Research Plan

1. Objectives

The work proposed here focuses on intercomparing mean dynamic ocean topography (DOT) products for the Southern Ocean, assessing their uncertainties, evaluating what these products allow us to learn about dynamics of the Antarctic Circumpolar Current (ACC), and determining priority areas for improving both geoid and DOT estimates.

Over the past two decades, satellite altimetry has emerged as a central tool for oceanographic research. Starting with the Geosat Exact Repeat Mission in 1986, a succession of radar altimeters (ERS-1, TOPEX/Poseidon, ERS-2, GFO, Jason, Envisat, Jason-2) have provided time series of absolute sea surface height. Oceanographers are most interested in studying the geostrophic flow in the ocean: strong currents such as the ACC correspond to strong sea surface height gradients:

\[ u = -\frac{g}{f} \frac{\partial \eta}{\partial y} \quad \text{and} \quad v = \frac{g}{f} \frac{\partial \eta}{\partial x}. \]

where \( u \) and \( v \) are zonal and meridional velocities, \( g \) is gravity, \( f \) is the Coriolis parameter, and \( \eta \) is sea surface height. Satellite altimeters do an excellent job of measuring the time-varying eddy component of \( \eta \), but cannot determine the time-mean geostrophic flow, because the time-invariant sea surface height signal associated with ocean circulation, the DOT, is dwarfed by the more dramatic changes in absolute sea surface height due to the Earth's geoid. Studies of ocean circulation nearly always require knowledge of both the time-mean and time-varying parts of the circulation, whether to study eddy-mean flow interactions or to track changes in total circulation. As a result, over the years, oceanographers have resorted to a broad range of strategies to estimate the time-invariant DOT. These include methods based on physical oceanographic hydrographic observations (e.g. Qiu, 1995, Sallée et al, 2008), methods employing in situ upper ocean velocity measurements (Niiler et al, 2003; Rio and Hernandez, 2003), methods based on independent determinations of the geoid from gravity data (e.g. Tapley et al., 2003, 2005; Pavlis et al., 2008), hybrid methods that combine geoid observations with oceanographic data (e.g. Rio and Hernandez, 2004; Maximenko and Niiler, 2005), and methods using assimilating ocean models (e.g. Wunsch and Heimbach, 2007; Stammer et al., 2007).

Each of the strategies used to estimate mean DOT introduces its own pitfalls. Faced with this plethora of choices, one of the greatest challenges for physical oceanographers has been deciding which DOT fields to use and determining what their uncertainties and biases really are. The challenge is compounded by the fact that DOT products are generally too smooth to resolve the small-scale structures that matter for ocean dynamics, such as the narrow jets that comprise the ACC. For geodesists, similarly, uncertainties in DOT have led to real challenges in assessing the geoid, particularly over the data poor Southern Ocean, as Topic 2.1 of the NURI 2009 call for proposals indicates. The primary objective of the work proposed here is to address the dual concerns of physical oceanographers and geodesists by quantifying the differences between the suite of available geoids and corresponding dynamic ocean topography fields. We will evaluate their biases and uncertainties, and prioritize the steps that will be needed in order to improve them.
2. Anticipated Results

The results of the proposed work will include two major components, each of which will be presented at conferences and written for publication as one or more scientific papers.

- The first part of our work will be a statistical comparison of the available DOT fields in order to inventory the characteristics and likely biases of the different fields, the resolved length scales, and the impact of different means on estimates of transient-mean flow interactions. One result will be an estimate of uncertainty in the DOT products.

- The second part of our work will use the formal statistical machinery of the 1/6° resolution Southern Ocean State Estimate (SOSE) assimilating model (Mazloff, 2008; Mazloff et al., 2009) to assess which of the available DOT (or geoid) fields are most consistent with all other available ocean observations. SOSE is a Southern Ocean regional version of the global assimilating model developed by the MIT component of the consortium for Estimating the Circulation and Climate of the Ocean (ECCO, www.ecco-group.org). The SOSE machinery will allow us to evaluate a priori uncertainty estimates. Comparison of the SOSE DOT with DOTs from coarse resolution state estimates (and from other sources) will allow analysis of error covariance length scales. In addition to publishing a paper on these results, as needed we will prepare a technical summary of model results with more extensive details to guide further improvements in geoid estimates. The model assimilation itself produces a time-dependent absolute DOT field and an estimate of the mean DOT. This estimate is a synthesis of all available measurements, and so has the potential to be superior to other products if the model physics and observational uncertainty estimates are adequate. As time permits, we will take advantage of SOSE sensitivity studies to assess where new in situ measurements of gravity (or other geophysical variables) would be most useful in improving estimates of DOT and correspondingly of Southern Ocean circulation.

3. Applicability to NGA Needs

The proposed work will respond directly to NGA needs by providing a detailed assessment of DOT derived from NGA’s EGM08 geoid model in comparison with other geoid models and other DOT fields. We will identify geoid/DOT products that are most consistent with ocean circulation and will estimate uncertainties in DOT fields. The work will specifically evaluate regions where future data collection might be most useful by taking advantage of the machinery of SOSE to examine the sensitivity of ocean transport calculations to changes in the accuracy of the mean dynamic ocean topography.

4. Approach

Science

Our approach focuses on intercomparing available choices for DOT and testing their applicability for probing the physics governing the Southern Ocean and the response of the Southern Ocean system to changing climatic conditions. We propose a two-pronged approach, focused first on developing a descriptive characterization of the DOT fields and then on using the formalism of SOSE to assess DOT performance and refine uncertainty estimates.
The research proposed here concentrated on the Southern Ocean and the ACC, not just because the NUR-2009 call for proposals identifies it as a prime region of interest, but also because it remains one of the most difficult regions in the world for which to determine mean DOT and one where the availability of a good DOT will enable some of the greatest research advances. This is true due to a confluence of different problems. The region is geographically remote and notorious for high winds and large waves. As a result ship-based measurements are limited in availability, both for gravity and physical oceanographic variables. Moreover, the region experiences persistent cloud cover, obscuring satellite measurements in the visible (i.e. ocean color) and infrared (i.e. sea surface temperature). Thus altimetry remains the only viable tool to obtain extended time series of the mean ocean features and their variability.

Our first objective is to identify a suite of DOT fields to intercompare. We will focus on fields that are commonly used in research applications, and we propose to consider oceanographic estimates of DOT, as well as gravity-based geoids. Earlier work for the North Atlantic (Bingham and Haines, 2006) considered a similar range of DOT products. Our effort will update their list with an emphasis on newer fields that take advantage of GRACE and GOCE observations and with a particular focus on the research challenges in the Southern Ocean. Here we summarize types of available data fields that we propose to consider, and Figures 1 and 2 show samples of four of these fields, highlighting their different spatial structures.

- **Dynamic topography from hydrographic atlas data.** For oceanographers, one of the easiest approaches to estimating DOT has been to compute dynamic topography from atlas data derived from in situ measurements collected by oceanographic ships (e.g. Qiu, 1995, Sallée et al, 2008). One pitfall in this approach is that atlas data can provide a poor representation of time-averaged conditions, because ship-based observations are sparse (and seasonally biased) in the Southern Ocean. A more serious potential problem is that estimates of dynamic topography from hydrography depend on choosing a mid-depth reference level at which velocities are assumed to be zero, an assumption that is clearly erroneous in the ACC, where flow is observed to be eastward at all depths, and bottom velocities as large as surface values (~70 cm/s) have been reported (Chereskin et al, personal communication). Formally, the reference level must be above the shallowest topography, and as a result atlas data are likely to underestimate the total meridional gradient in DOT. Here we propose to minimize this effect by using a statistical regression to fill gaps near topography, so that we can reference our dynamic topography to 3500 m depth (Gille, 2003).

- **DOT derived using surface drifter data.** Surface drifter data provide an independent estimate of upper ocean velocities. Typically DOT has been inferred by combining drifter velocities with ship-based hydrographic data (Niiler et al, 2003; Rio and Hernandez, 2003). Drifter velocities provide a measure of total ocean velocity, thus avoiding the reference level problem of hydrographic data. However, the data are imperfect. Although surface drifters are intended to follow upper ocean currents, they experience a certain amount of wind slip, and to date no wind slip correction has been developed for the high wind conditions that prevail in the Southern Ocean (e.g. Pazan and Niiler, 2001). Moreover, the mapping procedure used for hybrid methods may over smooth small-scale features in the mean.

- **Direct geoid measurements.** DOT can also be derived from satellite measurements of the Earth's gravity field from GRACE (and eventually GOCE) in combination with satellite altimetry (e.g. Tapley et al., 2003, 2005; Foerste et al., 2008; Pavlis et al., 2008). These
fields have the advantage of being largely independent of oceanographic data but the disadvantage of having coarse spatial scales that may not resolve the small-scale structures of major ocean currents. Early gravity-derived geoids were particularly problematic for the Southern Ocean because of the overwhelming lack of ground truth data in the region and because of satellite sampling issues associated with the presence of ice at the southern end of the domain. The most recent of these DOT fields include the GFZ Potsdam EIGEN-5S (satellite only) and EIGEN-5C (combined satellite and other data) geoids (Foerste et al., 2008), and the EGM08 geoid (Pavlis et al., 2008), which represents a careful merging of satellite gravity measurements with other available observations. These fields offer some promise for enabling substantially improved DOT estimates.

- **Hybrid fields.** More recent oceanographic studies have used a hybrid approach, merging geoid data with in situ oceanographic data to produce an optimal mean DOT (Rio and Hernandez, 2004; Maximenko and Niiler, 2005). The hybrid approach may minimize the potential biases introduced by surface drifter wind slip, but because of the mapping procedure, it is unclear how successful these fields are at capturing small-scale features in mean DOT.

- **Model mean.** Our assimilating model, SOSE, and the coarser resolution MIT-ECCO model both provide estimates of mean DOT that are consistent with all available oceanographic observations (see Figure 2). ECCO fields have served as useful benchmarks in recent evaluations of DOT (e.g. Bingham and Haines, 2006; Stammer et al, 2007; Foerste et al, 2008; Pavlis et al, 2008), and the higher resolution afforded by the regional SOSE model provides a window into smaller scale structures in the DOT.

- **Statistical strategies.** Strong currents, such as the Gulf Stream or the ACC, have roughly Gaussian velocity jets that meander northwards and southward over time. A non-linear fitting procedure can be used to reconstruct the mean from altimetric sea surface height variability (e.g. Kelly and Gille, 1990; Gille, 1994). This approach can be used to estimate the narrow structure of time-mean jets without requiring smoothing over 100s of km, but it has no value far from the main current core, unless it is merged with another larger-scale determination of DOT.

We will begin our assessment of DOT fields by carrying out a statistical intercomparison of the fields. This step is important, because it will allow us to characterize the differences between fields and the length-scales of features that they resolve. By looking at the fields closely first without recourse to a model, we can avoid confounding model-representation error with differences between DOT fields. Our analysis will address two general issues. First, in the spirit of Bingham and Haines (2006), we will examine the mean and standard deviation of all of the available mean DOTs. As Figure 1 indicates, different mean fields can differ substantially, particularly in their depiction of small-scale features. If errors in the DOT estimates are assumed to be random, then the standard deviation of all of the fields can serve as one useful bound on statistical errors in the mean fields.

Eddies can play an important role in driving mean flow or remove energy from large-scale currents, and in the Southern Ocean, characteristic eddy length scales can be as small as 10 km. Thus, we will look closely at the small-scale spatial structure of the DOT fields by computing wavenumber spectra and decorrelation length scales. While we have no ground truth for the true spatial structure of the DOT, particularly at high wavenumbers, we speculate that upper ocean temperature and velocity data collected from hydrographic field programs should
provide good estimates of the likely small-scale length-scales in the instantaneous DOT. Figure 3 shows dynamic topography from observations collected as part of the World Ocean Circulation Experiment (WOCE) in gold, along with estimates of instantaneous dynamic height determined by adding altimeter measurements onto a range of different mean DOTs. The scatter is substantial, and importantly, the latitude of the largest gradients can shift depending on the mean DOT, implying that the apparent instantaneous position of the ACC depends on the mean.

Figure 1. Examples of mean dynamic ocean topography (DOT) fields commonly used in physical oceanographic research. (Top left) Mean DOT from Gouretski and Jancke (1998) hydrographic atlas data, here computed relative to 3500 dbar (with interpolation to fill gaps in locations between 2500 and 3500 m depth). (Top right) Mean dynamic topography from hydrographic and drifter data (Rio and Hernandez, 2003). (Bottom left) GRACE dynamic ocean topography (Tapley et al., 2003). (Bottom right) EGM08 DOT (Pavlis et al, 2008). A constant offset has been added to each DOT to facilitate comparison.
Key ocean circulation questions depend on knowing the DOT, which defines the streamlines of the ACC. For many oceanographic applications, averaging along streamlines is more appropriate than averaging along lines of latitude. We propose to explore the sensitivity of these calculations to the specific choice of DOT. One obvious test is to examine how eddy-mean flow interaction calculations (e.g. Hughes and Ash, 2001; Hughes, 2005) depend on the choice of mean field. Another calculation of growing interest is to understand how estimates of horizontal diffusivity or particle advection derived from altimetric sea surface heights plus mean DOT (e.g. Marshall et al., 2006) vary depending on the choice of mean. A third application of growing importance for climate research is to understand how the apparent latitude of the jets that comprise the ACC changes depending on the choice of DOT, and in turn, how jet position responds to variations in wind forcing that might be associated with (anthropogenic) changes in the Southern Annular Mode, the leading order wind pattern that drives the Southern Ocean on climatic time scales (e.g. Dong, et al., 2006; Fyfe et al., 2007; Sallée et al., 2008).

Ultimately, quantitative intercomparisons are more easily completed if a cost function can be defined as a performance metric. For example, if we had a good, independent estimate of the true DOT for some corner of the ocean, then a natural cost function would be the root-mean squared (rms) misfit between DOT fields and truth. For the Southern Ocean, where data are sparse, no single data source is likely to provide sufficient information to constrain a cost function. An assimilating model offers a natural framework for defining a cost function measuring the consistency between multiple data types and ocean dynamics, and for the Southern Ocean, the SOSE is an obvious choice.

SOSE optimizes model-data misfit for the region south of 25°S during the time period from 2005-2007. Because it covers a shorter time period and smaller domain than ECCO, it is able to be run at higher spatial resolution and therefore does a better job resolving mesoscale features that are crucial to understanding the role of eddies and small-scale topographic features in the Southern Ocean.

**Figure 2.** (Left) Time-averaged DOT from 1/6° SOSE. (Right) Time-averaged DOT from 1° MIT-ECCO. Zero contour is adjusted so that these fields can be compared with those in Figure 1.
Figure 3. Instantaneous sea surface height along I08 WOCE line (approximately 90E) from WOCE hydrography (gold line), and from instantaneous altimetry plus a selection of estimated mean DOTs. The black line is from a statistical altimeter-based model that is only plausible in the core of the ACC, where gradients are steep. Note the large spread in the other sea surface height estimates.

A cost function is used to compare the SOSE solution to in situ observations (Argo profiling floats, conductivity-temperature-depth [CTD], Southern Elephant Seals as Ocean Samplers [SEaOS], and expendable bathythermographs [XBTs]), altimetric anomaly observations (Envisat, GFO, TOPEX/Poseidon/Jason), and other data sets (e.g. sea surface temperature and sea-ice concentrations). Reduction of the model-observation misfit is achieved by systematically adjusting the control variables (prescribed atmospheric state and initial conditions) in an iterative procedure. Constraints on the control variables ensure a physically realistic solution. The methodology used in developing SOSE is that of classical Lagrange multipliers, taking advantage of the existence of an “adjoint” model generated via automatic differentiation (Giering and Kaminski 1998; Heimbach et al. 2005). If an acceptable misfit can be found, the model solution, obtained by running the model freely forward with the adjusted control vector, becomes the state estimate. In a truly optimal state, and with all fields assumed Gaussian, residual misfits would be random white-noise whose square is a $\chi^2$ variable (Wunsch and Heimbach 2007). An optimal state estimate, however, is never truly achieved: the model physics are continually being improved, new data become available as does information about their error structure, and in practice, there are always lingering cost function terms which are too large or too small.

The Southern Ocean has been extensively observed in the last several years, and the present SOSE solution is largely consistent with this wealth of data (Wunsch and Heimbach 2007, Mazloff et al. 2009). SOSE undergoes continued development, which includes addition of observations and extension of its temporal duration. The coarse resolution global ECCO model provides boundary conditions for SOSE, and a common procedure is used to prepare data for assimilation into both models. Model improvement strategies are also shared between SOSE and
other ECCO groups. We will maintain interactions with ECCO researchers at MIT and elsewhere by participating in ECCO-community meetings through funding from separate projects. Currently we foresee extending SOSE forward in time to cover the entire intensive observation period of the International Polar Year (from 2007-09). Experience has shown that when a new data set is implemented to the nearly converged solution, one can expect the estimate to become largely consistent with these data in approximately 10 iterations of the adjoint method. This implies approximately 3 months of optimization time is required to bring SOSE into consistency with new DOT fields.

As part of the proposed work, we will simultaneously incorporate multiple DOT fields into the assimilation cost function and determine SOSE’s compatibility and sensitivity to them. Since SOSE is constrained separately to hydrographic observations, it makes little sense to use a DOT derived from hydrographic atlas data as a constraint, and our effort will focus on DOT fields constructed largely from geoid data or surface drifter data that are not otherwise used by SOSE. Error information is required for optimal use of DOT products. As noted above, we will rely on the rms differences between products to provide estimates of uncertainties for products that have not been released with uncertainty estimates.

SOSE was developed using DOT derived from EIGEN-GRACE-03S, and the current model mean state has converged towards this imposed DOT to the extent allowed by model physics and other ocean observational constraints. The approach that we propose of simultaneously constraining SOSE to multiple DOT fields is less computationally intensive than the approach adopted by Stammer et al. (2007), who completed separate optimization procedures for the global ECCO model using three different DOT fields. Thus we will be able to afford to allow SOSE to adjust fully to the altered DOT cost function. SOSE is well-suited for the type of data consistency test that we propose here. A similar approach to what we plan for DOT is currently used for sea surface temperature (SST): SOSE is constrained to observations from both infrared (AVHRR) and microwave (TMI AMSR-E) radiometers. The rms difference between the optimized SOSE solution for SST and the observational products is similar in magnitude to the rms difference between the two observational products themselves. As SOSE is constrained to a suite of independent ocean measurements, evaluating discrepancies in the three fields sheds light on the accuracy and bias of the satellite SST products.

Time and computational resources permitting, we will also consider running an experiment more like that of Stammer et al. (2007), who optimized ECCO separately to each of the DOT fields that they considered. Such an experiment would be expected to yield results similar to what we obtain through the more efficient approach of simultaneously constraining the model to multiple DOT fields, but it does offer a means to distinguish the effects of subtly different DOT constraints and to ask specifically how the performance of the assimilation changes depending on the a priori choice of DOT and the estimated uncertainty of the respective DOT products. These tests would allow us to examine the influence of DOT constraints on specific properties of the Southern Ocean, such as the total transport through Drake Passage and total ocean heat content.

In addition to estimating optimal ocean states that are consistent with available observations, SOSE can also be used to carry out sensitivity tests. Using the MIT-ECCO model, Losch and Heimbach (2007) carried out sensitivity tests to evaluate the impact of bottom topography on flow fields (see also Losch and Wunsch, 2003). For SOSE, a sensitivity experiment has been carried out to evaluate how transport through Drake Passage depends on data constraints. We propose to analyze these results to assess how DOT influences Drake
Passage transport. Sensitivity tests will allow us to identify specific geographic locations where improved observations of DOT would have the biggest impact on transport estimates. Time permitting, we can carry out a suite of alternate sensitivity tests to assess how other variables (such as transport through other parts of the Southern Ocean or the total heat content of the upper ocean) depend on DOT. Such tests can provide a statistical formalism for guiding geodesists in choosing where to direct future observational efforts.

The best way to test new data sets is to use them. We will take advantage of SOSE and the MIT-ECCO adjoint machinery to explore the aspects of Southern Ocean physical oceanography that depend most strongly on DOT. One key issue is ACC transport. Estimates from Drake Passage suggest that the total eastward transport of the ACC is about \((134 \pm 11) \times 10^6 \text{ m}^3 \text{s}^{-1}\) (Whitworth, 1983; Whitworth and Peterson, 1985; Cunningham et al., 2003), though there is some disagreement on this number, and it remains unclear whether the transport through other Southern Ocean choke points closely matches the Drake Passage transport and whether there is substantial westward recirculation within each of the three ocean basins. A well constrained SOSE hindcast will provide us with model fields needed to explore transport issues more carefully. A second key issue is topographic steering. The jets that comprise the ACC are believed to be tightly steered around Kerguelen Island in the south Indian Ocean and through the Eltanin and Udintsev Fracture Zones in the central Pacific Ocean (e.g. Gille, 1994). We are interested in evaluating the extent to which this topographic steering is evident in DOT fields (which in many cases may not have the spatial resolution needed to resolve the narrow fracture zones) and the extent to which SOSE is able to reconstruct the jet structure given the available DOT estimates. We are also interested in using SOSE to explore ACC response to the Southern Annular Mode, in parallel with the data-only analysis discussed above (e.g. Dong, et al., 2006; Fyfe et al., 2007; Sallée et al., 2008).

**Management**

Through the course of this project, we will meet approximately weekly to track progress towards our major objectives. In the proposed work, Mazloff will take charge of SOSE simulations, Griesel will carry out analysis of data along with SOSE and ECCO output, and Gille will provide overall guidance for the project. Through the course of the project, we will consult with other Scripps investigators who work on assimilation or on Southern Ocean processes. The work steps and milestones are here outlined by year and quarter.

**Y1. Q1.** Inventory available dynamic ocean topography fields and choose key fields for use in this analysis. Augment SOSE cost function to constrain to multiple DOT fields. Attend kick-off 4-day meeting.


**Q3.** Assess sensitivity of transient-mean flow interactions to choice of mean. Continue SOSE simulations and begin assessing results. Evaluate SOSE convergence to DOT products.

**Q4.** Write paper summarizing statistical intercomparison of dynamic ocean topography products. Prepare for and attend 4-day meeting.

**Y2. Q1.** Finalize SOSE simulations and continue analysis of results, with particular focus on
sensitivity of ACC transport to choice of mean. Determine where estimated DOT uncertainty fields may have been too conservative or too generous.

Q2. Continue analysis of SOSE simulations, examining the basic question of whether transient processes drive the mean flow or extract energy from the mean flow.

Q3. Finalize SOSE analysis, considering impact of findings for understanding Southern Ocean climate processes, including response to climatic shifts in Southern Annular Mode. Analyze SOSE results showing sensitivity of Drake Passage transport to DOT as a function of position.

Q4. Complete final publications based on SOSE findings. Write final reports, including an uncertainty map for SOSE. Prepare for and attend 4-day meeting.

Y3. If optional extension is supported, continue SOSE analysis by extending sensitivity tests to consider a range of cost functions in addition to Drake Passage transport.

Y4. Repeat and extend analysis using new DOT estimates from GOCE and GRACE.

Y5. Complete final analysis with emphasis on using SOSE for full IPY period to develop science results

5. Facilities and Equipment

Office space is available in the same building for all of the investigators involved in this project. This office space is adjacent to space occupied by other Southern Ocean researchers, and the project will benefit from daily informal interactions with specialists who are not directly funded by the project. Linux-based data and web servers with RAID back-up systems are available for this project. Server-class machines are operated in an air-conditioned machine room. Supercomputer requirements for SOSE are supported by NSF through a separate TeraGrid resource grant.

While the project can be completed with the current release of EGM08, the scope of the analysis and interpretation of results will be more extensive if we can be supplied with any updates to EGM08 that may become available, along with corresponding documentation outlining geographic locations of any in situ observations that may have been used (to facilitate assessment of geographic variations in the accuracy of the dynamic ocean topography) and formal estimates of accuracy. The project would benefit from close interactions with NGA scientists, particularly with a focus on choosing appropriate geoid and DOT fields and appropriate degree and order for geoid/DOT calculations.


No sub-awards or formalized collaborations are planned.

7. Student Training and Institutional Improvement.

Because of the short duration of this award, no student support is requested. The award will advance the skills of two postdoctoral investigators and will develop Scripps Institution of Oceanography capabilities with the Southern Ocean State Estimate code.


No other sources of funding have been sought for the specific research activities outlined in this proposal.