

Mean dynamic topography of the Arctic Ocean

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[1] ICESat and Envisat altimetry data provide measurements of the instantaneous sea surface height (SSH) across the Arctic Ocean, using lead and open water elevation within the sea ice pack. First, these data were used to derive two independent mean sea surface (MSS) models by stacking and averaging along-track SSH profiles gathered between 2003 and 2009. The ICESat and Envisat MSS data were combined to construct the high-resolution ICEn MSS. Second, we estimate the 5.5-year mean dynamic topography (MDT) of the Arctic Ocean by differencing the ICEn MSS with the new GOCO02S geoid model, derived from GRACE and GOCE gravity. Using these satellite-only data we map the major features of Arctic Ocean dynamical height that are consistent with in situ observations, including the topographical highs and lows of the Beaufort and Greenland Gyres, respectively. Smaller-scale MDT structures remain largely unresolved due to uncertainties in the geoid at short wavelengths. **Citation:** Farrell, S. L., D. C. McAdoo, S. W. Laxon, H. J. Zwally, D. Yi, A. Ridout, and K. Giles (2012), Mean dynamic topography of the Arctic Ocean, *Geophys. Res. Lett.*, *39*, L01601, doi:10.1029/2011GL050052.

1. Introduction

[2] Satellite laser and radar altimeters on ICESat and Envisat provide measurements of both sea ice elevation and sea surface height (SSH) over the Arctic Ocean to 86 °N and 81.5 °N, respectively. Discrimination of elevation measurements from open water and leads in the ice-covered Arctic Ocean provides, over time, details of both the time-variable and mean Arctic SSH. Knowledge of the mean sea surface (MSS) in particular is critical for investigating Arctic Ocean geostrophic circulation, and can be used to test regional and meso-scale numerical models [e.g., *Proshutinsky and Kowalik, 2007*] of mean dynamic topography (MDT) and freshwater transport via major ocean currents. The Arctic Ocean MSS can also be used to derive marine gravity anomalies in ice-covered waters [*Laxon and McAdoo, 1994*], and provides a useful reference surface for the extraction of sea ice freeboard from altimetric measurements of ice floe elevation. The MSS contains signatures due

to both the marine geoid (± 100 m) and dynamic ocean topography (± 1 m), such that altimetric sea surface heights when differenced with the geoid yield estimates of the MDT [*Wunsch and Gaposchkin, 1980*].

[3] Estimating the dynamic ocean topography on monthly time-scales using ICESat data has recently been demonstrated [*Kwok and Morison, 2011; Forsberg et al., 2007*]. However both of those estimates of MDT utilized subsets of the ICESat altimetry record together with the EGM2008 geoid model, which assimilates altimetric measurements and is thus contaminated with a residual ocean signal. In this note we describe a new ICESat-Envisat (ICEn) MSS model of the Arctic Ocean, derived from 5.5-years of ICESat laser altimetry and Envisat radar altimetry spanning 2003 to 2009. We difference the ICEn MSS with the GOCO02S geoid, derived from Gravity Recovery And Climate Experiment (GRACE) [*Tapley et al., 2003*], and Gravity field and steady-state Ocean Circulation Explorer (GOCE), satellite gravity data [*Pail et al., 2010*], to provide a satellite-only estimate of MDT for the entire Arctic Basin north of 70 °N to 86 °N. We demonstrate that combining the latest satellite-only altimetry and gravity measurements over the Arctic Ocean improves our capability for observing Arctic MDT.

2. Satellite Data

2.1. ICESat Laser Altimetry

[4] We utilize ICESat laser altimetry data from the October–November, February–March, and May–June observation periods, gathered over 5.5 years between October 2003 and April 2009 (see *Yi et al. [2011]* for specific laser operation dates). We exclude from our analysis data collected during the first and last campaigns, due to uncorrected range errors in the former, and the short 12-day time-span of the latter. The data are Release 428 processed using precision orbit, tidal, saturation and inverse barometer corrections with cloud-filtering techniques used to exclude data corrupted by forward scattering [*Zwally et al., 2008; Yi et al., 2011*]. Instantaneous SSH was calculated at the full (40 Hz) along-track resolution following the methodology of *Zwally et al. [2008]* and based on the assumption that the small laser footprint can distinguish thin ice and narrow leads, where the precision of lead elevations is ~ 2 – 3 cm [*Kwok and Morison, 2011*]. A MSS profile is computed for each reference ground-track, by stacking and averaging 16 repeat passes gathered during the 5.5-year observation period. At least seven SSH measurements were acquired for the majority of reference footprints, mitigating the impact of inter-campaign biases on the 5.5-year average. The dense along-track sampling (~ 50 m every 170 m) provided by ICESat is ideal for deriving MSS profiles even across steep sea surface slopes at continental shelf-breaks and over narrow bathymetric features.

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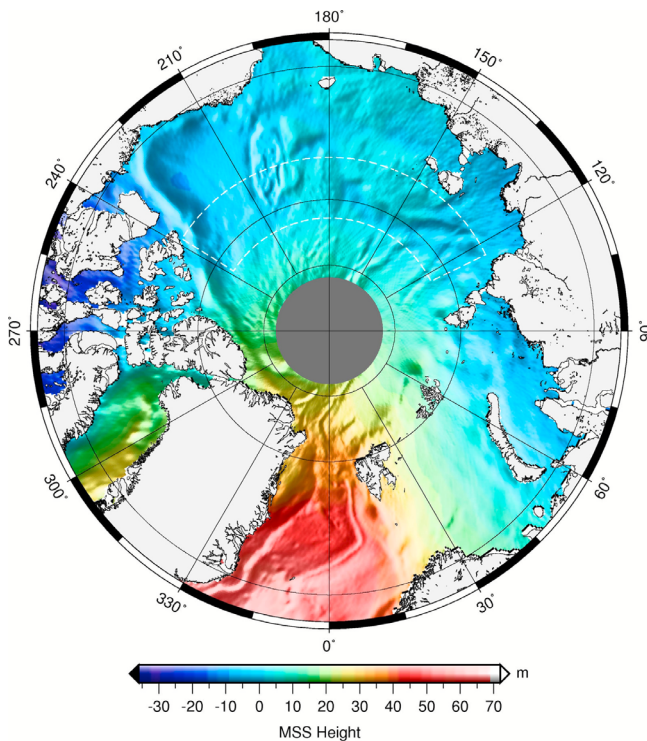


Figure 1. The ICEn Mean Sea Surface (MSS) model of the Arctic Ocean. Artificial illumination from 125°E has been added to emphasize topographical features of the MSS. The ICEn MSS is computed with respect to the Topex/Poseidon Reference Ellipsoid. A dashed-white box outlines Region A.

2.2. Envisat Radar Altimetry

[6] Using ERS radar altimetry *Peacock and Laxon* [2004] first described the discrimination of specular radar returns from leads to determine SSH in consolidated Arctic pack-ice. Since 2002 Envisat’s Radar Altimeter-2 (RA-2) has provided altimetry measurements over the Arctic to 81.5°N. Individual specular echoes have been selected to generate SSH profiles. The relative accuracy of Envisat lead elevation measurements is ~ 1 cm [*Connor et al.*, 2009]. Over the open ocean standard elevation data are used, while over sea ice the data are corrected for tracking errors using a “Gaussian + exponential” waveform model [*Giles et al.*, 2007]. The data have been processed using standard precision orbits, and corrections have been applied for ionospheric delay, wet and dry tropospheric delay, tides (ocean, ocean loading, long period, solid Earth), and the inverted barometer effect (using the MOG 2D model of *Carrère and Lyard* [2003]). The high resolution Envisat MSS was also constructed by stacking and averaging repeat-pass SSH measurements gathered during the 5.5-year observation period.

2.3. GOCO02S Satellite Gravimetric Geoid

[7] GOCE and GRACE satellite measurements are revolutionizing our knowledge of the Earth’s gravity field by producing precise mappings of the global geoid. Since GOCE operates in a lower orbit than GRACE (~ 260 km compared to ~ 460 km), and employs on-board satellite gravity gradiometry, it resolves shorter wavelength components of the

gravity field than GRACE and has already improved global gravity in the wavelength band ranging from spherical harmonic degree 100 to 250 (~ 160 – 400 km) [*Pail et al.*, 2010]. Here we use the GOCO02S geoid, a geopotential model derived from the latest satellite gravity based on 8 months of GOCE data, 7 years of GRACE data, GPS tracking data, and CHAMP data [*Goiginger et al.*, 2011]. In contrast to the Arctic Gravity Project (ArcGP) [*Kenyon and Forsberg*, 2008] and Earth Gravitational Model 2008 (EGM2008) [*Pavlis et al.*, 2008] geoids, which assimilate satellite altimetry, GOCO02S is a purely gravitational model. At wavelengths greater than 500 km the accuracy of satellite gravimetric geoid is comparable to altimetry measurements, at ~ 2 cm [*Pail et al.*, 2010].

3. The ICEn MSS

[8] Measuring SSH in ICESat data over the open ocean can be affected by long-wavelength ocean waves. Therefore, the ICESat MSS is computed for the ice-covered Arctic Ocean only. Envisat MSS measurements are available over both the ice-covered and open ocean, thereby providing coverage south to 66°N. To eliminate any seasonal signals not captured during ICESat’s intermittent measurement campaigns, a subset of Envisat data were selected for temporal coincidence with ICESat observations. The combined ICESat-Envisat MSS, the ICEn MSS of the Arctic Ocean, was constructed as follows: Envisat data were used exclusively south of the ice edge to 66°N, ICESat and Envisat data were used north of the ice edge to 81.5°N, ICESat data were used exclusively above 81.5°N to 86°N. Individual along-track MSS height profiles were combined on a grid with longitude spacing of $1/20^\circ$ and latitude spacing of $1/50^\circ$ using a weighted “nearest-neighbor” interpolation scheme to create the ICEn MSS. The ICEn MSS provides continuous mapping of basin-scale Arctic Ocean topography to 86°N (Figure 1), and updates and extends the first mapping of the Arctic MSS [*Peacock and Laxon*, 2004]. The variability of the MSS reflects both sea floor topography and density variations in the oceanic crust and upper mantle [*Peacock and Laxon*, 2004; *Laxon and McAdoo*, 1994]. Artificial illumination of the surface (Figure 1) reveals that the ICEn MSS resolves the steepest sea surface slopes associated with bathymetrically prominent features such as the Mohns-Knipovich, Lomonosov and Gakkel Ridges, and the shelf-breaks off Eastern Greenland and north of the Canadian Arctic Archipelago.

4. Assessment of Satellite Altimeter MSS Models

[9] We assess the spatial resolution of the ICESat and Envisat MSS models via comparison with the recently published DNSC08 MSS, a global field that provided the first Arctic MSS map complete to 90°N [*Andersen and Knudsen*, 2009]. The DNSC08 MSS combines satellite radar (ERS-2 and Envisat) and laser (ICESat) altimetry, with the ArcGP.06 geoid beyond 86°N [*Kenyon and Forsberg*, 2008].

[10] We conduct statistical analyses of the ICESat-only, Envisat-only, and DNSC MSS models in “Region A”, an area bounded by the coordinates 116°E–238°E, 76.8°N–81.4°N (white box, Figure 1). This represents the largest area in the central Arctic that is uncontaminated by island chains

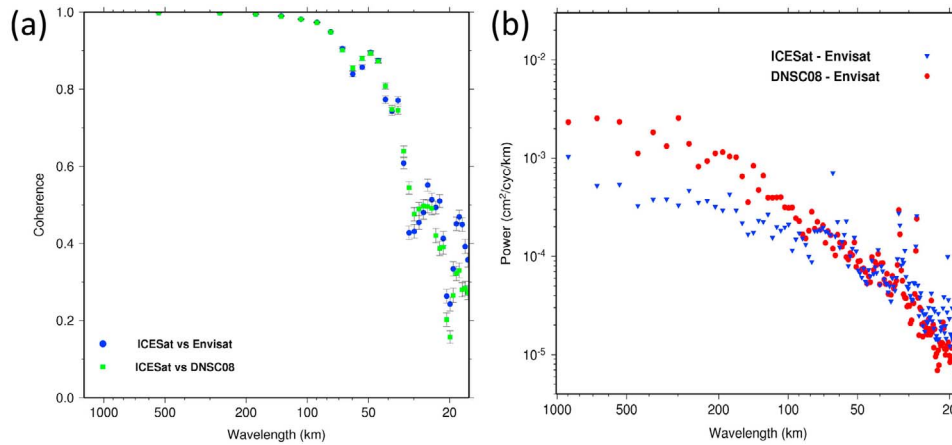


Figure 2. (a) Log-normal graph of the coherency between the ICESat and Envisat MSS models (blue dots) and the ICESat and DNSC08 MSS models (green squares) within Region A (see text). (b) Log-log graph of the MSS noise power spectrum, where the difference between the ICESat and Envisat MSS models (blue squares), and the Envisat and DNSC08 MSS models (red dots) is calculated within Region A, across the wavelength band 15–1000 km.

and sampled by both ICESat and Envisat. There is excellent agreement in the mean difference (5 cm) and standard deviation (2 cm) between the ICESat and Envisat MSS models in Region A (not shown). The comparison between either the ICESat or Envisat MSS fields and the DNSC08 MSS reveals a larger mean difference, with an offset of 19–21 cm and a standard deviation of 7–8 cm. This offset may be due to the treatment of altimetry data in the construction of the DNSC08 MSS at high northern latitudes, where *Andersen and Knudsen* [2009] use alternative methodologies to estimate altimetric SSH and apply a number of offset corrections.

[11] Coherency between the three MSS models in Region A is above 0.5 at wavelengths greater than ~ 30 km (Figure 2a), indicating agreement in the expression of topographical features wider than ~ 30 km. At shorter wavelengths however there is higher coherency between the ICESat and Envisat MSS fields, than between the ICESat and DNSC08 fields (Figure 2a). While the ICESat MSS and Envisat MSS use full-resolution along-track data (40 Hz and 20 Hz respectively), 1 Hz (i.e., 1 s) SSH observations were used in the construction of the DNSC08 MSS *Andersen and Knudsen* [2009]. Short wavelength features are therefore attenuated in DNSC08 and could contribute to the lower coherency observed at short wavelengths (Figure 2a). We also calculate the power spectrum of the differences between the models in Region A, to examine noise in the MSS fields in the wavelength band 15–1000 km (Figure 2b). Superior agreement (lower noise) between ICESat and Envisat, than with the DNSC08 MSS is indicated, particularly at wavelengths > 75 km. Residual orbit errors in the ICESat and Envisat data (appearing as ground-track striations in the MSS fields) may contribute to higher noise levels at shorter wavelengths.

[12] Taken together the results show greater agreement between the satellite-only Arctic Ocean MSS models derived independently from ICESat and Envisat altimetry, with no overall bias between these fields, compared to the current state-of-the-art (e.g., DNSC08). This demonstrates that by retaining the high-resolution along-track data provided by

satellite altimeters, the expression of even extremely narrow topographical features can be resolved.

5. Mean Dynamic Topography

[13] Basin-scale estimates of MDT are vital for estimating ocean structure at both short and long wavelengths for ocean circulation studies and validation of geostrophic current velocity from models. Arctic Ocean MDT remains poorly constrained due to a lack of widespread and routine observational data. The MDT, h_{MDT} , reported with respect to a temporal averaging period, may be determined as the difference between the altimetric MSS height (h_{MSS}) and the geoid (h_G): $h_{MDT} = h_{MSS} - h_G$, where the effects of tides, atmospheric pressure fluctuations, and sea ice elevation have been removed from h_{MSS} . Knowledge of h_G to an accuracy of a decimeter or better is required to accurately derive MDT across the Arctic Basin. We compute two independent estimates of the long-term, 5.5-year, Arctic MDT spanning 2003 to 2009. The estimates represent the longest-term measurement of Arctic MDT currently feasible using ICESat data and temporally coincident Envisat data. Our approach reduces the affects of seasonal signals and inter-campaign bias, or other altimetric range errors, and thus represents an improvement over previous MDT mappings using subsets of the ICESat data record [e.g., *Kwok and Morison*, 2011; *Forsberg et al.*, 2007]. First we difference the high-resolution ICESat MSS with the EGM2008 geoid (Figure 3a). We compare this preliminary estimate of Arctic MDT to a second, satellite-only estimate computed relative to the GOCO02S geoid (Figure 3b). Attenuation of short-wavelength gravity signals is inversely proportional to the altitude of GOCE (~ 260 km) and necessitates some filtering of the MDT field. Filtering also reduces residual noise in the MSS field due to unmodeled tidal or atmospheric effects, ground-track striation, etc. Here we filter both MDT fields using an isotropic Gaussian filter with a 250 km half-wavelength. A zonal MDT profile across the Arctic Basin at 83 °N, between 135 °E and 250 °E (Figure 3c) illustrates the value of filtering in reducing noise. There are notable differences

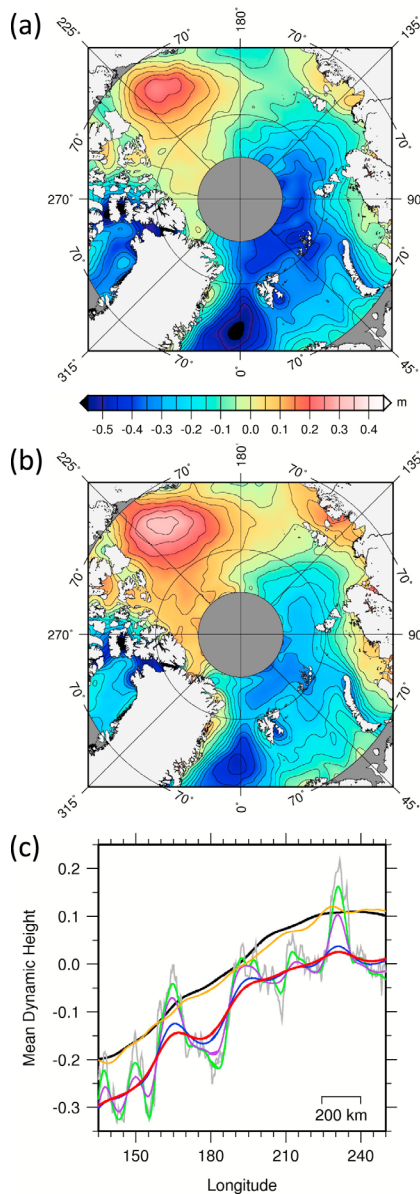


Figure 3. (a) Mean dynamic topography of the Arctic Ocean computed by differencing the ICEn MSS with the EGM2008 geoid. (b) MDT computed by differencing the ICEn MSS with the GOCO02S geoid. Contour lines have been added at 0.05 m intervals. (c) MDT profiles along a zonal band at 83°N, from 135°E to 250°E, with GOCO02S MDT (red) and EGM2008 MDT (black) filtered using a 250 km half-width Gaussian filter (HWGF). The unfiltered EGM2008 MDT (grey) field illustrates noise due to remaining geoid errors and ground track striations in the ICEn MSS. The EGM2008 MDT filtered using intermediate 50 km (green), 100 km (purple) and 200 km (blue) HWGF, and the GOCO02S MDT filtered at 200 km (orange), are also shown.

between the two MDT estimates including an overall offset of 9 cm across the Arctic Basin.

[14] Our MDT maps (Figures 3a and 3b) reveal the primary large- and meso-scale steady-state circulation features of the Arctic Ocean, and are consistent with the mean dynamical height climatology, derived from in situ

observations [Arctic Climatology Project, 1997], including the Beaufort Gyre, a topographical high of ~ 0.35 m centered at $\sim 215^\circ\text{E}$, 74°N , and a ~ 0.85 m gradient in the dynamic topography across the Arctic Basin to the Greenland Gyre, a low of ~ -0.5 m centered at 0°E , 75°N in the northern Greenland Sea. Additional circulation features including the East Greenland Current and Transpolar Drift are resolved, particularly in the satellite-only estimate (Figure 3b).

[15] Figure 3a reveals anomalies in the Canada Basin (at 240°E , 79°N) and Lincoln Sea (83°N , 300°E) as well as meandering MDT contours in the eastern Arctic ($82\text{--}85^\circ\text{N}$, $60\text{--}175^\circ\text{E}$). Remaining uncertainties in the EGM2008 geoid are the likely contributor to these anomalies. Figure 3c reveals noise in the MDT field derived using EGM2008, particularly at 150°E , 165°E , 181°E , and 230°E , that is not present in the MDT derived using GOCO02S. EGM2008 is derived from a combination of airborne, surface and submarine gravimetry with GRACE data at long wavelengths and satellite altimetry over the oceans. While EGM2008 yields a highly accurate geoid (to ~ 0.06 m) over the major ocean basins [Pavlis et al., 2008], geoid errors are substantially larger in the Arctic, particularly short-wavelength errors of several decimeters to 1 m (D. C. McAdoo et al., Gravity of the Arctic Ocean from satellite data with validations using airborne gravimetry, manuscript in preparation, 2011), where ArcGP is used as a primary input. Furthermore, since EGM2008 assimilates altimeter data in the Arctic Ocean it is hence contaminated by residual ocean signals. GOCO02S, derived entirely from satellite gravity data, is free from sea surface topography signals and thus provides an improved approach for accurate derivation of Arctic MDT on basin scales [Tapley et al., 2003].

6. Summary

[16] We have constructed a new MSS model of the Arctic Ocean, the ICEn MSS, derived from a combination of 5.5 years of ICESat-laser and Envisat-radar altimetry. The ICEn MSS mapping has high spatial resolution and contains details of the steepest sloping sea surface topography, representing a significant improvement over comparative MSS models such as the DNSC08 MSS. Indeed due to the remaining short-wavelength errors in sectors of the best available Arctic geoids, high-resolution altimetric MSS models, such as the ICEn MSS, provide a useful reference surface for more accurate derivation of sea ice freeboard from CryoSat-2, IceBridge and ICESat-2 altimetry. Additionally, along-track sea surface slopes will be used to improve models of the Arctic marine gravity field.

[17] Differencing the high-resolution ICEn altimetric MSS and the recently released GOCO02S geoid, provides for the first time a new, satellite-only estimate of Arctic Ocean MDT filtered to 250 km. Filtering of the MDT remains necessary to remove residual noise in both the MSS and geoid fields, and thereby restricts the wavelength at which features may be resolved. We compared the satellite-only MDT to an independent estimate derived using the EGM2008 geoid. The GOCO02S geoid, constructed entirely from satellite gravity and free from sea surface topography signals, provides a superior approach for accurate derivation of Arctic Ocean MDT on basin scales, in contrast to EGM2008, which assimilates altimeter data. Our satellite-only MDT estimate describes the major features of Arctic Ocean dynamical

height including the Beaufort and Greenland Gyres, the Transpolar Drift and East Greenland Current, and reveals a steep MSS gradient from the Pacific to Atlantic sectors of the Arctic. Resolving the more detailed, small-scale structure of Arctic Ocean circulation such as stationary eddies remains elusive; the paucity of short-wavelength detail in the geoid has now become the limiting factor.

[18] The use of satellite-only data for deriving MDT demonstrates that long-term observation of Arctic Ocean circulation is now possible. Satellite radar altimeters, such as CryoSat-2, continually profile the Arctic Ocean throughout the year, such that analysis of the full, long-term radar altimeter dataset should provide details of seasonal SSH variability. The ICEn MSS offers complete coverage from 66 °N to 86 °N; new observations from CryoSat-2 should help to fill the “polar hole” above 86 °N to 88 °N. Observational continuity into the latter half of this decade is expected with the launch of ICESat-2 planned for 2016. Together with future advances in Arctic geoid modeling these satellite altimetry data will improve our understanding of Arctic Ocean circulation and its inter-annual variability.

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