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Lecture Note on Ocean Data Assimilation and Assimilation of Altimetry data

by

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1. Global Ocean Data Assimilation System

Ocean data assimilation is a mathematically rigorous process, which combines the ocean observations and ocean models to take out the important information of the ocean circulation and associated thermocline fields. We know that the ocean observations are sparse and incomplete over the time. The main purposes of ocean assimilation are suitably combine model and observation to monitor the ocean circulation, and predict the ocean circulation at different spatial and temporal scales. The data assimilation approaches vary significantly in term of the assimilation method, observations assimilated, and also in term of forecast error covariance, model biases, observation errors and the quality control procedure for different types of observation. Various ocean data assimilation products were developed during the Global Ocean Data Assimilation Experiment (GODAE, Bell et al., 2009). In these data assimilation products, both model and observation are assumed as erroneous. The models have errors due to deficiencies in the model physics, grid resolution, lateral boundary conditions, and atmospheric forcing while the observations have error due to instrument or representative error. One important impact of the data assimilation is to counter the tendency of ocean models to drift away from reality. A large number of methods for combining model and observational data are described in the literature. These methods are classified in three classes: Variational methods such as 3DVar or 4DVar (Lorenc, 1986) based on the minimization of a coast function that measures the differences between the model and the observations, the various levels of approximation to the extended Kalman filter also called as sequential schemes (Daley, 1991), and ensemble-based schemes such as ensemble Kalman filter (Evensen, 1994). Each of these approaches has its own advantages and disadvantages with respect to the approximations made, complexity and computational cost.

The fundamental equation of variational data assimilation is based on an incremental cost function.

$$J(\delta x) = \frac{1}{2}\delta x^T B^{-1}\delta x + \frac{1}{2}(d - H\delta x)^T R^{-1}(d - H\delta x) \quad \text{..............................} \quad (1)$$

Where, the increment $\delta x = x - x_b$ is the difference between the state vector x and its background estimate x_b, $d = y - H(x_i)$ is the innovation vector. Y is the observation vector and $x_i = M_{t_o \to t_i}(x_b)$. the notation $M_{t_o \to t_i}$ indicates the nonlinear propagation of model from the background state to the state at i^{th} time. **B** and **R** are the model background error covariance and observed error covariance respectively. R is a diagonal matrix with the assumption of uncorrelated observation errors. The operator H is the observation operator while matrix **H** denotes the linearized observation operator.

The Nucleus for European Modelling of the Ocean (NEMO) is a widely used state-of-the-art modelling framework developed by the NEMO European Consortium (Madec and the NEMO team 2008). The model has the different modelling components (Ocean Physics, sea ice, Iceberg, biogeochemistry, and data assimilation) for research studies, operational forecasting, and climate applications. The global NEMO model at ORCA025 tripolar grid has variable grid resolution in latitude with 28 km near the equator reducing to 7 km near the North Pole. It also has 75 vertical levels with more vertical levels near the surface to better resolve shallow mixed layer especially for capturing diurnal variability. The horizontal and tracer diffusion is performed using a biLaplacian operator along geopotential levels and Laplacian along isopycnals, respectively. The horizontal tracer advection scheme is based on total-variation-diminishing (TVD) scheme. Vertical mixing parameterization is parameterized using the turbulent kinetic energy (TKE) scheme (Gaspar et al. 1990) with enhanced vertical diffusion using convection parameterization. The linear free surface and an energy and enstrophy conserving scheme is used. Further, the global seasonal varying climatological river runoff is used. The model's bathymetry is derived from the ETOPO1 & GEBCO data sets. The stand-alone global NEMO model is used to generate 10 days global ocean model.

In NCMRWF, the global NEMO based Variational (NEMOVar) assimilation system is running at ORCA025 configuration with 75 vertical levels (Waters et al., 2014). It is based on the three dimensional variational assimilation with first guess at appropriate time (3DVar FGAT). A key feature of NEMOVar is a set of multivariate linearised balance relations. Further, it assimilates the satellite and in situ observations of SST, in situ observations of temperature and salinity profile, altimeter observation of SLA and satellite observations of sea ice concentration through 24 hour assimilation cycle. The background information is derived from the model which is forced by the surface boundary conditions from the National Centre for Medium Range Weather Forecasting (NCMRWF) Unified Model (NCUM; Sumit Kumar et al., 2018) using the CORE bulk formulae scheme. These forcing fields include longwave radiation, shortwave radiation, precipitation, snowfall rate, 10 m temperature and humidity fields at 3-hr time interval and 10 m wind speed at 1-hr time interval. The observations and model first guess are used as input to NEMOVar for generating ocean increments which is gradually applied to model using 24 hour increment analysis update (IAU) step to create the global ocean analysis (figure 1). This analysis is further used to initialize the stand-alone global

NEMO model to forecast up to 10 days and also used to initialize the ocean component of global atmosphere-ocean model. Table-1 indicates the details of global ocean data assimilation system.

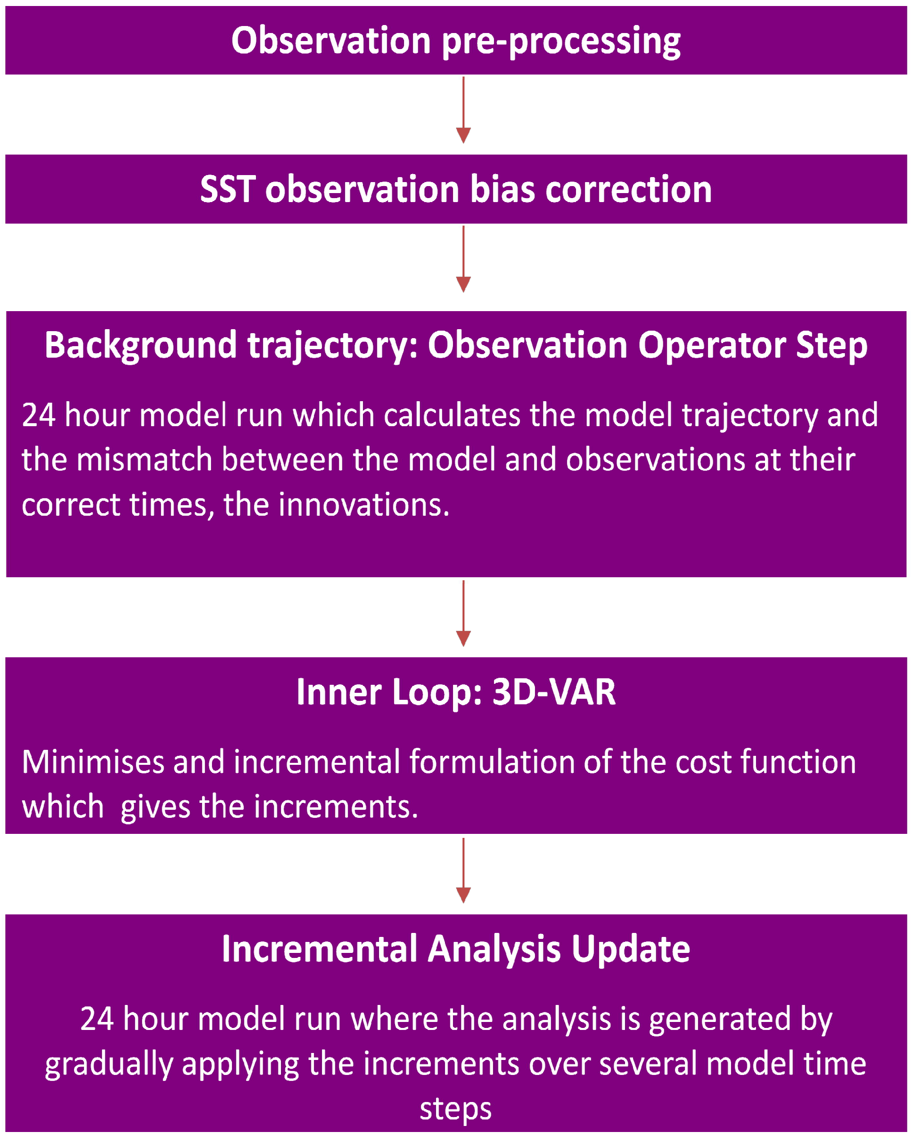

Figure 1: Assimilation cycle of NEMO based variational assimilation system

Table-1: Details of Global Ocean Data Assimilation System

	Ocean Data Assimilation System
Model and its Resolution	Nucleus for European Modelling of the Ocean (NEMO); ¼ horizontal degree and 75 vertical levels
Domain	Global
Vertical Mixing	Turbulent Kinetic Energy (TKE)
Bathymetry	ETOPO1 & GEBCO data sets
Data Assimilation	NEMO based Variational (NEMOVar) assimilation system with 40 iterations
Observations Assimilated	Sea Surface Temperature (Satellite & In situ), Sea level anomaly from altimeter, temperature and salinity profiles from GTS/ARGO/XBT, Sea Ice Concentration from satellite
Assimilation Cycle	24 hours
Time Step	20 min
River runoff	seasonal varying climatological river runoff
Surface forcing and resolution	NCMRWF unified Model (NCUM) at ~12 km (3 hourly for radiation, temperature and humidity, 1 hourly 10 m winds)

2. Impact of Altimeter derived sea level anomaly data assimilation on the variational assimilation system

Altimeter data provide measurements of dynamic topography over the global ocean. This dynamic topography from the altimeter can be directly converted into geostrophic currents. The main features of ocean circulation are a series of gyres and eddy which have spatial variability across the entire ocean. However, the altimeter data is used the sea surface slop information to detect the dynamics of gyres and eddies. Further, the long term altimeter data helps to understand the climate changes related to sea level rise due to the global warming as well as polar ice melting. The following geophysical parameters are estimated with altimeter measurements.

1. Ocean circulation and sea level variability
2. Ocean surface wind speed
3. Significant Wave Height
4. Deep Sea Bathymetric Features
5. Land and Sea Ice:
6. Assimilation of sea level data in Ocean models:

The assimilation of altimeter data is complex task due to the projection of the surface information onto the sub-surface density structure which requires coherent adjustments of both temperature and salinity to maintain the Temperature-Salinity (T-S) balance. Further, the altimeter data provides the sea level information with respect to the reference ellipsoid. However, to assimilate sea surface height (SSH) in a dynamical model, we need the sea level information relative to the Earth's geoid. Here, the geoid geoid is the shape that the ocean surface would take under the influence of the gravity of Earth, including gravitational attraction and Earth's rotation. Figure 2 shows the instantaneous sea surface, mean sea surface height (MSSH), geoid and reference ellipsoid. The SSH with respect to geoid is defined as

$$\eta = \langle \eta \rangle + \delta\eta \quad \text{(2)}$$

Where, < η > is the mean dynamic topography (MDT) with respect to geoid and, δη is the sea level anomaly measured by the altimeter. However, the MDT cannot be determined from the altimeter data without knowledge of the Earth geoid.

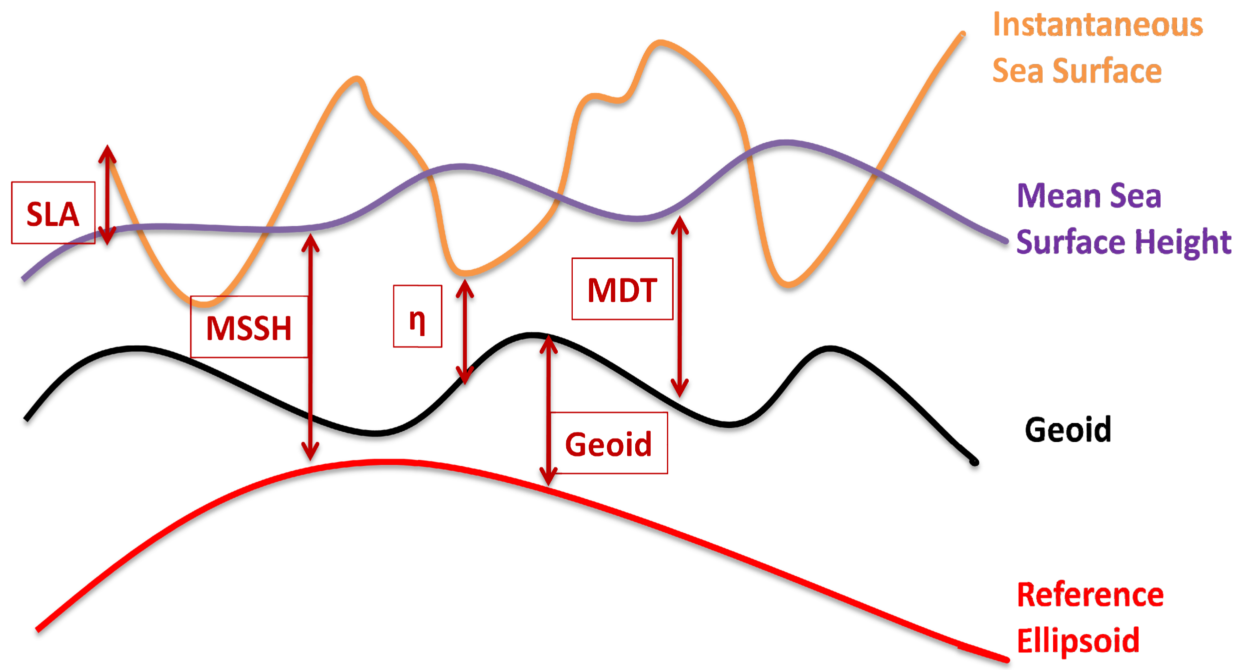

Figure 2: Schamatic diagram of various oceanic parameters such as instantaneous sea surface, mean sea surface, geoid and Ellipsoid.

$$\langle \eta \rangle = MSSH - Geoid \quad (3)$$

where, MSSH is the mean surface height obtained from the long term of altimeter data. However, the development of gravity missions such as Gravity Recovery And Climate Experiment (GRACE), Challenging Minisatellite Payload (CHAMP), and Gravity field and steady-state Ocean Circulation Explorer (GOCE) gives estimates of the geoid and hence provides the information about the mean dynamic topography. Knowledge of the geoid has improved greatly, leading to more accurate estimates of the MDT such as provided by the National Aeronautics and Space Administration or by the CLS Space Oceanography Division. Various papers related to SSH assimilation in ocean models have been published with a focus on regional and global scales (Martin, Hines, and Bell, 2007; Lea *et al*., 2008; Ratheesh *et al*., 2015).

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