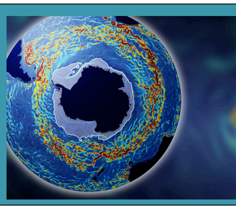

Southern Ocean hydrography and circulation

The Southern Ocean State Estimate (SOSE) resource

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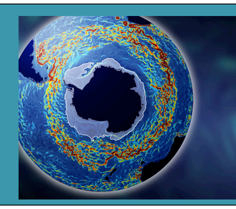
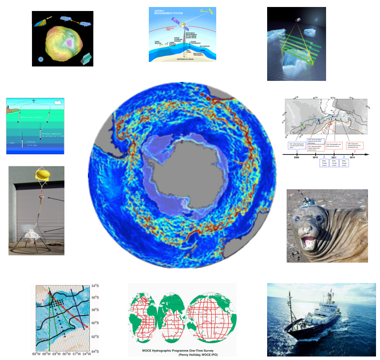


PROJECT GOAL

To attain a 2005 to present model solution of the ocean consistent with available observations in support of Southern Ocean science



METHOD

SOSE is a science resource; the method of 4d-var optimization with a multi-year assimilation window is chosen. SOSE is not optimized sequentially, so there are no unphysical jumps in the governing dynamics. There are no terms nudging towards observations either. SOSE obeys model dynamics and thermodynamics first (hard-constraint).

Briefly, the method is as follows:

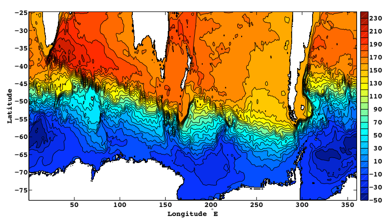
- Determine the forward model state, $\mathcal{L}(u,v,w,t,s,p)$
- Model inputs are "control parameters", $\boldsymbol{u}$
  (e.g. param. coef., ini. cond., atm. state)
- Define the cost function. Here a sum of weighted model state – observation misfits:
  $\mathcal{J}(\boldsymbol{u}) = \Sigma\{\mathcal{L}_i - obs_i\}^2 \sigma_i^{-2} + \Sigma\{\boldsymbol{u}_i - data_i\}^2 \sigma_i^{-2}$
- Model state, and thus cost, is a function of controls: $\mathcal{L}(\boldsymbol{u})$
- Optimization problem: adjust controls to minimize the cost function
- Adjoint model gives the gradient of $\mathcal{J}$ wrt $\boldsymbol{u}$: $\nabla_u \mathcal{J}(\boldsymbol{u})$
- This information is used to determine the updated controls: $\boldsymbol{u}^{n+1} = \boldsymbol{u}^n + \Delta\boldsymbol{u}$ and iteratively minimize the cost

For more on the method see Wunsch, *Discrete Inverse and State Estimation Problems with Geophysical Fluid Applications*, 2006

The state estimation software has been developed by the ECCO consortium www.ecco-group.org

SOSE setup

- ECCO software, using MITgcm with adjoint generated by TAF AD tool
- Domain is 78° South to 24.7° South
- 1/6° Horizontal resolution (eddy permitting)
- 42 depth levels (partial cells)
- Initial and northern boundary conditions derived from and constrained to G. Forget's (2010) 1° resolution global state estimate (OCCA)
- Atmospheric boundary layer scheme, with atmospheric state constrained to NCEP reanalysis
- KPP mixed layer parameterization
- Full (and adjointable) coupled sea-ice model
- Resources currently provided by TACC & NCAR



Mean vertically integrated transport streamfunction in Sverdrups from SOSE. The zero contour is the Antarctic coast, and the contour interval is 10 Sv. At the top of the plot, in red-orange, are the anti-cyclonic subtropical gyres. The Indian Subtropical Gyre transport is greater than the gyre transports of the Atlantic and Pacific Subtropical Gyres. At the bottom of the plot, in dark blue, are the cyclonic Polar Gyres. The Weddell Gyre ~295°E to ~50°E transport (40±8 Sv) is double the Ross Gyre (~150°E to ~240°E) transport (20±5 Sv). Between the polar and subtropical gyres is the strong eastward transport (153±5 Sv through the Drake Passage) of the Antarctic Circumpolar Current System (the ACC is in blue to orange). This current tracks poleward over the South Indian and South Pacific Oceans. Equatorward excursions of the ACC are abrupt, with the Falkland (or Malvinas) Current (~310°E) being the most significant meridional shift. (from Mazloff et al. JPO 2010)

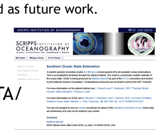
SOSE status

Diagnostics for the best estimate of the 2005 to 2007 Southern Ocean state are available on the SOSE server (and upon request)

Years 2008 to 2009 (will extend to 2010 and beyond as soon is feasible) are currently being optimized in effort to best assist the IPY effort.

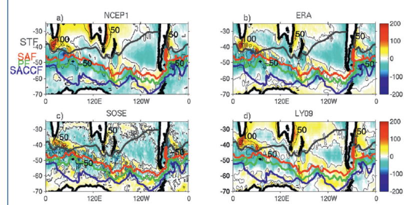
Efforts to improve model (e.g. ice dynamics), optimization software (e.g. descent algorithm), constraint structure (e.g. representation of error covariance), and constraints (e.g. acoustic tomography, atmospheric, and biogeochemical observations) are ongoing or planned as future work.

SOSE available at:
http://sose.ucsd.edu/DATA/



RESULTS (Cerovecki *et al.* JCli. 2011)

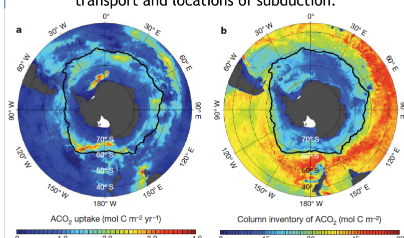
- NECP reanalysis was used as the first-guess atmospheric state
- Ocean state estimation (SOSE) corrected many of the known biases in NCEP atmospheric flux
- The ocean is an integrator of air-sea fluxes. Through assimilation ocean obs. can improve atmospheric reanalysis
- SOSE derived atmospheric surface state is consistent with the SOSE ocean state – making it a desirable product for studies of water mass formation, eddy heat flux, etc.



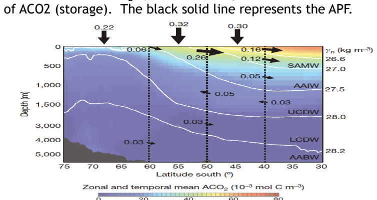
The 2005-2007 average net air-sea heat flux (the sum of latent, sensible, net longwave, and net shortwave heat flux components), estimated by (a) NCEP1, (b) ERA, (c) SOSE, and (d) Large and Yeager (LY09) in Wm^{-2}. Positive values denote ocean heat loss. Contour interval is 50 Wm^{-2}. Thick colored line are climatological positions of the fronts given by Orsi et al. (1995): Subtropical Front (ST, black), Subantarctic Front (SAF, red), Polar Front (PF, green) and Southern ACC front (SACC, blue).

RESULTS (Ito *et al.* Nature 2010)

Discrepancy between locations of anthropogenic carbon (ACO_2) uptake and storage is accounted for by Ekman transport and locations of subduction.



Uptake and inventory of ACO_2 determined from SOSE. Left: the 2005-2006 mean ACO_2 uptake rate. Right: the column inventory of ACO2 (storage). The black solid line represents the APF.

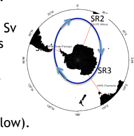


Vertical structure of ACO_2 transport. Major density layers (differentiated by white lines) are defined using neutral density: sub-Antarctic mode water (SAMW), Antarctic intermediate water (AAIW), upper circumpolar deep water (UCDW), lower circumpolar deep water (LCDW) and Antarctic bottom water (AABW). The size of each black arrow is proportional to the magnitude of integrated ACO_2 flux, and displayed only for fluxes greater than 0.02 PgCyr^{-1}. Background color shading indicates zonally and temporally averaged ACO_2.

RESULTS (Griesel *et al.* JGR, submitted)

Mean dynamic ocean topography (MDT) is very uncertain in SO due to lack of *in situ* geoid observations. Available MDT products are also questionable representations of the true mean, largely due to high temporal variability in the region.

Volume conservation could not be attained from velocities fields constructed using hydrography and thermal wind, and using MDT products as reference velocities.



Implied ACC transport at "choke points" in Sv
- "±" gives sensitivity to chosen end points
- The transport through SR2 is ~1 Sv lower than SR1 due to flow through the Arctic.
- The transport through SR3 is ~15 Sv greater than SR1 and SR2 due to flow around Australia (the Indonesia Throughflow).

Product	SR1: Drake Passae 65°W	SR2: Africa 20.5°E	SR3: Tasma-nia 145°E	SR1 – SR2
SOSE (ocean assim.)	147 ± 5	145 ± 15	159 ± 3	2
Maximenko and Niiler	159 ± 4	98 ± 18	187 ± 7	61
AVISO (CNES-CLS09)	172 ± 6	135 ± 31	164 ± 4	37
GRACE (GGM02C)	142 ± 2	188 ± 23	175 ± 3	-46
DOT2008A (EGM08)	151 ± 3	136 ± 13	167 ± 4	15

Evaluation of the MDT products with SOSE suggests satellite only products (GGM02 and EGM08) are most consistent with ocean observations and physics. Adding ocean drifter information may not be helping due to inadequate wind slip corrections.

Product	Iteration 49 "Cost"	Iteration 59 "Cost"	Percent Cost Decrease
Maximenko and Niiler	2.1	1.7	16%
AVISO (CNES-CLS09)	2.2	1.8	18%
GRACE (GGM02)	1.8	1.5	19%
DOT2008A (EGM08)	1.9	1.5	20%

PUBLICATIONS USING SOSE RESOURCE

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Firing, Y. L., T. K. Chereskin, and M. Mazloff, 2011: Vertical structure and transport of the Antarctic Circumpolar Current in Drake Passage from direct velocity observations. *Journal of Geophysical Research*, **116**.

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Ledwell, J. R., L. C. St. Laurent, J. B. Girton, and J. M. Toole, 2010: Diapycnal mixing in the antarctic circumpolar current. *Journal of Physical Oceanography*, **41 (1)**, 241–246, doi:10.1175/2010JPO4557.1.

Lu, J. and K. Speer, 2010: Topography, jets, and eddy mixing in the southern ocean. *Journal of Marine Research*, **68 (3-4)**, 479–502.

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Sallée, J. and S. Rintoul, 2011: Parameterization of eddy-induced subduction in the Southern Ocean surface-layer. *Ocean Modelling*, **39 (1-2)**, 146–153.

Thompson, A. F., P. H. Haynes, C. Wilson, and K. J. Richards, 2010: Rapid Southern Ocean front transitions in an eddy-resolving ocean GCM. *Geophysical Research Letters*, **37 (23)**.

Woloszyn, M., M. Mazloff, and T. Ito, 2011: Testing an eddy-permitting model of the southern ocean carbon cycle against observations. *Ocean Modelling*, **39 (1-2)**, 170–182.

Images provided by cDrake project, DIMES project, AVISO, ESA, NASA, NOAA