Assimilation of altimetry in a mesoscale model of northeast New Zealand waters: Upwelling, uplift and fertilization of the coastal ocean in a western boundary current

John Wilkin
Institute of Marine and Coastal Sciences, Rutgers University, New Jersey, USA
Stephen Chiswell and John Zeldis
NIWA, New Zealand

Abstract

Altimeter sea surface height observations in the East Auckland Current, New Zealand, are projected to subsurface temperature and salinity anomalies using statistical methods and assimilated into a regional mesoscale model of deep-ocean shelf-sea interaction.

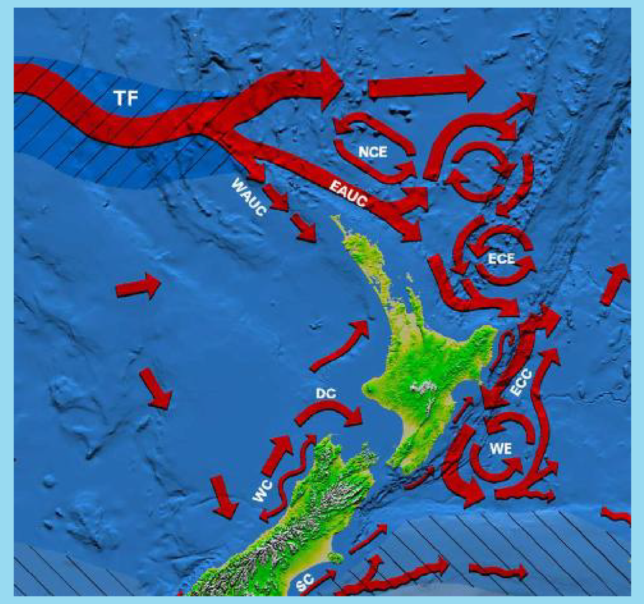
In northeast New Zealand waters vertical empirical orthogonal functions (EOF) of subsurface temperature anomalies are significantly correlated with 0/2000db dynamic height (EOF-1; 60% variance) and sea surface temperature (EOF-2; 18% variance). Observed in situ dynamic height correlates well with altimeter sea level anomalies, and therefore a significant fraction of subsurface mesoscale thermal variability can be inferred directly from satellite observations. Salinity can be reliably estimated from the T-S relation.

These satellite-derived 3-dimensional temperature and salinity analyses are assimilated in a 5-km resolution model (ROMS: Regional Ocean Modeling System) of local waters using an intermittent optimal interpolation scheme (Dombrowsky and De Mey, 1992). Typical a priori errors of the subsurface projection are inferred by estimating subsurface hindcast skill compared to data withheld from the EOF computation.

1. Oceanographic setting and motivation

The East Auckland Current (EAuC) is a component of the western boundary current of the South Pacific subtropical gyre. Fed by the Tasman Front (TF), it carries warm Tasman Sea water southeastward along New Zealand's northeast coast.

Pesistent recirculating features - the North Cape (NCE) and East Cape (ECE) eddies - inhibit the formation of a continuous EAuC and contribute to significant variability in the boundary current transport.



Theories of deep-ocean/shelf-sea exchange along this coast (Sharples, 1997) propose roles for both wind-driven coastal upwelling and the dynamic uplift of deep waters by intermittent acceleration of the western boundary current.

Together, these processes regularly fertilize northeast New Zealand coastal waters, and interannual variability in primary production appears related to these upwelling and uplift circulation mechanisms. Seasonal stratification and tidal mixing also influence cross-shelf fluxes.

By employing data assimilation in a model of the western boundary current and adjacent shelf circulation, hindcasts are produced of interannual variability in the mesoscale circulation and associated upwelling and uplift processes. The model complements observational studies of regional physical, biological, and geochemical deep-ocean/shelf-sea interaction.

References:

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Dombrowsky, E. and P. De Mey, 1992: Continuous assimilation in an open domain of the northeast Atlantic: 1. Methodology and application to AthenA-88, J. Geophys. Res., 97, 9719-9731.

Ridgway, K. , J. Dunn and J. Wilkin, 2002: Ocean interpolation by 4-dimensional weighted least squares: Application to the waters around Australasia, J. Atmos. Oceanic Technol., in press.

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Shchepetkin, A., and J. McWilliams, 1998: Quasi-monotone advection schemes based on explicit locally adaptive dissipation. Monthly Weather Review, 126, 1541-1580.

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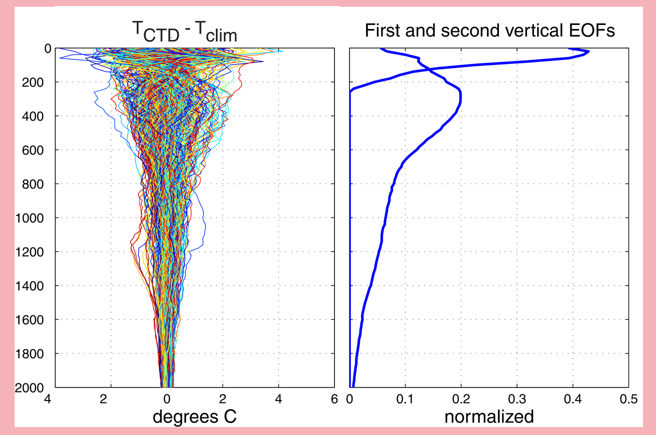
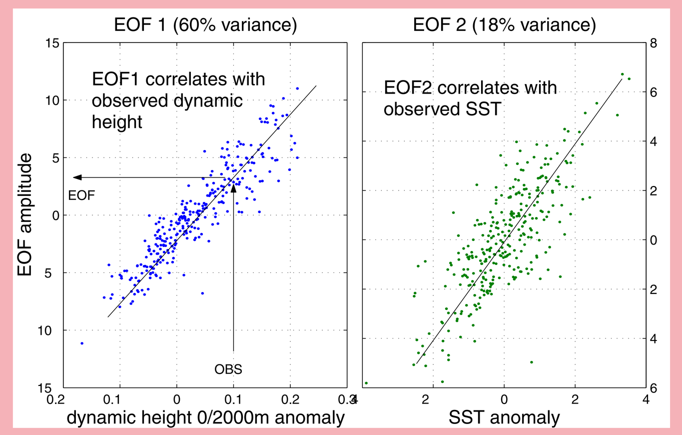
2.1 Subsurface projection of satellite data using EOFs

Sea surface height (SSH) anomalies from TOPEX/Poseidon and ERS-2 altimetry, and AVHRR sea surface temperature, are used to infer subsurface temperature and salinity anomalies using empirical orthogonal functions of observed hydrographic data.

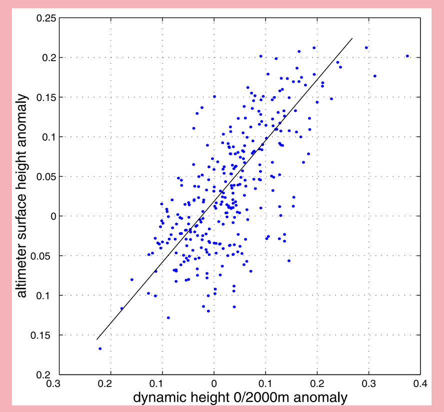
Vertical EOFs were computed for anomalies of T(z),S(z) with repect to seasonal climatology (Ridgway et al. 2002).



Hydrographic observations of dynamic height (0/2000db) and surface temperature can together infer 78% of the surface mesoscale temperature variability.



In situ dynamic height correlates with altimeter SSH, so subsurface T'(z) can be estimated solely from satellite using regression relations and the EOF mode structures (Chiswell 2002).



Satellite SSH and SST, with EOF mode structures, give 3-dimensional $T_{analysis}$

$$T_a(x,y,z,t) = T_{climatology} + c_1{*}SSH(x,y,t){*}EOF_1(z) + c_2{*}SST(x,y,t){*}EOF_2(z)$$

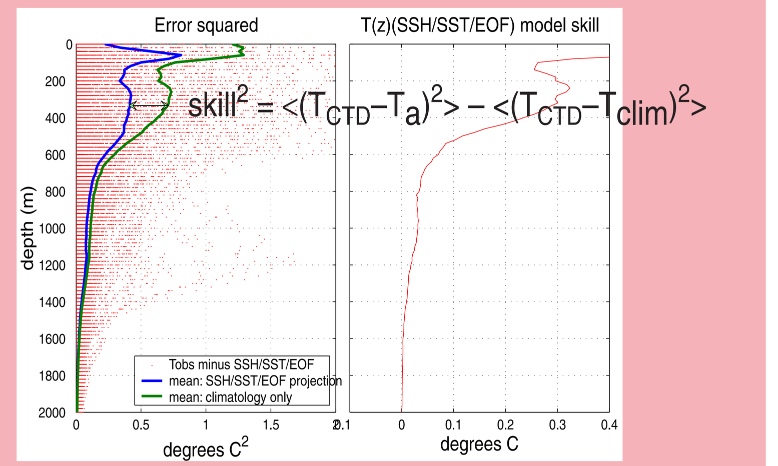
Adding the anomaly profiles to seasonal climatology achieves a 3-dimensional analysis $T_a(z)$ of temperature, derived from mesoscale satellite observations. A salinity analysis S_a can be reliably inferred from the T-S relation in these waters.

The scheme is simple, has low computational cost, and is readily implemented with historical (for hindcasting) or operational satellite data sets.

2.2 Expected skill for subsurface T, S, u, v

Data assimilation by OI requires *a priori* estimates of the expected error in T_a,S_a. Errors were estimated by comparing satellite-derived T,S to withheld hydrographic CTD profiles, and asking:

How much better do we do than if we had just used climatology?



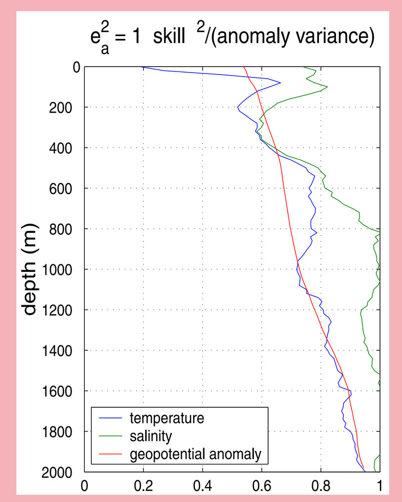
The reduction in the mean squared error of T_{CTD}-T_a compared to T_{CTD}-T_{clim} is denoted the "skill" of the subsurface projection scheme.

Expected error variance for the analyses is defined as $e_a^2 = 1 - \textit{normalized skill}^2$, where the normalization is with respect to the anomaly signal variance.

$e_a^2 = 0.4$ (e.g.) indicates 60% of the mesoscale variance is predicted by the satellite data analysis scheme.

$e_a^2 = 1$ means the projection of satellite data provides no better estimate of true T,S than would climatology.

Typically, e_a^2~1 below 800 m depth. In this case, the observations carry no weight in the assimilation: the model **is not** nudged toward mean climatology.



e_a^2 is estimated separately for T and S. Geostrophic velocity is also assimilated, with errors estimated from geopotential anomaly at depth z relative to 2000 db.

Summary

A statistically-based analysis scheme has been developed to infer mesoscale subsurface temperature and salinity variability from satellite SSH and SST observations. The method has useful "skill" up to 800m below the surface.

By quantifying the subsurface analysis skill, an objective estimate of the expected error is formed that is subsequently used as an a priori estimate of data error in a data assimilating regional model (ROMS) of northeast New Zealand waters.

The analysis and assimilation schemes are simple and require only modest computational effort. This allows the implementation of data assimilation in a high resolution, geographically realistic, circulation model, for interannual hindcasting of mesoscale variability in a western boundary current region.

The input data are limited to satellite SSH and SST, and surface meteorological fluxes. Therefore, the regional model, with data assimilation, could be implemented in an operational nowcast/forecast mode using e.g. Jason-1, MODIS, and meterological forecast data.

The model simulates observed coastal upwelling and adjacent deep-ocean uplift processes that are driven by winds and remotely-forced boundary current variability.

Future work will implement the ROMS coupled NPZD biological model to consider seasonal and interannual variability in nutrients, primary production, ecosystems, and carbon export.

3. ROMS: Regional Ocean Modeling System

ROMS features:

Primitive equations; terrain-following (-like) coordinates; split-explicit treatment of external/internal modes.

Vertical discretization: Conservative parabolic splines reduce pressure gradient error of -coordinates.

Horizontal advection: 3rd-order upstream bias advection - velocity dependent hyper-diffusion dissipation.

Time stepping: 3rd-order predictor-corrector maintains volume conservation and constancy preservaton.

(Shchepetkin and McWilliams 1998,2002a,b).

EAuC model formulation:

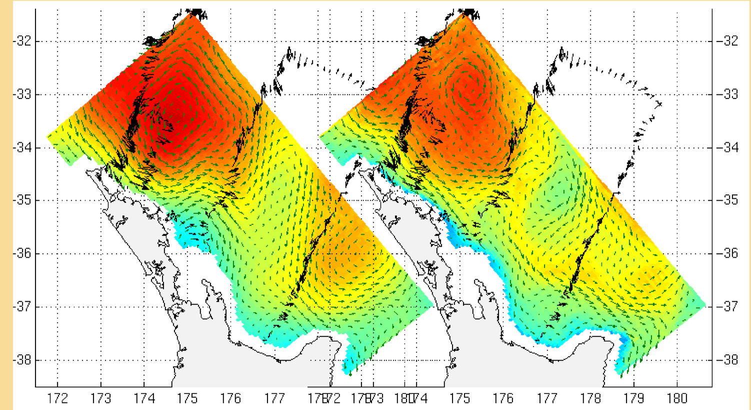
5-km grid; 20 levels; inflow/outflow radiation+nudging open boundaries; daily NCEP reanalysis surface fluxes; k-profile parameterization vertical turbulence closure.

Temperature, salinity, and velocity are assimilated. Intermittent optimal interpolation (OI) assimilation melds model forecast (e.g. T_f) with the satellite-derived subsurface analysis (T_a). The weights are set by the expected errors of the analysis e_a^2 and forecast e_f^2. q = correlation of forecast and data (Dombrowsky and De Mey 1992):

$$T_{melding} = wT_a + (1\text{-}w)T_f\,; \qquad w = \frac{e_f^2 - qe_fe_a}{e_a^2 + e_f^2 - 2qe_fe_a}$$

e_f^2 is assumed to grow exponentially with a specified time scale (10 to 50 days).
e_a^2 is set to 1 in depths < 1000m, i.e. data **are not** assimilated on the slope or shelf.

4. Results



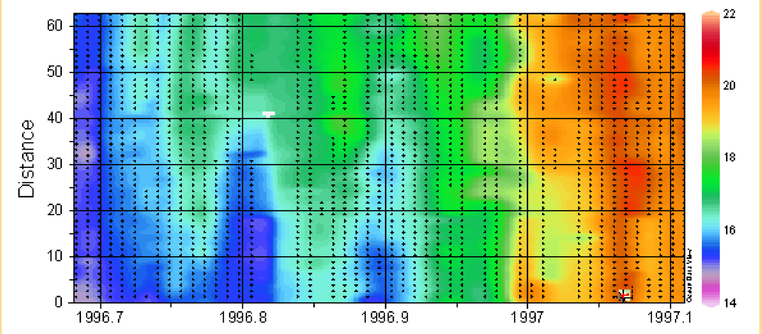
Left: Temperature and geostrophic velocity at 100m inferred from satellite SSH and SST, compared to shipboard ADCP velocity (black vectors)

Right: ROMS hindcast temperature and velocity compared to the same ADCP velocity observations.

The EAuC has established a coherent band of cool water along the shelf edge due to uplift of isotherms in the boundary current.

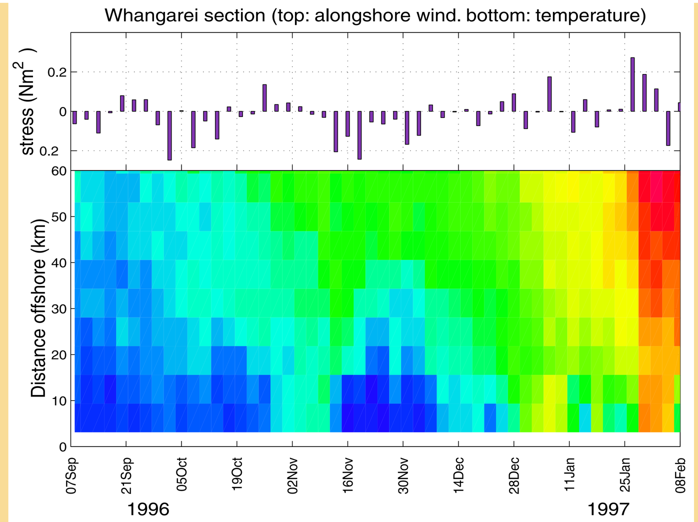
SST observations and model along Whangarei section (location on map below)

AVHRR SST shows upwelling favorable northwesterly winds cause cooling in mid-Oct and late-Nov 1996. Downwelling winds in Jan-1997 cause subtropical water intrusions into the coast.



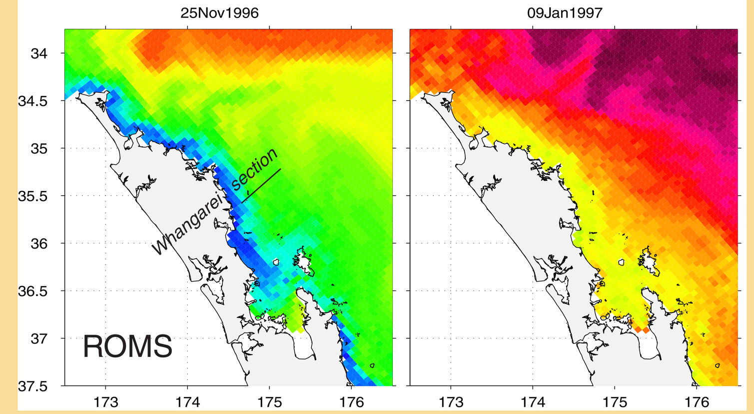
*Note: SSH/SST **are not** assimilated in waters shallower than 1000m.*

Whangarei section (top: alongshore wind. bottom: temperature)

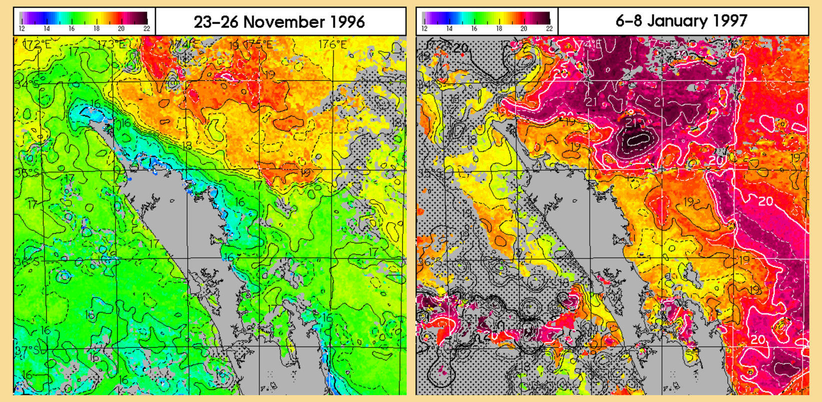


ROMS shows a corresponding cooling and warming response in coastal waters.

Wind-driven upwelling conditions



Downwelling and onshore advance of warm subtropical waters



AVHRR SST