State Estimation for Analyzing Southern Ocean Budgets and Properties

Matt Mazloff
Scripps Institution of Oceanography
September 2017

Coauthors: this talk covers material from


State Estimation for Analyzing Southern Ocean Budgets and Properties

Matt Mazloff
Scripps Institution of Oceanography
September 2017

Talk summary:
• The Southern Ocean is a windy, energetic, and complex region where schematics are major simplifications
• Synthesizing all available information into a state estimate allows quantification of budgets, bringing scientific understanding to the region
• An overview of the fundamental balances of the Southern Ocean is presented, relying heavily on work led by SIO students and post-docs
Southern Ocean State Estimation

A modern general circulation model, the MITgcm, is least squares fit to all available ocean observations. This is accomplished iteratively through the adjoint method. The result is a physically realistic estimate of the ocean state. SOSE is being produced by Matthew Mazloff as part of the ECCO consortium and funded by the National Science Foundation. Computational resources are provided in part by NSF XSEDE.

You are encouraged to use our results, but please be aware of the disclaimer and terms of use. Some data are preliminary and may not be suited to your needs.

RESULTS: The 2005-2010 Southern Ocean State Estimate (SOSE)

RESULTS: The 2008-2012 Biogeochemical Southern Ocean State Estimate (B-SOSE)

SOSE: A 2005 to 2010 physical state estimate.
BSOSE: A 2008 to 2017 BGC state estimate.

More than 75 publications have used this resource.
The vertically integrated transport streamfunction of the Southern Ocean
The meridional overturning streamfunction of the Southern Ocean

Fasullo and Trenberth 2008
The meridional overturning streamfunction of the Southern Ocean
The meridional overturning streamfunction of the Southern Ocean

Volume transport in depth space [m]

Neutral density space [kg/m³]

Latitude °S
The meridional heat transport of the Southern Ocean

We find a poleward total heat transport at all latitudes (red line)
The meridional buoyancy transport of the Southern Ocean

Total buoyancy transport (black line) is positive indicating equatorward buoyancy transport.
The meridional heat and freshwater transport of the Southern Ocean
Sea ice redistributes freshwater

Precipitation plus run off

From atmosphere and land

Sea ice redistribution

Sea-ice redistribution

Net flux into the ocean

To ocean

Abernathy et al. 2016
Southern Ocean Fundamentals Summary #1

Speer et al. 2000

- \( \sim 30 \text{ Sv} \) equatorward Ekman transport
- \( \sim 0.3 \text{ PW} \) poleward heat transported
- Stability achieved via equatorward freshwater transport (\( \sim 1 \text{ Sv} \)), maintained via freshwater redistribution by sea ice
- Water mass exchange:
  - Warm waters move poleward
  - Fresh waters move equatorward
The heat budget of the Southern Ocean

The zonal mean heat flux \([\text{Wm}^{-2}]\) is small residual of a complex 4-D structure
The heat budget of the Southern Ocean

\[
\frac{\partial T}{\partial t} = \frac{Q_{\text{net}}}{\rho c_p dz} - u_g \cdot \nabla_H T - u_a \cdot \nabla_H T - w \frac{\partial T}{\partial z} + \kappa_H \nabla^2_H T + \kappa_z \frac{\partial^2 T}{\partial z^2} + K_T^{\text{turb}}
\]

Temperature tendency, air-sea flux, geostrophic advection, Ekman advection, vertical advection, diffusion

Net air-sea heat flux [Wm^{-2}]:
Mean heat flux is small residual of a highly *temporally* variable field

Zonal anomaly of sea surface temperature [°C]:
Mean heat flux is a small residual of a highly *spatially* variable field
The heat budget of the Southern Ocean

Net air-sea heat flux: asymmetry accounted for with mean geostrophic advection

Kerguelen Plateau  Macquarie ridge and Campbell Plateau  Drake Passage

Cumulative integral of heat budget terms within the ACC

mean geostrophic advection
eddy geostrophic advection
eddy vertical advection
mean vertical advection

Negative heat flux in Pacific sector due to the mean geostrophic advection
\[
\frac{\partial T}{\partial t} = \frac{Q_{\text{net}}}{\rho c_p dz} - u_g \cdot \nabla_H T - u_a \cdot \nabla_H T - \omega \frac{\partial T}{\partial z} + \kappa_H \nabla^2_H T + \kappa_z \frac{\partial^2 T}{\partial z^2} + K_T^{\text{turb}}
\]

Temperature tendency, air-sea flux, geostrophic advection, Ekman advection, vertical advection, diffusion.

Average heat budget terms in ACC.

Atlantic and Indian sectors  Pacific sector
\[
\frac{\partial T}{\partial t} = \frac{Q_{\text{net}}}{\rho c_p} - u_g \cdot \nabla_H T - u_a \cdot \nabla_H T - w \frac{\partial T}{\partial z} + \kappa_H \nabla^2_H T + \kappa_z \frac{\partial^2 T}{\partial z^2} + K_T^{\text{turb}}
\]

Temperature tendency
air-sea flux
geostrophic advection
Ekman advection
vertical advection
diffusion

Atlantic and Indian sectors minus Pacific sector
The heat budget of the Southern Ocean

- Asymmetry in air-sea heat flux driven by geostrophic advection

- How does one sustain a mean geostrophic heat transport across Drake Passage latitudes where no land boundaries exist?

\[ \rho \circ f \oint v_g \, dx = \oint p_x \, dx = 0, \]
The heat budget of the Southern Ocean

- Asymmetry in air-sea heat flux driven by geostrophic advection

How does one sustain a mean geostrophic heat transport across Drake Passage latitudes where no land boundaries exist?

\[ \rho_0 f \oint u_g \, dx = \oint p_x \, dx = 0, \quad \rho_0 f \oint \theta u_g \, dx \neq 0 \]

Exchange: warm/salty moves poleward and cold/fresh moves equatorward
Southern Ocean Fundamentals Summary #2

- ~30 Sv equatorward Ekman transport
- ~0.3 PW poleward heat transported
- Stability achieved via equatorward freshwater transport, maintained via freshwater redistribution by sea ice
- Implies exchange of warm/salty and cold/fresh waters
- Upper ocean geostrophic volume transport across Drake Passage latitudes is negligible.
- Warm salty poleward transport is accomplished by zonal asymmetries in the mean geostrophic flow
Southern Ocean Fundamentals
Summary #2

- Warm salty poleward transport is accomplished by water mass exchanges via zonal asymmetries in the *mean* geostrophic flow

Executive summary of Southern Ocean dynamics:
“water pushes on water sometimes, land other times”
-Jessica Masich, Ph.D., UCSD
The meridional overturning streamfunction of the Southern Ocean
The mean momentum input is the residual of a complex 4-D structure.
The time-mean zonal wind stress [Nm$^{-2}$]

Mean upper 3,700m bottom form stress [Nm$^{-2}$]: “water push on land”

- Kerguelen Plateau (Balances 13% of zonal wind stress between 42°S to 65°S)
- Campbell Plateau and Macquarie Ridge (20%)
- East Pacific Rise (3%)
- South America, Drake Passage (42%)
- Mid-Atlantic Ridge (4%)

Figures from J. Masich
Bottom form stress: methodology

\[ \Delta p_b = p(x_E) - p(x_W) \]
The time-mean zonal wind stress [Nm$^{-2}$]

Mean upper 3,700m bottom form stress [Nm$^{-2}$]: “water push on land”

Kerguelen Plateau (Balances 13% of zonal wind stress between 42°S to 65°S)
Campbell Plateau and Macquarie Ridge (20%)
East Pacific Rise (3%)
South America, Drake Passage (42%)
Mid-Atlantic Ridge (4%)

Figures from J. Masich
Interfacial form stress: “water push on water”

Consider the layer bound by 28.2 kg/m$^3$ and the seafloor, on 1 Dec 2007:

\[ V_{\text{geostrophic}} = V_{\text{IFS}} + V_{\text{BFS}} + V_{\text{TFS}} \]

\[ \gamma = 28.2 \text{ kg m}^{-3} \text{ at } 60^\circ \text{S} \]

Slide from J. Masich
The meridional overturning streamfunction of the Southern Ocean
IFS and BFS reveal the meridional overturning circulation (MOC)

Meridional overturning streamfunction

Meridional layer transport

Latitude
Components of the MOC

Air pushes on water

Water pushes on water

Water pushes on land
Components of the MOC

Air pushes on water

Water pushes on water

Water pushes on land
$V_{IFS}$ in layers

Light

Deep

Bottom
IFS and BFS reveal the meridional overturning circulation (MOC)

Meridional overturning streamfunction

Meridional layer transport
Southern Ocean Fundamentals Summary #3

- Warm/salty and cold/fresh exchange is accomplished by zonal asymmetries in the mean geostrophic flow.
- Vertical integral of momentum budget is:
  
  \[
  \text{air pushes water} + \text{water pushes land} = \text{air pushes land}
  \]

- Water pushes on water component on momentum budget (i.e. interfacial form stress; IFS) allows buoyancy constraints to be satisfied.
- In doing so IFS sets overturning strength.
Air-sea CO$_2$ flux [mol m$^{-2}$ yr$^{-1}$] from B-SOSE 2008 - 2012 solution
Influence of the MOC on the dissolved inorganic carbon (DIC) budget

BSOSE mean fields:

Air sea carbon flux [mol m$^{-2}$ yr$^{-1}$]

Air sea heat flux [W m$^{-2}$]

950 m mean DIC [μmol kg$^{-1}$]

950 m heat inventory [GJ m$^{-2}$]
Influence of the physical overturning circulation on the dissolved inorganic carbon budget

Components of advective transport divergence of DIC averaged over upper 650m [mol C m\(^{-3}\) y\(^{-1}\)]

Figures from I. Rosso
Influence of the physical overturning circulation on the dissolved inorganic carbon budget

Seasonal DIC budget in Weddell Gyre

Figures from I. Rosso

[Graph showing seasonal DIC budget in Weddell Gyre]
Southern Ocean Fundamentals
Summary #4

- Wind stress inputs momentum
- Bottom form stress removes momentum
- Interfacial form stress redistributes momentum throughout water column, allowing buoyancy constraints to be satisfied and setting the overturning strength
- The overturning strength regulates carbon and nutrient distributions
- Buoyancy constraints and carbon fluxes are both very sensitive to sea ice cover. And sea ice cover is changing!

Ice season duration trend
1979 to 2015

Calculated following the method of Stammerjohn et al. 2008
Sea ice and clouds blanket the Weddell Sea around Antarctica in this satellite image from September 25, 2017. A SOCCOM float surfaced within the 60,000 km² polynya (center) at the location marked in yellow. Image from MODIS-Aqua via NASA Worldview; sea ice contours from AMSR2 ASI via University of Bremen.

Contact: Ethan Campbell, University of Washington
Southern Ocean
Talk Summary

• The Southern Ocean is a windy, energetic, and complex region
• Synthesizing all available information into a state estimate allows quantification of budgets, bringing scientific understanding to the region