Assimilating Inferred Velocity Observations from Float Positions to Improve an Ocean Model's Prediction Skill

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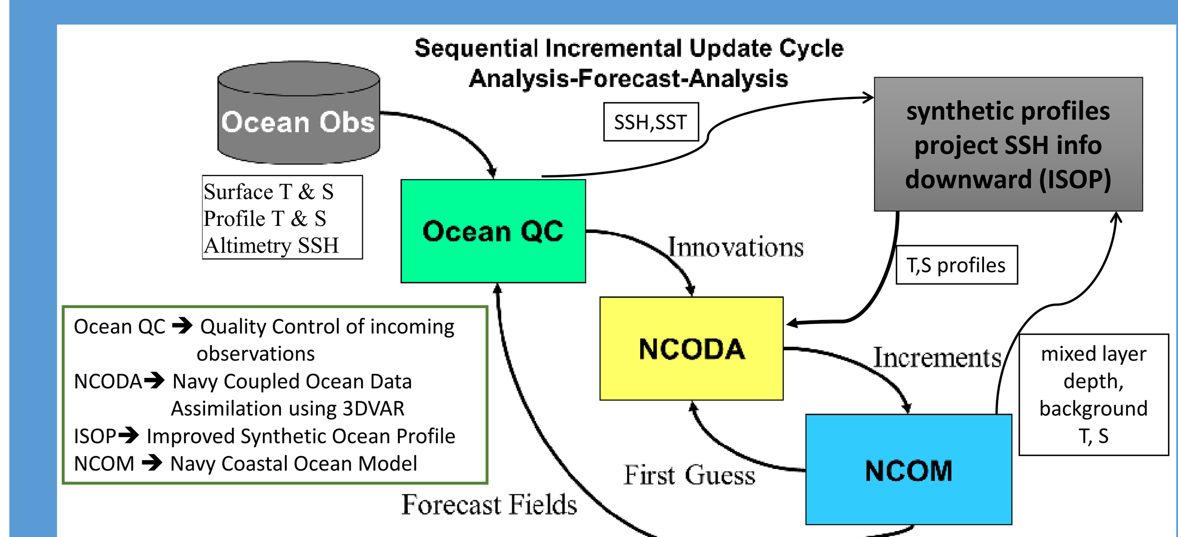
Abstract

The Navy Coupled Ocean 3D Variational Data Assimilation (NCODA-VAR) system is one of the primary tools that the Navy uses operationally to ingest, process, quality and control, and assimilate ocean observations in near-real time in order to regularly update and improve the forecast skill of several different operational ocean prediction systems. One of the primary deficiencies of NCODA, however, is its inability to properly assimilate velocity observations. It lacks the mechanism to correlate velocities with temperature and salinity, which the analysis needs in order to be dynamically stable. A covariance database has been constructed using historical ocean observations, and implemented within NCODA in order to cross-correlate velocity observation with temperature and salinity throughout the water column in order to produce dynamically consistent analyses.

Using this updated version of NCODA, velocity observations can be inferred from consecutive float positions at the cruising depth of the float, and then assimilated to better constrain the positions of ocean-fronts and eddies. Experiments were performed in the RIMPAC region surrounding the Hawaiian Islands where a number of float observations are available.

The Ocean Analysis and Prediction System



The Navy Coupled Ocean Data Assimilation System (NCODA):
NCODA uses 3DVAR to assimilate observations of temperature (T) and salinity (S) with a previous forecast from the Navy Coastal Ocean Model (NCOM) to create an analysis to be used as the initial conditions for the next forecast. Up to now, NCODA has only been able to assimilate T and S observations, because, there were no mechanisms to correlate velocity observations with T and S observations. NCODA does use sea surface height (SSH) observations from altimetry, but they are converted to synthetic profiles of T and S using ISOP (discussed in the next section). NCODA's 3DVAR equation is as follows:

$$\delta\mathbf{x} = \mathbf{VCH}^T\left(\mathbf{HCH}^T + \mathbf{P}^{-1}\mathbf{RP}^{-1}\right)^{-1}\mathbf{P}^{-1}\mathbf{d}$$

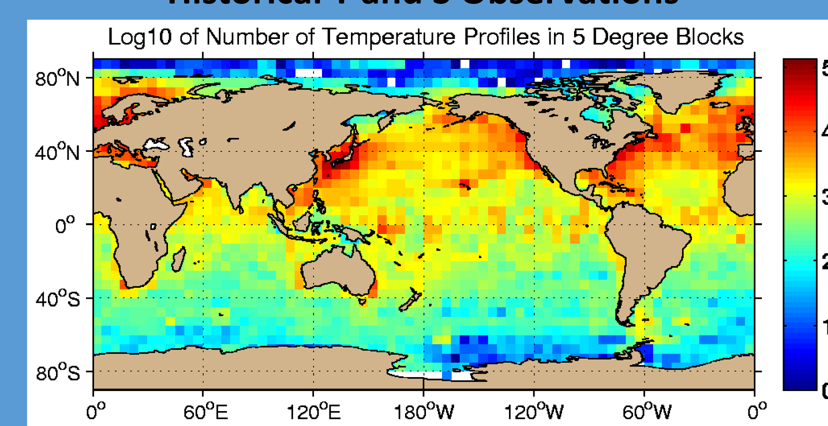
$\delta\mathbf{x} = x_a - x_b$ = Analysis increments (*n x 1*); the difference between the new analysis and the previous forecast (background).
V = Square root of the diagonal elements of the background error covariance (*n x n, diagonal*).
C = Correlation matrix (*n x n*).
H = Interpolator from observation space to grid space (*k x n*).
P = **HVH**^{T} = projection of **V** on to the observation-space (*k x k, diagonal*).
R = Observation error variance matrix (*k x k, diagonal*).
d = $\mathbf{y} - \mathbf{Hx_b}$ = Innovations (*k x 1*); the difference between the observations and the interpolated previous forecast.
k = number of observations
n = number of grid points

The calculation of the correlation matrix (**C**) within NCODA is split into a horizontal and a vertical component. There are several available options within NCODA to compute these correlations; in most applications, the second order autoregressive (SOAR) model is used to compute horizontal correlations, and the vertical correlations can now be computed using the ISOP database. ISOP provides the capability for NCODA to compute cross-correlations between the different variable types: T, S, geopotential, and velocity, therefore producing dynamically consistent analyses regardless of what observation types are assimilated. In addition to being able to assimilate velocities, NCODA is also able to now directly assimilate SSH observations without having to compute synthetic T and S profiles.

Vertical Covariances from the Improved Synthetic Ocean Profile (ISOP) Database

- There are millions of historical T and S profiles throughout the globe in the ISOP database. ISOP is constructed into a global, monthly-binned, 3D, gridded product at 0.5° horizontal resolution.
- An EOF decomposition was performed on the historical T and S data in each ISOP bin. The first 6 modes of this decomposition were saved.

Historical T and S Observations



$$B = \underbrace{U}_{\text{Standard deviation}}\overbrace{C}^{\text{correlation}}U^T = U\underbrace{\Gamma\Lambda\Gamma^T}_{\text{EOF decomposition}}U^T$$

covariance

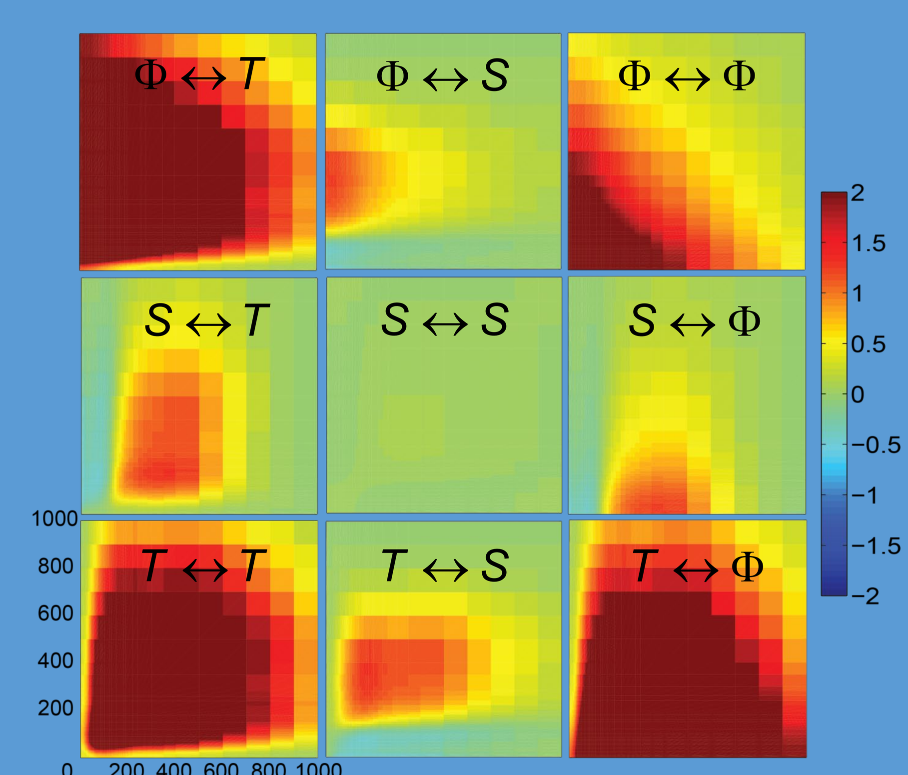
$\Gamma \rightarrow$ eigenvectors, $\Lambda \rightarrow$ eigenvalues

- The covariance information for T and S was then extended to include geopotential using the equation of state.

$$B = \langle \acute{Y}\acute{Y}^T\rangle = \begin{bmatrix} \acute{X}\acute{X}^T & \acute{X}\acute{X}^T\alpha^T G^T \\ G^T\alpha^T\acute{X}^T\acute{X} & \alpha\acute{G}X\acute{X}^T G^T\alpha^T \end{bmatrix}$$

$$X' = \begin{bmatrix} T_1 - \bar{T}_1 \\ \vdots \\ T_N - \bar{T}_N \\ S_1 - \bar{S}_1 \\ \vdots \\ S_N - \bar{S}_N \end{bmatrix} \qquad Y' = \begin{bmatrix} T_1 - \bar{T}_1 \\ \vdots \\ T_N - \bar{T}_N \\ S_1 - \bar{S}_1 \\ \vdots \\ S_N - \bar{S}_N \\ \Phi_1 - \bar{\Phi}_1 \\ \vdots \\ \Phi_N - \bar{\Phi}_N \end{bmatrix}$$

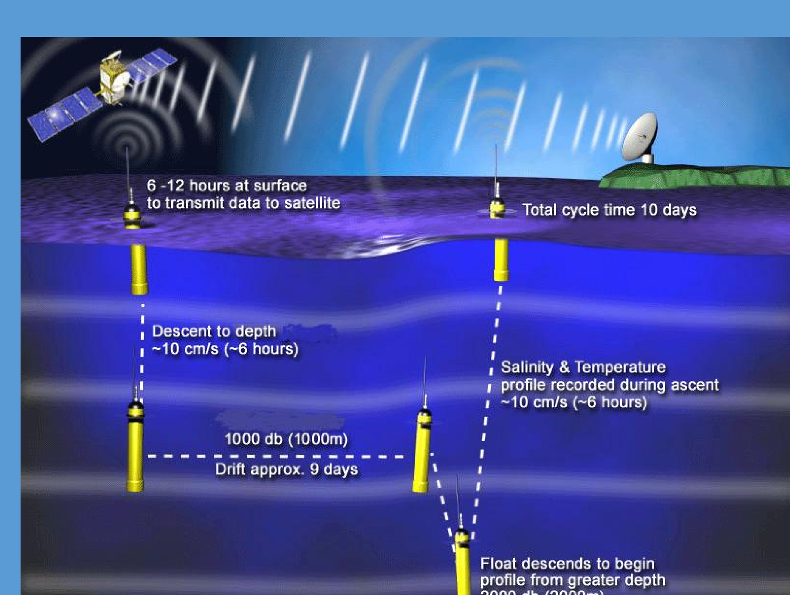
G is an integral over pressure of specific volume anomaly
α is a linearization of specific volume anomaly (linearized around mean state)



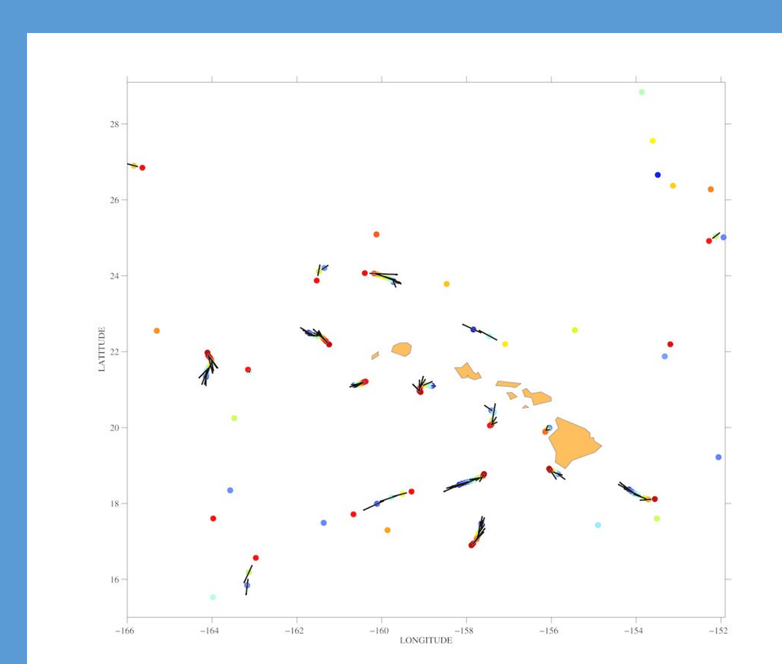
The following plot is an example of the resulting multivariate vertical covariances between temperature, salinity, and geopotential over the upper 1000 m at a random location during the month of January.

Methodology for Assimilating Velocity observations from floats

In addition to being able to provide profiles of T and S observations periodically when the float ascends from its drifting depth, an Eularian velocity observation can be inferred. This is done by calculating the distance between two consecutive surfacing's and dividing by the time between them. This method makes a number of assumptions, such as: (1) the float is drifting in the same direction the whole time it is underwater and (2) the ascending and descending of the float is ignored.



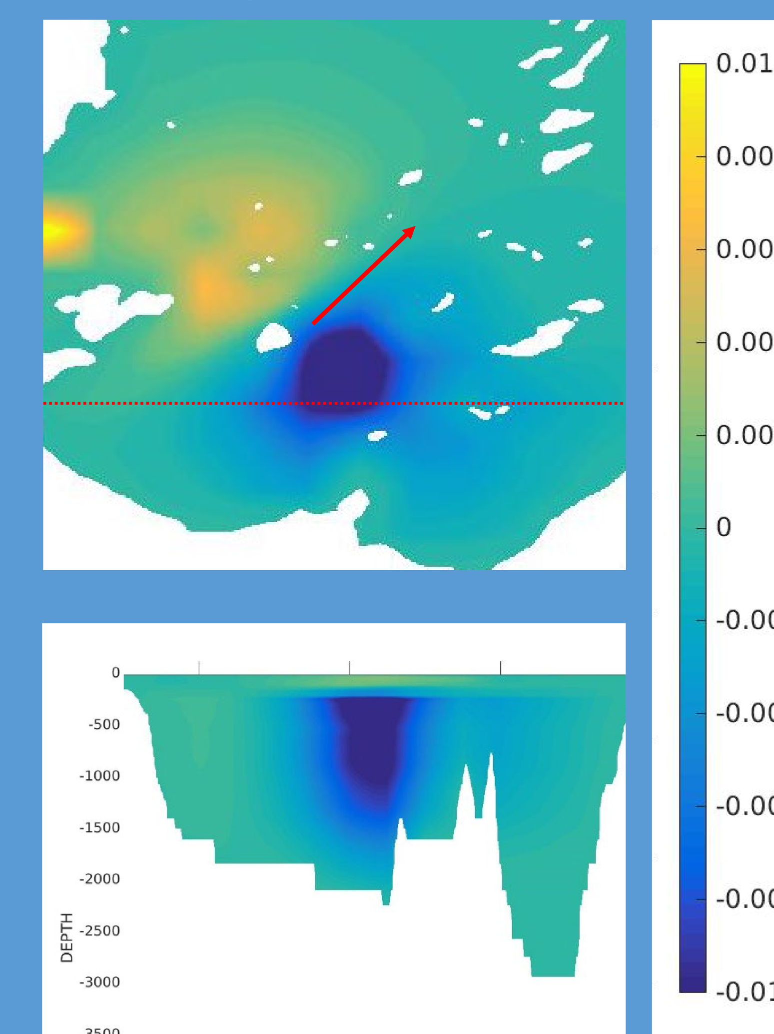
An algorithm has been added to NCODA to estimate the velocities from surfacing floats. Below is an example of the algorithm for a series of floats in the Hawaiian region. In this plot the dots represent multiple surfacing's of the different floats. The dots are color coded to represent time: from red (old) to blue (new). The lines are the calculated velocity vector at each of the surfacing's.



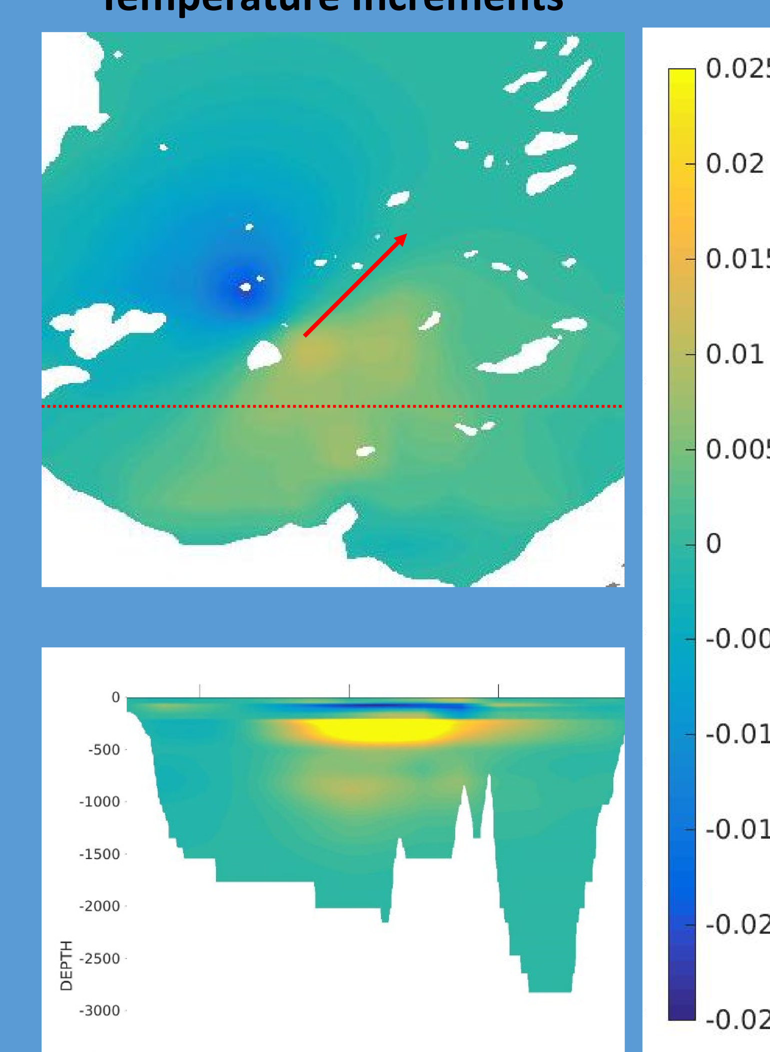
Results

The following is an example of the resulting geopotential and temperature increments (**δx**) resulting from assimilating a pair of velocity observations (a u- and v- component) at ~600m depth. Both innovations are equal to **d** = 0.1 m/s. The red arrow in the plots below represent the assimilated velocity and the dashed red line signifies the location of the vertical slice.

Geopotential Increments



Temperature Increments



Conclusions

There is a lack of ocean observations to begin with. So if it is possible to obtain additional information from already existing platforms, then that would be extremely beneficial. Velocity observations would be a valuable addition to the assimilation system, since they would improve the prediction of frontal positions, eddy shapes, etc…. Velocity assimilation has already been verified to work well within our 4DVAR system. However, we don't have the capability of using 4DVAR for all of our domains, especially are larger, higher resolution ones. In these cases we are restricted to using 3DVAR, and velocity assimilation will help to improve their accuracy.

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