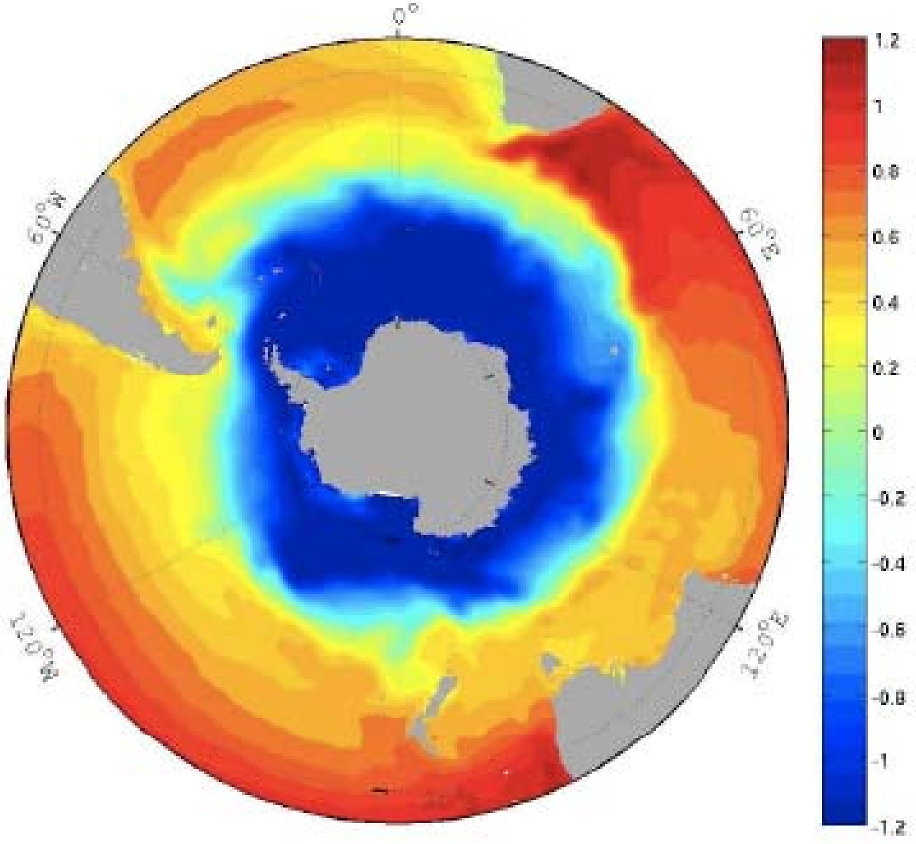
Assessing Mean Dynamic Ocean Topography Using State Estimation Constraints

Sarah Gille,
Matt Mazloff
Bruce Cornuelle,

with
Alexa Griesel,
Thomas Krzemien

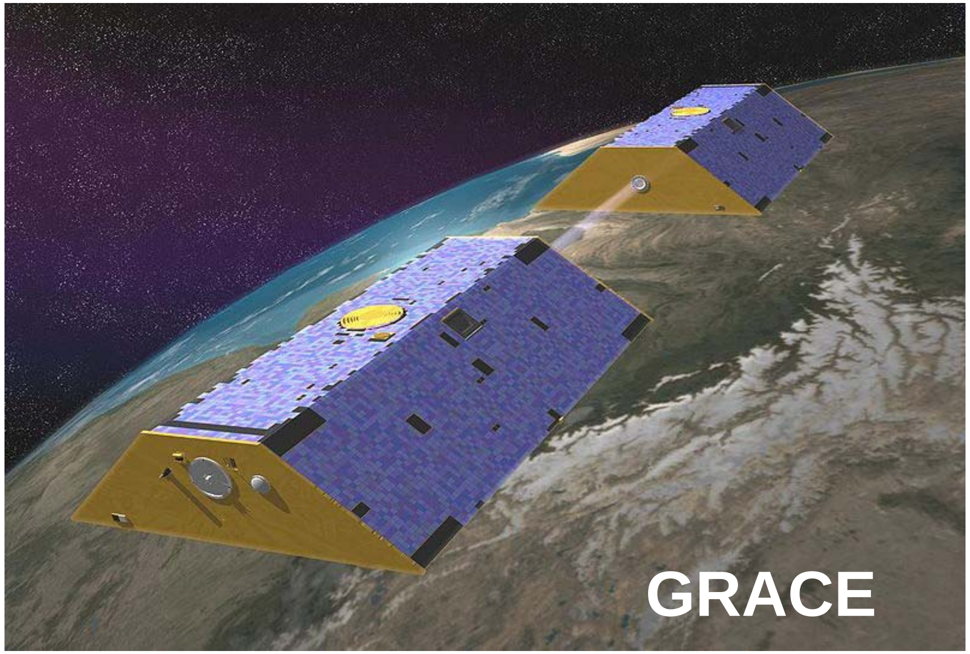
Scripps Institution of Oceanography, UCSD



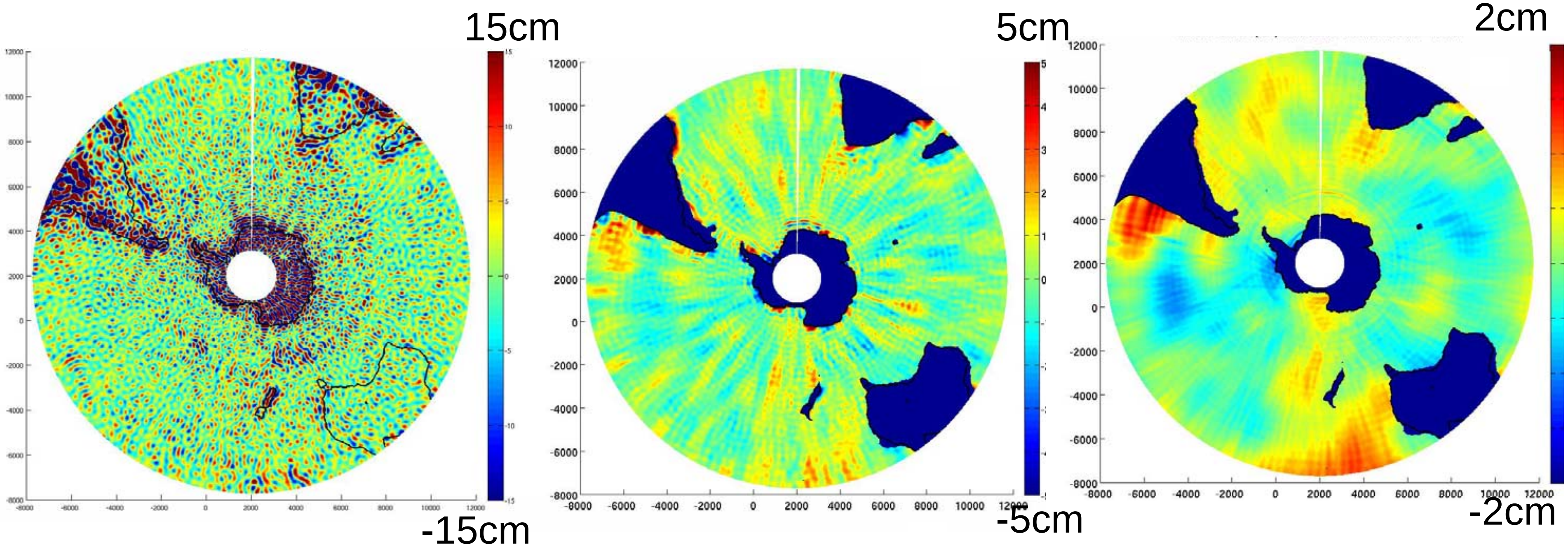
Dynamic Ocean Topography:
DOT2008A = MSS(DNSC08B) - Geoid(EGM08)

Challenge

- Evaluate new releases of geoids (from GRACE and GOCE) and new mean sea surface products.
- Ocean mean dynamic topography provides a stringent constraint on geoid performance. Want cm-scale accuracy (for mean dynamic topography)
- How to we deal with fact that geoid estimates are more accurate for large scale than for small scale?



Evaluated 2 geoid estimates: **EGM08** (Pavlis et al, 2012) & **TIMR3** (Pail et al, 2011)



No smoothing
(Omission error)

400 km smoothing
Commission error

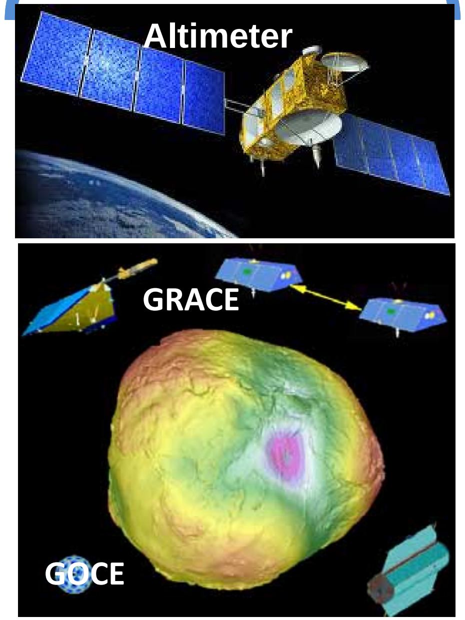
1500 km smoothing
Water mass shifts?

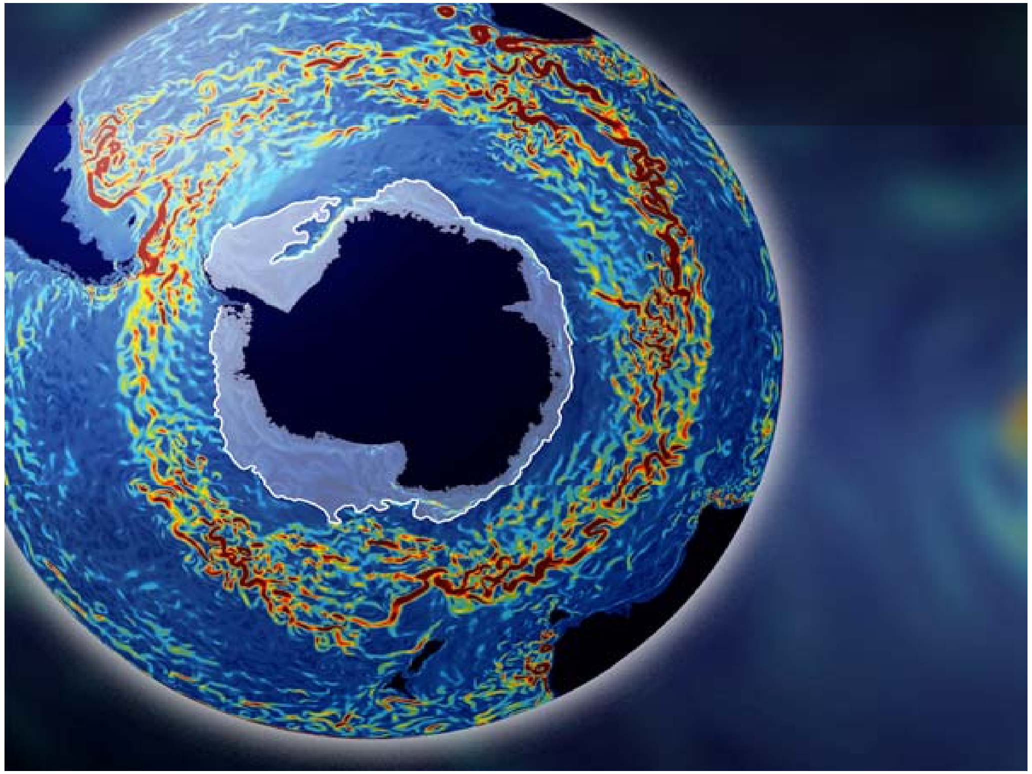
TIMR3 minus EGM08, both to degree 180

An ocean model–observation synthesis to evaluate geoid products

~ 10^7 In Situ Measurements

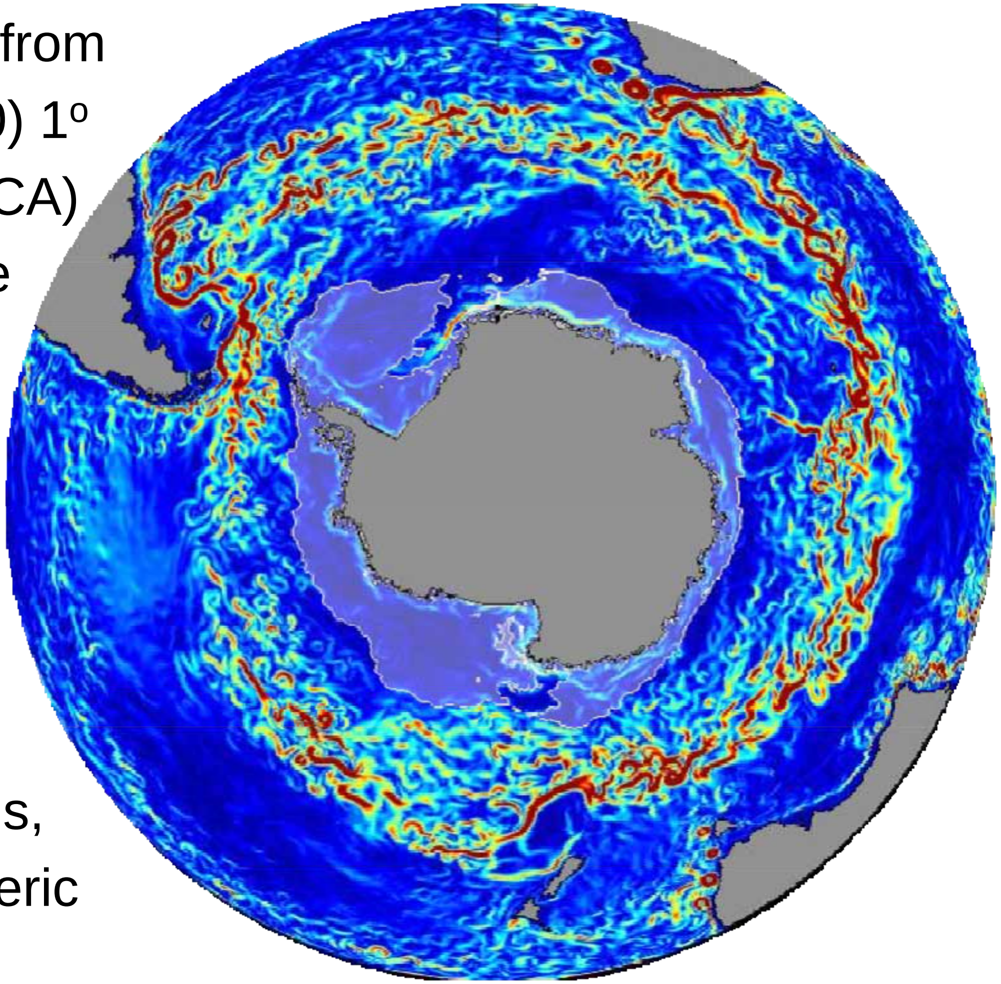
~ 10^9 Remote Measurements





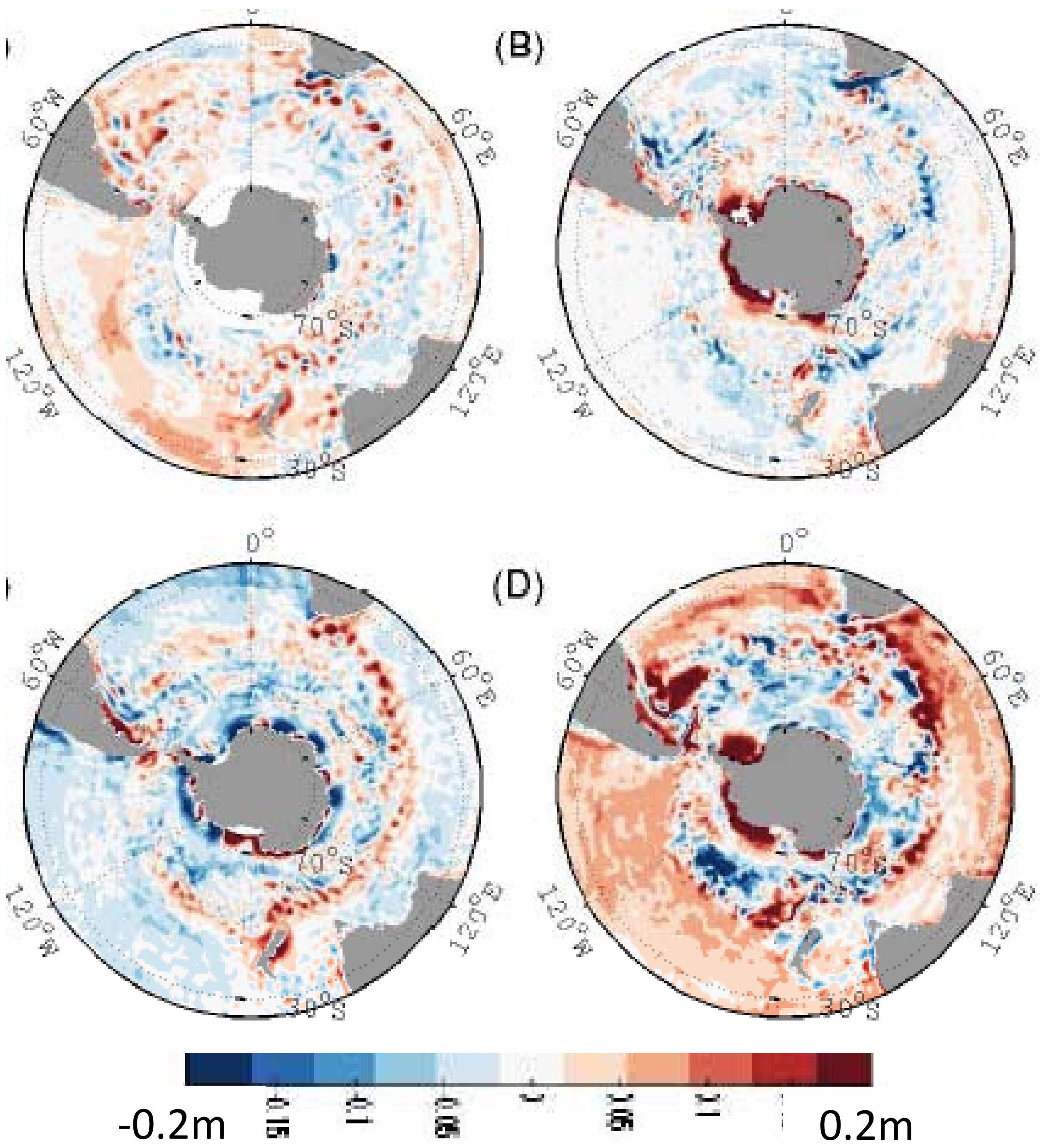
Southern Ocean State Estimate (SOSE)

Southern Ocean State Estimate (SOSE) Configuration



- 78^0 South to 24.7^0 South
- $1/6^0$ Horizontal resolution (eddy permitting)
- 42 depth levels (partial cells)
- ICs and open northern BCs derived from and constrained to G. Forget's (2010) 1^o resolution global state estimate (OCCA)
- Atmospheric boundary layer scheme
- Constrained to ERA-Interim re-analysis atmospheric state
- KPP mixed layer parameterization
- Full sea-ice model
- Adjoint generated via AD tool TAF
- Currently optimizing years 2008-10
- Currently controlling: initial conditions, northern boundary condition, atmospheric state.

MDT products are problematic



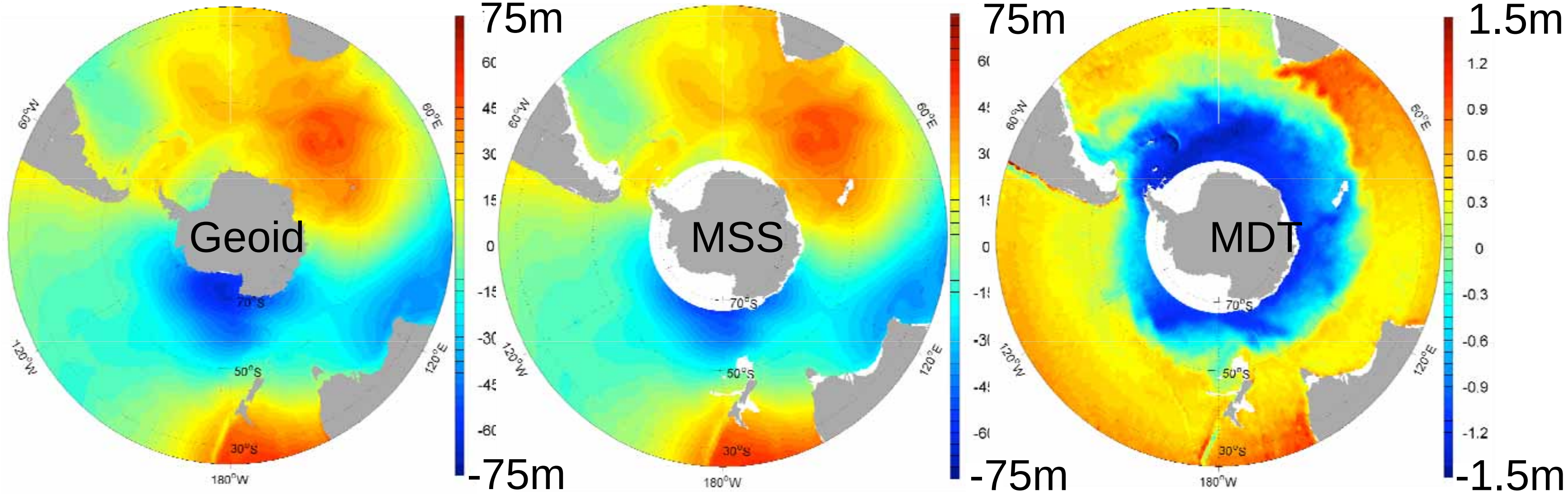
Differences in various MDT estimates [m]. Difference of DOT08A with (A) GGM02C (B) CNES-CLS09 (C) MN05 (D) SOSE

- Most evaluated were inconsistent with ocean mass conservation
- Differ substantially in regions of strong currents and complex topography, implying the sea state is a primary cause of the discrepancy.
- Accounting for temporal representation discrepancies is difficult due to substantial processing of products

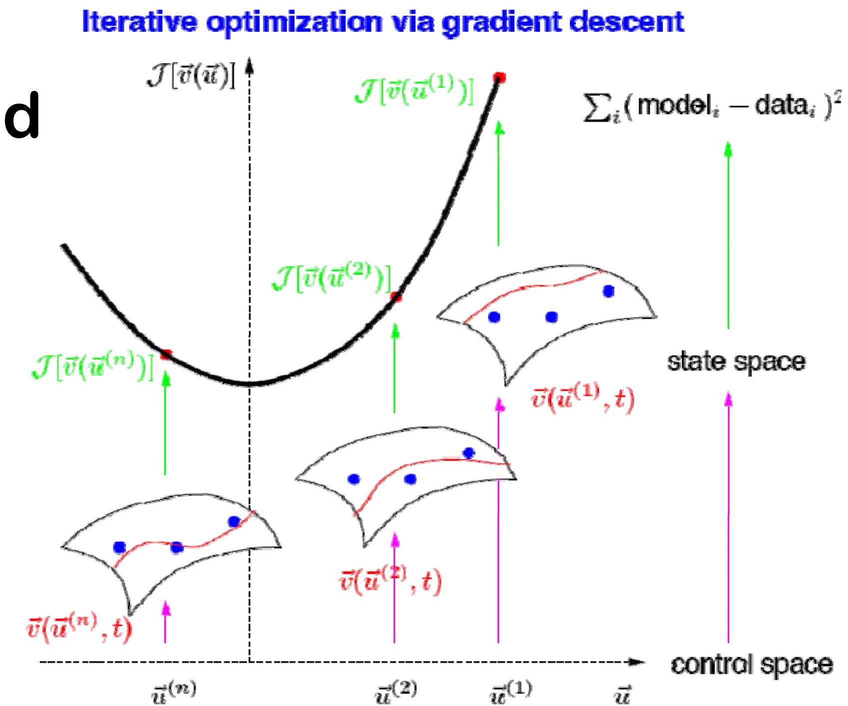
Griesel, Mazloff, Gille, JGR, 2012

Derive Mean Dynamic Topography: MDT = MSS – Geoid

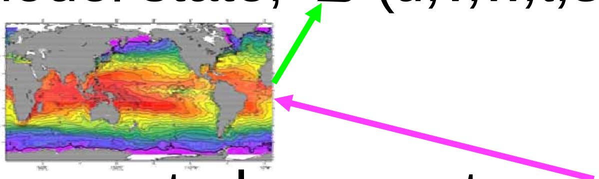
- Mean sea surface (MSS) products
  - Jason 1&2 averaged from 2008 to 2010 (RADS)
  - DNSC08 and DTU10
- Geoid products
  - TIMR3 (a GOCE only product)
  - EGM08 (GRACE + other gravity data)



Adjoint method (4D-Var): weighted least squares optimization



Find forward model state, $\mathcal{L}$ (u,v,w,t,s,p)



Model inputs are control parameters, ***u***

(e.g. param. coef., ini. cond., atm. state)

Define cost function: here a weighted model-observation misfit

$$\mathcal{J}(\mathbf{u}) = \Sigma\{\mathcal{L}_i - obs_i\}^2 \sigma_i^{-2} + \Sigma\{\mathbf{u}_j - data_j\}^2 \sigma_j^{-2}$$

Model state, and thus cost, is a function of controls: $\mathcal{L}(\mathbf{u})$

Optimization problem: adjust controls to minimize the cost

Adjoint model gives the gradient of $\mathcal{J}$ with respect to ***u*****:** $\nabla_{\mathbf{u}}\mathcal{J}(\mathbf{u})$

Use this information to infer update, $\Delta\mathbf{u}$, of controls:

$\mathbf{u}^{n+1} = \mathbf{u}^{n} + \Delta\mathbf{u}$ and iteratively minimize cost

Measuring the goodness of fit (cost) of an observationally inferred mean dynamic topography (MDT) to an ocean model derived MDT.

MDT cost is the weighted squared difference of the model MDT and the observed MSS minus the geoid:

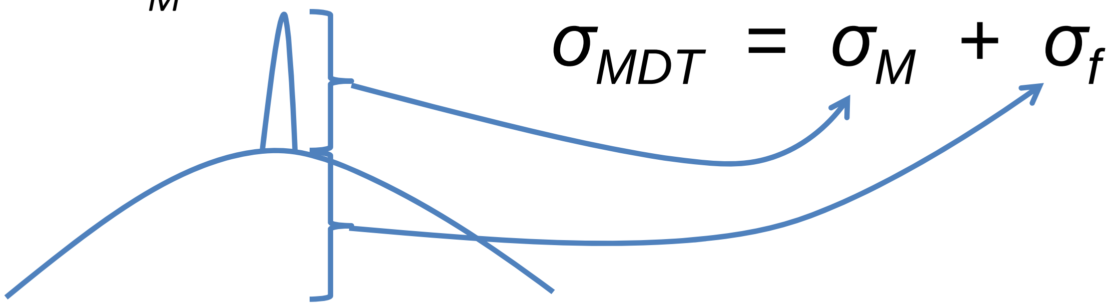
$$J_M = [MDT_{\text{model}} - (MSS - G - F)\ ]^2 \sigma_M^{-2} + F^2 \sigma_f^{-2}]$$

Uncertainty, σ_M, results from altimeter accuracy, standard error in sampling, model representation, and uncertainty in the geoid

Computational limits allow only error variances to be prescribed in σ_M.

Account for correlated error by solving for a smooth adjustment field, *F(x,y)*

“Soaking up” correlated error into *F* allows significant reduction of the magnitude of σ_M.

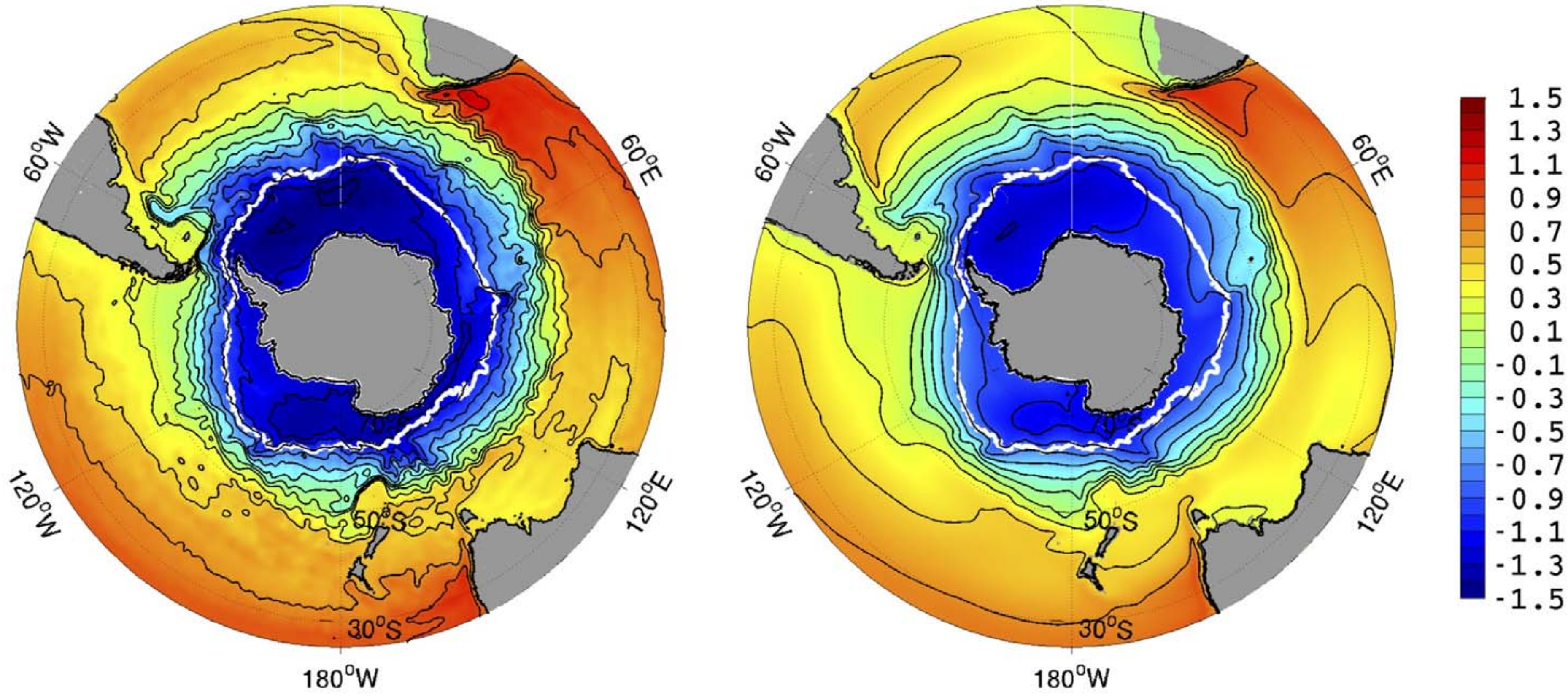


$$\sigma_{MDT} = \sigma_M + \sigma_f$$

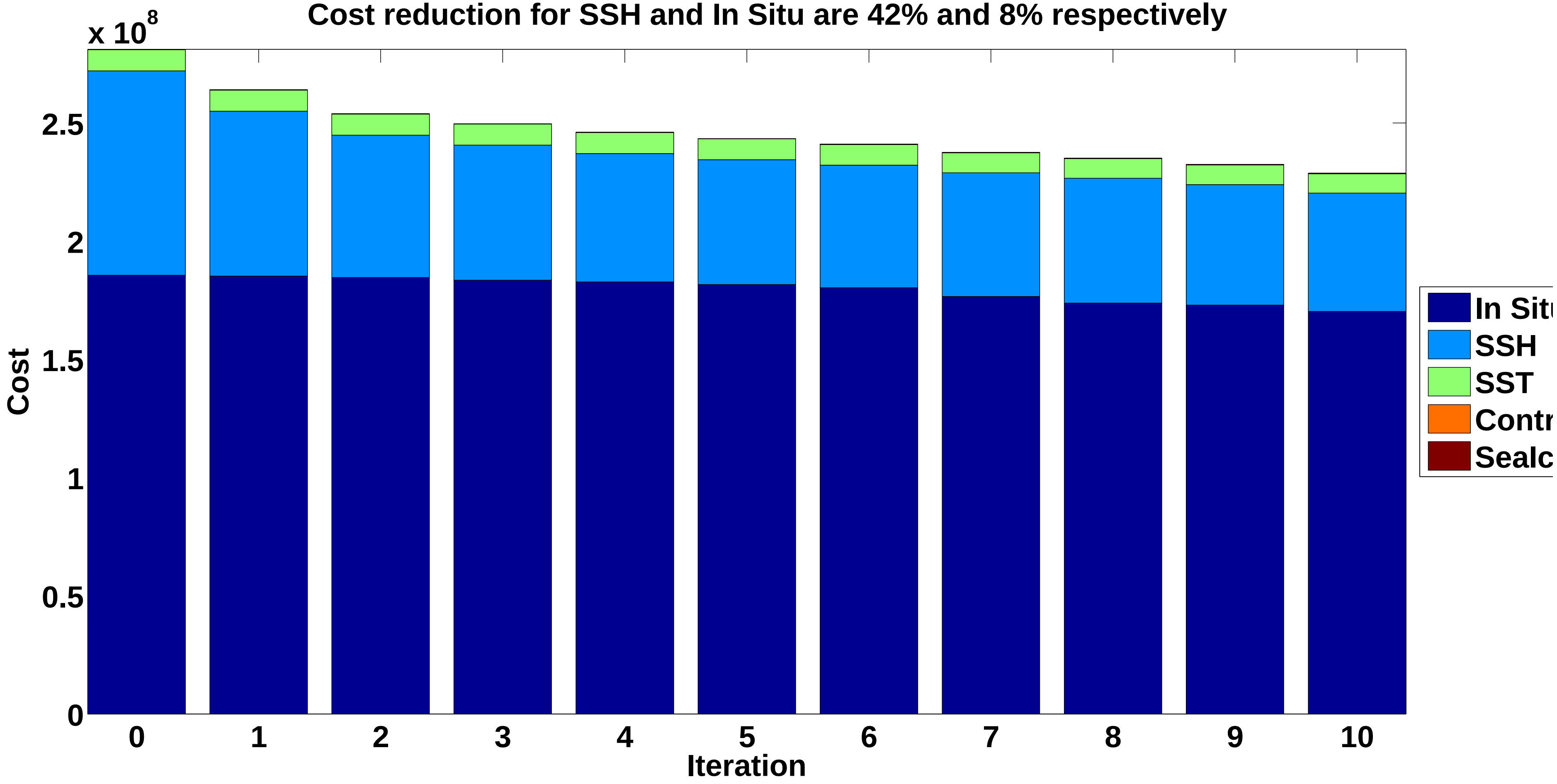
Solving for *F* yields an estimated MDT adjustment

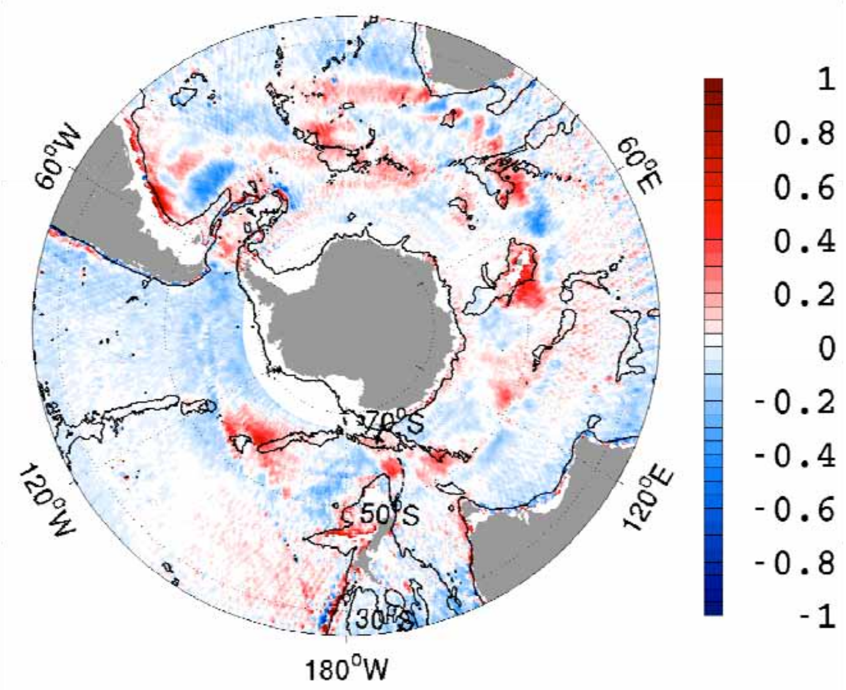
To develop the methodology for evaluating product consistency with our knowledge of ocean physics we first use a test bed 1/3^o resolution (non-eddying) solution.

Mean dynamic topography from eddy permitting solution (left) and from 1/3^o degree test bed (right).



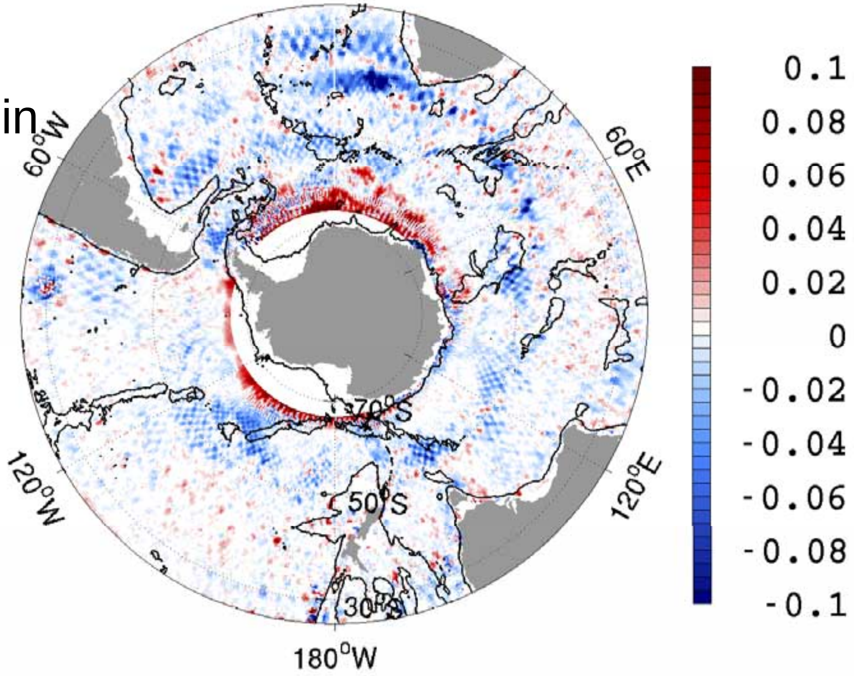
10 iterations in the 1/3° test bed. Cost (i.e. weighted misfit squared) with respect to sea surface height constraints was reduced 42%



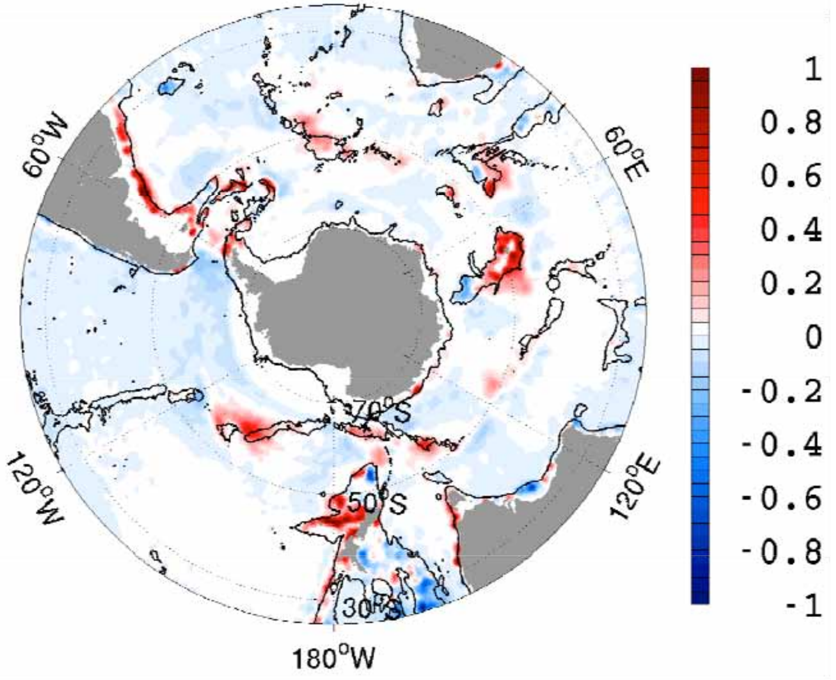


Initial MDT Misfit (m)

Change in absolute value of misfit



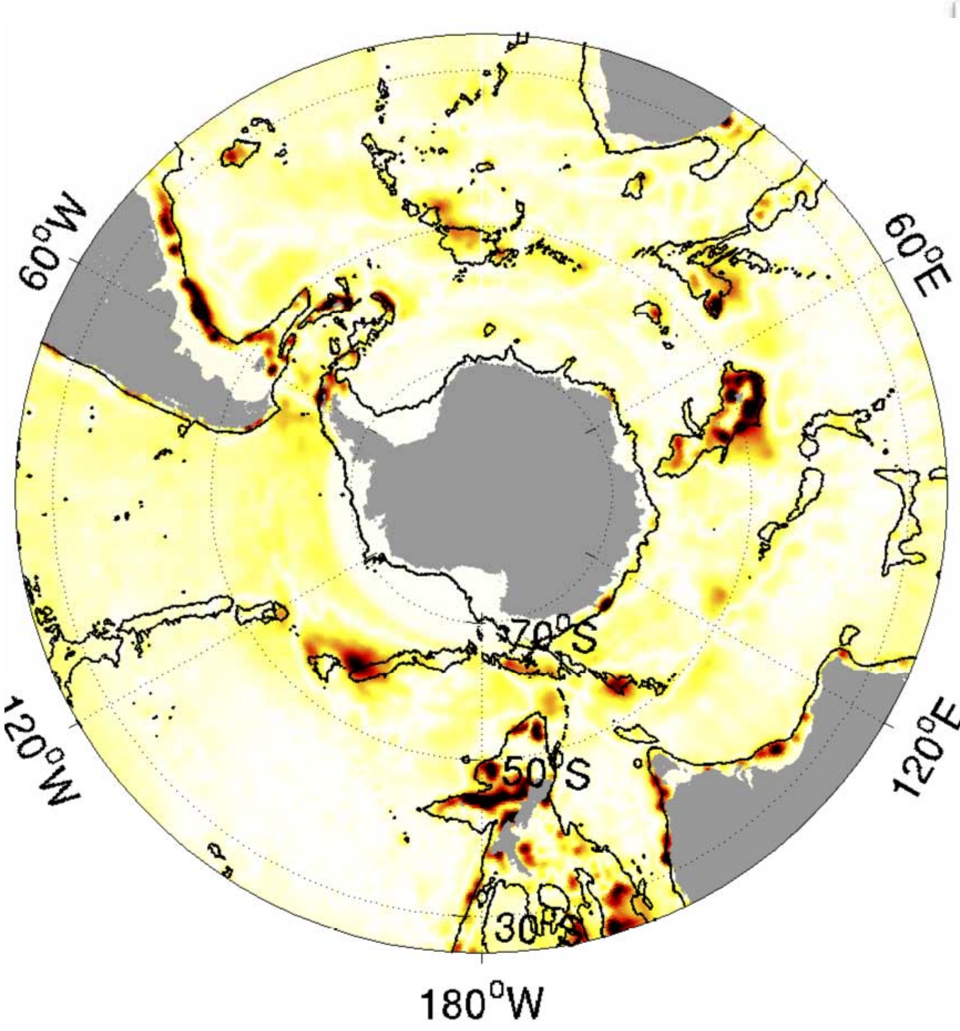
MDT adjustment field

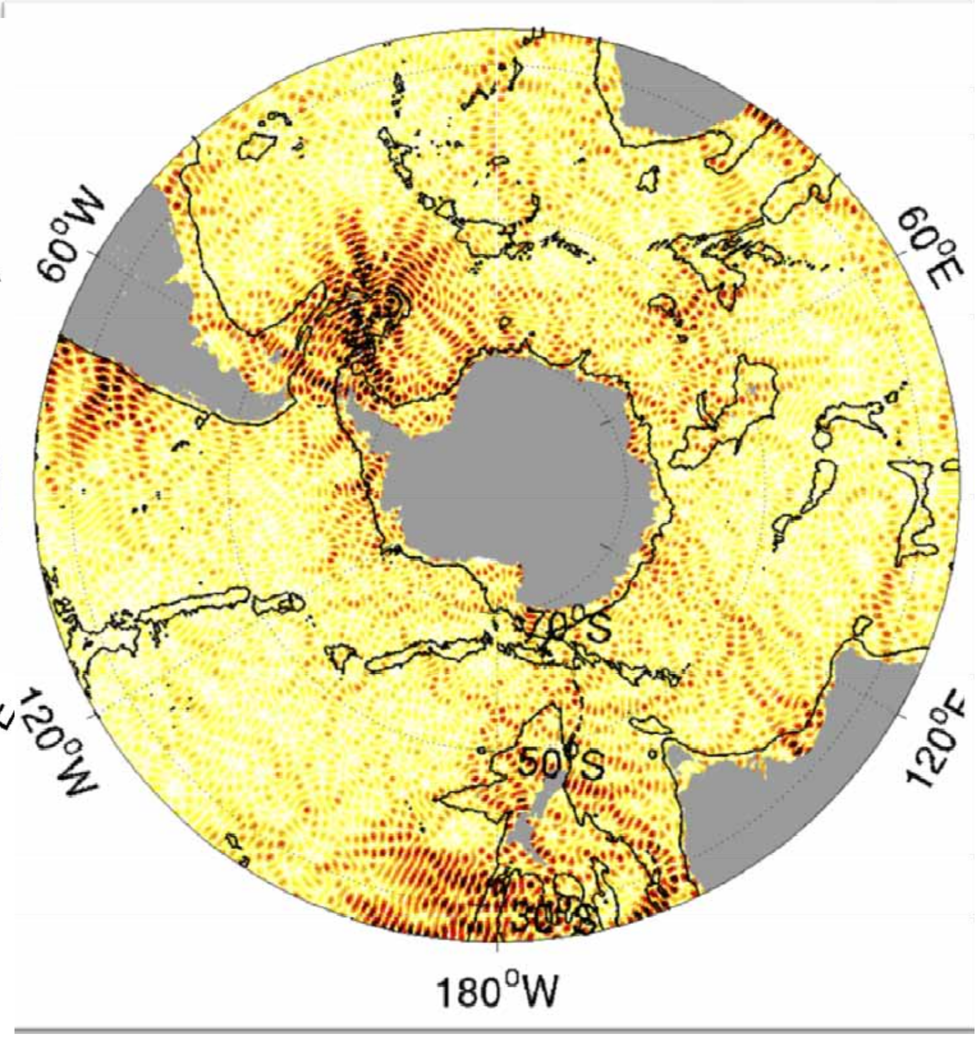


Neither misfit change nor adjusted field looks exactly like initial misfit

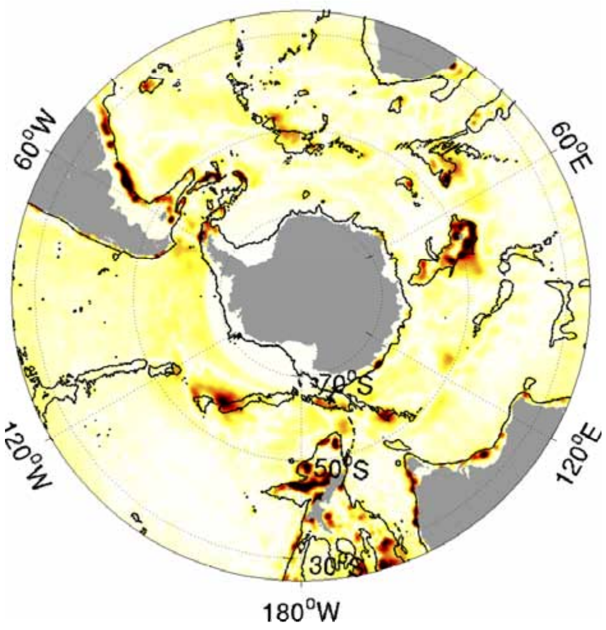
Absolute value of the estimated MDT adjustment

Absolute value of the difference of TIMR3 degree 200 and degree 180: i.e. where higher-resolution information provided by the GOCE satellite has improved the geoid



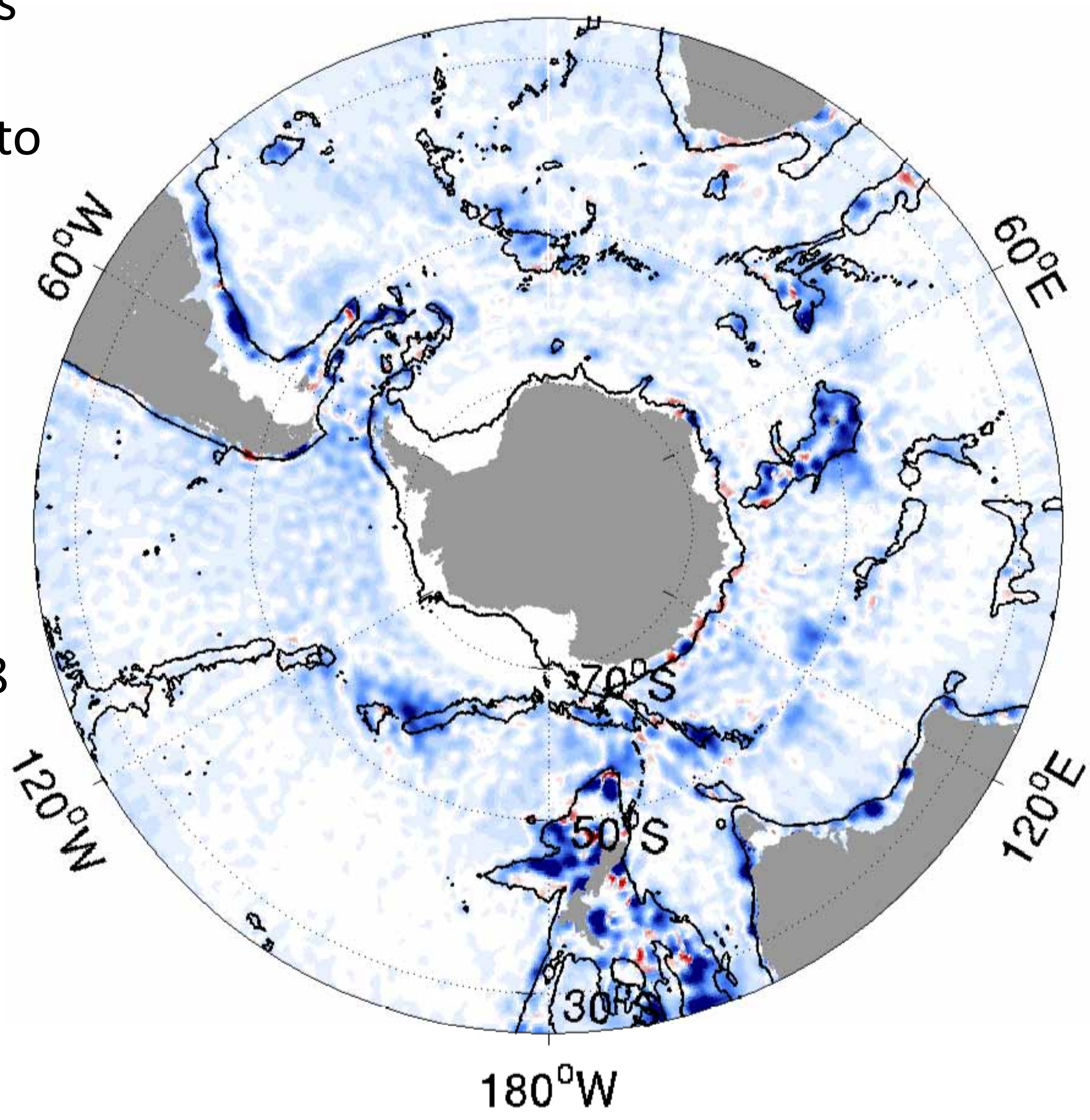


Summary



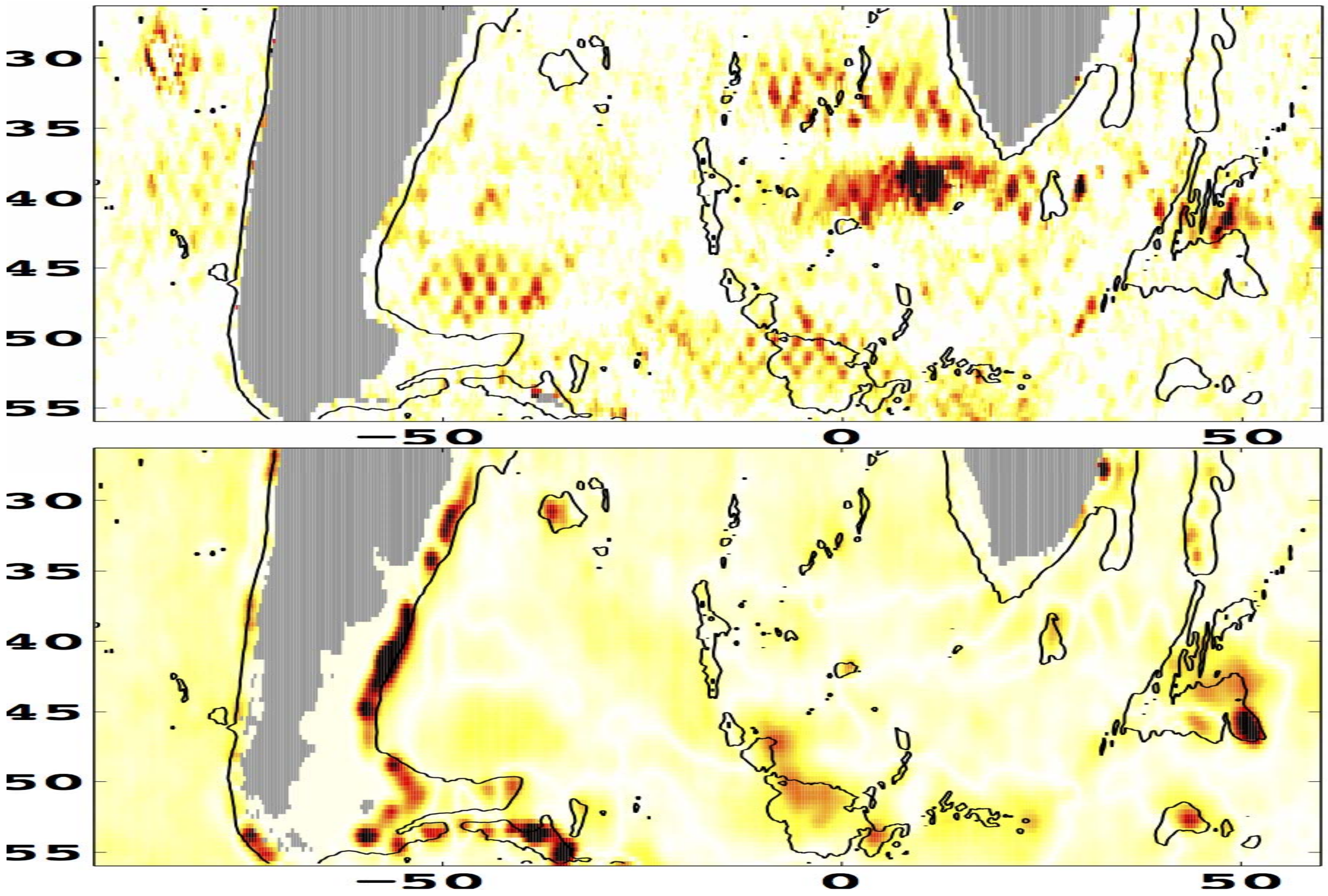
- Use geoid and mean sea surface height to constrain assimilating model (SOSE).
- Account for spatially correlated error in ocean assimilation constraints, by solving for error structure.
- Large error structure coincides with locations where GOCE is providing refined geoid structure.

- Absolute value of the adjustment for EGM08 minus absolute value of the adjustment for TIMR3, both to degree 180.
- Blue (red) denotes better model consistency with EGM08 (TIMR3)
- The other constraints are far more consistent with EGM08 to degree 180. This is partly because EGM08 is informed by altimetric measurements of sea surface height from degree ~90 to 180



- Extra slides

Top: Where misfit was reduced by changing the ocean state
Bottom: Absolute value of the estimated MDT adjustment

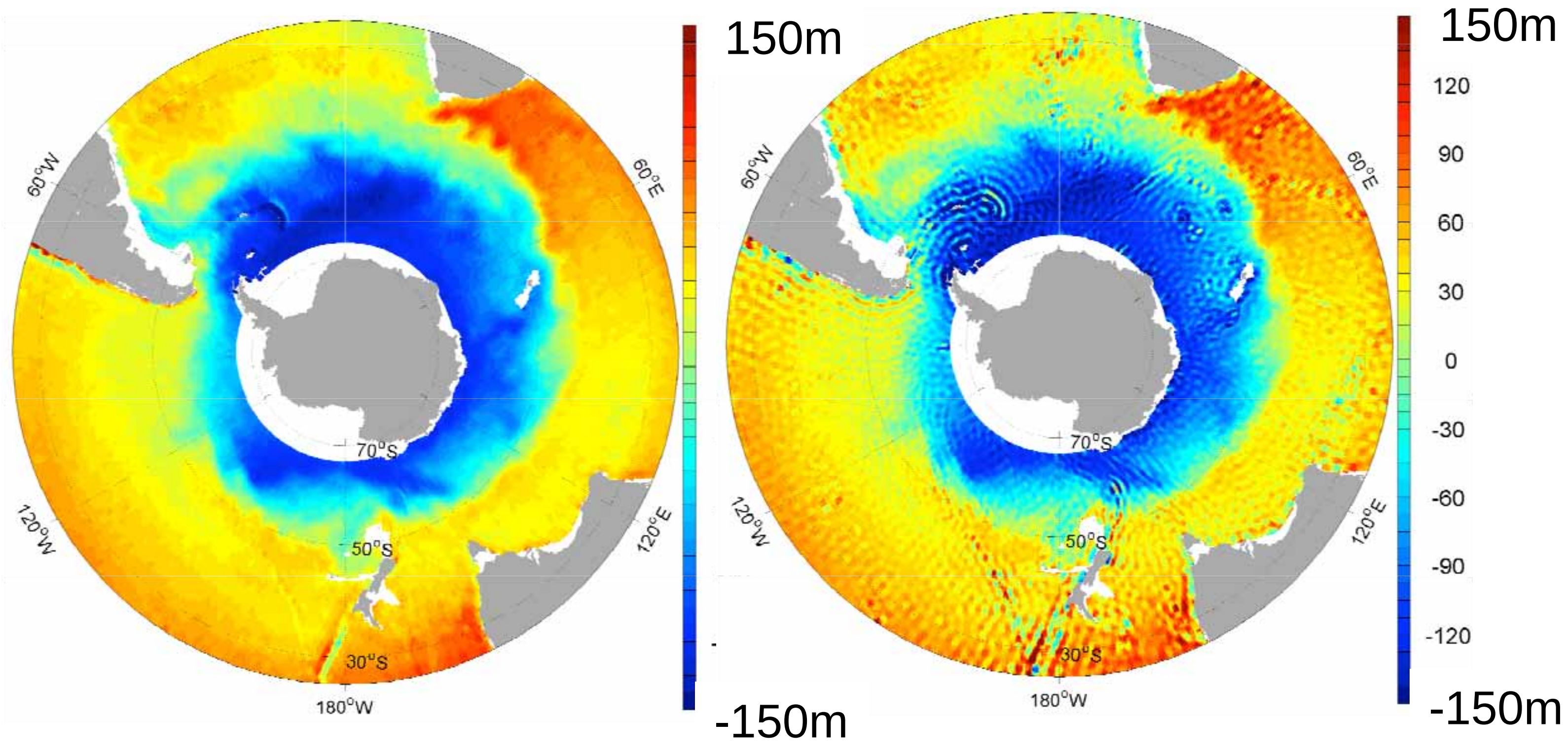


We evaluated two gridded geoid estimates:

- **EGM08** (Pavlis et al, 2012) estimate of both high and low degree geoid relying largely on GRACE observations.
- **TIMR3** (Pail et al, 2011) estimate of low degree geoid relying on GOCE

The GRACE-GOCE performance cross-over is around degree 140

The gridded geoid is required to high degree,
MDT [cm] using EGM08 to degree 2190 (left) & degree 180 (right)



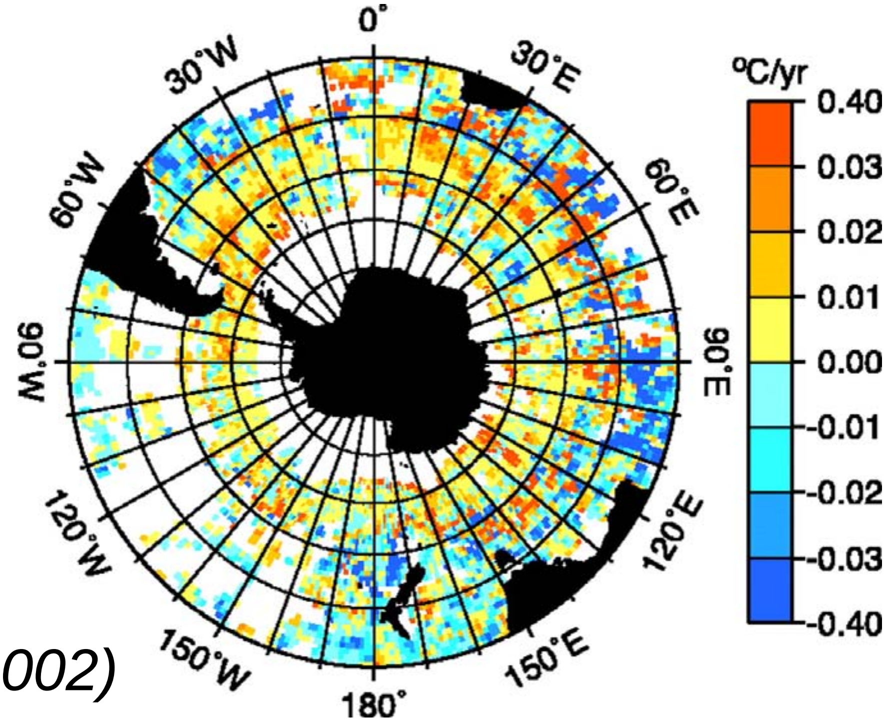
We focus on the Southern Ocean MDT. Reasons:

Difficulty, and thus a stringent test of products:

- Observational challenges: remote & presence of ice
- Ocean has high temporal variability & short length-scales

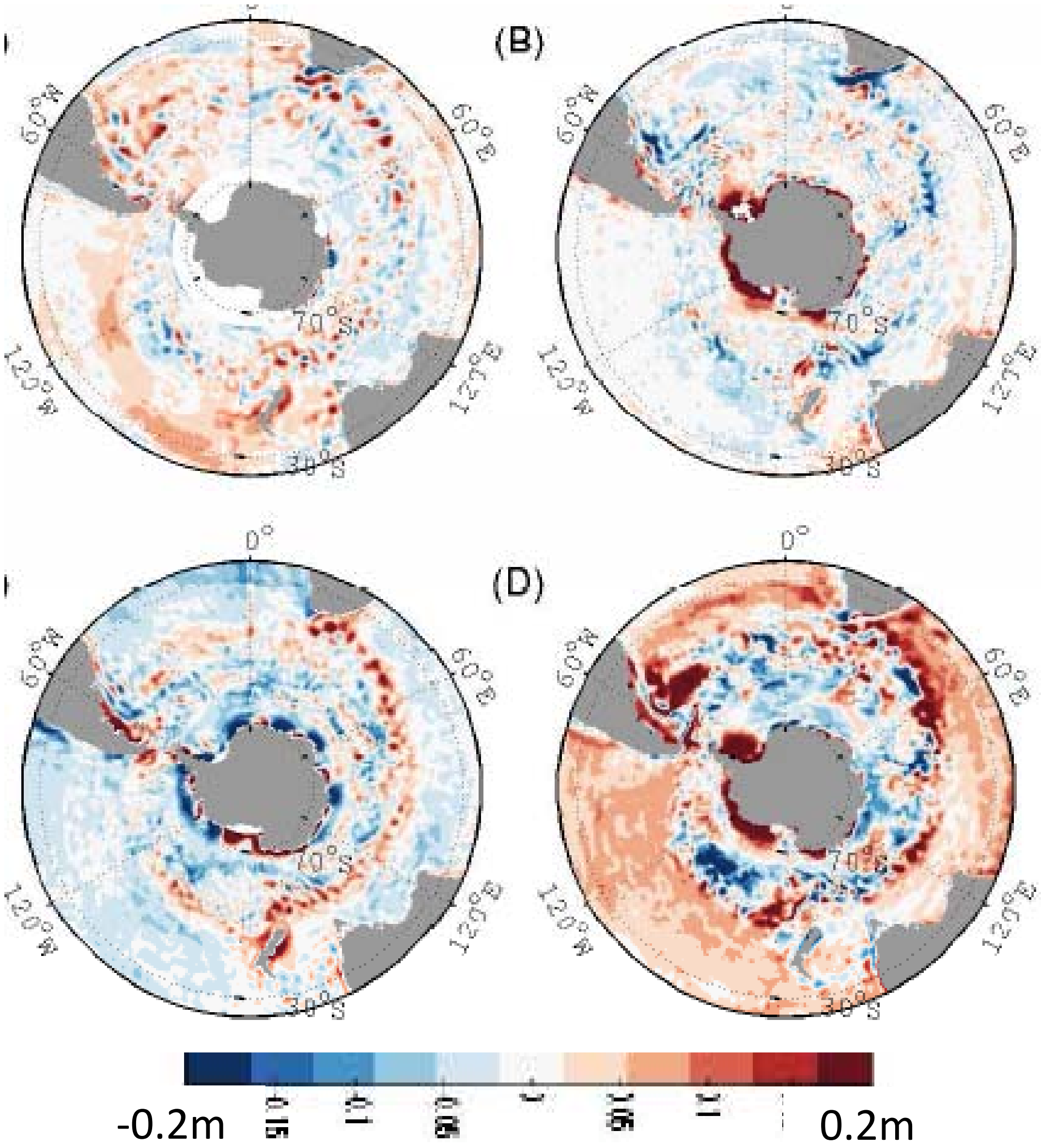
Importance to the Earth system:

- Transport: connects the other major ocean basins and one of the few regions where the deep ocean is connected to the surface
- Key role in climate system via heat and carbon exchange with the atmosphere. Major source of nutrient resupply.
- Undergoing significant change with implications for glacial melt and thus sea level rise



Long-term warming trends in the Southern Ocean (Gille, Science, 2002)

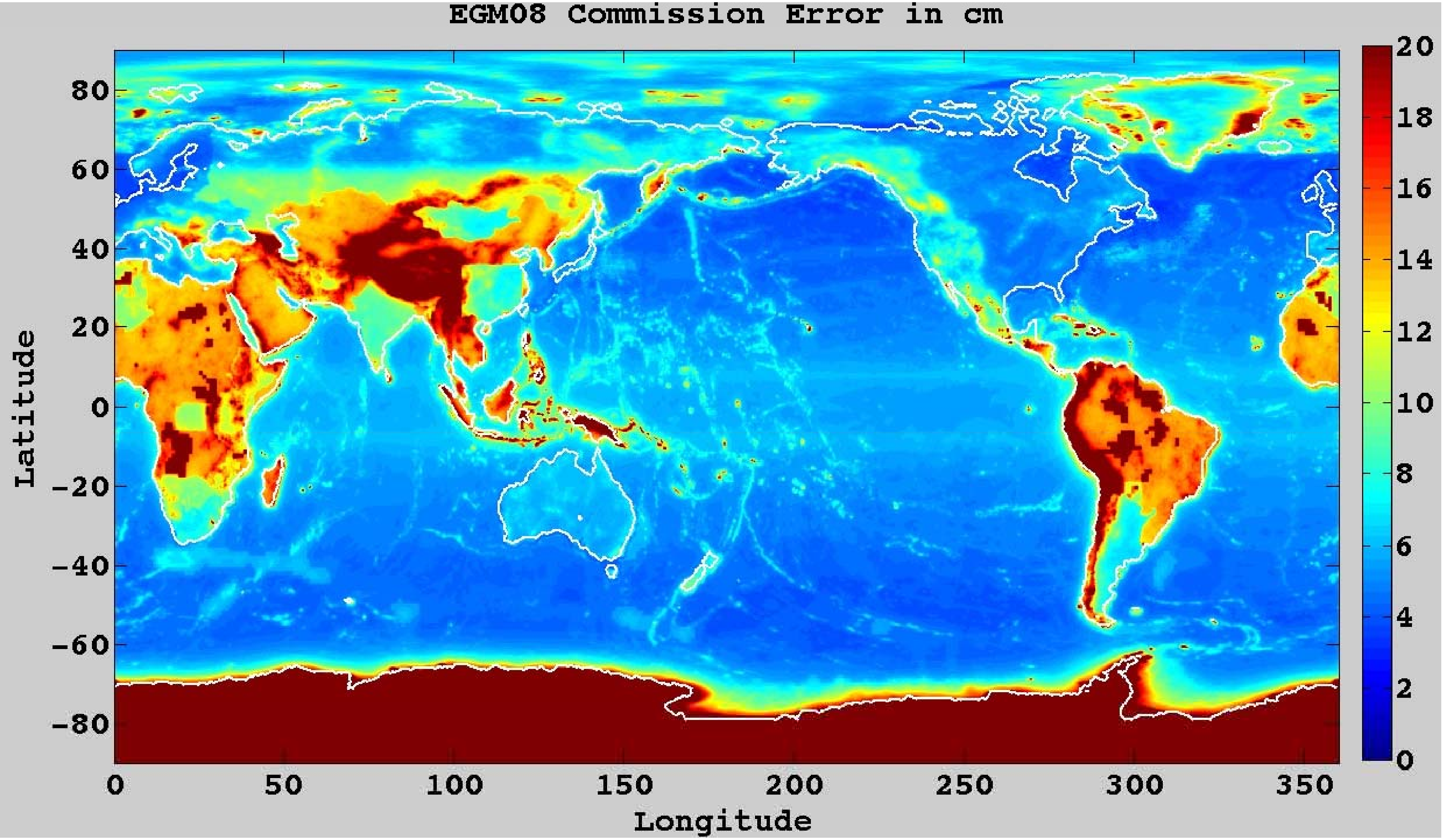
MDT products are problematic



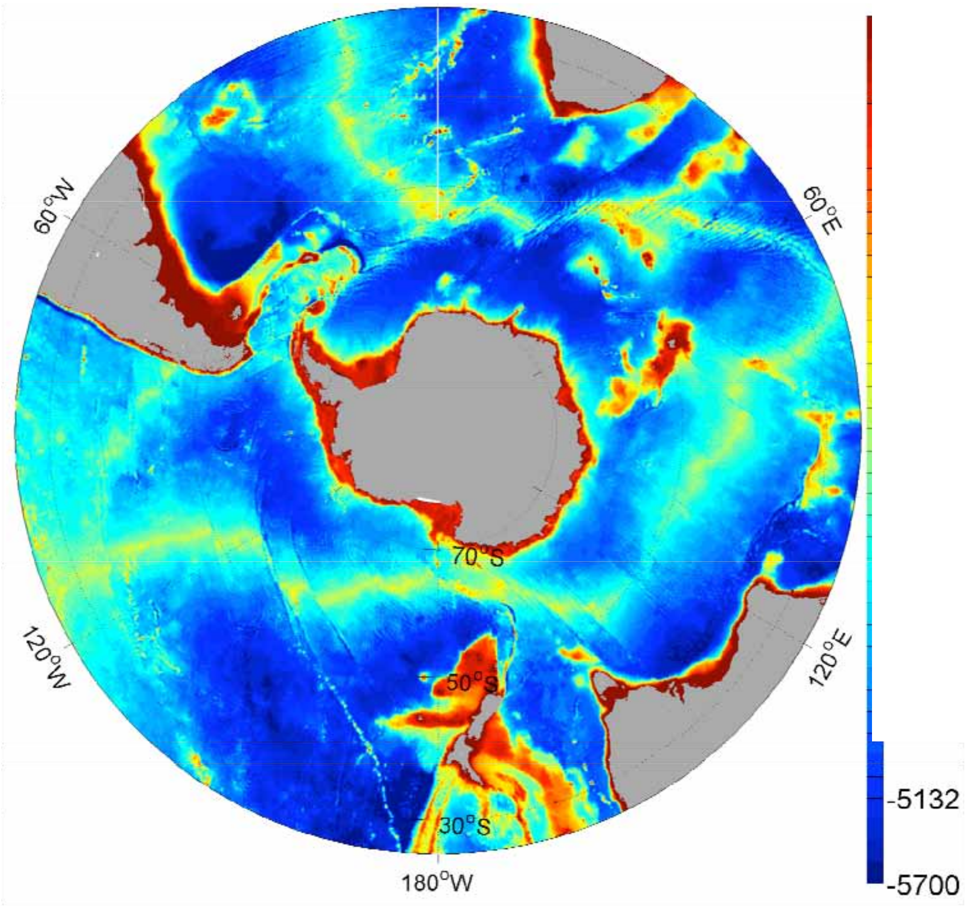
Differences in various MDT estimates [m]. Difference of DOT08A with (A) GGM02C (B) CNES-CLS09 (C) MN05 (D) SOSE

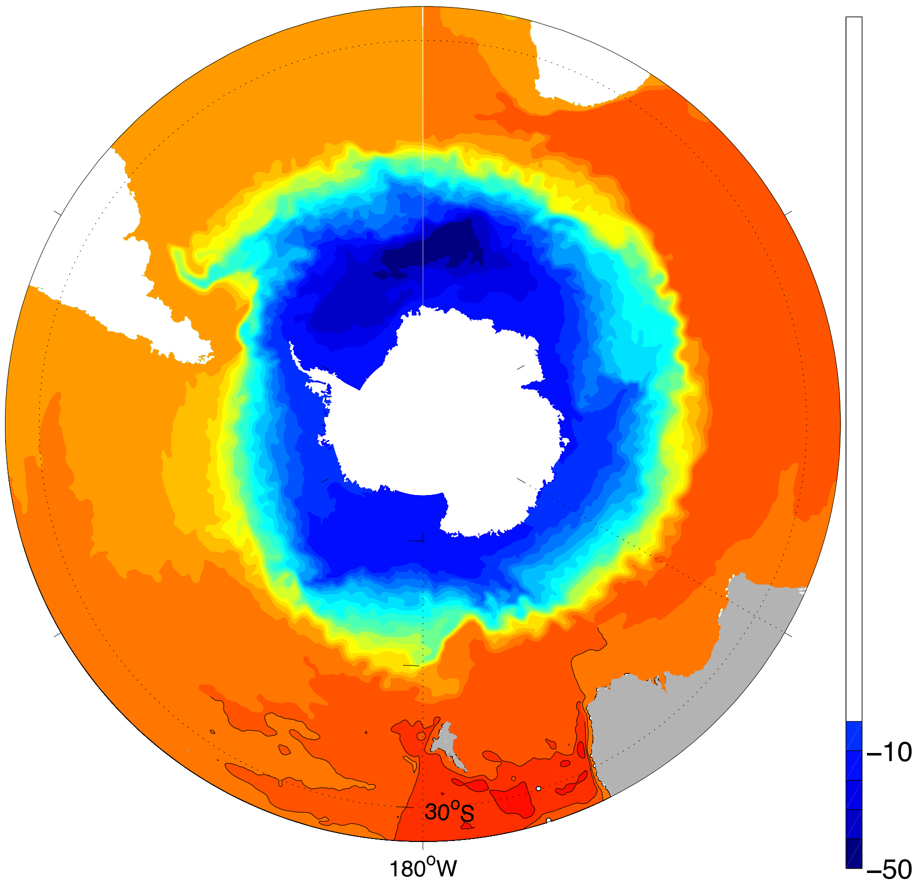
- Most evaluated were inconsistent with ocean mass conservation
- Differ substantially in regions of strong currents and complex topography, implying the sea state is a primary cause of the discrepancy.
- Accounting for temporal representation discrepancies is difficult due to substantial processing of products
- More practical to use gridded geoid products combined with temporally relevant MSS

Nominal commission field for EGM08 [cm]



SOSE bathymetry in meters (left) and SOSE streamfunction in Sv (right)





Reference information

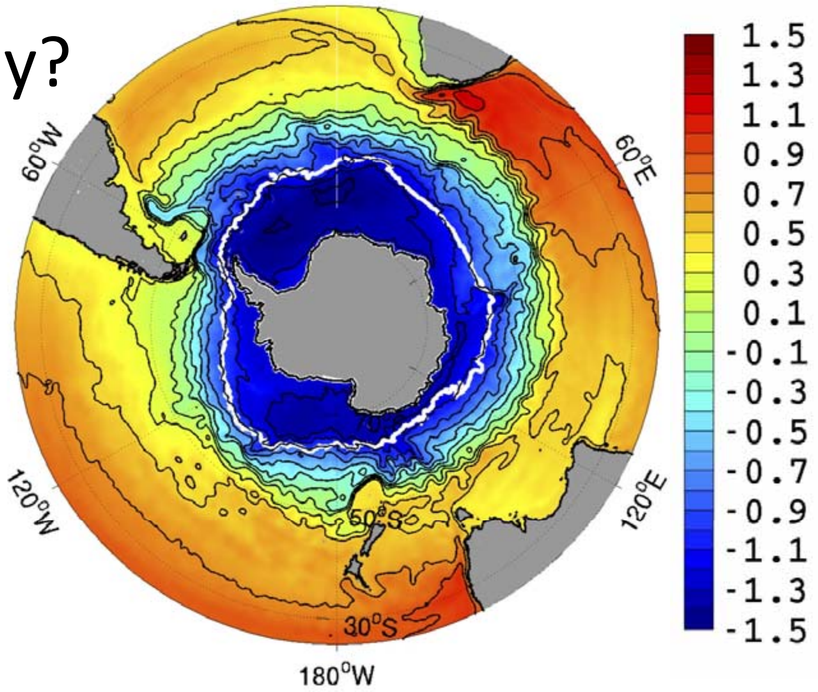
TIMR3: Pail R., S. Bruinsma, F. Migliaccio, C. Foerste, H. Goiginger, W.-D. Schuh,E. Hoeck,M. Reguzzoni, J.M. Brockmann, O. Abrikosov, M. Veicherts, T. Fecher, R. Mayrhofer, I. Krasbutter, F. Sanso, and C.C. Tscherning (2011): First GOCE gravity field models derived by three different approaches, *J. Geodesy*, 85, DOI 10.1007/s00190-011-0467-x

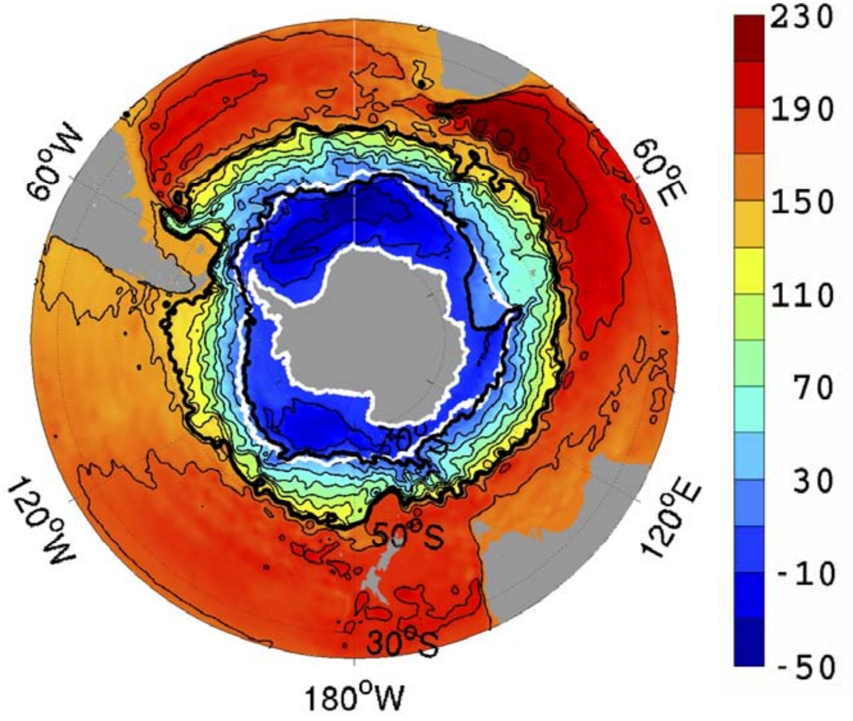
EGM08: Pavlis, N. K., S. A. Holmes, S. C. Kenyon, and J. K. Factor (2012): The development and evaluation of the Earth Gravitational Model 2008 (EGM2008), J. Geophys. Res., 117, B04406, doi:10.1029/2011JB008916.

Griesel A., M. Mazloff, and S.T. Gille (2012): Mean dynamic topography in the Southern Ocean: Evaluating Antarctic Circumpolar Current transport. J. Geophys. Res., 117, C01020, doi:10.1029/2011JC007573

What is dynamic ocean topography?

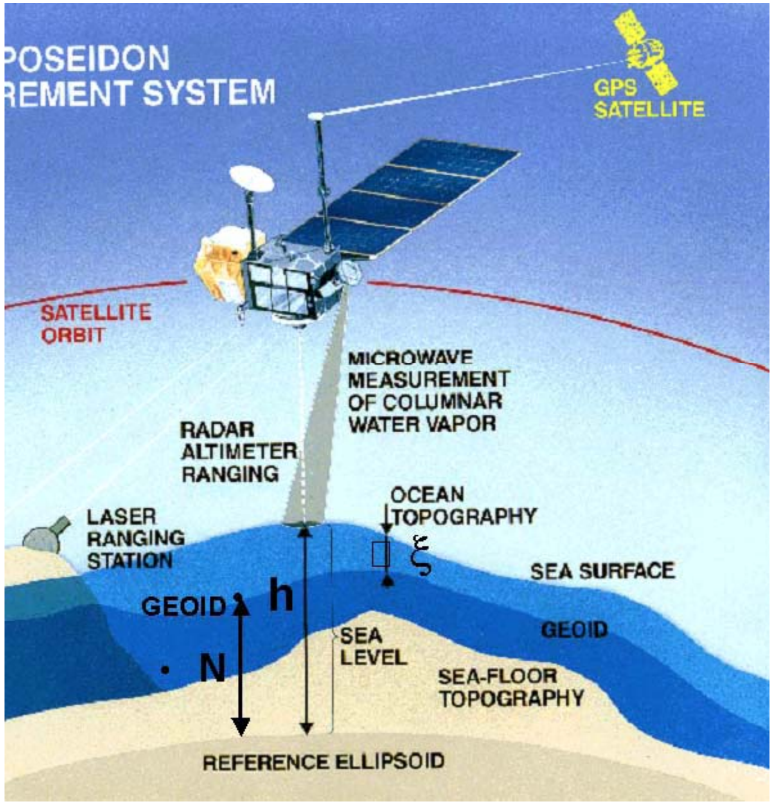
- Height of sea surface relative to geoid, due to ocean circulation.
- Gradients indicate ocean currents
- Top: mean dynamic ocean topography (MDT) in meters
- Bottom: vertically integrated transport streamfunction in Sverdrups = $10^6 m^3/s$

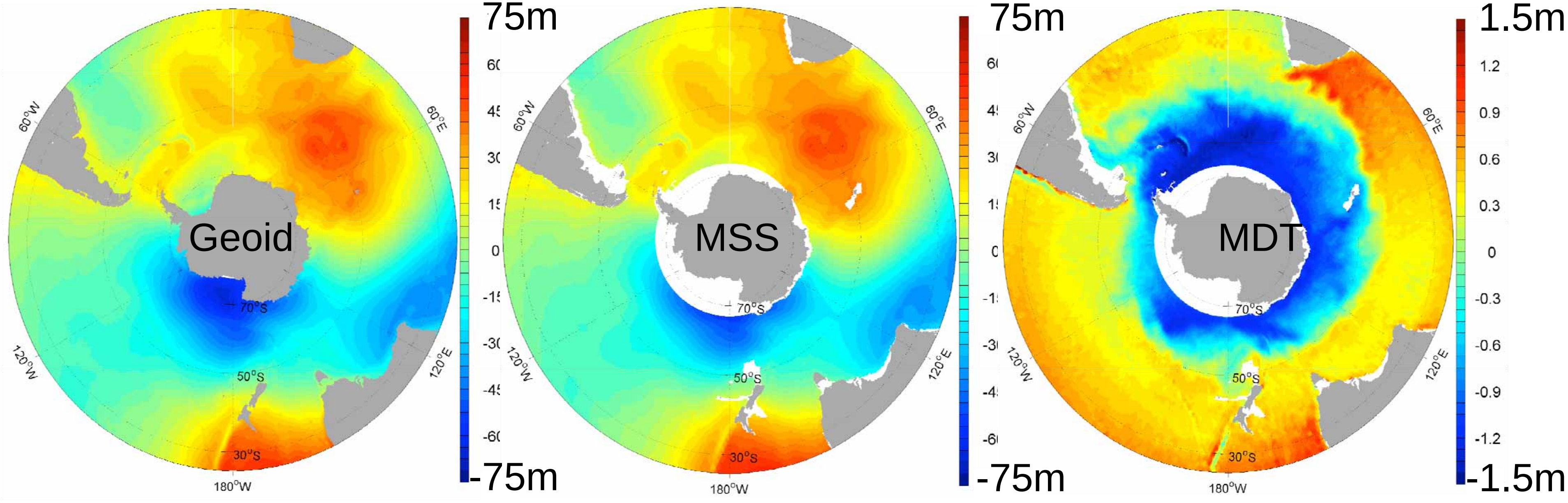




Determining dynamic ocean topography

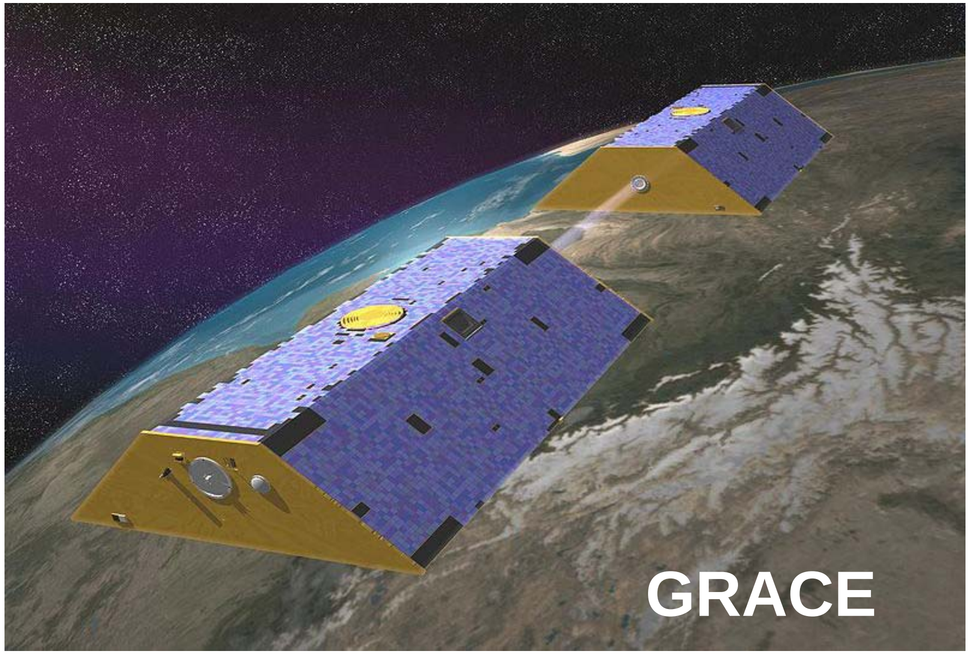
- High-precision satellite altimeters give mean sea surface height (MSS)
- The small residual between MSS and geoid is the mean dynamic ocean topography (MDT)
- MDT uncertainty is combination of uncertainty in both MSS and geoid: $\sigma_{MDT}^2 = \sigma_{MSS}^2 + \sigma_{geoid}^2$





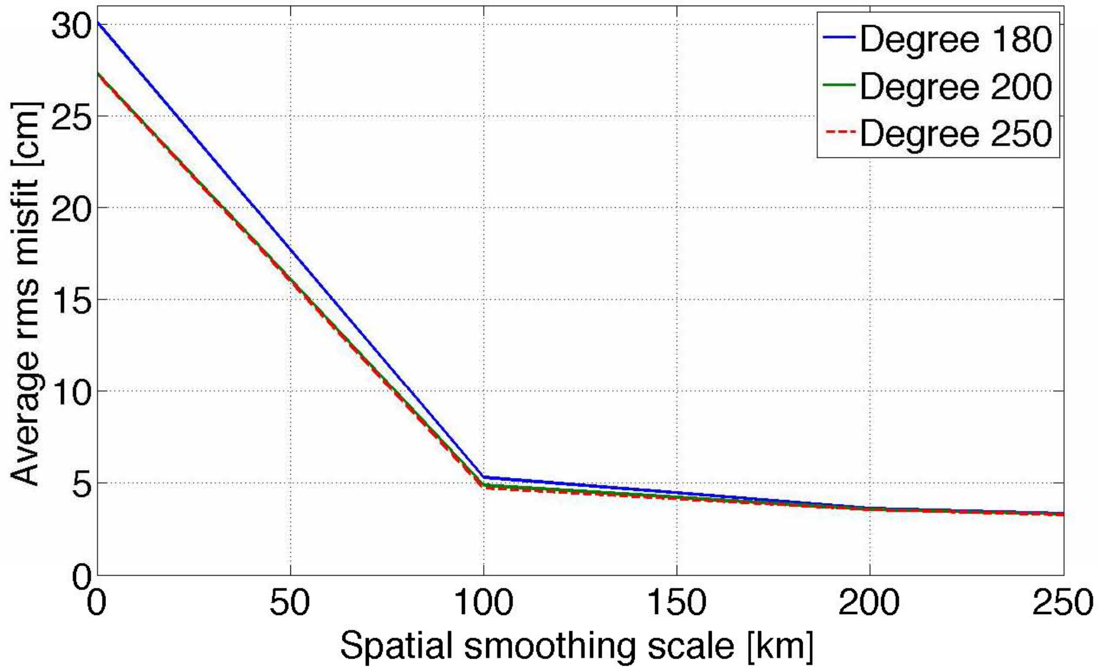
Geoid Determination

- The Gravity Recovery And Climate Experiment (GRACE) yields estimates of the Earth's geoid to ≈250km.
- Independent validations (e.g. orbit fit tests) have proven the geoid error quite small on length scales greater than ≈110km
- The Gravity field and steady-state Ocean Circulation Explorer (GOCE) and other planned satellite missions aim to further increase spatial resolution
- Terrestrial observations and satellite altimetry are used to determine the geoid at higher-wavelengths.



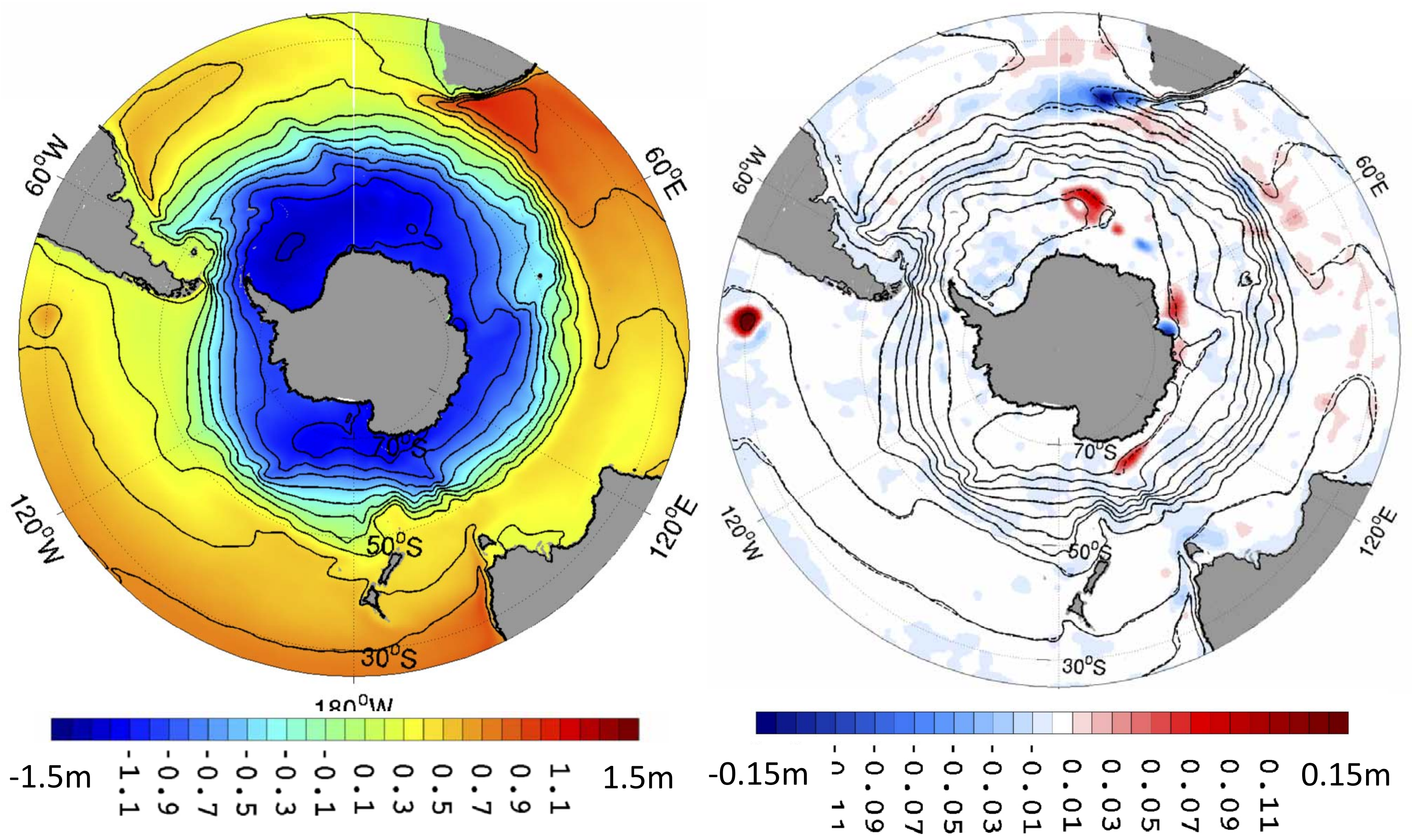
- RMS difference of TIMR3 to degree 180, 200, and 250 to various high resolution geoid estimates is consistent for each product.
- Mean RMS difference is 29.6cm, 27.2cm, and 27.2 cm for degree 180, 200, and 250 respectively. An ~8% reduction in misfit.

VS	EGM08 (degree 2190)
TIMR3 (degree 180)	29.78
TIMR3 (degree 200)	26.96
TIMR3 (degree 250)	26.90



When misfit smoothed the difference vanishes at ~100km, as expected

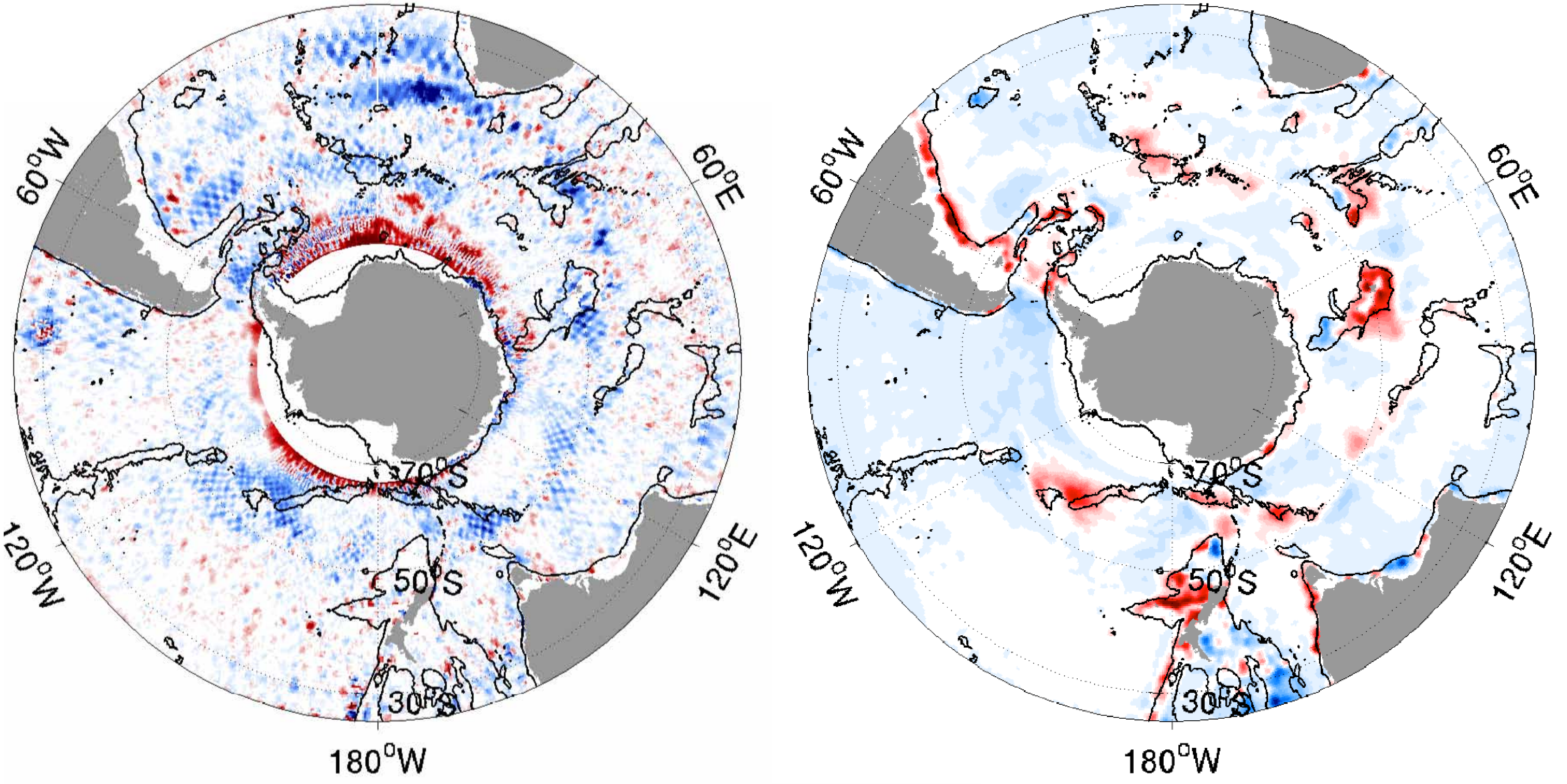
- Conclusions regarding added value thus far of the Gravity field and steady-state Ocean Circulation Explorer (GOCE)
    - Degree 200 appears better than 180
    - Degree 250 does not show obvious improvement over 200
    - Misfit (≈5cm) is found at all spatial scales (partly due to time variability of the geoid)



Left: Optimized mean dynamic topography (MDT) in 1/3^{o} model

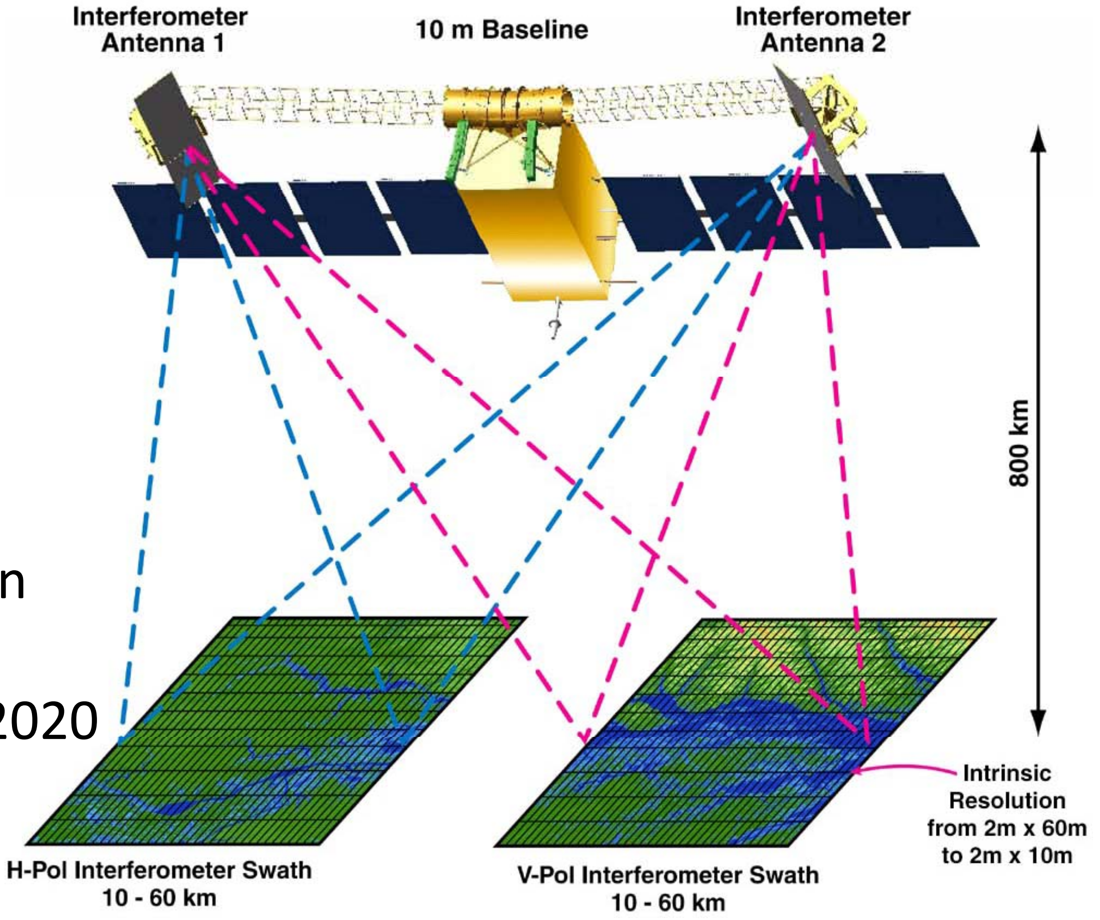
Right: Change in MDT due to optimization

Results from the optimization:
Left: Misfit accounted for by changing the estimated MDT
Right: Adjustment made to the MDT constraint



Future work

- Continued analysis and optimization of adjustment field
- Partition adjustment field – can we determine what component is due to geoid errors as oppose to mean sea surface errors, etc?
- Transition method of accounting for error correlation in ocean synthesis to other groups and for other observational platforms
- Evaluate new geoid products
- Prepare for swath altimetry



The Surface Water Ocean Topography (SWOT) altimeter will launch in 2020