounding is that of refraction based uncertainty. A poor understanding of oceanographic variability can lead to inadequate sampling of the water mass and the uncertainties that result from this can dominate the uncertainty budget of even state-of-the-art echosounding systems. Though dramatic improvements have been made in sensor accuracies over the past few decades, survey accuracy and efficiency is still potentially limited by a poor understanding of the “underwater weather”.

Advances in the sophistication of numerical oceanographic forecast modeling, combined with ever increasing computing power, allow for the timely operation and dissemination of oceanographic nowcast and forecast model systems on regional and global scales. These sources of information, when examined using sound speed uncertainty analysis techniques, have the potential to change the way hydrographers work by increasing our understanding of what to expect from the ocean and when to expect it. Sound speed analyses derived from ocean modeling system’s three-dimensional predictions could provide guidance for hydrographers during survey planning, acquisition and post-processing of hydrographic data. In this work, we examine techniques for processing and visualizing of predictions from global and regional operational oceanographic forecast models and climatological analyses from an ocean atlas to better understand how these data could best be put to use to in the field of hydrography.

Introduction

Survey planning is an important pre-survey exercise that involves assessing the desired outcomes of a seabed mapping mission and then determining what needs to be done to accomplish the goals. Planning activities can include, for example:

- Designing survey layout and prescribing line spacing and/or orientation.
- Determining when to conduct the operation based on traffic, weather, and other environmental factors.
- Selecting calibration sites for echosounders.
- Planning installation locations for vertical and/or horizontal control equipment.
- Providing additional guidance to field personnel on environment aspects that should be taken into consideration in the field, e.g. exceptionally large tidal ranges, high currents, areas of high risk for safety of personnel and equipment, etc.
- Choosing appropriate instrumentation with an uncertainty and/or resolution that meets the project needs.

When faced with the particular task of choosing appropriate mapping instrumentation, survey planners can turn to uncertainty models, e.g. the HGM model (Hare et al., 1995), to help decide which survey instrumentation to choose and how best to configure and operate it. Uncertainty models can help guide the instrumentation selection process (or the line spacing decision process when instrument choice is fixed) as they allow for estimation of the total propagated uncertainty (TPU) of all the survey system components across the operating depth and angular range of a particular sonar. Manufacturers of mapping system components typically provide reasonable estimates of the uncertainty characteristics of their products and it is possible to perform a pre-analysis to ascertain how the mapping system will operate as a whole in terms of achievable accuracies.

Though hardware uncertainty profiles are widely available (and are verified by the community), the survey planner must make some assumptions about the uncertainty that will result from oceanographic variability, this being one of the largest sources of uncertainty due to the refracting effect of temperature and salinity variations in the water on acoustic signals propagating through it. Not only is oceanographic variability one of the largest sources of uncertainty in multibeam echosounding, it is also the most difficult to estimate at the planning stage. Examining existing recommended survey “best practice” documentation, e.g. IHO (2005) or NOAA (2012), sheds little light on how to approach this problem prior to arrival in the field. The IHO Manual of Hydrography (IHO, 2005), in its section on Hydrographic Survey Planning, recommends survey planners to:

“Estimate likely spatial or temporal changes in sound velocity regime and plan initial sound velocity probe coverage. ... Estimate sounding error budget and compare to the survey specification.” (p. 413)

Later in the same document, the IHO recommends the following:

“The initial observations of sound velocity should be conducted to allow determination of the spatial and temporal variations across the entire survey

area. A grid of observation points should ensure representative sampling is conducted over the whole survey area in a methodical and timely fashion. This data, together with other environmental factors such as climate, fresh water inflow, any seasonal variations and seabed topography, will determine the frequency at which SV profile observations are conducted.” (p. 456)

Whereas this is good advice for personnel in the field who are about to start surveying, it does little to help estimate the impact of oceanographic related uncertainties at the project planning stage. Even having such a grid of observation points does little to help the surveyor as there are very few tools to turn this data (sound speed/temperature/salinity profiles) into meaningful information that can be acted upon. Without the ability to anticipate the effects of oceanographic variability on the survey design, the project planner must hope for the best but prepare for the worst. Two common approaches are:

- **Planning for reduced useable coverage:** Though a system may be able to sound over a wide sector, e.g. 140°, the *useable* sector is reduced in the planning stages in anticipation of poor performance at the outer edges of the sector. The pessimistically reduced coverage increases the number of survey lines that would be required to map a given area. This increases overall project time and costs estimates though both time and costs can potentially be saved if oceanographic conditions are favorable.
- **Allocating underway profiling systems to the project:** Under way oceanographic profiling systems, e.g. Furlong et al. (1997) and Rudnick and Klinke (2007), allow field personnel to measure oceanographic properties while underway as often as required with little impact on the overall time to complete the survey. These types of systems can prove invaluable in areas of dynamic oceanographic variability, e.g. Hughes Clarke et al. (2000), Beaudoin et al. (2009). Due to the increased sophistication in deployment hardware and control components of these types of systems, both capital costs and ongoing maintenance costs are much higher relative to those of traditional sampling instrumentation and *these costs cannot be recovered if the hardware is not needed.*

Faced with these important decisions at the planning stage, surveyors often turn to colleagues to assess how others have fared in particular areas of operation. There is value in this approach; however, much of the advice from colleagues can be very subjective in nature and is not always useful. It can also be tied to a specific time of year and may not necessarily apply to the upcoming survey that is being planned for.

In this work, we explore the use of climatological ocean atlases and oceanographic modeling systems to help hydrographic surveyors understand the “underwater weather” that can severely limit the achievable accuracies of echosounding data. Ray tracing spatial variability analysis methods are applied to 3-D analyses such as the World Ocean Atlas (WOA) and 3-D oceanographic forecast modeling systems such as the NOAA Chesapeake Bay Operational Forecast System (CBOFS) or the NOAA Global Real-Time Ocean Forecast System (RTOFS). The output of these analyses provides a “Weather Map” for hydrographers that shows much promise, even in these preliminary stages of research.

Ocean Climatologies and Forecast Systems

It is important to make the distinction between ocean climatologies and forecast systems as the two products are used in this work but they represent fundamentally different views of the ocean. These differences must be appreciated when exploring how they can be applied to the field of seafloor mapping.

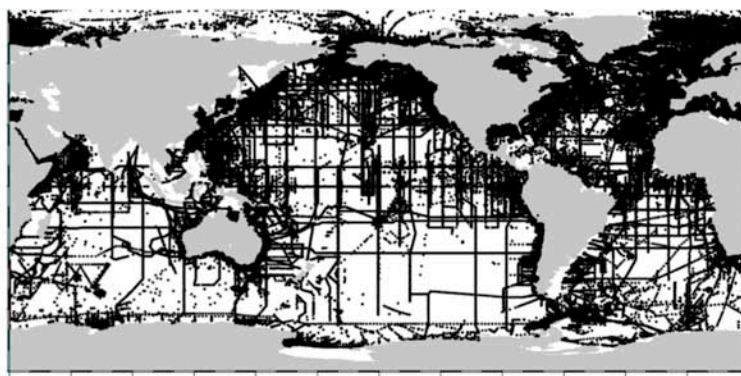
An oceanographic climatology provides a discretized representation of a scalar value, at some prescribed depth level or over a series of depth levels, over a specified region from non-synoptic observations and is meant to serve as a model representing the mean conditions for the epoch for which the climatology is constructed. In principle, this is very similar to the procedure of preparing bathymetric grids from soundings. Climatologies vary in several aspects: source data, coverage, resolution, construction techniques, etc, all of which can greatly influence the fidelity of the climatological fields. The output of the climatology is then a representation of the average value of a particular field, e.g. temperature or salinity, for a prescribed period. For example, one might prepare a map of the average sea surface temperature for the month of July using databases of oceanographic measurements collected over a span of decades.

A forecast system typically uses a climatology to establish its initial conditions. The forecast system's 3-D fields are then updated using numerical models and additional input data, e.g. sea surface temperature and height as measured by satellite, wind forecasts, river input, precipitation, etc, to arrive at an approximation of current conditions. The numerical model can be run into the future to provide forecasts with some of the input to the forecast, e.g. wind, being themselves forecasts from other types of numerical models.

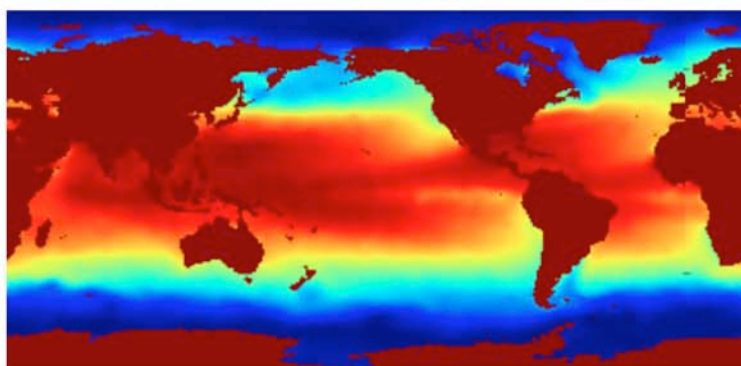
An analogy can be drawn between oceanographic and meteorological products: an oceanographic forecast system is comparable to a weather forecast and an oceanographic climatology is comparable to a region's mean temperature as based on a long time-series of temperature measurements, i.e. the 30 year climatological mean temperature. An analogy with water levels can also be made: an oceanographic forecast system is similar to a tidal prediction whereas the climatology would be comparable to the mean sea level derived from averaging a long time-series of water measurements.

World Ocean Atlas

The World Ocean Atlas (WOA) climatology is a standard data product of the U.S. National Oceanographic Data Centre (NODC), it has its roots in the first global oceanographic climatology, i.e. that constructed by Levitus in the early 1980s (Levitus, 1982). Referring to Fig.1, it is built solely from the World Ocean Database (WOD), a large (>9 million observations) database of worldwide oceanographic measurements maintained by the NODC (Boyer et al., 2009). Oceanographic measurements are maintained in the WOD in a standard format that preserves metadata associated with the cast, instrumentation, cruise, quality control procedures, etc.



World Ocean Database:
Database of oceanographic observations (CTDs, XBTs, etc)



World Ocean Atlas:
Regular global grid of temperature, salinity (and other fields)
estimated from WOD observations for 33 depth levels

Figure 1. World Ocean Database, distribution of measurements and World Ocean Atlas grids derived from WOD measurements. The upper plot shows the geographic distribution of the >600,000 CTD measurements in the WOD (after Boyer et al., 2009).

The WOA consists of a set of objectively analyzed (1° grid) climatological fields of in situ temperature, salinity, dissolved oxygen, Apparent Oxygen Utilization (AOU), percent oxygen saturation, phosphate, silicate, and nitrate at standard depth levels for annual, seasonal, and monthly compositing periods for the world ocean (Loncarnini et al., 2010; Antonov et al., 2010). The fields are available at 33 standard depth levels extending from the sea surface to 5,500 m depth. The annual and seasonal grids extend from the ocean's surface to 5,500 m whereas the monthly grids extend only to 1,500 m. In addition, several statistics are also available for 1° and 5° squares at each standard depth levels and for various compositing periods (annual, seasonal and monthly fields). The atlas fields include analyzed mean fields, difference fields, grid point fields, number of observations, standard deviation, standard error, unanalyzed mean, and interpolation error. Editions of the WOA have been released in 1994, 1998, 2001, 2005 and 2009 with each edition incorporating WOD observations that had been acquired/submitted since the previous edition. The 2001 edition is of particular interest to this work as it included a high resolution $1/4^\circ$ set of grids along with the usual 1° and 5° products.

Referring to WOD coverage map shown in Fig. 1, there are obviously areas of the world's oceans with sparse data coverage thus there is the potential for interpolation errors in the gridded WOA products.

Oceanographic Forecast Model Systems

During the last decade major strides have been made in the development and operational implementation of numerical oceanographic circulation forecast modeling systems. Oceanographic forecast systems throughout the world now provide nowcasts or analyses and forecast guidance of the three dimensional physical conditions of water bodies ranging from the global ocean to seaports and forecast horizons ranging from 36 hours to 7 days. The predictions from these forecast modeling systems are important for a variety of applications including search and rescue missions, commercial and recreational shipping, determining the fate of pollutants discharged in coastal waters, and support of ecological forecasts such as Harmful Algae Blooms.

In the U.S., NOAA's National Ocean Service (NOS) and National Weather Service (NWS) are developing together a national oceanographic forecast modeling backbone capability, in cooperation with the U.S. Navy and academic partners, to provide forecast guidance of the physical state of the U.S. coastal waters, Great Lakes, and the ocean basins. The NWS' National Centers for Environmental Prediction (NCEP) operates the Real-Time Ocean Forecast System that provides 3-D forecast guidance for the global oceans out to 6 days into the future.

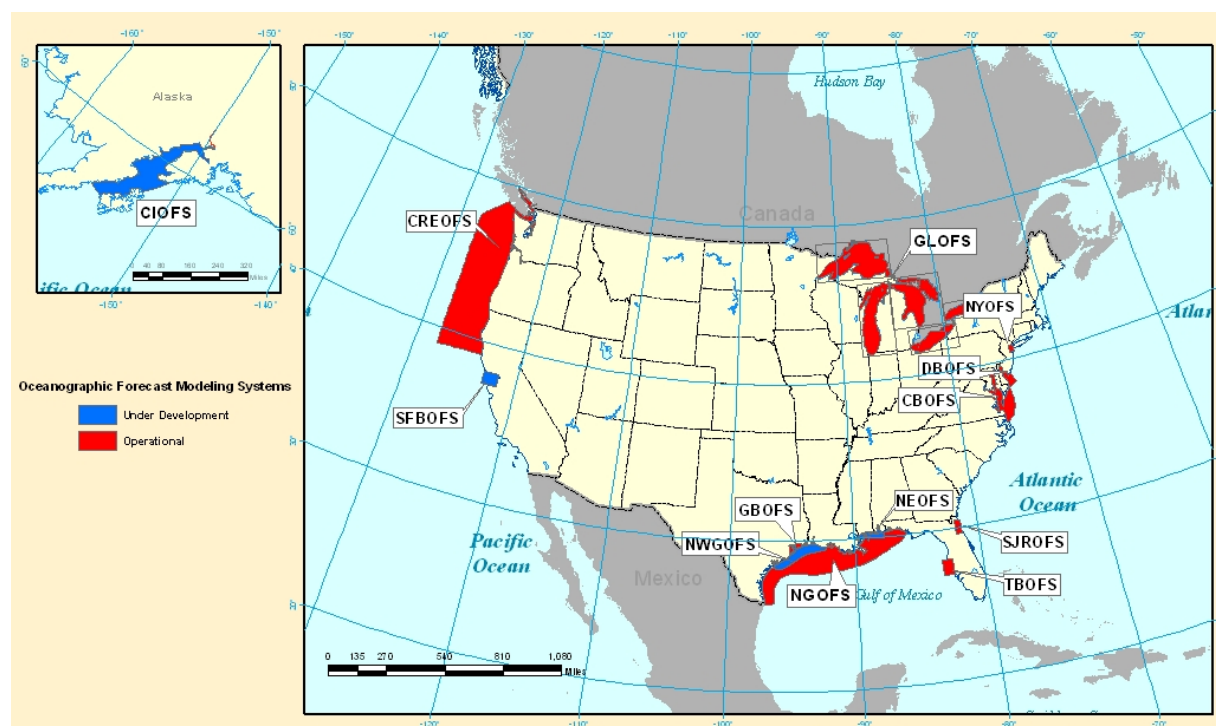


Figure 2. NOAA/National Ocean Service Operational Coastal Forecast Modeling Systems as of January 15, 2013.

NOS has focused on the U.S. coastal waters and presently has 13 operational forecast systems (OFS) including ones for the Columbia River Estuary (CREOFS), Galveston Bay (GBOFS), North Gulf of Mexico (NGOFS), Tampa Bay (TBOFS), St. Johns River (SJOFS), Delaware Bay (DBOFS), Chesapeake Bay (CBOFS), Port of NY and NJ (NYOFS), and five lake domains of the Great Lakes (GLOFS). Within the next two years, NOS will implement new OFS for San Francisco Bay (SFBOFS) and also high-resolution nests in the NW and NE portions of the Gulf of Mexico (NWGOFS and NEGOFs). The NOS forecast systems provide guidance out to 36 or 60 hours. A map depicting NOS' present coastal forecast systems and ones planned by FY2015 is given in Fig. 2.

The operational oceanographic forecast systems have two modes of operations called nowcast or hindcast cycle and forecast cycles. The nowcast or hindcast cycle uses the previous nowcast for its 3-D initial conditions and is driven by surface meteorological (e.g. surface winds, radiation and heat fluxes) analyses from global or regional numerical weather prediction to generate nowcasts for the past hour or last 2 days. Remotely-sensed and *in situ* data are often assimilated by the model to improve its prediction. Coastal forecast systems have open ocean boundaries that are estimated from ocean basin-scale forecast models. On the inland boundary, river conditions are often based on near-real-time discharge observations from river gages.

The forecast cycle uses the latest 3-D nowcast and is driven by prediction from meteorological from global or regional numerical weather prediction to generate forecast guidance out to 1 to 7 days. Again for the coastal forecast systems, the open boundary conditions are estimated from the larger ocean basin models. For the river input, conditions are usually based on persisting observations into the future or climatological data.

For this study, forecast guidance was used from a global-scale and estuarine-scale oceanographic forecast modeling systems, the Global RTOFS and CBOFS, respectively. Descriptions for CBOFS and RTOFS are given next.

CBOFS

The Chesapeake Bay Operational Forecast System is a NOS numerical oceanographic prediction system that provides nowcasts and short-range forecast guidance of 3-D currents, water temperature/salinity as well as surface water levels for the Bay and adjacent shelf waters (Lanerolle et al., 2011). The development and implementation of CBOFS was a joint project of the NOS/ Coast Survey Development Laboratory's Marine Modeling and Analysis Programs, NOS' Center for Operational Oceanographic Products and Services (CO-OPS), NWS/NCEP Central Operations and Rutgers University. Sample model output is shown in Fig. 3.

The three-dimensional ocean model used by the new version of CBOFS is the Rutgers University's Regional Ocean Modeling System, a community-based, free-surface, hydrostatic, primitive equation ocean model which uses stretched, terrain-following sigma coordinates in the vertical and curvilinear coordinates in the horizontal (Shchepetkin and McWilliams, 2004). The CBOFS grid has 332 x 291 points in the horizontal. The finest grid resolutions in the x- and y-directions are 34 m and 29 m, respectively, and the coarsest resolutions are 4,895 m and 3,380 m,

respectively. The vertical grid follows the terrain and consists of 20 model levels. The CBOFS domain was designed to include the whole of the Chesapeake Bay and a section of the shelf to allow a realistic interaction between the shelf and the entrance to the Bay.

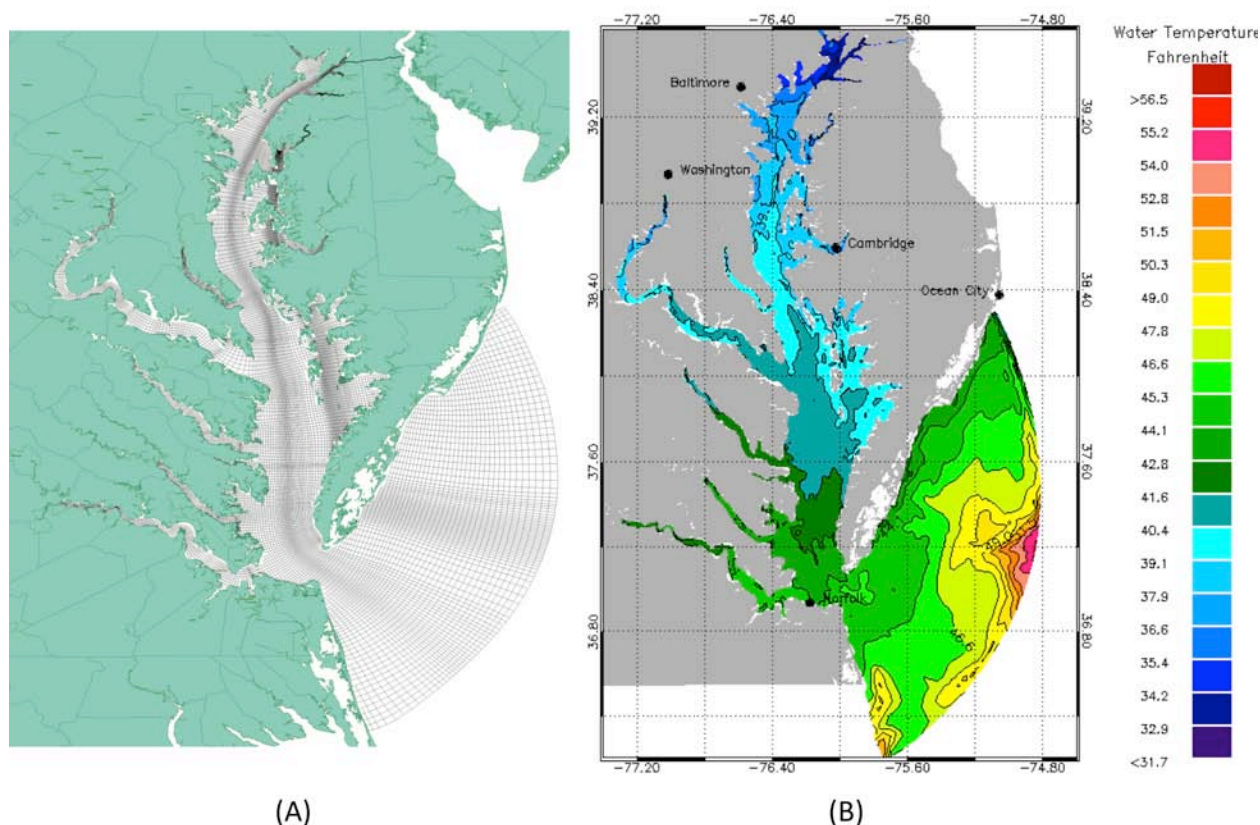


Figure 3. CBOFS model grid (A) and sample output of forecasted sea surface temperature (B). Salinity and sea surface height are also computed by the forecast system. Temperature and salinity are computed for 20 depth levels throughout the spatial domain of the model. Images (A) and (B) accessed from NOAA Tides and Currents website (<http://tidesandcurrents.noaa.gov/ofs/cbofs/>).

CBOFS has four daily nowcast and forecast cycles at 0, 6, 12, and 18 UTC and operates within NOS Coastal Ocean Modeling Framework (COMF). The meteorological forcing for CBOFS nowcast cycles is provided by hourly surface wind and surface heat flux analyses and very short-range forecasts from NWS/NCEP North American Mesoscale (NAM) weather prediction modeling system, 4 km nest covering CONUS. River discharge is estimated using near-real-time observations from U.S. Geological Survey river gages. Oceanographic conditions on CBOFS' lateral boundary on the shelf are estimated based on subtidal water level forecast guidance from NWS Extra-Tropical Storm Surge (ETSS) Model and adjusted by observed subtidal water levels at NOS water level gauges, tides from Advanced CIRCulation Model (ADCIRC) ec2001 tide database, and NCEP Global RTOFS temperature and salinity nowcasts.

The CBOFS forecast cycles rely on meteorological forcing provided by forecast guidance from the 4 km CONUS nest of NAM model. The river discharge is estimated by persisting the most recent observations for the entire forecast period. On the lateral boundary, future water levels are estimated based on subtidal water level forecast guidance from the NWS Extra-Tropical Storm Surge Model and tides from the Advanced CIRCulation Model (ADCIRC) while water

temperature and salinity conditions are based on NCEP Global RTOFS forecast guidance. Displays of CBOFS nowcasts and forecast guidance can be seen at tidesandcurrents.noaa.gov/ofs/cbofs/cbofs.html and at nowcoast.noaa.gov.

RTOFS

The Global RTOFS is operated by NWS/NCEP and is based on an eddy resolving $1/12^\circ$ global HYCOM (HYbrid Coordinates Ocean Model) (Mehra et al., 2011). The ocean model configuration has 32 hybrid layers and a horizontal grid size of (4500 x 3298). The grid has an Arctic bi-polar patch north of 47°N and a Mercator projection south of 47°N through 78.6°S . The coastline is fixed at 10 m isobath with open Bering Straits. The potential temperature is referenced to 2000 m depth (sigma-2) and the first level is fixed at 1 m depth. The dynamic ocean model is coupled to a thermodynamic energy loan ice model and uses the KPP mixed layer formulation. Sample imagery of sea surface temperature is shown in Fig. 4.

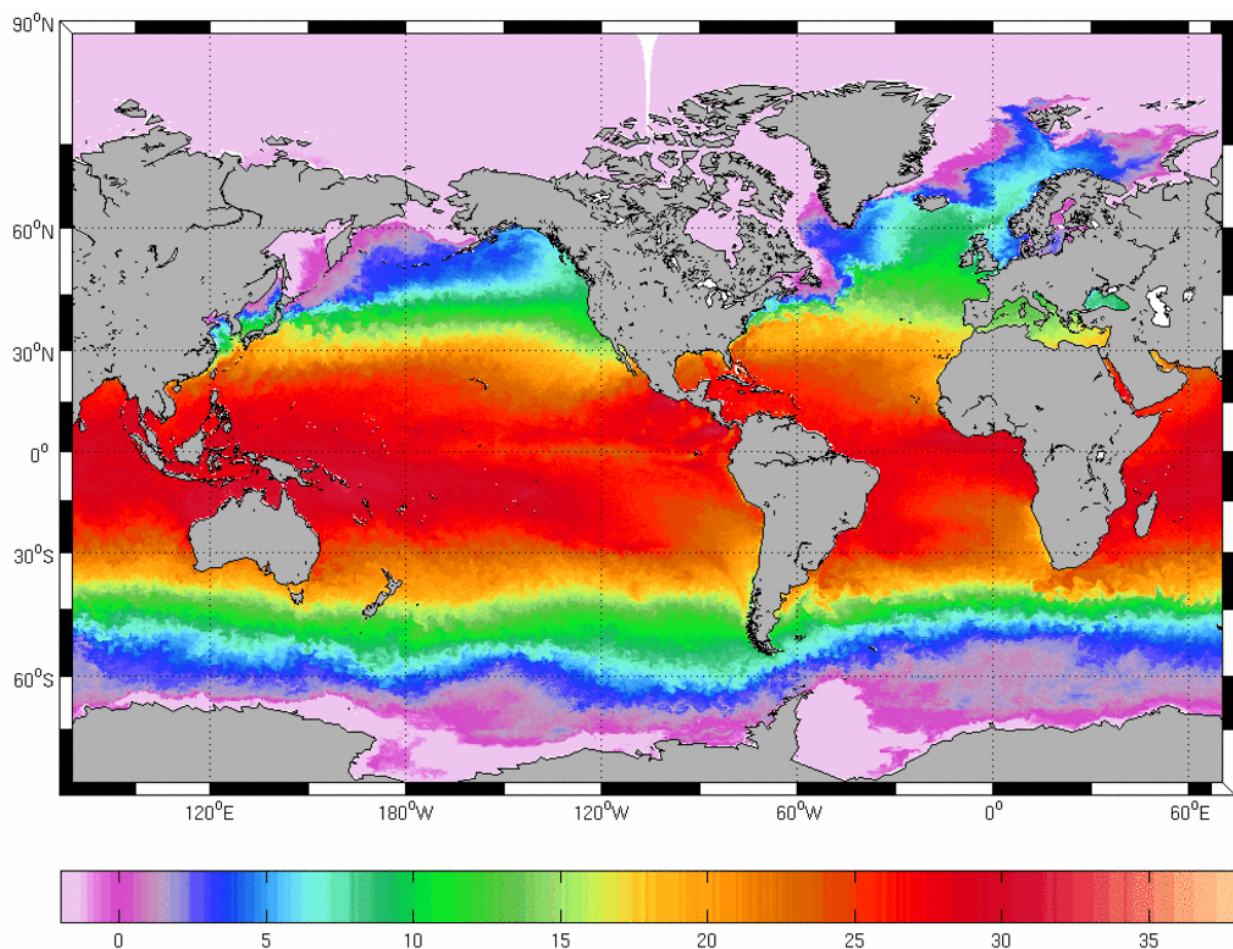


Figure 4. Sea surface temperature RTOFS Nowcast for Feb. 22, 2013 (image from <http://polar.ncep.noaa.gov/global/>).

RTOFS runs once a day and produces two-day nowcasts and 6-day forecasts using the daily initialization fields produced at NAVOCEANO using NCODA, a 3-D multi-variate data

assimilation methodology. The data types assimilated include in-situ profiles of water temperature and salinity and remotely sensed sea surface temperatures, sea surface heights, and sea-ice concentrations. RTOFS is forced with 3-hourly momentum, radiation and precipitation fluxes from NCEP's operational Global [Weather] Forecast System (GFS).

Methods

When in the field, our understanding of the oceanography is limited by the types of measurements that are typically taken in support of the mapping operations:

- High-resolution (~ 1 -Hz) surface sound speed measurements or thermosalinograph (TSG) measurements; these measurements are made at the surface only
- High-resolution vertical sound speed or CTD profiles; these are made infrequently with time spans of hours between casts with traditional sampling methods.

Oceanographic models can provide synoptic overviews of the area of interest that *in situ* observations cannot. One of the challenges is to convert oceanographic model data into hydrographic information, part of which is collapsing three-dimensional, time-varying fields of temperature and salinity into two-dimensional representations that have meaning to hydrographers. Many methods are being explored to achieve this goal; in this work we focus on the problem of quantifying the effects of spatial variability in the 3-D field using ray trace analysis techniques.

Variability Analysis

Localized estimates of sounding uncertainty can be derived using Variability Analysis techniques outlined in Beaudoin et al. (2009). A ray tracing simulation is performed using a set of sound speed profiles derived for a selected location and the immediate neighboring grid cells in an oceanographic model grid, as in Fig. 5. The discrepancy amongst the final ray traced depths indicates the impact of the spatial variability at that location, this value is then computed throughout the spatial domain of the model and presented as a “Weather Map” which highlights areas of high spatial variability as *uncertainty fronts* where hydrographers must work harder to sample oceanographic variability.

An example is shown in Fig. 6. in which the 3-D oceanographic variability is assessed in terms of echosounding depth uncertainty for an east-west section of a portion of the Gulf Stream. This particular example depicts an investigation along an east-west transect where any given location only examines the immediately neighboring profiles to the east and west. The ray tracing analysis in this case is exactly as depicted in Fig. 5 where three sound speed profiles are computed from the model and three ray paths are used for the analysis.

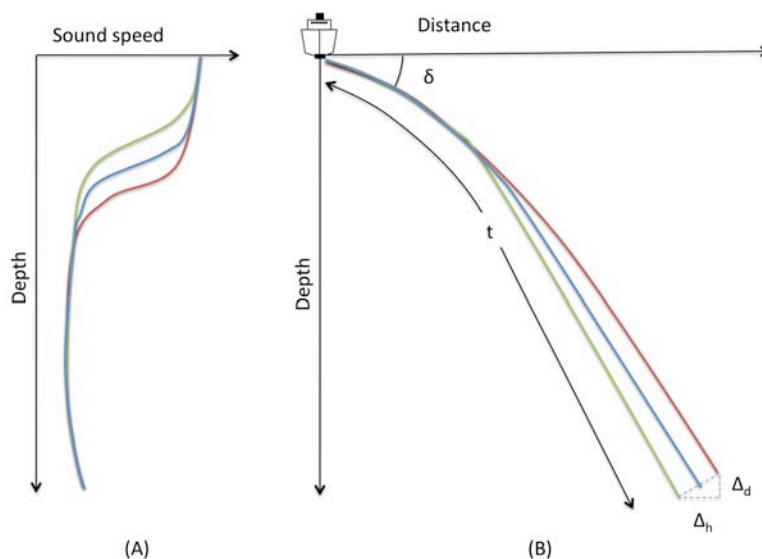


Figure 5. Ray tracing evaluation of oceanographic variability. The three sound speed profiles in (A) are all ray traced in (B) with a common surface sound speed, depression angle (δ) and travel time (t). The dispersion of the ray paths at their terminal points, i.e. Δ_d and Δ_h , serves as an indicator of the impact of oceanographic variability on oblique echo sounding uncertainty.

The techniques discussed in Beaudoin et al. (2009) involve exploring the variation in sounding uncertainty across the entire potential sounding sector. In this work we limit the analysis to the ray trace terminal points for a beam angle of 60° and we use the mean surface values from the ensemble of profiles being analyzed as the common surface sound speed used to ray trace all the profiles in the ensemble. In cases where the bundle of rays being examined extend to different depths (due to the differing maximum depths of their associated sound speed profiles), the examination is halted at the shallowest depth.

The ray tracing analysis integrates the effect of oceanographic variability over the entire depth range at a location and allows for capture of variability at all depths over the spatial scale spanned by the set of casts used in the analysis, in this case 8 NM in the east-west direction only. For an example, from longitudes 72°W - 73°W in Fig. 6 there is variability due to surface effects and variation in the thermocline base depth. Another example is seen between longitudes 66°W - 67°W ; the surface temperature map shows little spatial variability along this section of the east-west transect, however, it is clear that the base of the thermocline is changing depth over the same section. The ray trace uncertainty estimate captures the effect at depth, even when there is no apparent change in oceanographic properties at the surface.

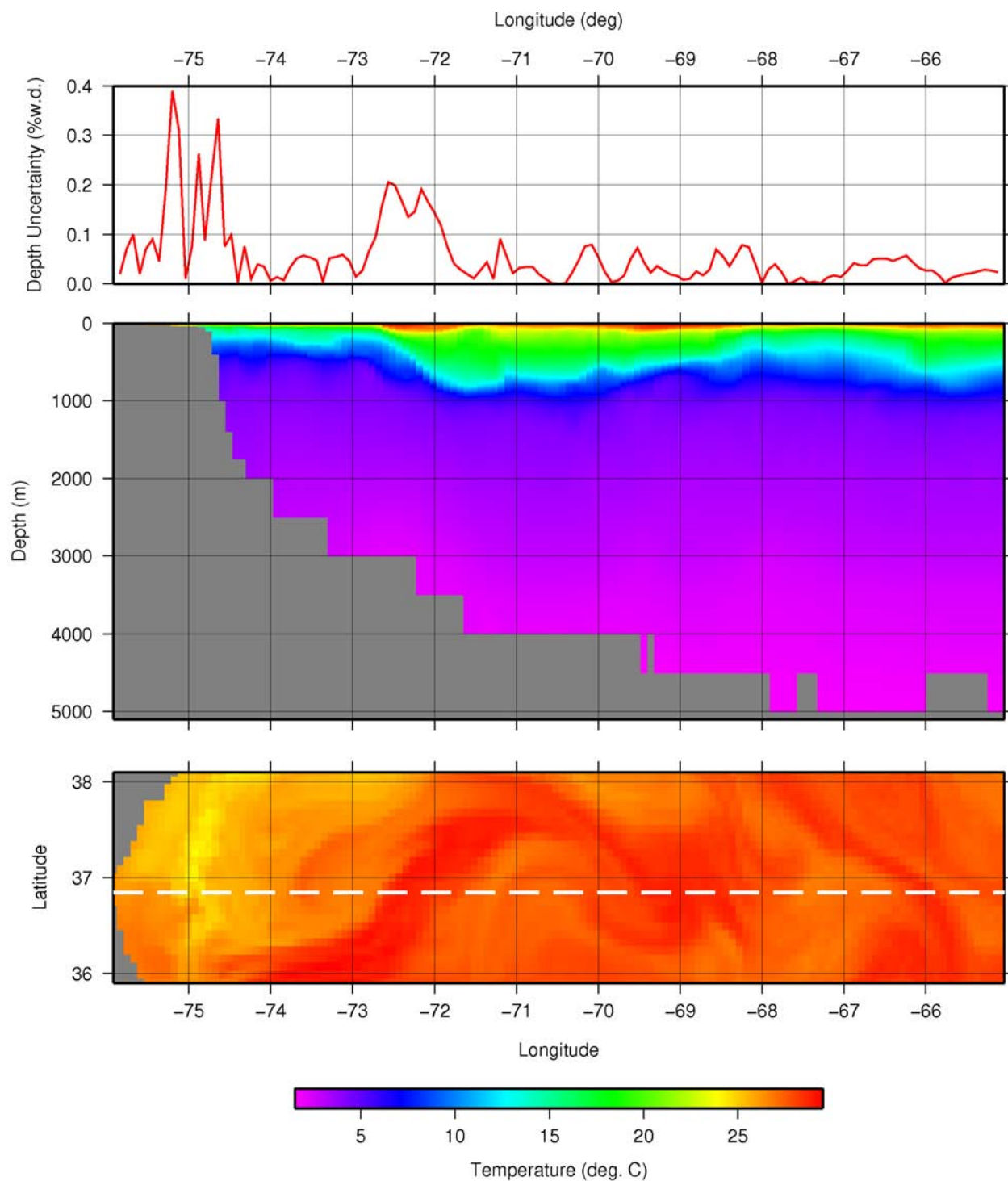


Figure 6. Example of variability analysis across spatial domain of an oceanographic model. The lower plot shows a map of the surface temperature from RTOFS of a portion of the Gulf Stream off the east coast of the US, the middle plot shows the temperature variation with depth for the white dashed line in the lower plot. The upper plot shows how the oceanographic variability in the east-west direction affects multibeam echosounding measurements by computing the parameter Δd (Fig. 5) for each location along the east-west transect by comparing the sound speed profile at that location to its easterly and westerly neighbors. All plots have a common x-axis in units of degrees longitude.

For clarity and explanation purposes, the example in figs. 5 and 6 only examined neighboring profiles to the east and west of a given location for a total of three profiles and three ray paths. The technique proposed in this work extends in more directions by allowing for an examination of neighboring sound speed profiles to the north and south, as well as the profiles in the northeast, southeast, southwest and northwest directions. This gives a total of nine sound speed profiles (one central profile and eight neighbors) and nine ray paths, evaluated at a beam angle of 60° (depression angle of $\delta=30^\circ$). In the case of RTOFS, the analysis area is a box measuring 10 NM in the north-south direction and ~ 8 NM in the east-west direction (this corresponds to distance spanned by three grid nodes in these directions with a grid node spacing of 5' of latitude and longitude). The evaluation of the depth discrepancy, as shown in Fig. 5, remains the same, however with nine data points. Repeating the analysis across a larger spatial domain of the RTOFS model yields the Weather Maps shown in Fig. 7 for the Gulf Stream region, Fig. 8 shows the RTOFS sea surface temperature for the same area for reference.

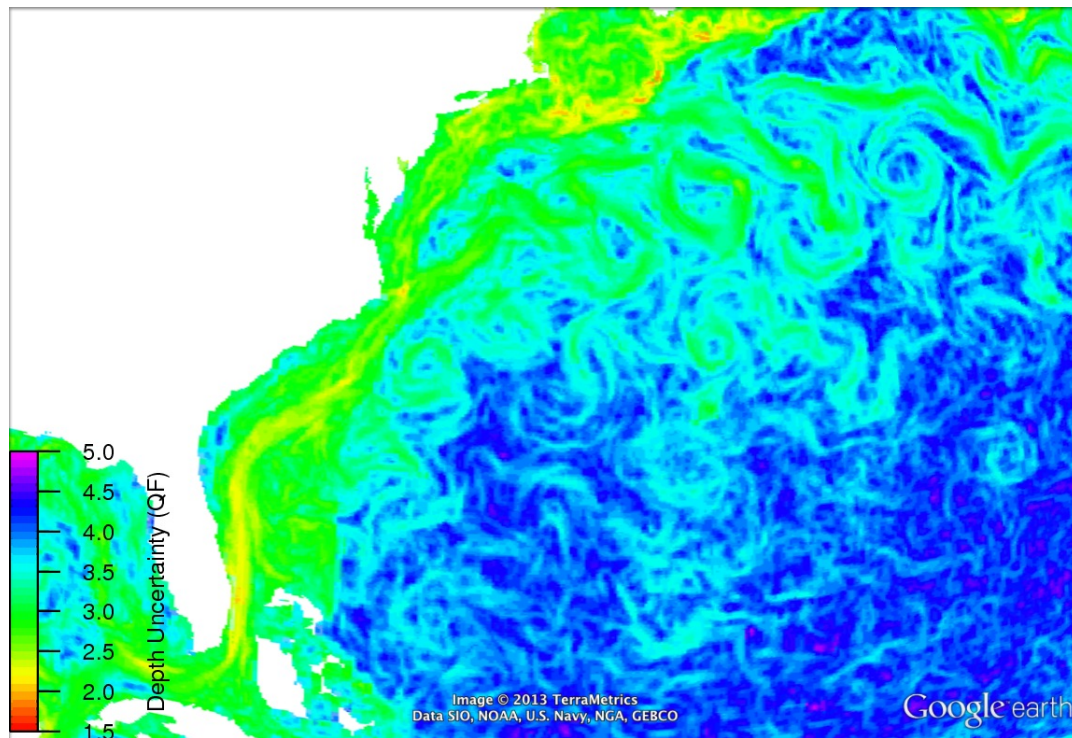


Figure 7. Localized refraction uncertainty Weather Map from RTOFS model, date 2012-09-05. Gulf Stream meanders dominate offshore whereas shelf break mixing creates the most spatial variability on the edge of the continental shelf relative to the inner shelf. In contrast, the deep ocean to the southeast has minor spatial variability, at least according to the RTOFS model.

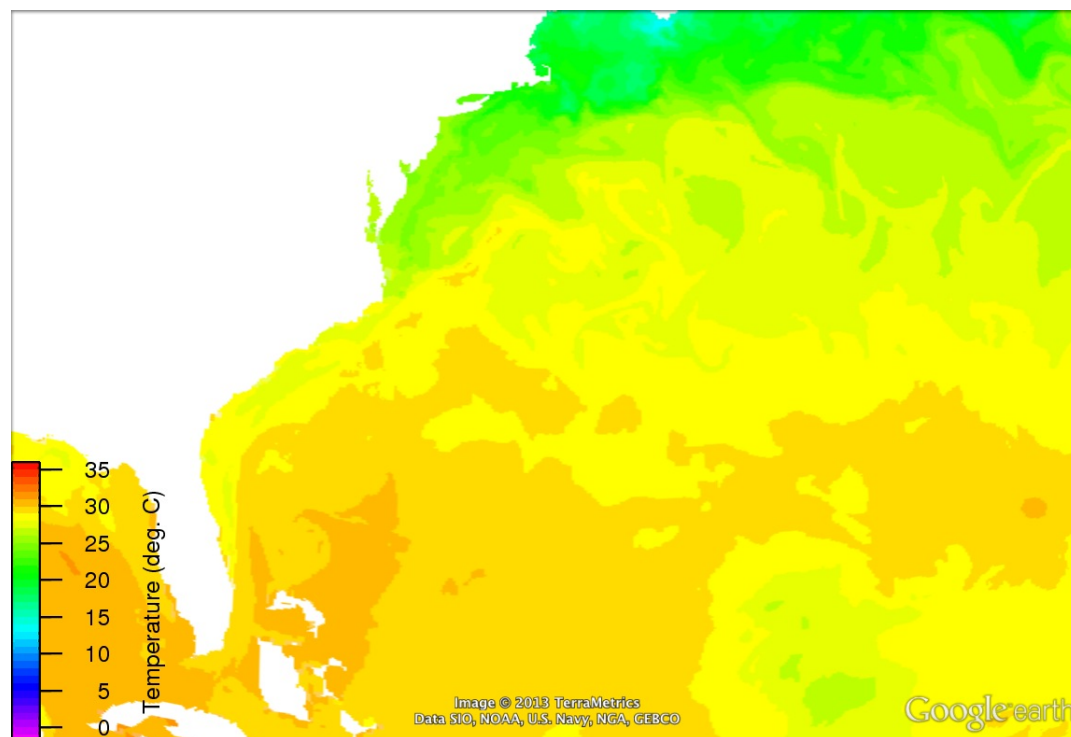


Figure 8. Sea surface temperature from RTOFS model, date 2012-09-05.

Visualization

The Weather Map color scale in Fig. 7 is logarithmic and is useful in portraying global effects where the dynamic range of the uncertainty estimates can be quite large when considering all possible scenarios. A direct comparison of a linear and logarithmic color scale is shown in Fig. 9.

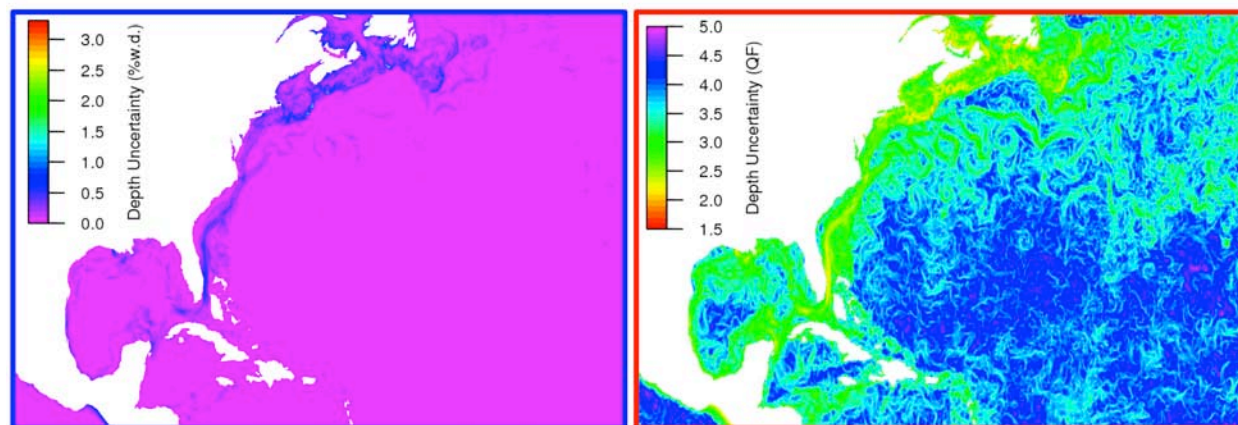


Figure 9. Linear vs. logarithmic representation of depth uncertainty (left and right, respectively). A worldwide analysis gives maximum depth uncertainties of $\sim 3.5\%$ w.d., however, these locations are in the minority, thus a linear color scale that spans the range 0-3.5% w.d. does not allow for an appreciation of all the information that the analysis could be providing as the majority of the analysis output is below 0.5% w.d. Expressing the depth uncertainty logarithmically enhances the detail in the Weather Map analysis. In this particular example, the variability due to mixing at the continental shelf break dominates the linear image whereas the meanders of the Gulf Stream are barely discernible, being roughly an order of magnitude weaker. The logarithmic representation enhances both types of variability.

For a logarithmic representation of uncertainty, the method used by Lurton (Lurton and Augustin, 2010; Lurton et al., 2010) is followed and the bathymetric depth uncertainty due to localized oceanographic effects is characterized using a Quality Factor (QF):

$$QF = -\log_{10}(\Delta_d/d)$$

Where:

- Δ_d is the depth discrepancy determined through the ray tracing analysis (Fig. 5)
- d is the depth

The QF allows for an order of magnitude assessment of the depth uncertainty with higher values indicating a smaller oceanographic impact on depth uncertainty, e.g.

- 10% w.d. uncertainty has a QF of 1
- 1% w.d. uncertainty has a QF of 2
- 0.1% w.d. uncertainty has a QF of 3

This representation is the opposite of what is typically encountered when dealing with uncertainty where larger numerical values are associated with larger uncertainty. With the QF, favorable oceanographic conditions can be considered to be “high quality” water in which to work, this corresponds to the higher QF. Conversely, difficult conditions are considered “low quality” and they have a lower QF.

For reference, Table 1 shows the QF associated with IHO depth uncertainty specifications for common survey orders of accuracy (IHO, 2008).

Table 1. QFs associated with IHO Survey Order Depth Uncertainties.

IHO Survey Order	Allowable Depth Uncertainty (%w.d.)	Allowable Depth Uncertainty (QF)
Special Order	0.75%	2.12
Order 1	1.3%	1.88
Order 2	2.3%	1.64

Spatial Resolution

To explore the limitations of various oceanographic data products, a series of Weather Maps (Figs. 10-12) were produced for the Gulf of Mexico for the following oceanographic models:

- 2009 WOA, 1° resolution, monthly mean temperature/salinity
- 2001 WOA, 1/4° resolution, monthly mean temperature/salinity
- 2013 RTOFS, 1/12° resolution, daily nowcast temperature/salinity

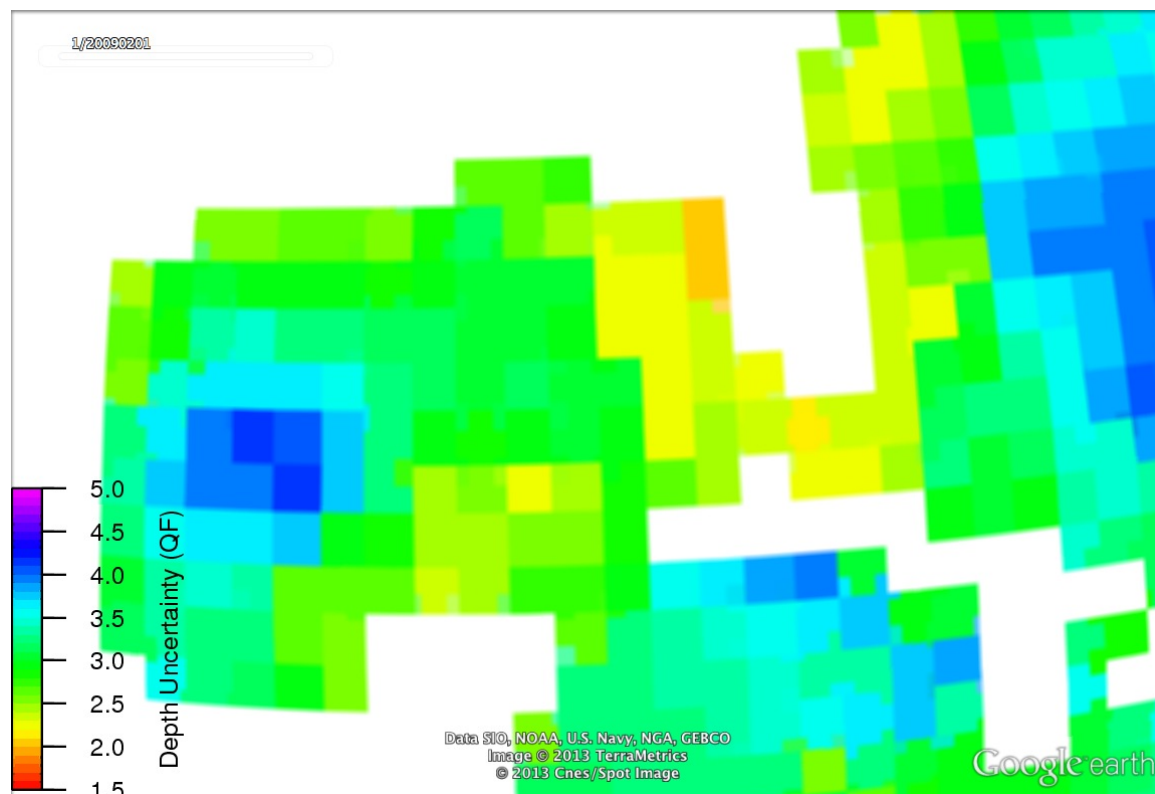


Figure 10. SVP Weather Map derived from WOA2009 1° model for February. Spatial resolution is 60NM.

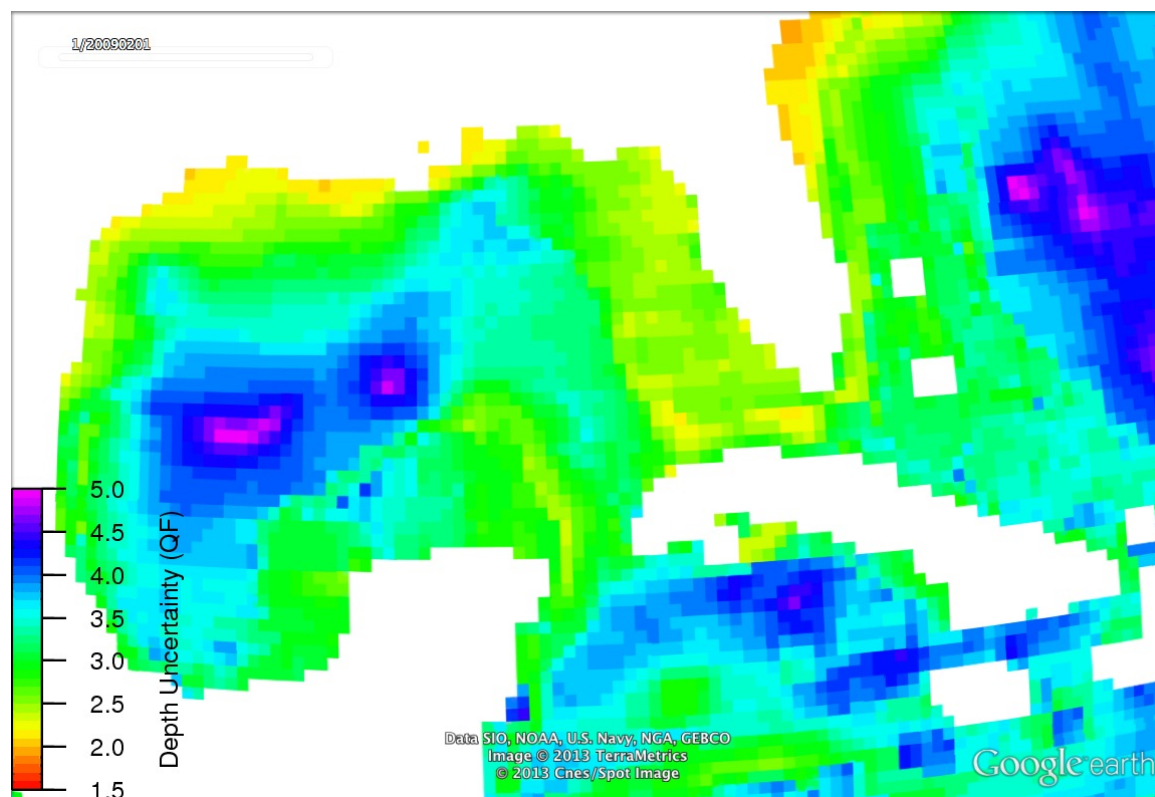


Figure 11. SVP Weather Map derived from WOA2001 1/4° model for February. Spatial resolution is 15NM.

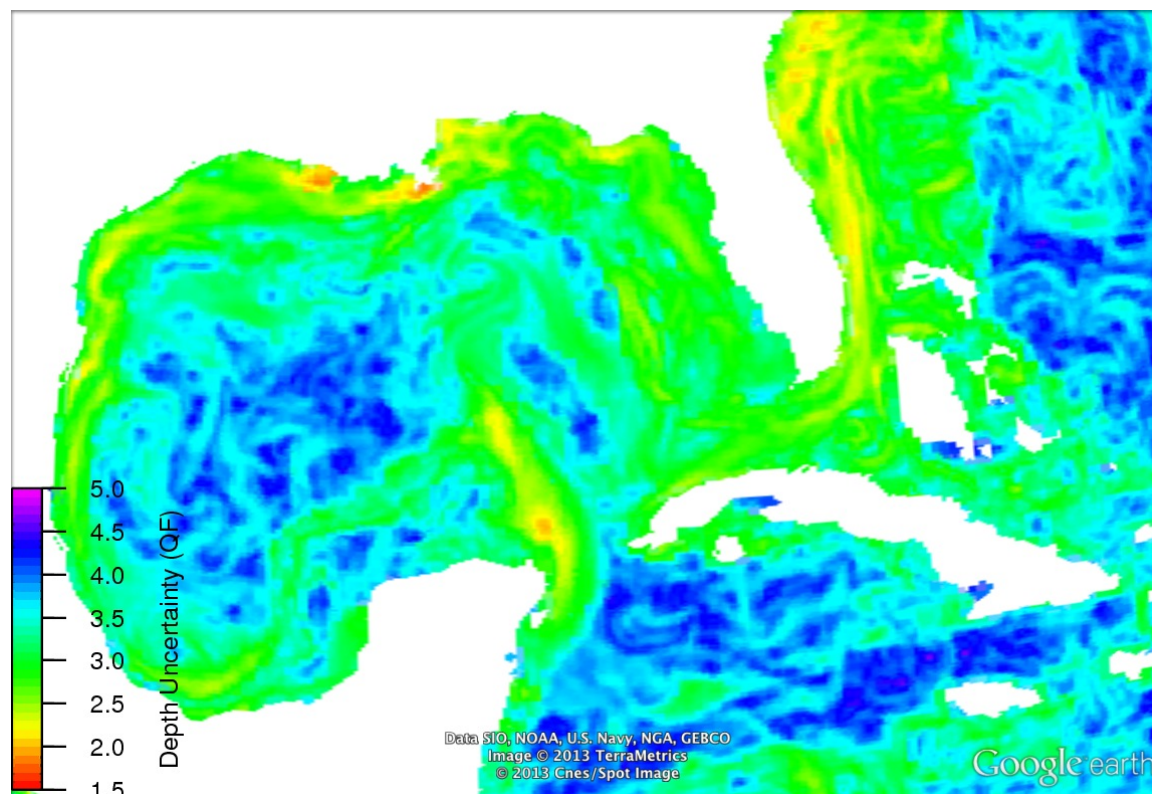


Figure 12. SVP Weather Map derived from RTOFS 1/12° model for February 18th, 2013. Spatial resolution is 5NM.

Though the exact same analysis parameters are applied for figs. 10-12, the three resulting maps provide different information for several reasons. Firstly, all three are derived from atlases or forecast systems with inherently different resolutions. Secondly, the WOA products are heavily smoothed in order to reduce aliasing and interpolation errors due to the sparse and irregular temporal and spatial distribution of input data in the WOD, with smoothing applied on the order of hundreds of kilometers such that the resolvable spatial wavelengths of oceanographic phenomena are larger than the grid cell resolution (Boyer et al., 2009; Antonov et al, 2010). Finally, the spatial extent over which the node-by-node analysis is done differs between the three maps:

- 2009 WOA, 1° resolution: 120 NM x 108 NM
- 2001 WOA, 1/4° resolution: 30 NM x 27 NM
- 2013 RTOFS, 1/12° resolution: 10 NM x 9 NM

Nonetheless, the three maps provide similar information, albeit at different scales and resolutions. For example, the western central deep part of the Gulf of Mexico and the deep ocean east of Florida both exhibit little spatial variability and high variability areas are seen on the inshore side of the Gulf Stream off the coast of Florida and Georgia in all three scenarios. The continental shelf on Florida's gulf coast also exhibits high variability in all three cases.

It is important to point out again that the ray trace analysis halts at the shallowest common depth in a particular ensemble of sound speed profiles being analyzed. In the case of the 1° WOA, this can lead to situations, for example, where a very shallow profile on the continental shelf is compared to the upper portion of a very deep profile 120 NM offshore. This is not a particularly

meaningful comparison, especially when one considers the scale at which hydrographic surveys are planned and conducted. For this reason, the coarse WOA grid is probably only useful when examined at global scales. The same problem can occur in the 1/4° WOA and RTOFS products, although at smaller scales. It is possible that the profile depth mismatch could be contaminating uncertainty estimates in areas of where the depth varies over the spatial extent of the examination, this being an aspect that remains to be clarified in this research.

Potential Applications

The ray tracing analysis method is applicable for models of any resolution, however, it is useful to investigate what types of information can be derived from each. A series of potential use case scenarios are explored below for global and regional models and forecast systems.

Global: RTOFS and WOA

With modeling forecast systems, such as RTOFS, it is possible to compute forecasts with higher spatial resolution and with, hopefully, increased fidelity over products generated from analyses using static models such as WOA that provide only historic annual, seasonal and monthly means and thus have no nowcasting or forecasting capability. That is not to say that climatologies such as WOA are not useful. They can provide useful guiding information on larger spatial and temporal scales.

A Weather Map showing the full global extent of the RTOFS model is shown in Fig. 13 for 2012-09-05. The same type of map is shown for the 1° WOA in Fig. 14. Several high variability features are immediately apparent in both, although with different resolving capability: the Gulf Stream off the east coast of North America; the Kuroshio Current off the east coast of Japan; the front that marks the northern edge of the Antarctic Circumpolar Current; the Agulhas Current off the southern tip of Africa; and the fronts where Arctic waters meet with more southerly water masses in the Bering Sea and in the Norwegian and Greenland Seas. Most continental shelves also exhibit high spatial variability relative to the open ocean with some having pronounced shelf break fronts, most notably on the seaward side of Georges Bank, the Scotian Bank and the Grand Banks (refer to Fig. 9 for a higher resolution image of this).

Higher variability is evident around mid-ocean ridges and island chains for two reasons: (1) bathymetric features can cause mixing at depth and can destroy deep stratification, e.g. dulling the base of a thermocline, and (2) even if the bathymetric features do not reach up into the oceanographic structure, the ray tracing analysis output is divided by the water depth thus the same depth discrepancy may result over a ridge as over the adjacent abyssal plains, however, the deeper water depths away from the ridges attenuate the depth variability signal.

Maps like those in figs. 13 and 14 are important since they permit, perhaps for the first time, the hydrographer to appreciate where the areas of high water column variability are. Some of these troublesome areas were previously known via local or “tribal” knowledge but now this knowledge is available to all via objective and quantitative methods.

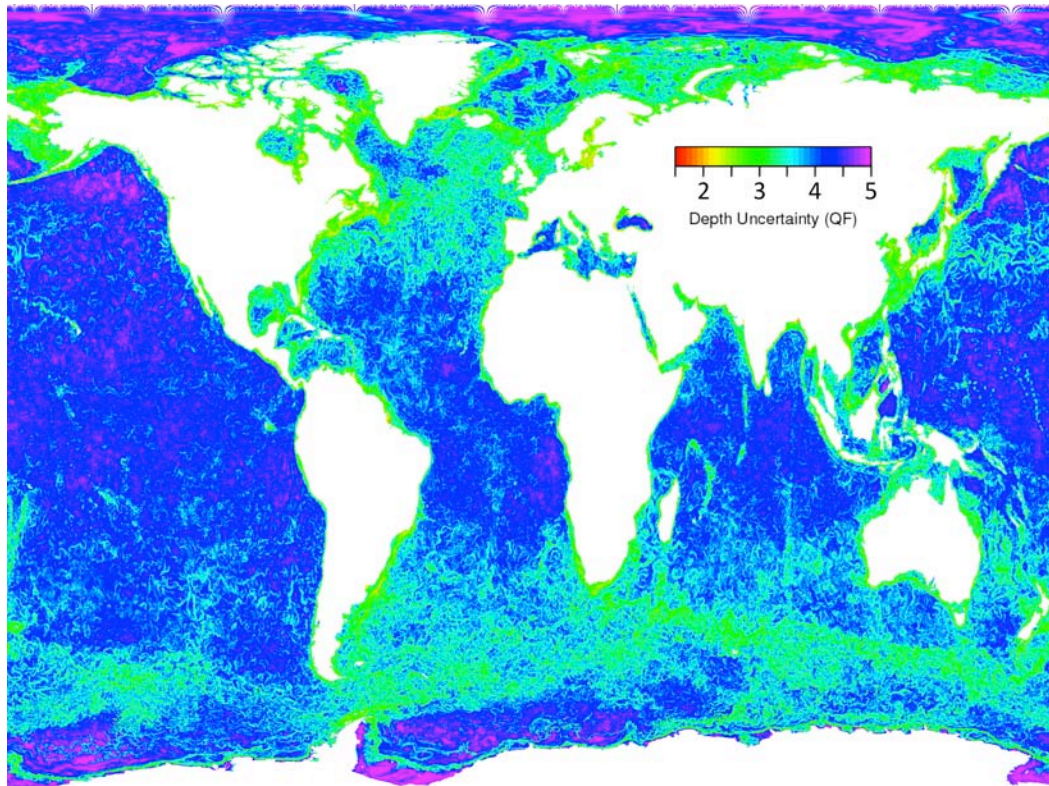


Figure 13. Global Weather Map derived from RTOFS for 2012-09-05.

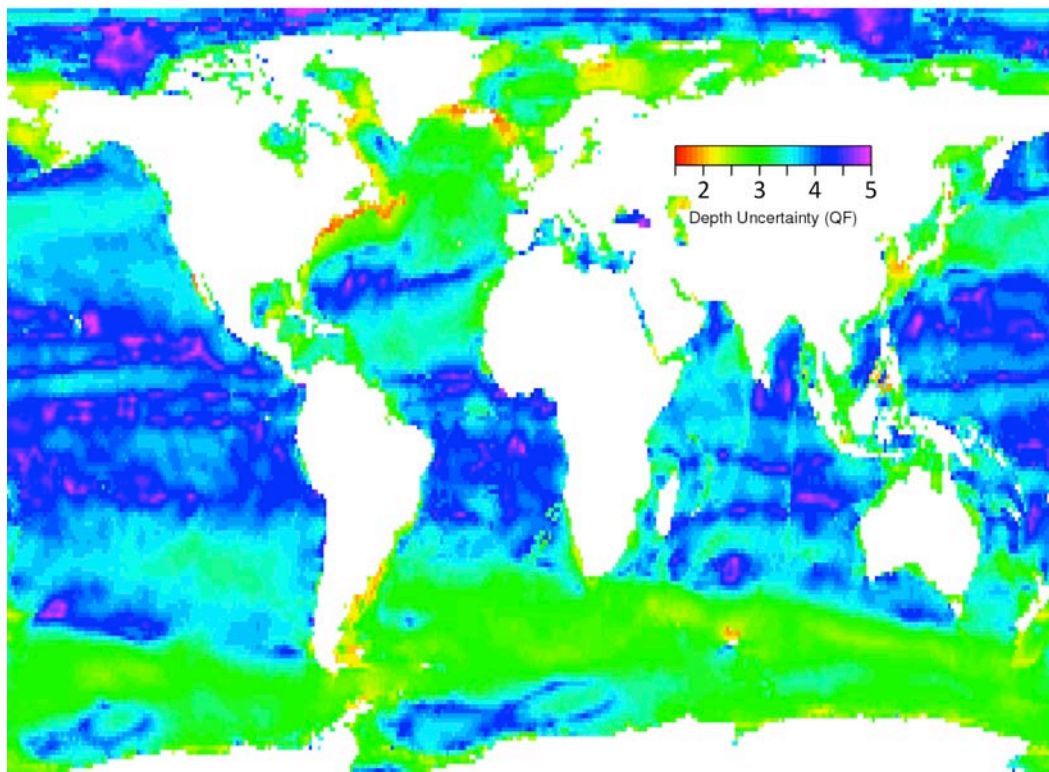


Figure 14. Global Weather Map derived from WOA 2009 1° for month of September.

Seasonal effects can be assessed by examining the monthly $1/4^\circ$ WOA2001 temperature and salinity fields. Weather maps have been produced for the Gulf of Mexico and U.S. Eastern seaboard (Fig. 15). These show seasonal variations in the expected level of echosounding uncertainty due to oceanographic spatial variability in many areas. There are clear seasonal patterns in some areas, e.g. the inner continental shelf just north of Cape Hatteras where there is pronounced spatial variability in the Winter months but less so during the Summer. Others areas exhibit low spatial variability that appears incoherent from month to month, e.g. the deep ocean east of Florida and Georgia.

A map of the dynamic range of QF, based on the monthly examinations of Fig. 15, is shown in Fig. 16; this highlights areas where there is a large variation between the highs and lows of QF throughout the year and helps to isolate areas where a seasonal signal is likely to be present. Using this map to focus on areas with strong seasonal variation, it is then possible to trace back to the months where uncertainty was at a minimum and maximum in an effort to deduce the best and worst times of year to work in a given area (Fig. 17). For the most part, the continental shelf exhibits the strongest seasonal signal and appears favorable to surveying efforts in late Summer and early Fall. On the other hand, mid to late Winter presents the worst conditions when near shore water is cooler relative to the warm Gulf Stream waters offshore resulting in a pronounced thermal gradient between the two water masses (Fig. 18). In Summer conditions (Fig. 19), this thermal gradient is lessened as the continental shelf water warms to temperatures similar to the Gulf Stream. One notable exception is on George's Bank in the Gulf of Maine where the opposite is true: Winter months are optimal and Summer months present the most challenging conditions.

Studies of seasonal variation in echosounding uncertainty on large scales like this can help managers of survey fleets to work around the problem of oceanographic variability or to better equip vessels with appropriate sound speed sampling instrumentation and protocols in the event that difficulties cannot be avoided. These preliminary results need to be verified and also investigated with higher resolution models such as RTOFS and CBOFS to better appreciate the finer scale information that is not represented in the coarse WOA grids. Though the coarse atlases indicate optimal seasons for hydrographic surveying, these findings could very well be negated once higher resolution models are examined since the WOA grids depict, after all, the average conditions only.

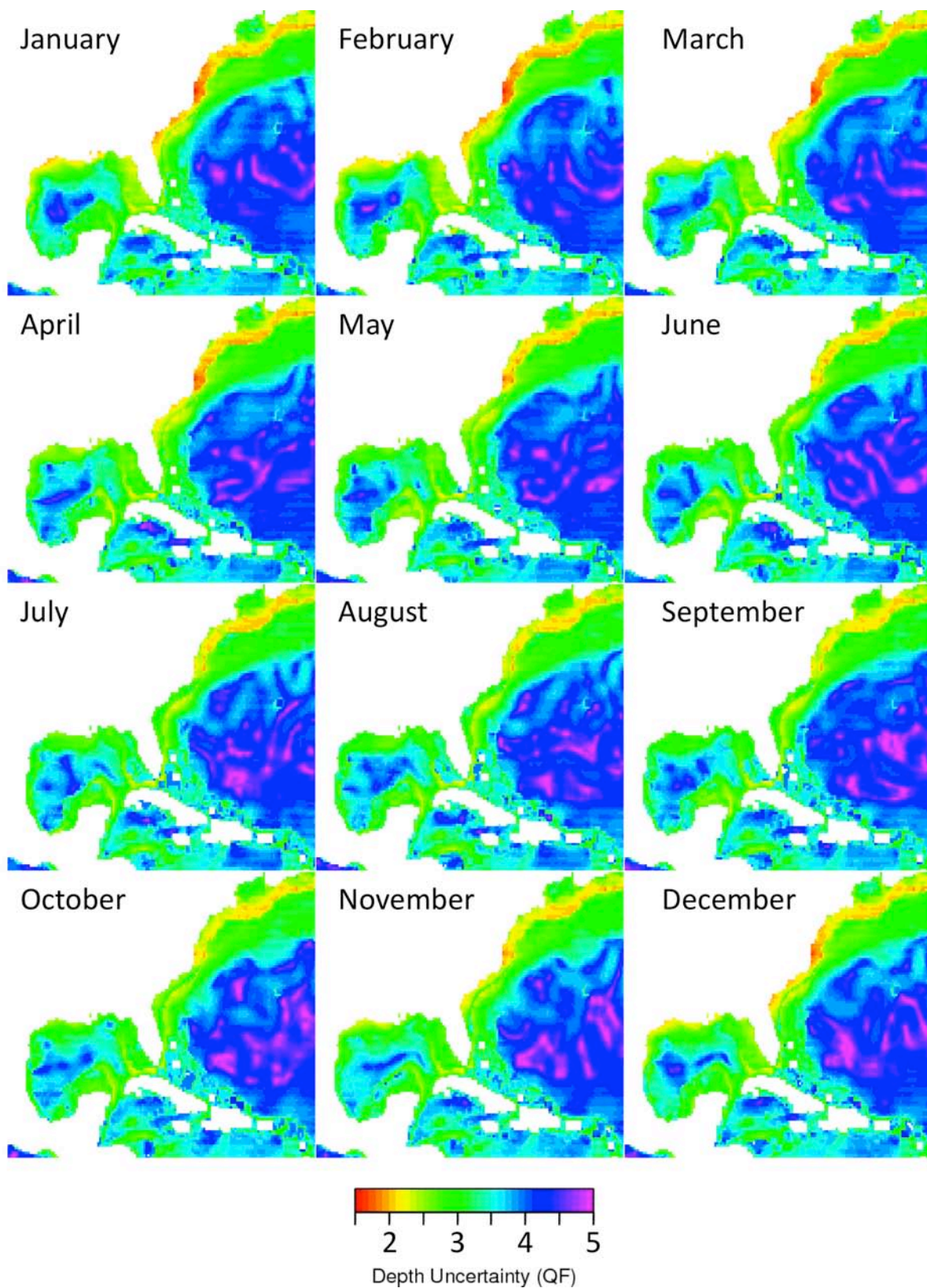


Figure 15. Monthly SVP Weather Maps derived from WOA2001 (1/4°) for Gulf of Mexico and U.S. Eastern seaboard.

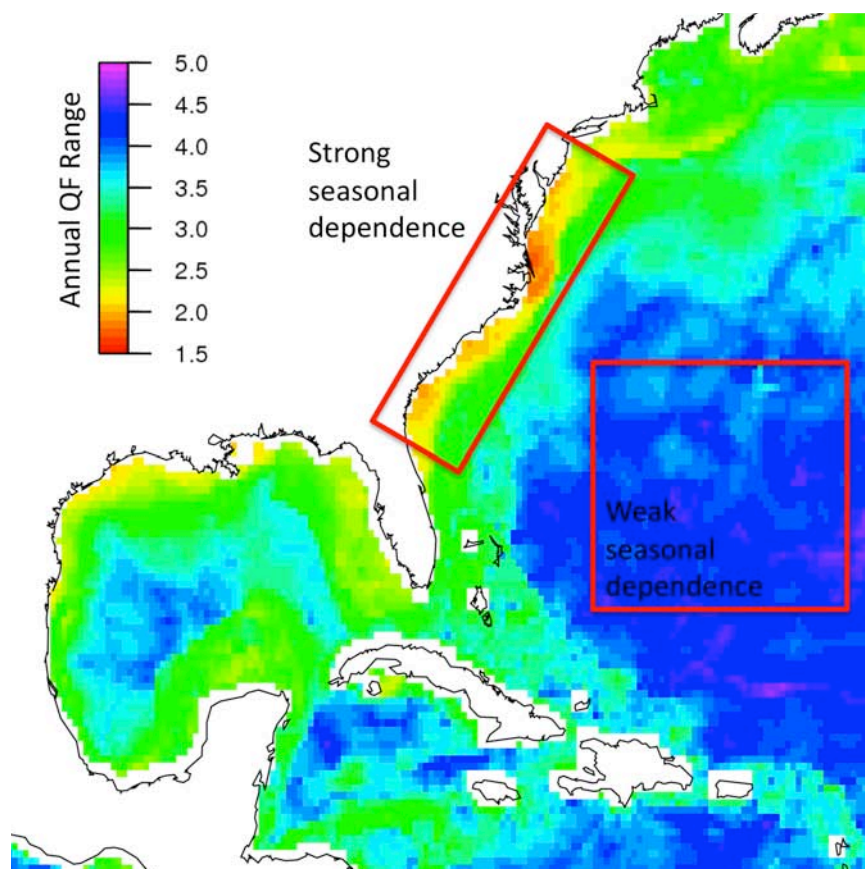


Figure 16. Annual range of QF based on WOA2001 ($1/4^\circ$) ray tracing analysis based on monthly QF analyses (Fig. 15). Areas with strong seasonal effects exhibit a large difference between the highest and lowest QF over the course of the year, e.g. the inner shelf along the eastern seaboard. The WOA predicts weak seasonal dependence in the open ocean.

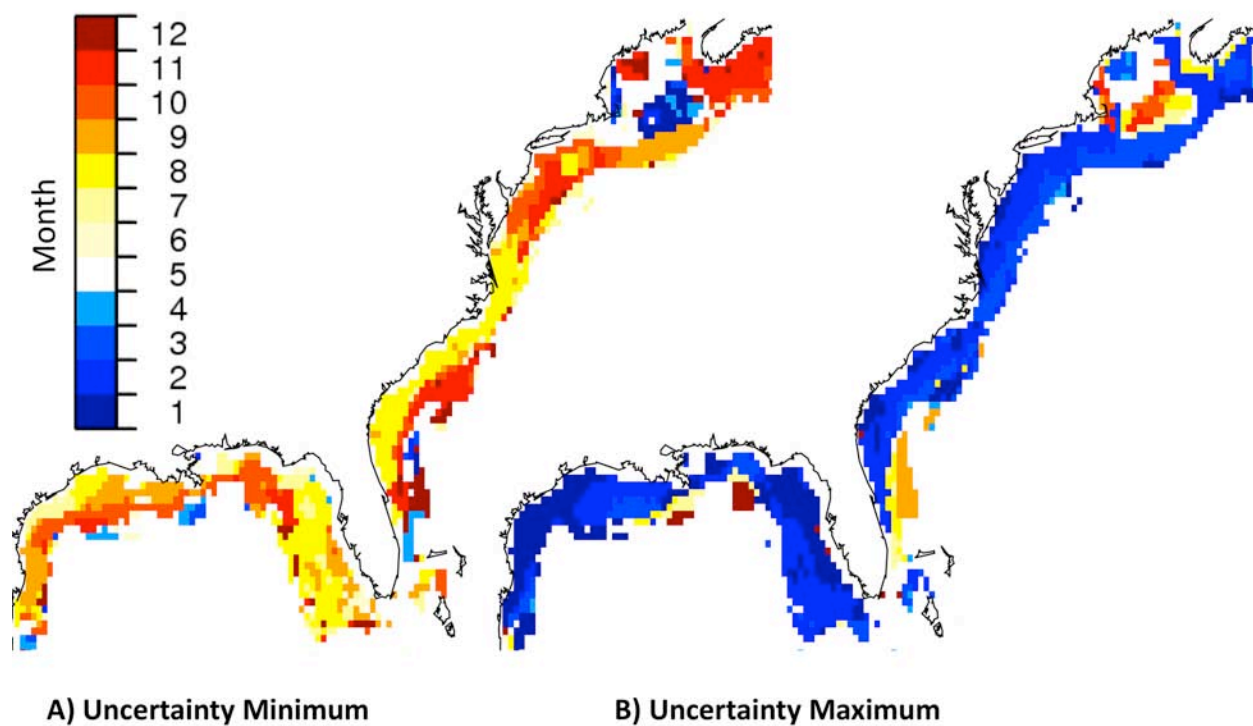


Figure 17. QF minima and maxima by month as indicated by analysis of the WOA2001 1/4° climatology. This analysis is limited to areas whose annual QF range exceeds 3.0 (0.1%w.d.). White areas indicate areas where seasonal range in QF fell above the QF threshold, indicating that there is little seasonal variation in the spatial oceanographic variability over the course of a year.

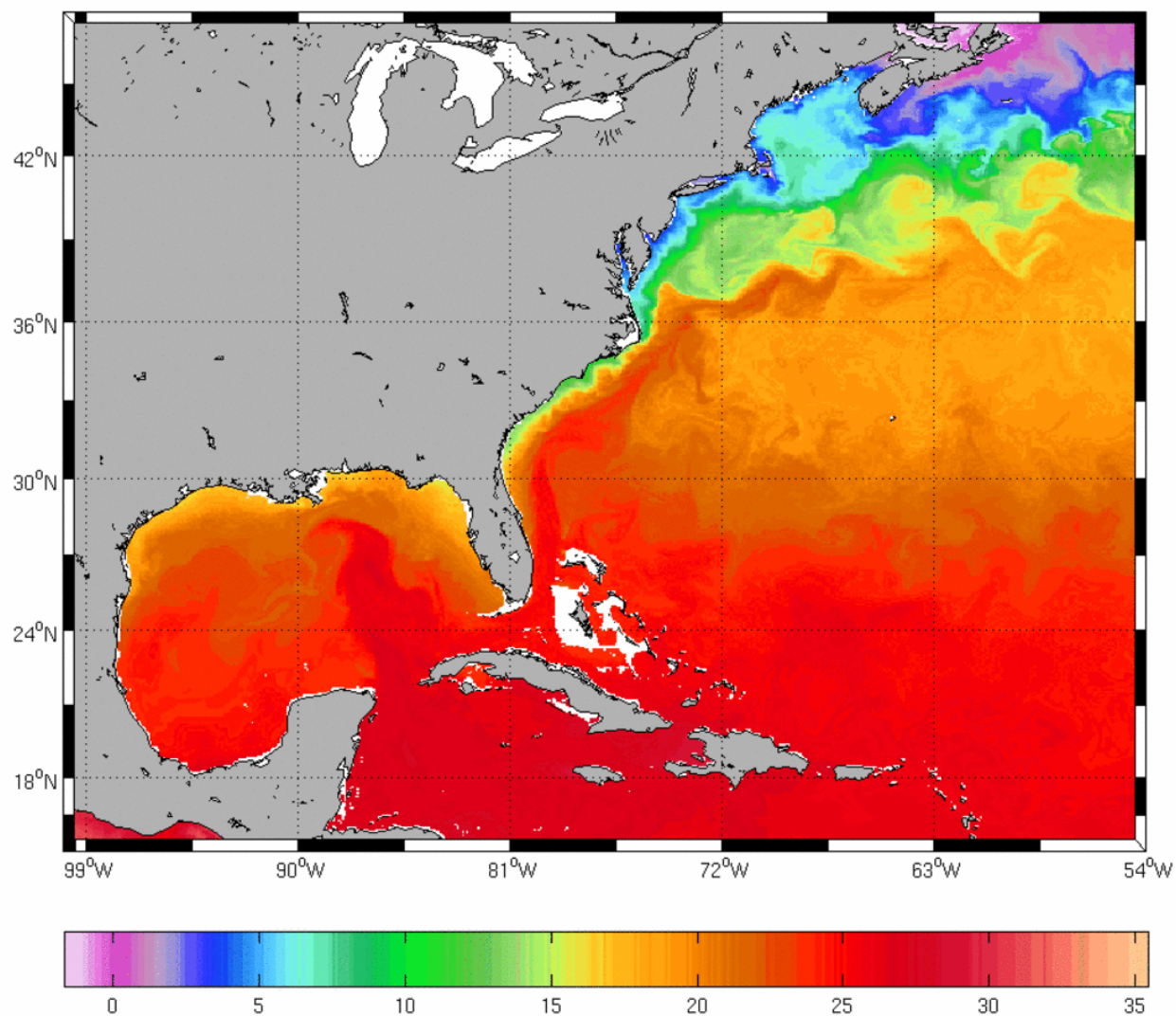


Figure 18. Sea surface temperature in Gulf Stream region from RTOFS model nowcast for 2013-02-24. Note the pronounced surface thermal gradient on the continental shelf north of Cape Hatteras and the formation of eddies between the warm and cold water masses, this being a significant source of spatio-temporal variability. Image from <http://polar.ncep.noaa.gov/global/>.

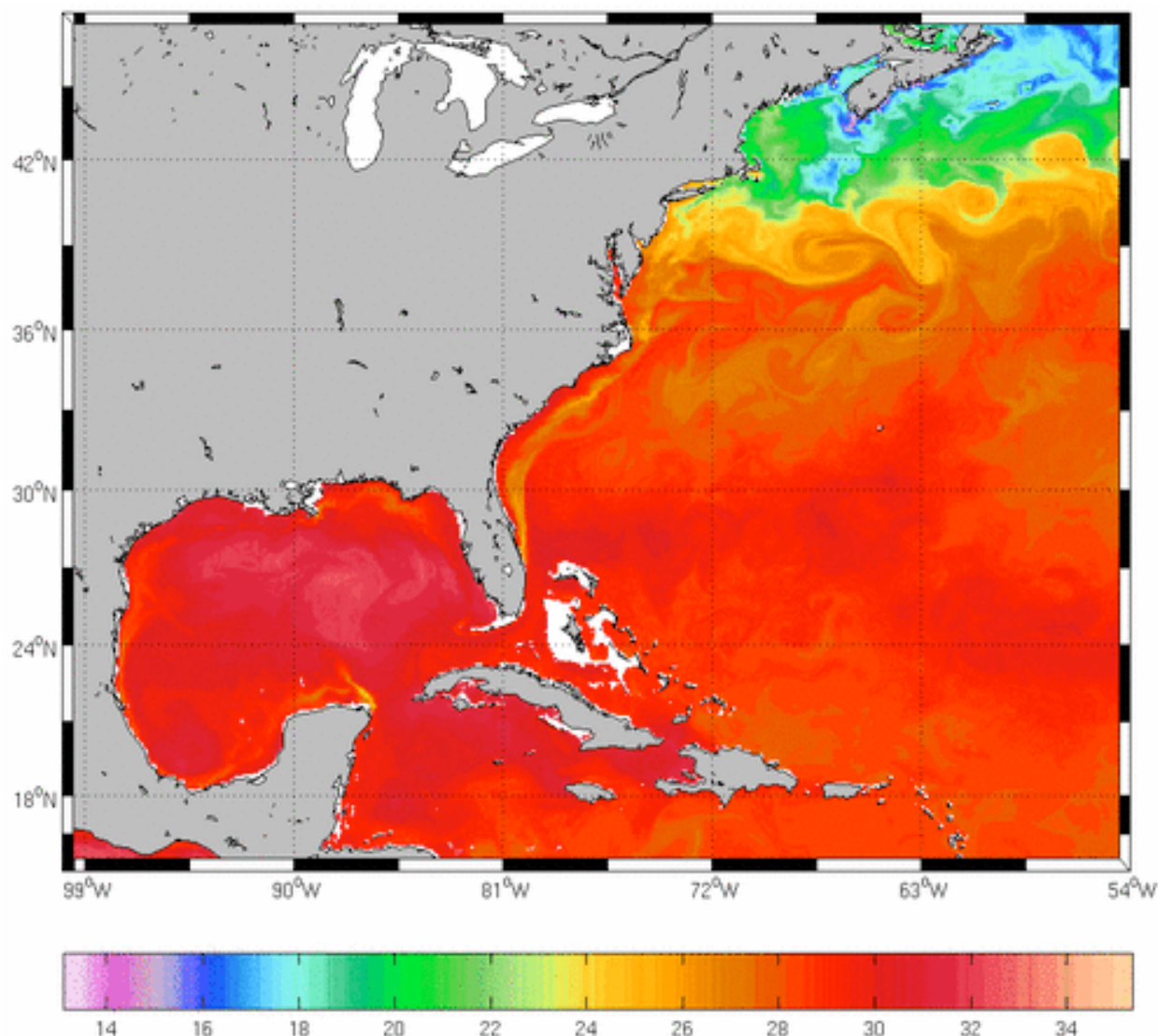


Figure 19. Sea surface temperature in Gulf Stream region from RTOFS model nowcast for 2012-07-30. Note that the strong surface thermal gradient pointed out in Fig. 18 has migrated northward to the New England area. Though eddies still occur in the Cape Hatteras region, the thermal gradient is much less pronounced thus there is less impact from the spatio-temporal variability from a hydrographic surveyor's point of view. Image from <http://polar.ncep.noaa.gov/global/>.

Regional: CBOFS

Weather maps for shallow coastal forecast systems, such as CBOFS, allow for an examination at much higher spatial and temporal resolution. In the example shown in Fig. 20, prepared from the 2013-02-19 CBOFS nowcast, spatial variability is more pronounced at the mouth of the Chesapeake Bay relative to the offshore region and there are many sections with high variability throughout the estuary. These patterns of spatial variability vary as tidal currents advect the water in the estuary over the tidal cycle, as highlighted by the red box of Fig. 20 where the QF varies significantly along the outflow of the James River over a 6-hour period, for example. The severity of spatial variability in particular region is likely to vary seasonally with changes in river water and ocean water temperatures though this can only be confirmed with long-term

examination of model runs. Ray trace based forecast analyses such as these Weather Maps can allow for hydrographic surveyors to choose the timing of their work around the tidal cycle, this often being the predominant driving force of spatio-temporal variation in estuaries and coastal areas.

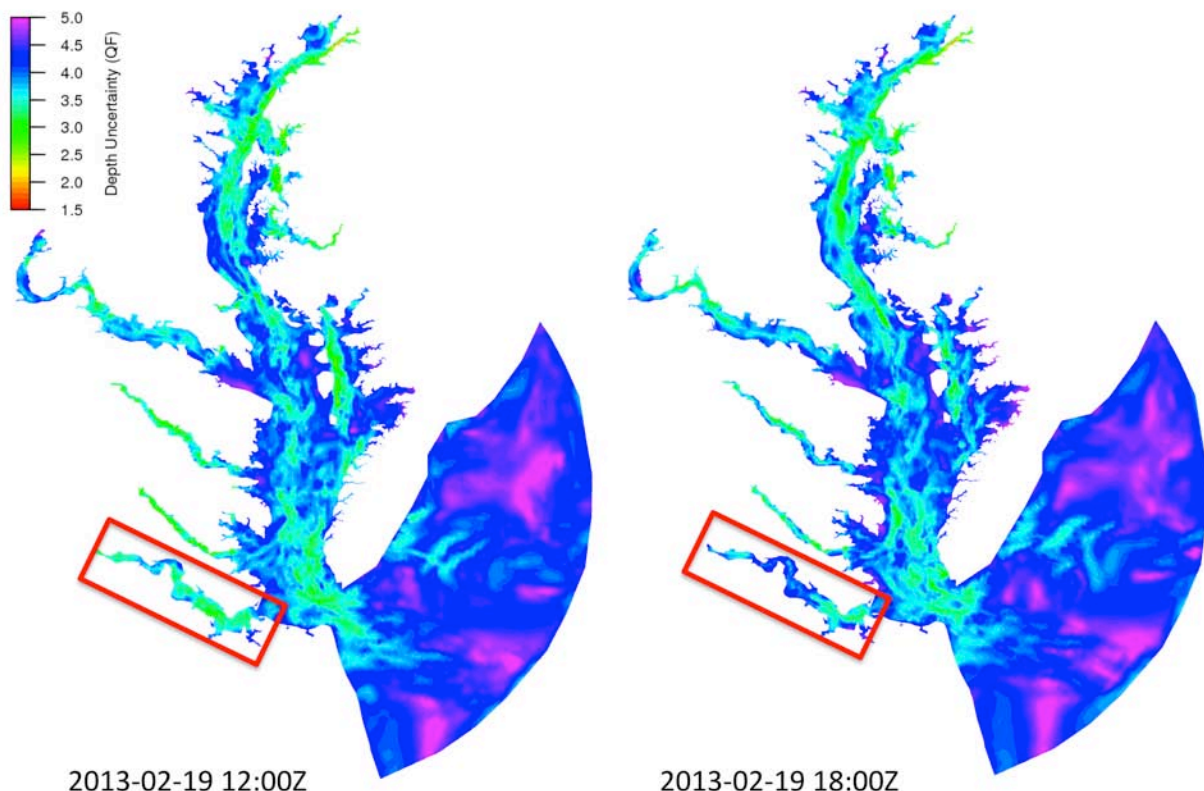


Figure 20. Regional Weather Map for Chesapeake Bay based on CBOFS, 2013-02-19 for 12:00 UTC and 18:00 UTC. Note variation in QF over 6 hour period in outflow of the James River into the Bay (red box).

Future Work

It is relatively straightforward to produce SVP Weather Maps but it is important to understand their limitations. The use case scenarios explored above show much promise but several research questions remain.

Firstly, there are known interpolation errors and biases in the WOA products in areas with sparse information. For example, the fidelity of WOA climatologies, particularly in Winter, is known to be low since the lack of observations biases the interpolation towards warmer Summer conditions (Steele et al., 2001). This has been observed in previous work with the WOA in the Canadian Arctic Archipelago (Beaudoin et al., 2006). The WOA climatologies cannot be used blindly and some work must be done to validate the temperature and salinity fields in areas with few observations. Forecast systems are likely to suffer from their own biases and uncertainties that are specific to forecast systems. In both cases, the impact of these biases needs to be assessed to ascertain whether or not they are limiting for the purpose that has been outlined in

this paper. Methods to test the fitness of purpose have been used with climatologies before, e.g. Beaudoin et al. (2006), however new methods may be needed to appreciate how climatology and forecast system errors affect the estimation of uncertainty front magnitude and positioning.

The ray tracing analysis approach only characterizes the localized echosounding uncertainty due to spatial variability at the resolution of the underlying oceanographic grid. They indicate the difference, in terms of ray tracing solution, of the water where you are versus the water at some distance away. The Weather Maps do not indicate the severity of the refraction in the first place, e.g. they do not distinguish between working in a well-mixed water mass in Winter versus working in a highly stratified environment in Summer and further work must be done to qualify and refine these types of maps. Additional layers of information, such as the refraction severity or degree of stratification, could help present the information in a more meaningful manner and could be used to qualify the spatial uncertainty front map that the ray tracing analysis provides.

The models also do not capture spatio-temporal variability at the finest of spatial and temporal scales and thus are always underestimating the potential sounding uncertainty to some extent. Field campaigns with high-resolution spatial measurements taken with underway profilers may allow for an initial assessment of the potential magnitude of this missing portion of the uncertainty forecast. Data collected by NOAA Ship *Fairweather* and NOAA Ship *Ferdinand R. Hassler* in the 2012 field season is being used to further this type of validation work.

Conclusion

In all the use case examples described above, it is an interesting exercise to identify sources of high variability and to trace back to the root oceanographic causes, however, one of the main advantages of the ray trace analysis based Weather Map is that the end user does not need to understand the oceanography in order to be able to plan water column sampling operations. The Weather Map identifies trouble spot areas that require additional resources, either time (due to reduced survey line spacing) or money (more sophisticated underway sampling equipment).

If deemed fit for the purpose, and if appropriate confidence levels can be assigned to uncertainty forecasts, oceanographic atlases and forecast systems could allow survey planners to

- Appreciate oceanographic difficulties before hand
- Anticipate sound speed related uncertainty and incorporate into timing of survey work
- Design an appropriate sampling strategy and choose appropriate equipment
- Monitor the effectiveness of the strategy in the field and react accordingly

Acknowledgments

This work was supported by NOAA under grants NA05NOS4001153 and NA10NOS4000073.

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