Quantifying Agulhas Leakage in a Coupled Climate Model

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PuPPY Scientific Computing

Climate Models

What is a climate model?

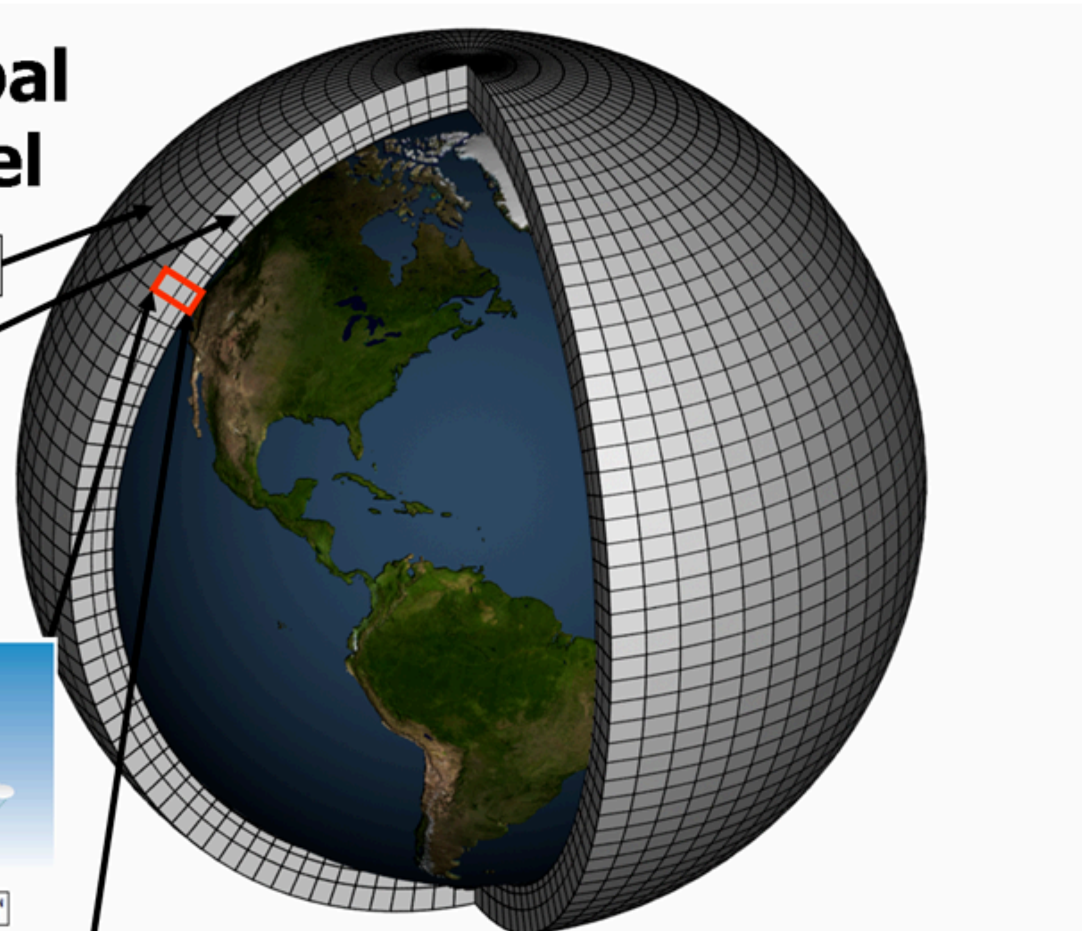
$$\rho\left[\frac{\partial u}{\partial t}+\frac{\partial u}{\partial x}u+\frac{\partial u}{\partial y}v+\frac{\partial u}{\partial z}w\right]=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+\rho g_x$$

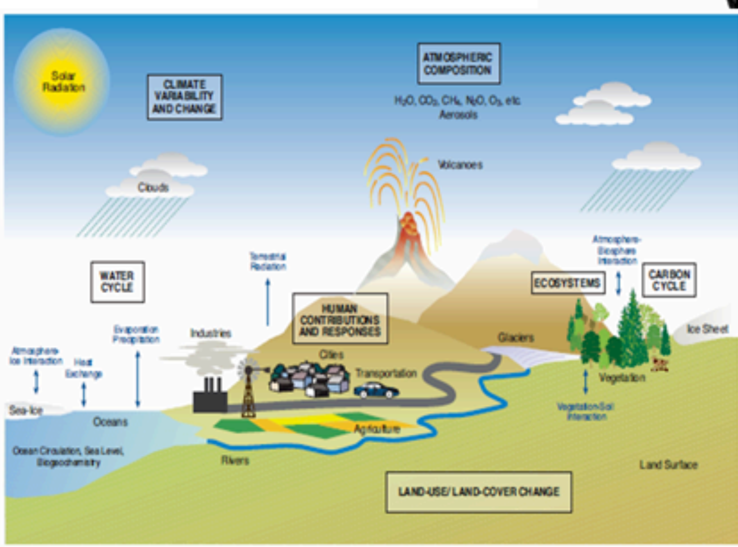
$$\rho\left[\frac{\partial v}{\partial t}+\frac{\partial v}{\partial x}u+\frac{\partial v}{\partial y}v+\frac{\partial v}{\partial z}w\right]=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+\rho g_y$$

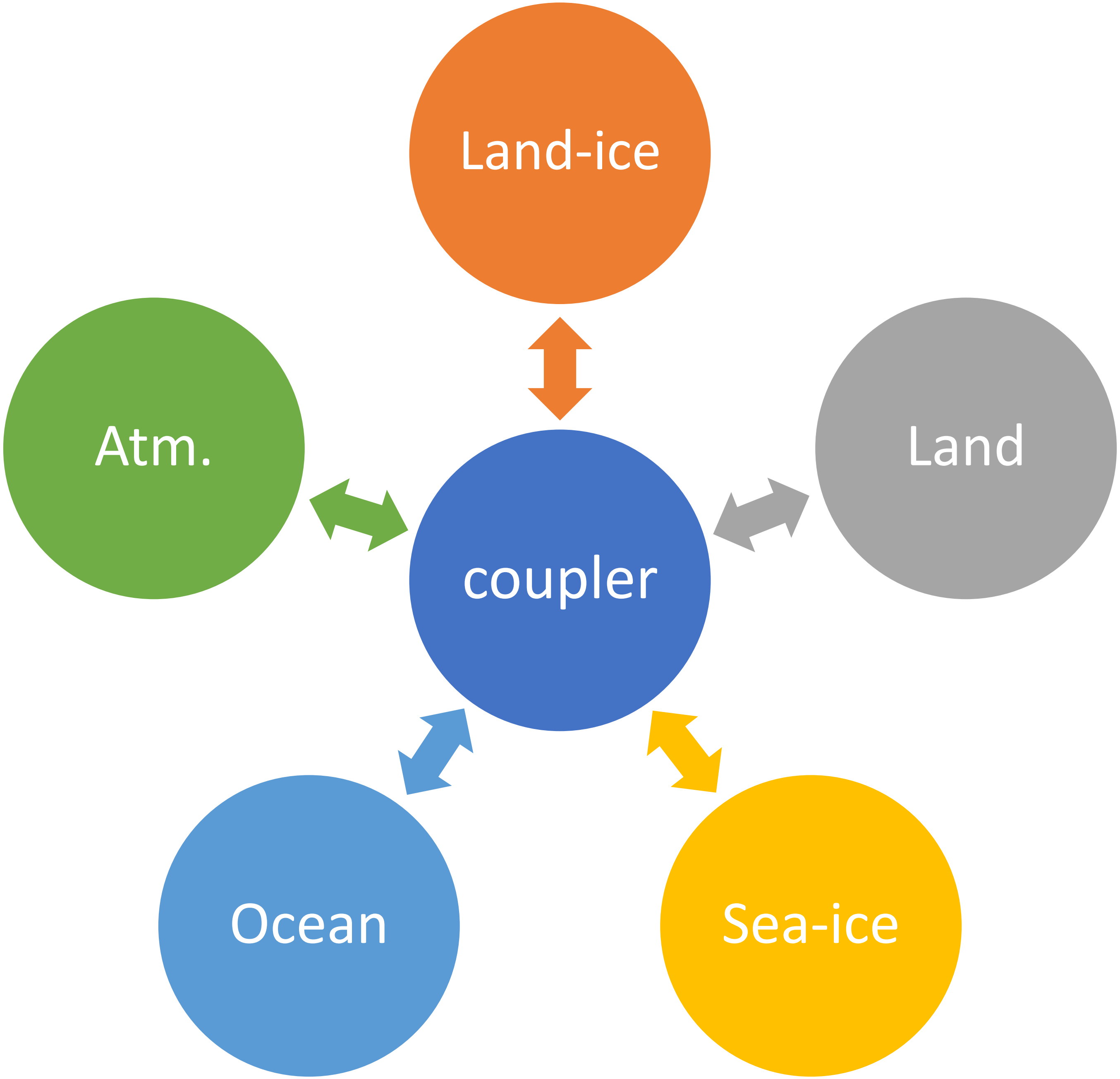
$$\rho\left[\frac{\partial w}{\partial t}+\frac{\partial w}{\partial x}u+\frac{\partial w}{\partial y}v+\frac{\partial w}{\partial z}w\right]=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho g_z$$

- The Navier-Stokes Equations in three dimensions.

Schematic for Global Atmospheric Model



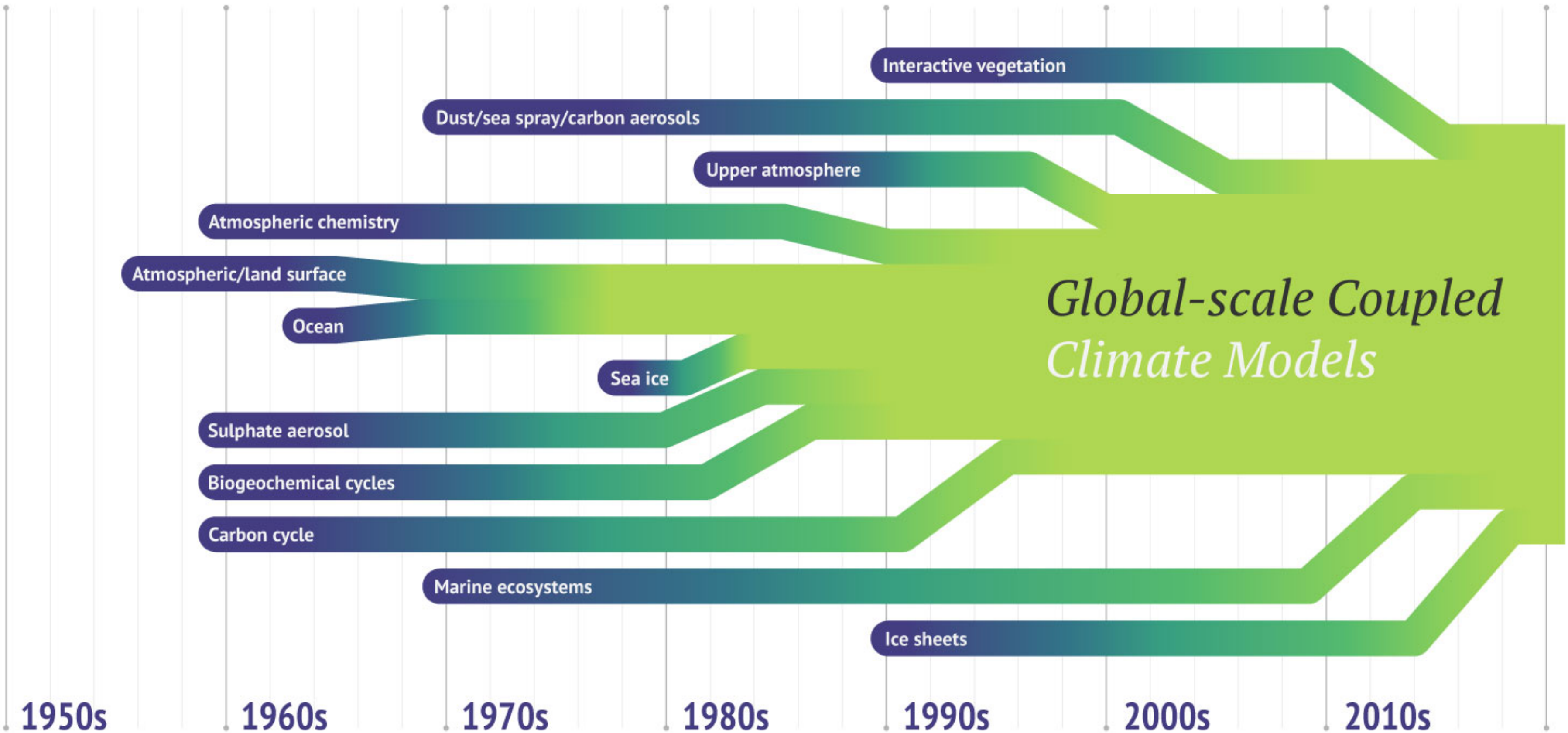




NCAR Community Earth System Model

Climate models

For decades scientists have been using mathematical models to help us learn more about the Earth's climate. Known as climate models, they are driven by the fundamental physics of the atmosphere and oceans, and the cycling of chemicals between living things and their environment. Over time they have increased in complexity, as separate components have merged to form coupled systems.

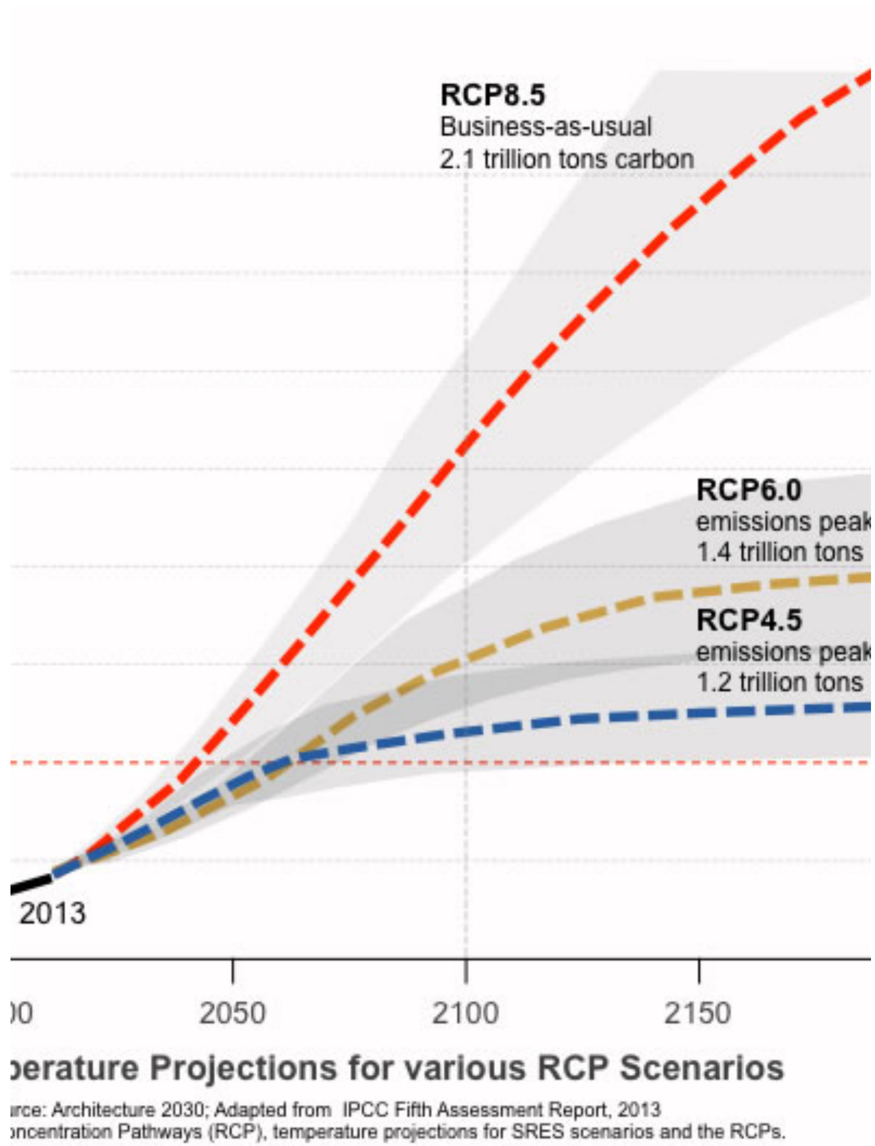


Note: There were some very simplified models before the dates mentioned.

CarbonBrief CLEAR ON CLIMATE

Why do we need climate models?

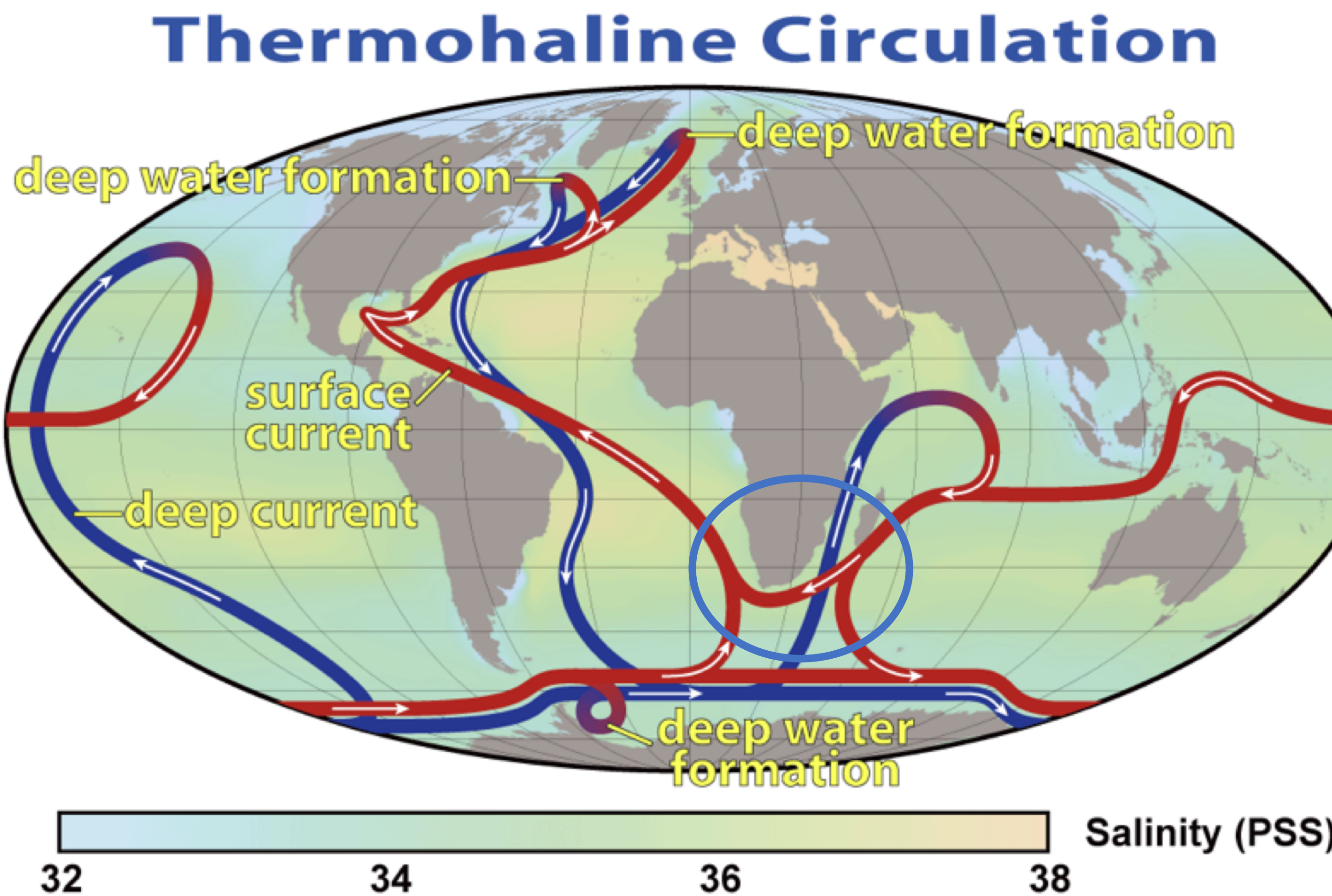
- Study the internal variability of the climate system
- Discern anthropogenic impacts from natural variability
- Our best tools to project future climate under different warming scenarios



From: https://architecture2030.org

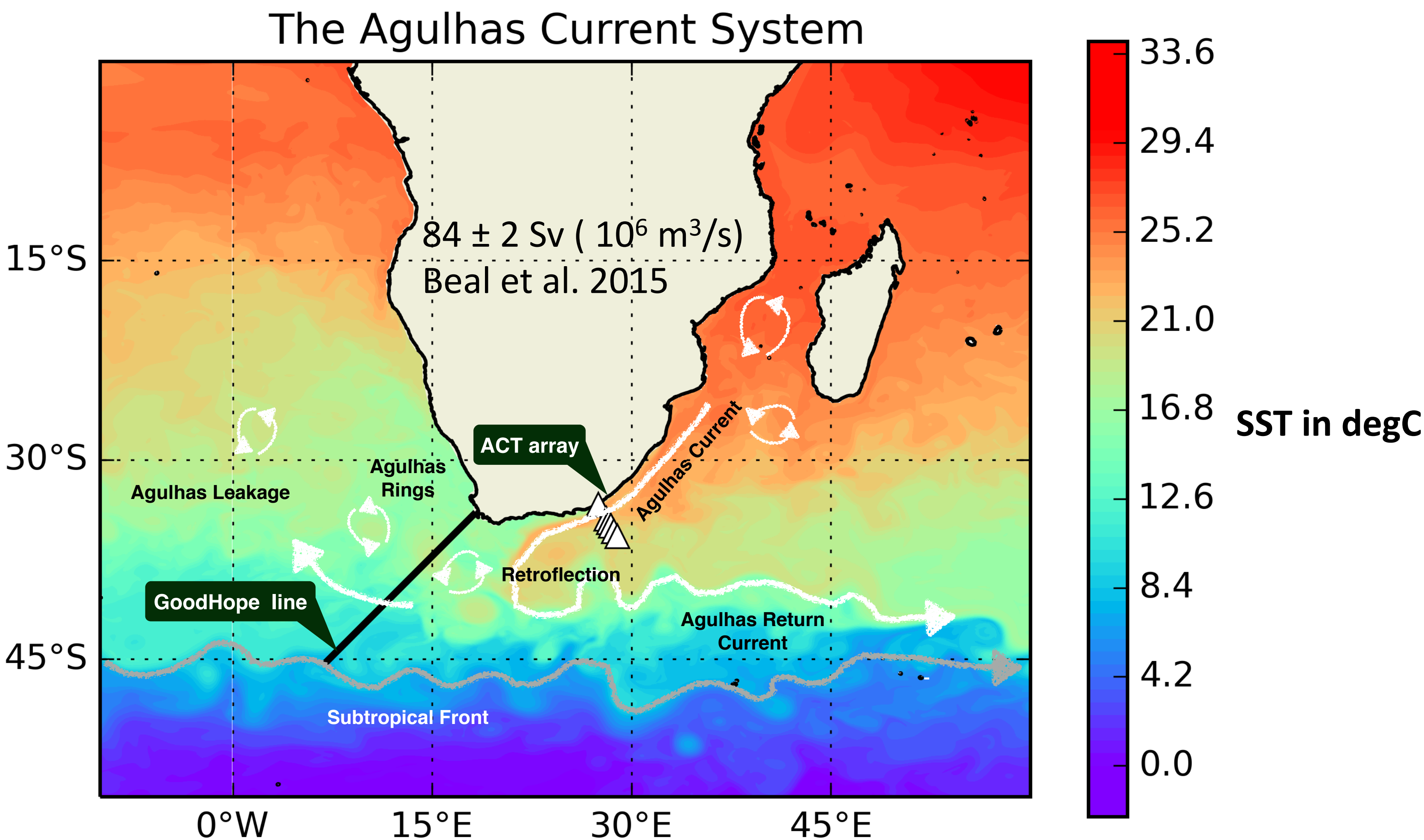
Agulhas Leakage

The ocean regulates climate by redistributing heat around the globe.

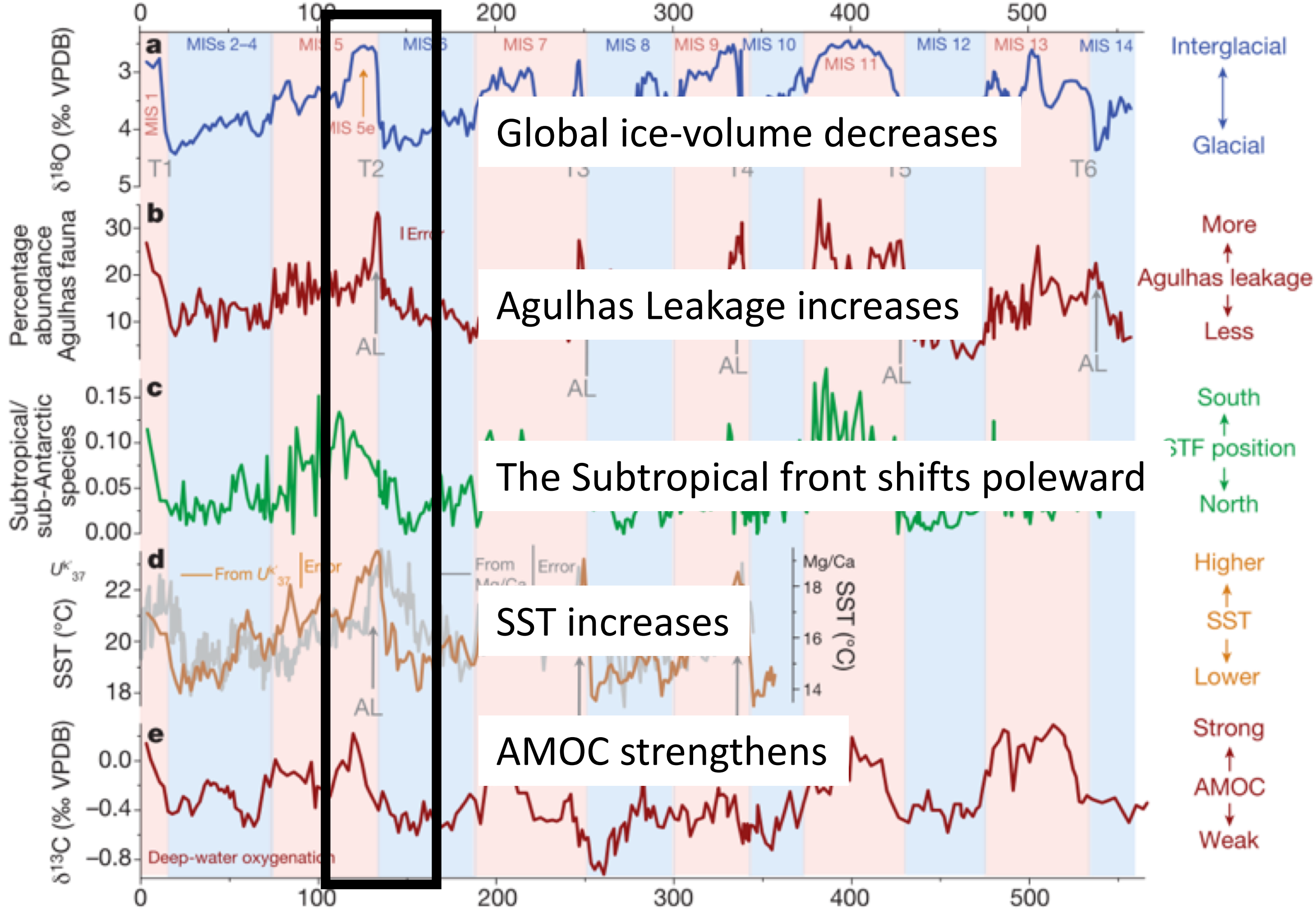


[CREDIT: Robert Simmon, NASA. Minor modifications by Robert A. Rohde]

Agulhas Current feeds the AMOC through the leakage of warm, saline waters from the Indian Ocean.

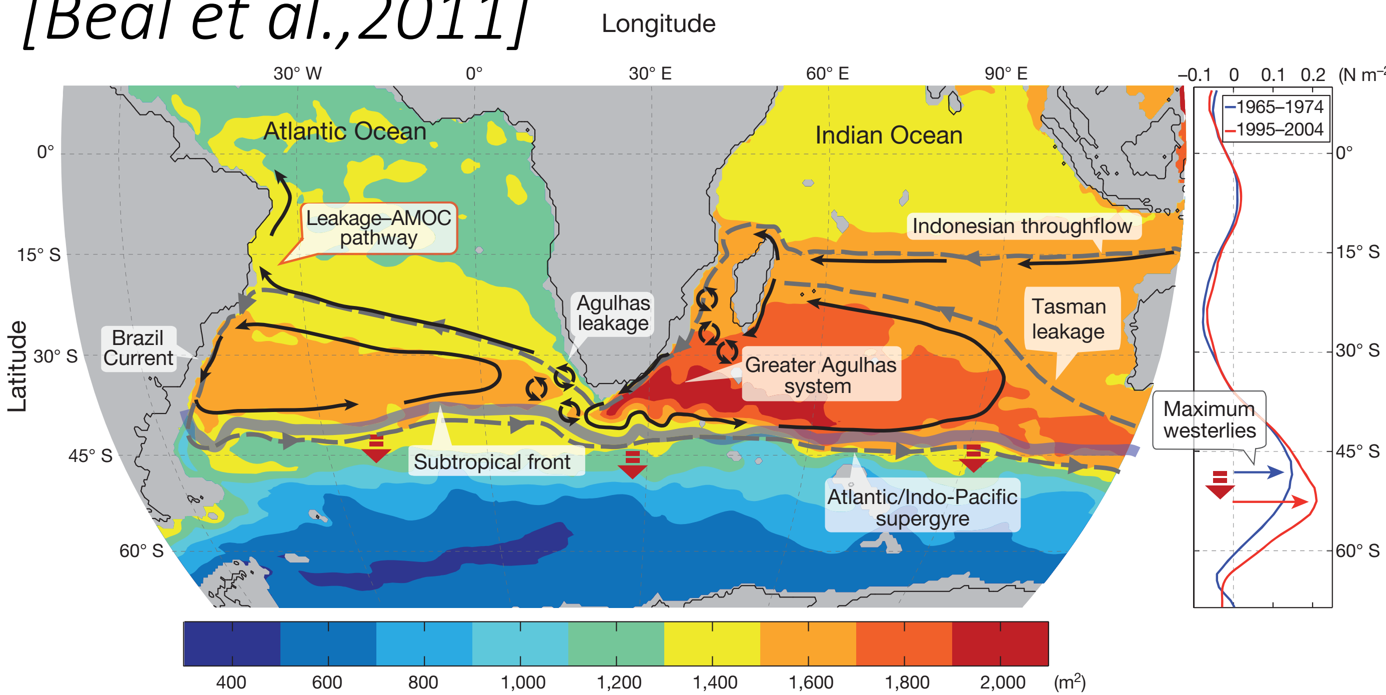


Present ← Past *[Beal et al., 2011]*



“Highly variable Agulhas leakage plays a crucial role in glacial terminations, timing of climate change and resulting resumption of the AMOC.” *[Peeters et al., 2004]*

“Ongoing increases in leakage under anthropogenic warming could strengthen the AMOC at a time when warming and accelerated meltwater input in the North Atlantic is predicted to weaken it.”
[Beal et al.,2011]



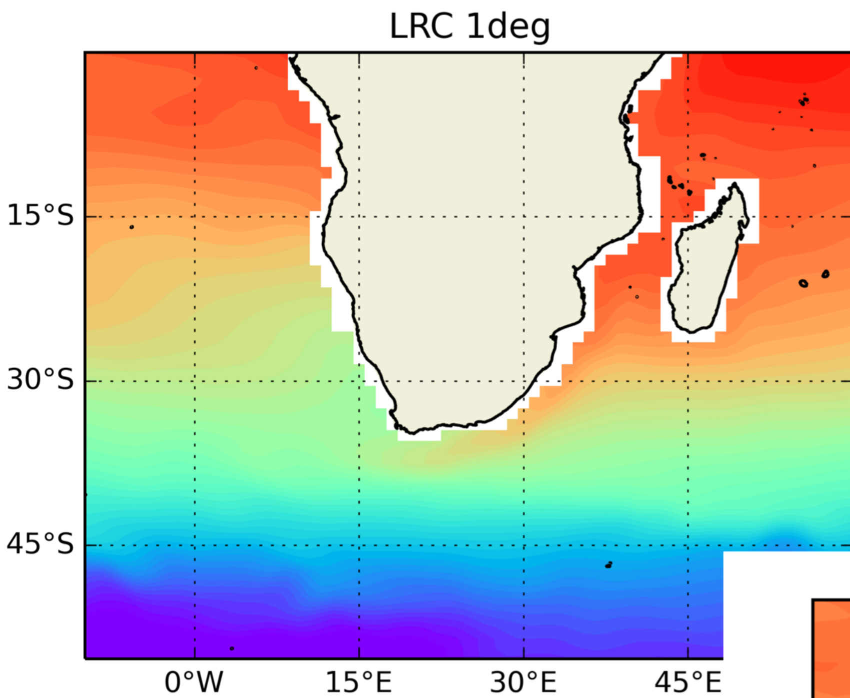
Poleward shift of westerlies
Zonal mean 20-110E

The Agulhas System embedded in the Southern Hemisphere Supergyre [Beal et al., 2011]

Quantifying Leakage

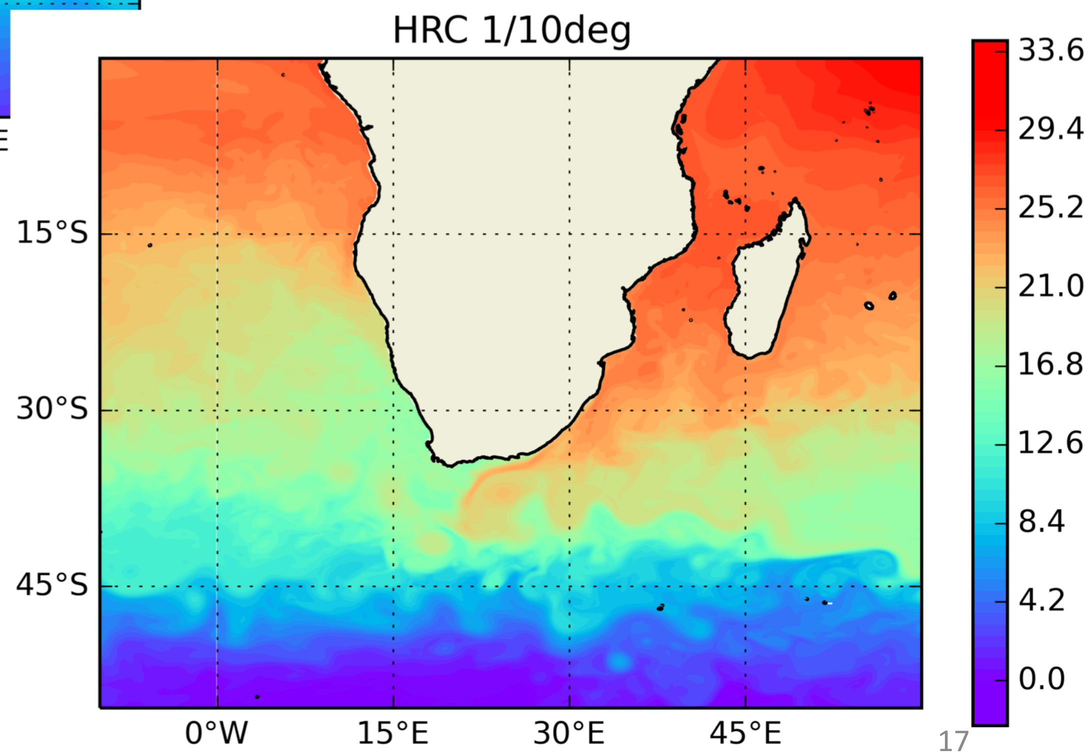
Modeling Agulhas leakage

- Many try to observe Agulhas Leakage, but there is yet an established way. Best estimate: 15 Sv (10^6 m^3/s) [Richardson 2007]
- Models of various complexity have been used to study Agulhas leakage since 1980s [de Ruijter et al., 1999]
- **Resolving** mesoscale features such as the Agulhas Rings and Retroflection is critical to capture Agulhas leakage realistically. [Biastoch et al., 2008]

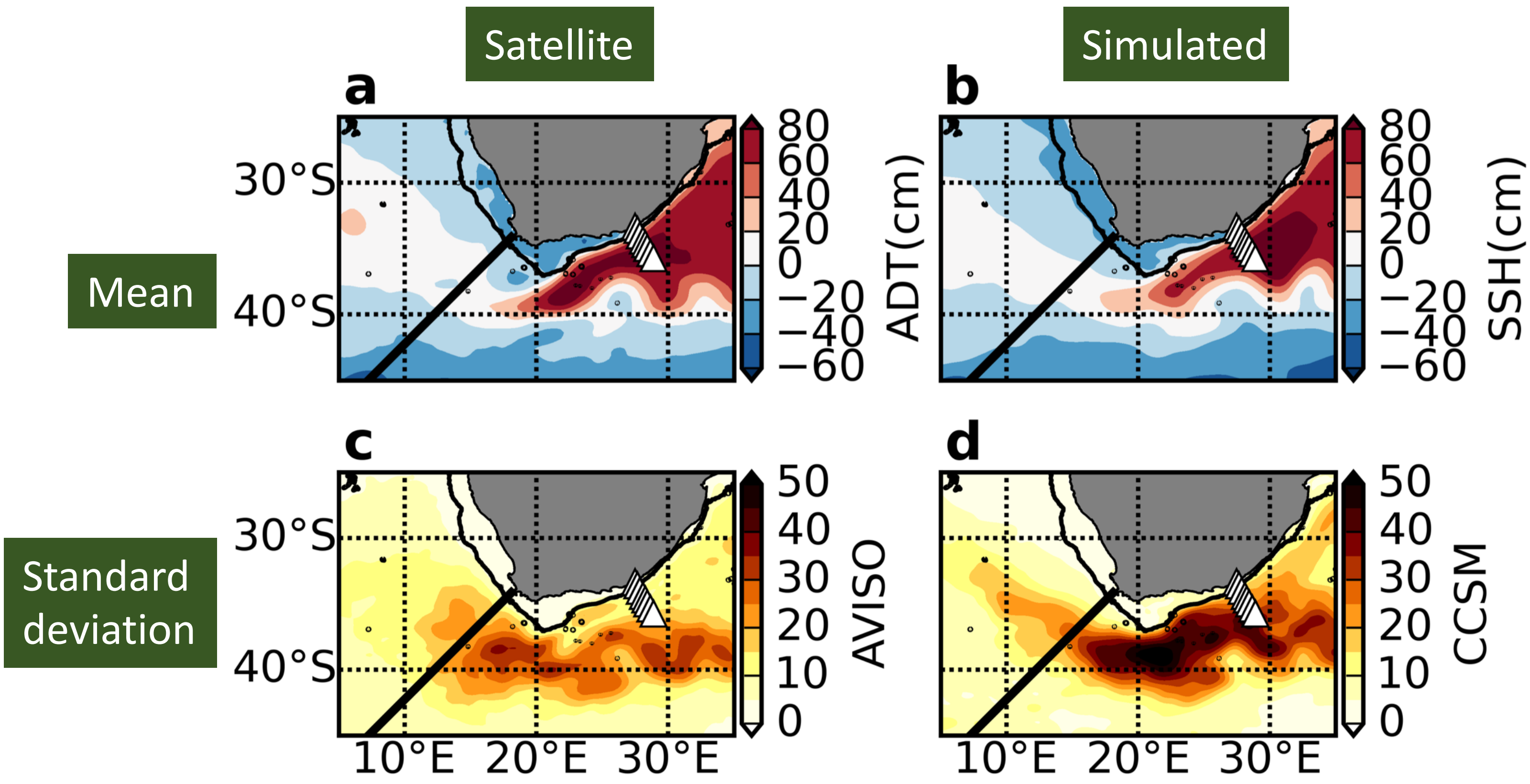


SST 1deg Ocn

1/10 deg

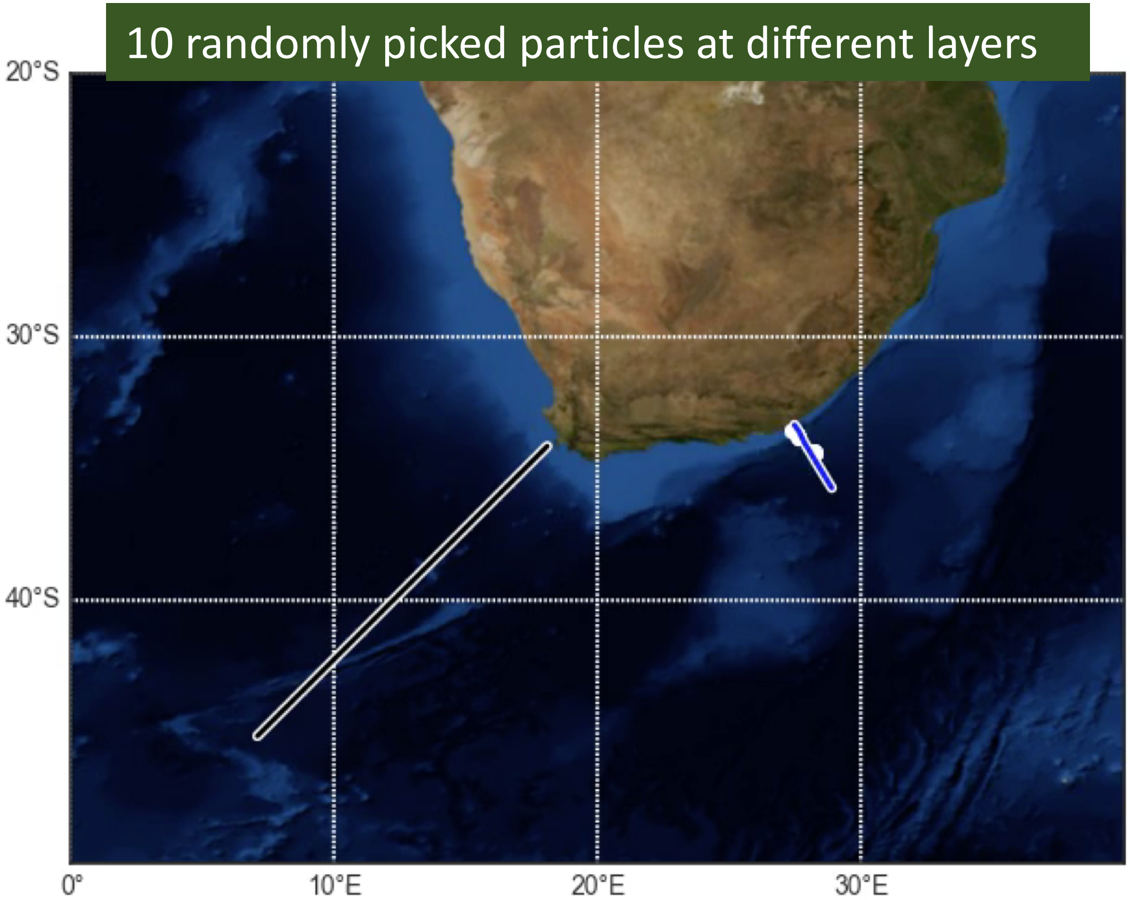


Simulated SSH compared to the observed ADT from satellite altimetry



- Strong recirculation near the ACT mooring array.
- Regular eddy path ways, associated with eastward bias of retroflection

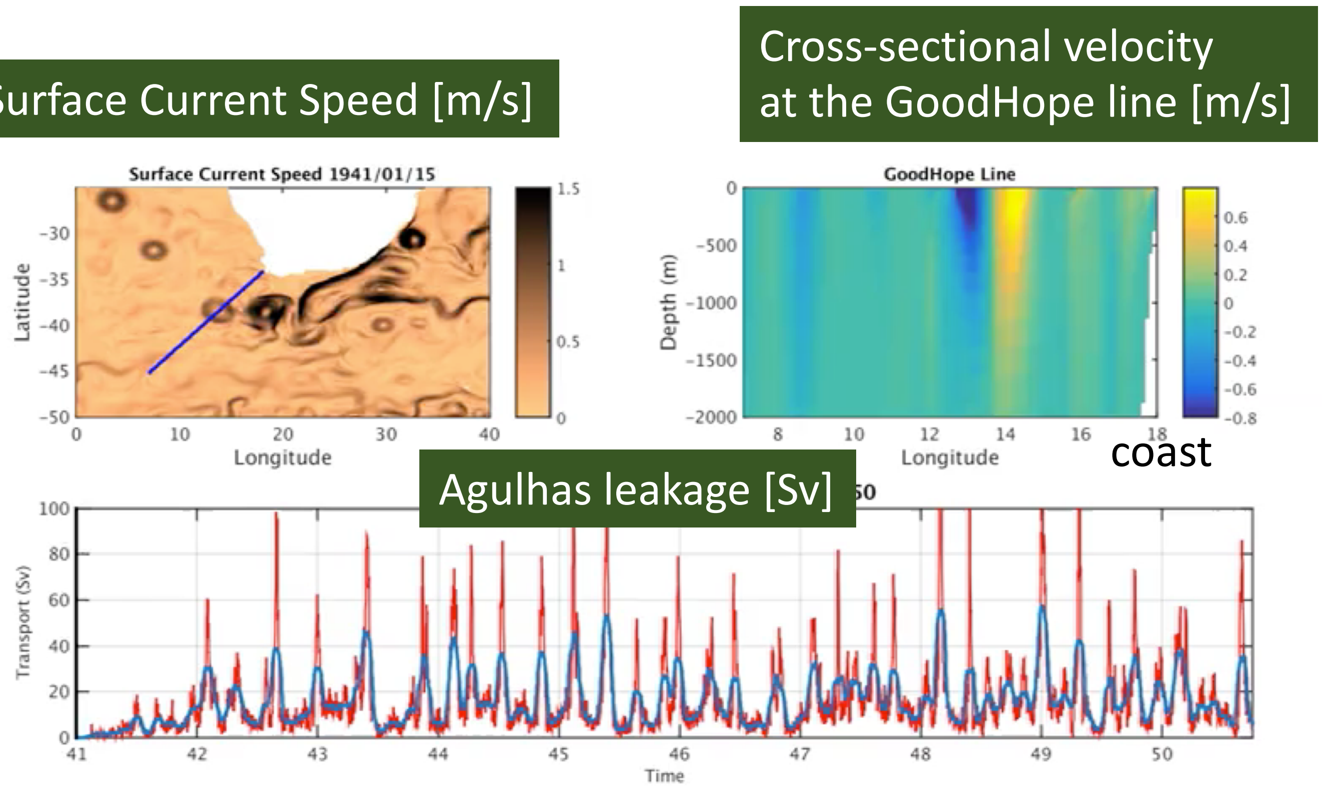
Agulhas leakage can be quantified using an offline Lagrangian particle tracking approach



- Release particles with attached volume transport
- Follow their trajectories for a specific period
- Sum up the particles that cross a control section at every time steps.

i.e. [Biastoch et al. 2009], [Durgadoo et al., 2013], [Weijer et al., 2012]

These peaks can be attributed to the passage of Agulhas rings across the GoodHope line

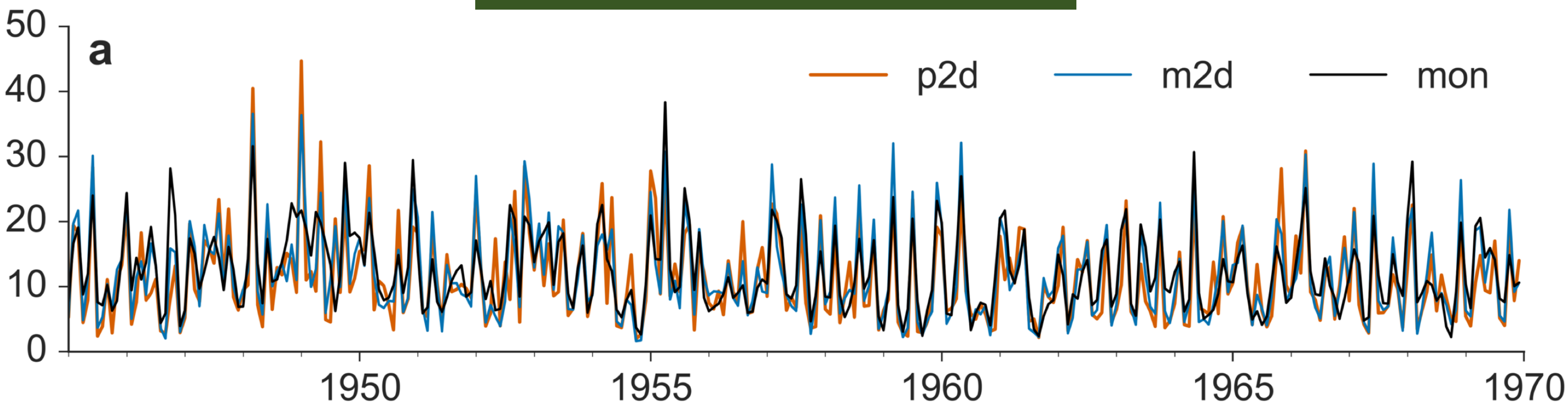


- 4 Rings per year, compared to 6 per year in observations [Elipot and Beal., 2015]

Findings

Using monthly velocity field to quantify Agulhas leakage variability at longer than seasonal time scales is sufficient

Monthly mean leakage timeseries



Mean [std]

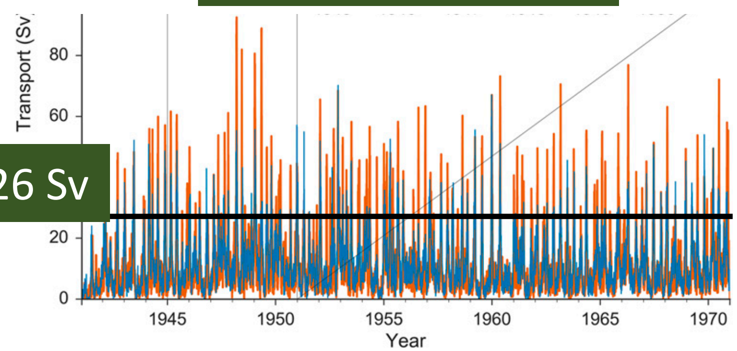
11.9[7.0]; 11.2 [7.0]; 12.3 [6.5]

r=0.88 r=0.71

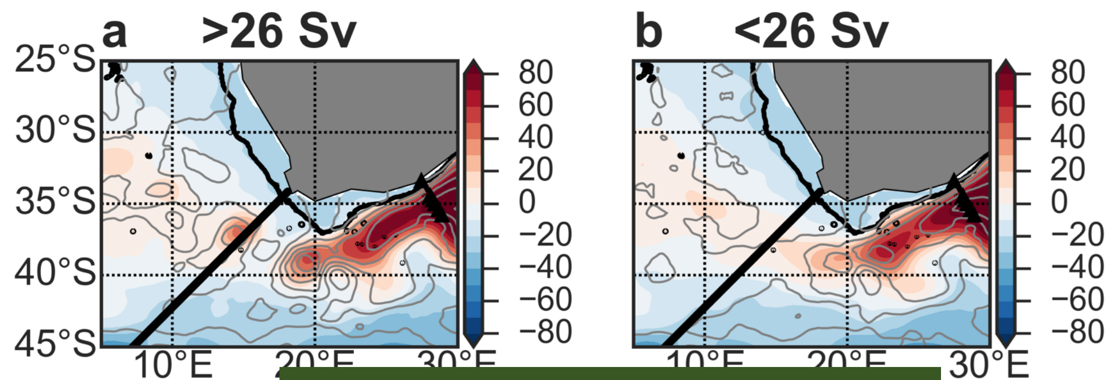
Case	Velocity fields	Release
p2d	Pentad to daily	daily
m2d	Monthly to daily	daily
mon	Standard monthly	monthly

47% of leakage transport are associated with passing rings

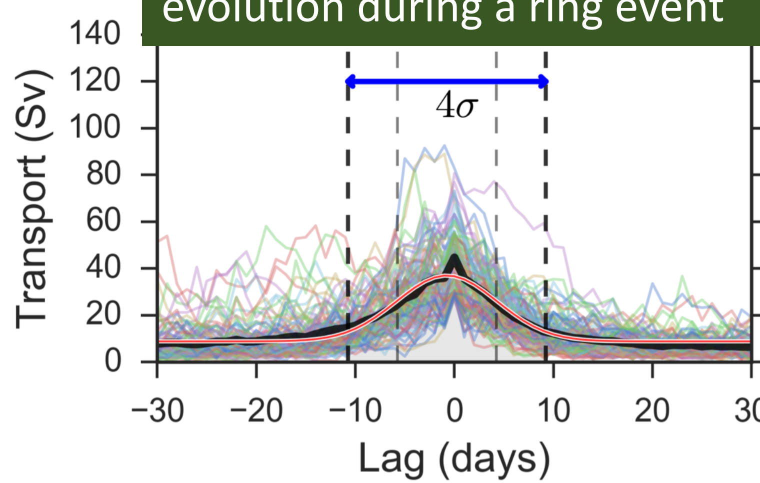
Leakage Timeseries



SSH composite (shading)
Barotropic Streamfunction (contour)



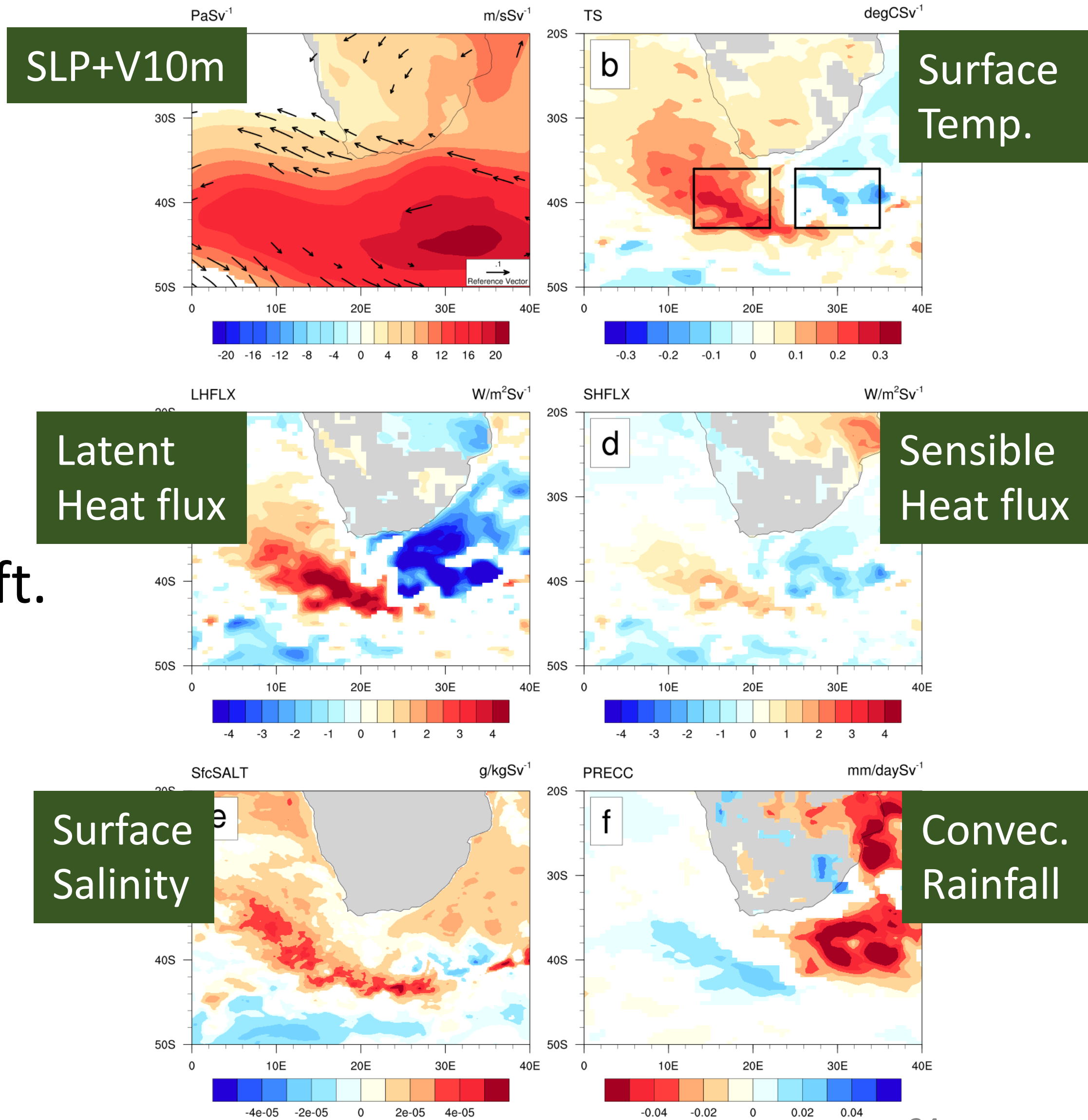
Ensemble of leakage transport evolution during a ring event

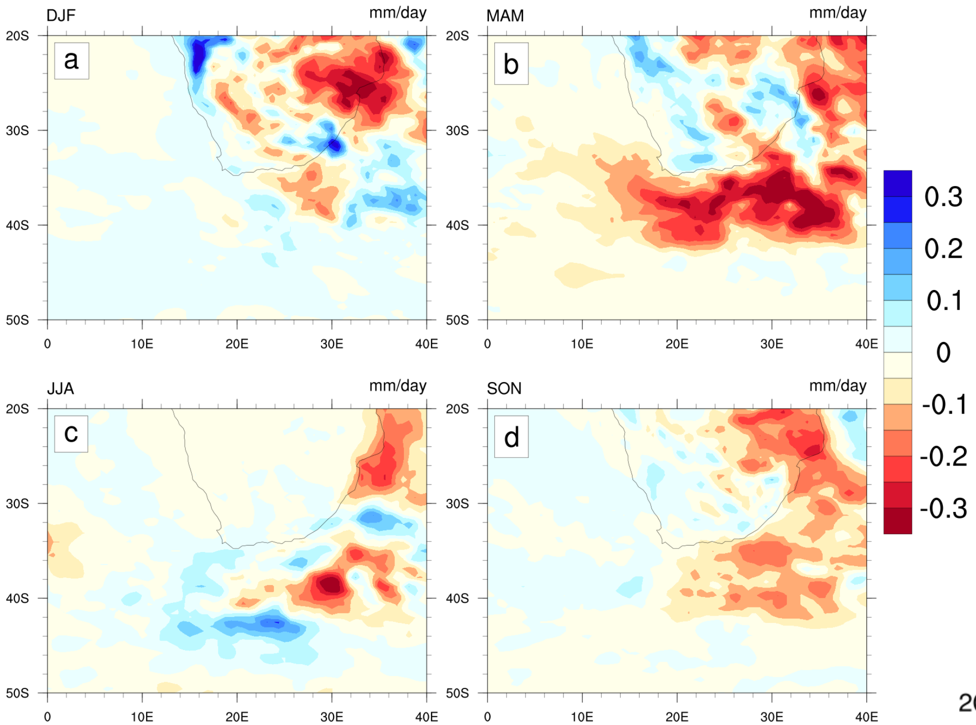


- 26 Sv threshold (90th percentile of p2d daily timeseries)
- 98 ring events during 1945-1970
- An idealized event lasts 20 days
- Divide the accumulated transport of 98 idealized rings by that for the entire period.

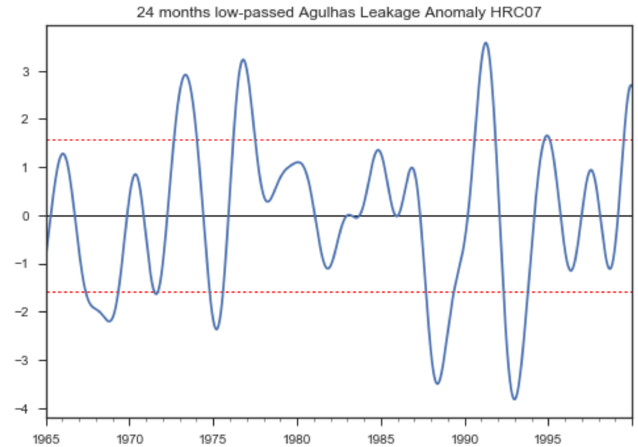
Local climate imprints of interannual leakage variability

- How much each variable increases, when leakage increases by 1 Sv.
- SLP regression is consistent with TAUX shift.
- TS and surface fluxes share a east-west contrasting pattern.

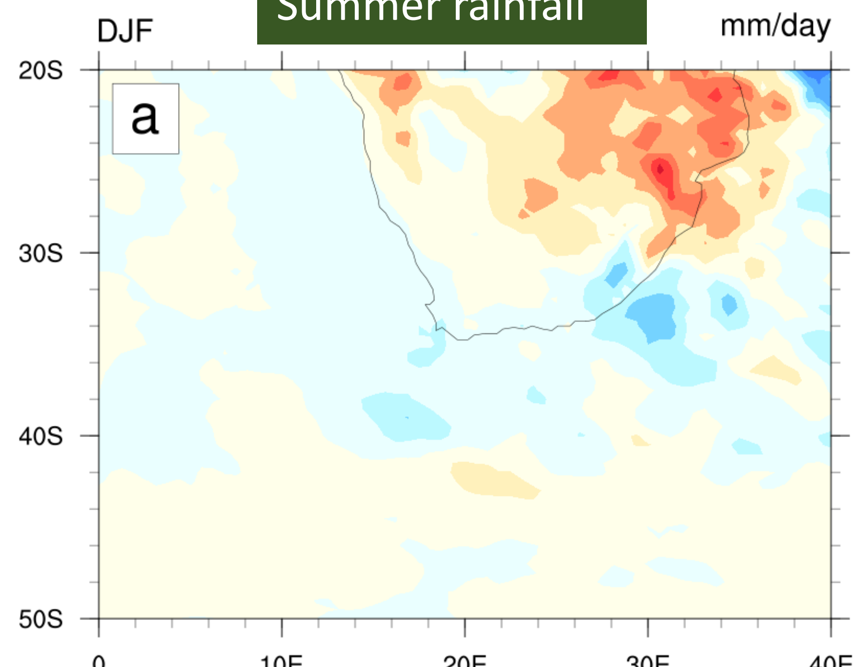




Model



MERRA reanalysis
Summer rainfall



- Using a SST based Agulhas leakage proxy following Biastoch et al. [2015]
- The reduced summer convective rainfall is consistent with our model
- Very different in other seasons.

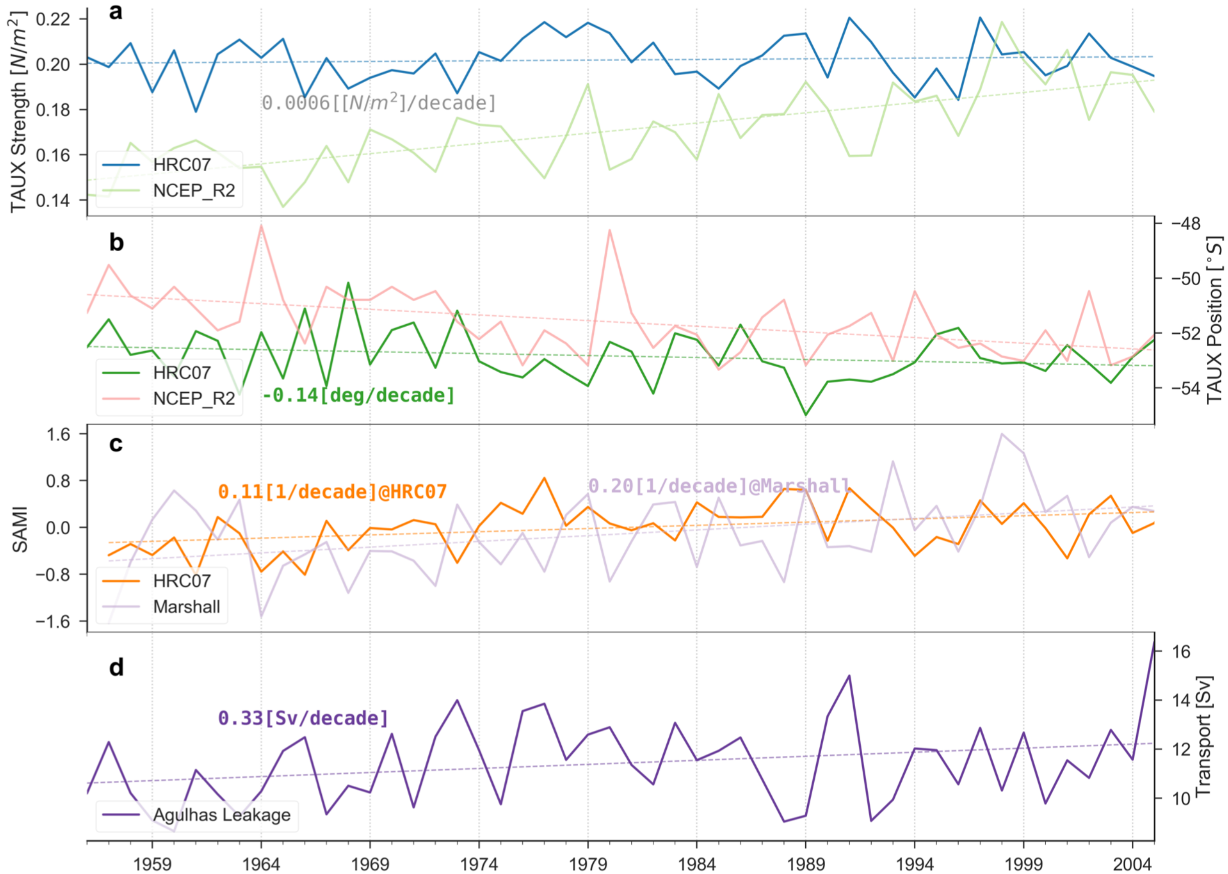
Decadal trends of westerlies and Agulhas leakage in the 20th century run.

Maximum westerlies magnitude 20S-70S

The latitude of such max. [Swart & Fyfe, 2012]

Observed [Marshall, 2003] vs model SAM index

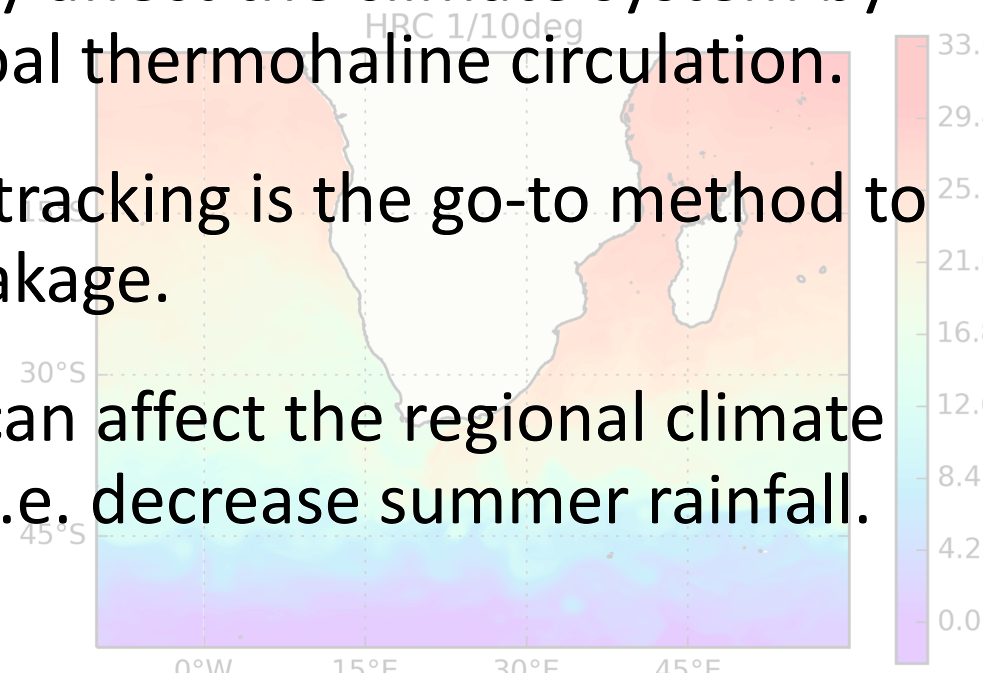
Agulhas leakage Transport



- 0.33 Sv per decade since 1956 in HRC07.
- 1.2 and 1.7 Sv/decade using Lagrangian particle [Biastoch et al. , 2009, 2015].
- 0.84 Sv/decade since the mid-1960s using a SST based proxy [Biastoch et al., 2015]
- Spurious westerlies trends in reanalysis [Marshall, 2003; Swart et al., 2015]

Summary

- Climate models are powerful tools to study the climate system and to project future climate.
- Agulhas leakage may affect the climate system by modulating the global thermohaline circulation.
- Lagrangian particle tracking is the go-to method to quantify Agulhas leakage.
- Leakage variability can affect the regional climate of southern Africa, i.e. decrease summer rainfall.



References

- Beal, L. M., and Coauthors, 2011: On the role of the Agulhas system in ocean circulation and climate. Nature, 472, 429–436, doi:10.1038/nature09983.
- Cheng, Y., D. Putrasahan, L. Beal, and B. Kirtman, 2016: Quantifying Agulhas Leakage in a High-Resolution Climate Model. J. Climate, 29, 6881–6892, doi:10.1175/JCLI-D-15-0568.1.
- de Ruijter, W. P. M., A. Biastoch, S. S. Drijfhout, J. R. E. Lutjeharms, R. P. Matano, T. Pichevin, P. J. Van Leeuwen, and W. Weijer, 1999: Indian-Atlantic interocean exchange: Dynamics, estimation and impact.*J. Geophys. Res*,**104**, 20885–20910, doi:10.1029/1998JC900099.
- Biastoch, A., C. W. Böning, F. U. Schwarzkopf, and J. R. E. Lutjeharms, 2009: Increase in Agulhas leakage due to poleward shift of Southern Hemisphere westerlies.*Nature*,**462**, 495–498, doi:10.1038/nature08519.
- Biastoch, A., J. V. Durgadoo, A. K. Morrison, E. van Sebille, W. Weijer, and S. M. Griffies, 2015: Atlantic multi-decadal oscillation covaries with Agulhas leakage. Nat Commun, 6, 10082, doi:10.1038/ncomms10082.
- de Ruijter, W., 1982: Asymptotic analysis of the Agulhas and Brazil Current systems. J. Phys. Oceanogr, 12, 361–373, doi:10.1175/1520-0485(1982)012<0361:AAOTAA>2.0.CO;2.

- de Ruijter, W. P. M., A. Biastoch, S. S. Drijfhout, J. R. E. Lutjeharms, R. P. Matano, T. Pichevin, P. J. Van Leeuwen, and W. Weijer, 1999: Indian-Atlantic interocean exchange: Dynamics, estimation and impact.*J. Geophys. Res*,**104**, 20885–20910, doi:10.1029/1998JC900099.

- Durgadoo, J. V., B. R. Loveday, C. J. C. Reason, P. Penven, and A. Biastoch, 2013: Agulhas Leakage Predominantly Responds to the Southern Hemisphere Westerlies. J. Phys. Oceanogr, 43, 2113–2131, doi:10.1175/JPO-D-13-047.1.
- Gordon, A. L., R. F. Weiss, W. M. Smethie, and M. J. Warner, 1992: Thermocline and Intermediate Water Communication Between the South Atlantic and Indian Oceans. J. Geophys. Res, 97, 7223–7240, doi:10.1029/92JC00485.
- Kirtman, B. P., and Coauthors, 2012: Impact of ocean model resolution on CCSM climate simulations. Clim Dyn, 39, 1303–1328, doi:.
- Loveday, B. R., J. V. Durgadoo, C. J. C. Reason, A. Biastoch, and P. Penven, 2014: Decoupling of the Agulhas Leakage from the Agulhas Current. J. Phys. Oceanogr, 44, 1776–1797, doi:10.1175/JPO-D-13-093.1.

References

- Paris, C. B., J. Helgers, E. van Sebille, and A. Srinivasan, 2013: Connectivity Modeling System: A probabilistic modeling tool for the multi-scale tracking of biotic and abiotic variability in the ocean. Environ. Model. Softw, 42, 47–54, doi:10.1016/j.envsoft.2012.12.006.
- Peeters, F. J. C., R. Acheson, G.-J. A. Brummer, W. P. M. de Ruijter, R. R. Schneider, G. M. Ganssen, E. Ufkes, and D. Kroon, 2004: Vigorous exchange between the Indian and Atlantic oceans at the end of the past five glacial periods. Nature, 430, 661–665, doi:10.1038/nature02785.
- Qin, X., E. van Sebille, and A. Sen Gupta, 2014: Quantification of errors induced by temporal resolution on Lagrangian particles in an eddy-resolving model. Ocean Modelling, 76, 20–30, doi:10.1016/j.ocemod.2014.02.002.
- Richardson, P. L., 2007: Agulhas leakage into the Atlantic estimated with subsurface floats and surface drifters. Deep-Sea Res. I, 54, 1361–1389, doi:10.1016/j.dsr.2007.04.010.
- Reason, C. J. C., and M. Rouault, 2002: ENSO-like decadal variability and South African rainfall. Geophys. Res. Lett, 29, 3, doi:10.1029/2002GL014663.
- de Ruijter, W. P. M., A. Biastoch, S. S. Drijfhout, J. R. E. Lutjeharms, R. P. Matano, T. Pichevin, P. J. Van Leeuwen, and W. Weijer, 1999: Indian-Atlantic interocean exchange: Dynamics, estimation and impact.*J. Geophys. Res*,**104**, 20885–20910, doi:10.1029/1998JC900099.
- Rouault, M., P. Penven, and B. Pohl, 2009: Warming in the Agulhas Current system since the 1980's. Geophys. Res. Lett, 36, L12602, doi:10.1029/2009GL037987.

- de Ruijter, W. P. M., A. Biastoch, S. S. Drijfhout, J. R. E. Lutjeharms, R. P. Matano, T. Pichevin, P. J. Van Leeuwen, and W. Weijer, 1999: Indian-Atlantic interocean exchange: Dynamics, estimation and impact.*J. Geophys. Res*,**104**, 20885–20910, doi:10.1029/1998JC900099.

- van Sebille, E., C. N. Barron, A. Biastoch, P. J. Van Leeuwen, F. C. Vossepoel, and W. P. M. de Ruijter, 2009: Relating Agulhas leakage to the Agulhas Current retroflection location.*Ocean Sci*,**5**, 511–521, doi:10.5194/os-5-511-2009.
- Weijer, W., and Coauthors, 2011: The Southern Ocean and Its Climate in CCSM4. J. Climate, 25, 2652–2675, doi:10.1175/JCLI-D-11-00302.1.