Southern Ocean Circulation and Climate Variability

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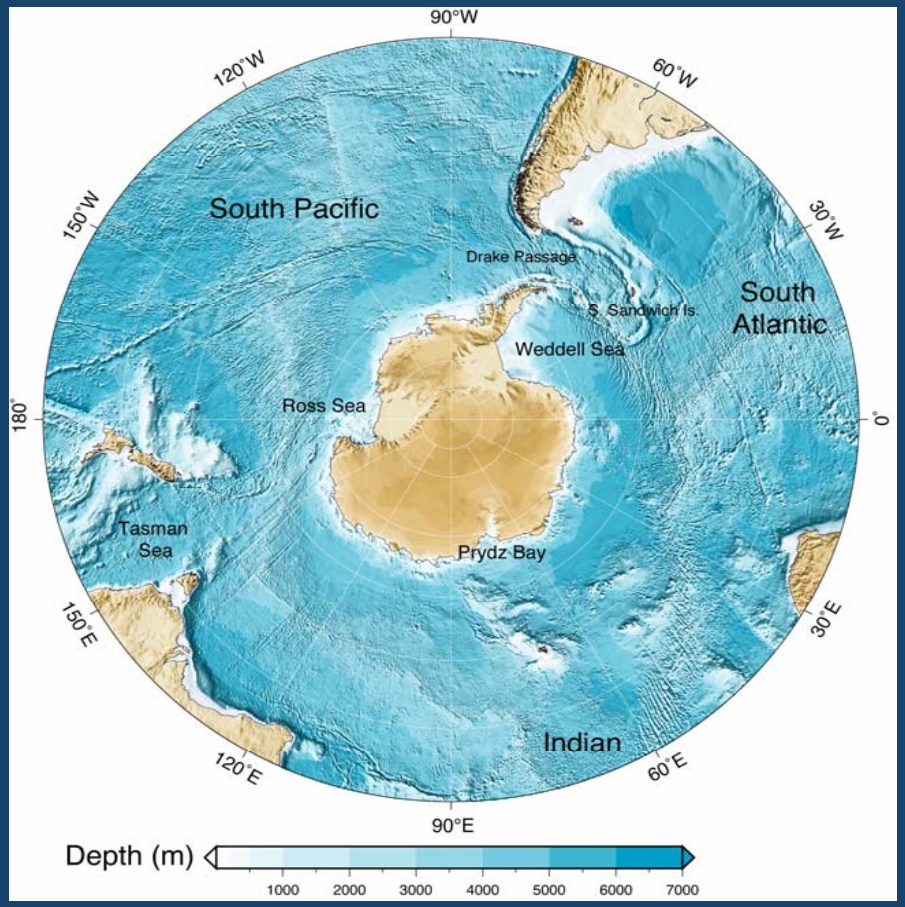
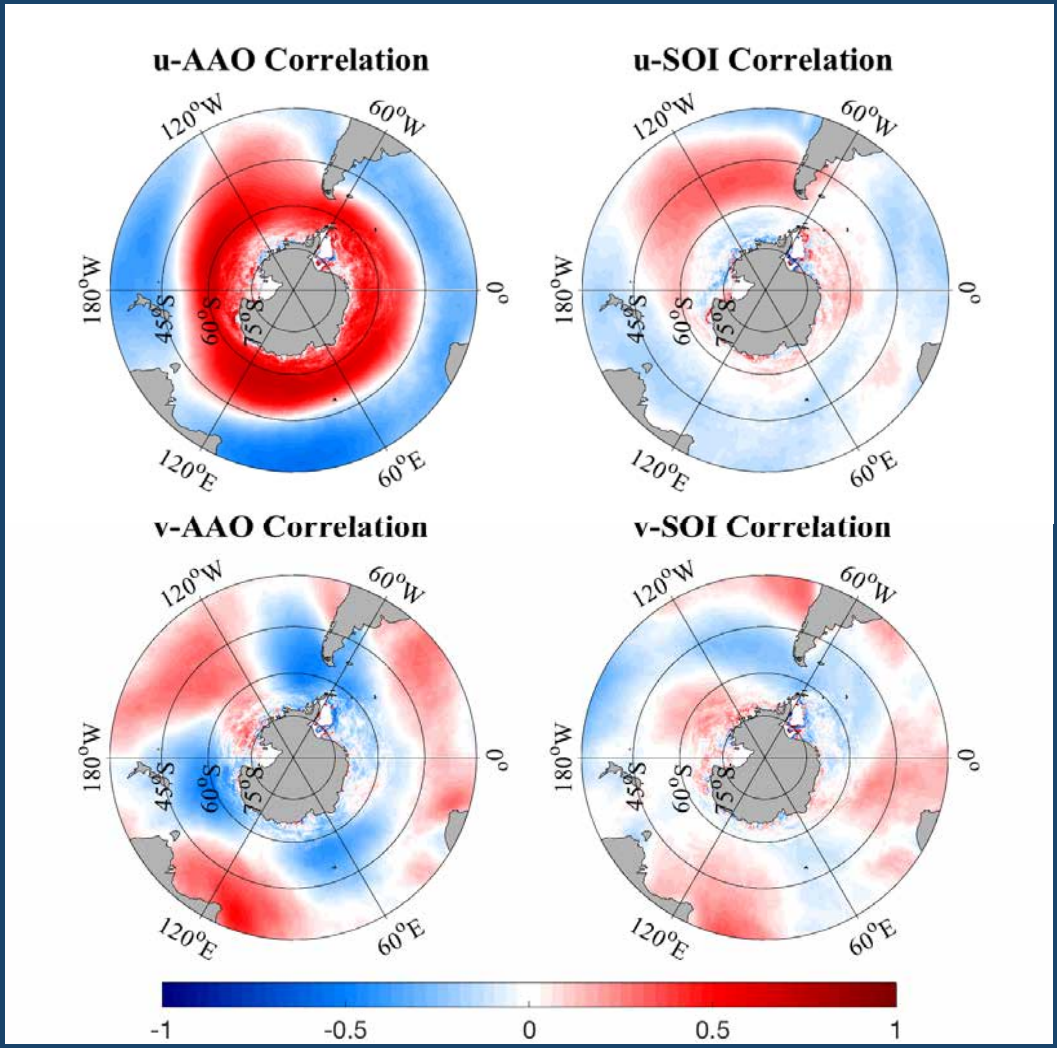
Southern Ocean- Back Ground

- The Southern Ocean (SO) is a major driving force in global climate.
- It represents 30% of the global ocean surface area, accounts for ~40% of the anthropogenic carbon dioxide uptake, as well as 75% of heat uptake within the last historical period
- ACC playing a noteworthy role in the global-scale MOC



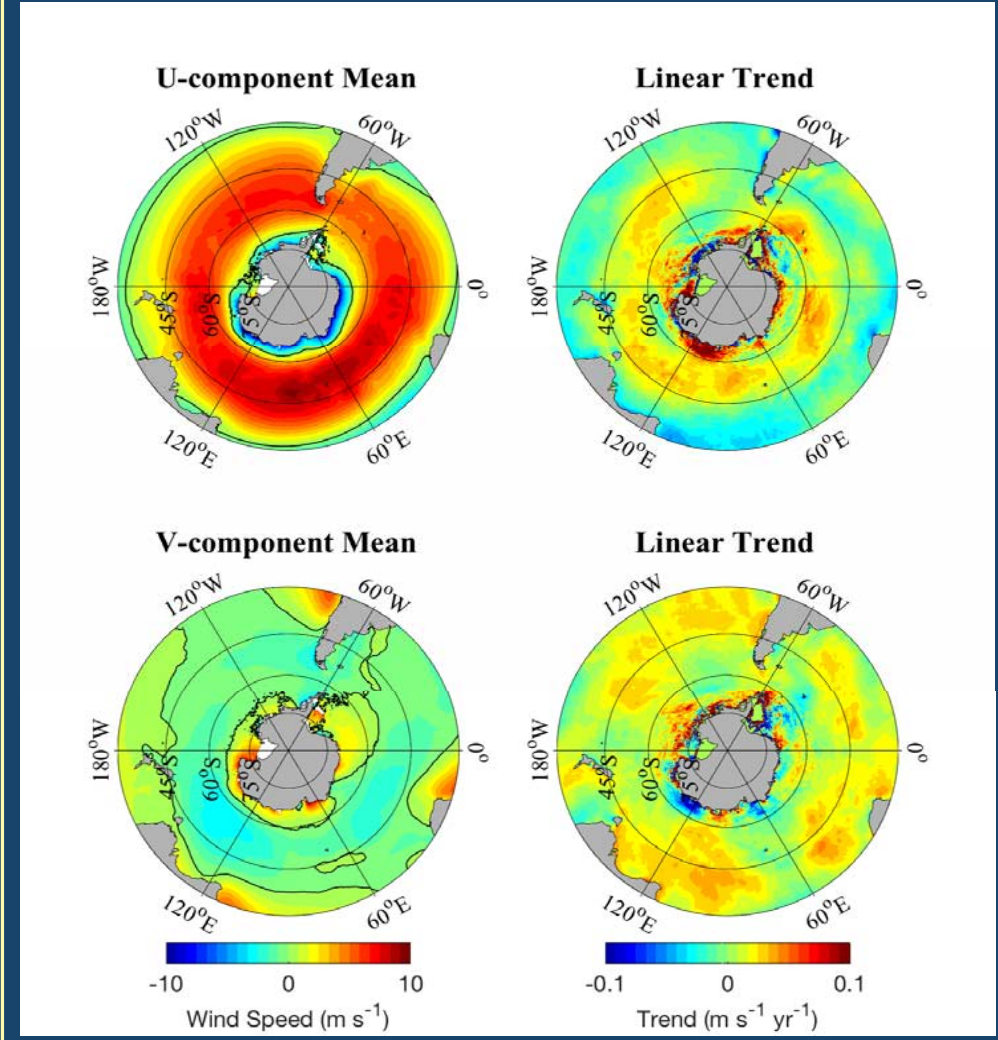
Southern Ocean - Winds



- The Antarctic Oscillation (AAO) is the dominate mode of variability than the Southern Oscillation Index (SOI)
- The westerly winds intensified throughout recent decades; and shifting poleward due to the increasing Antarctic oscillation (AAO)

NOAA's blended wind product 1988-2016

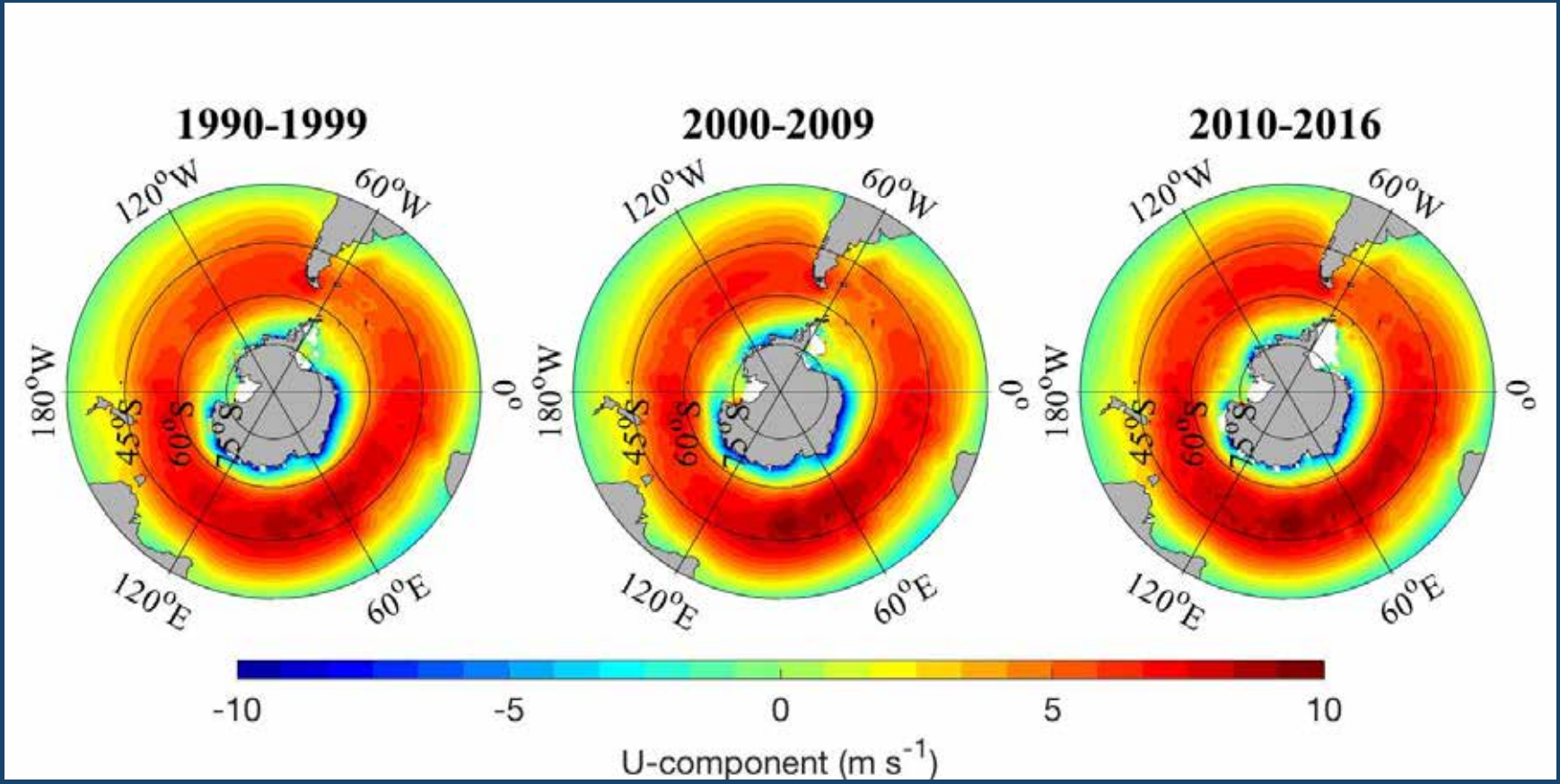
Southern Ocean - Winds



- Strong eastward winds Increasing within the Antarctic Circumpolar Current (ACC; 45°-60°S)
- Large spatial changes in Southern Ocean (SO) meridional component of winds
- Decreasing southward component of winds within the mid-latitude
- Decreasing coastal winds along Antarctica

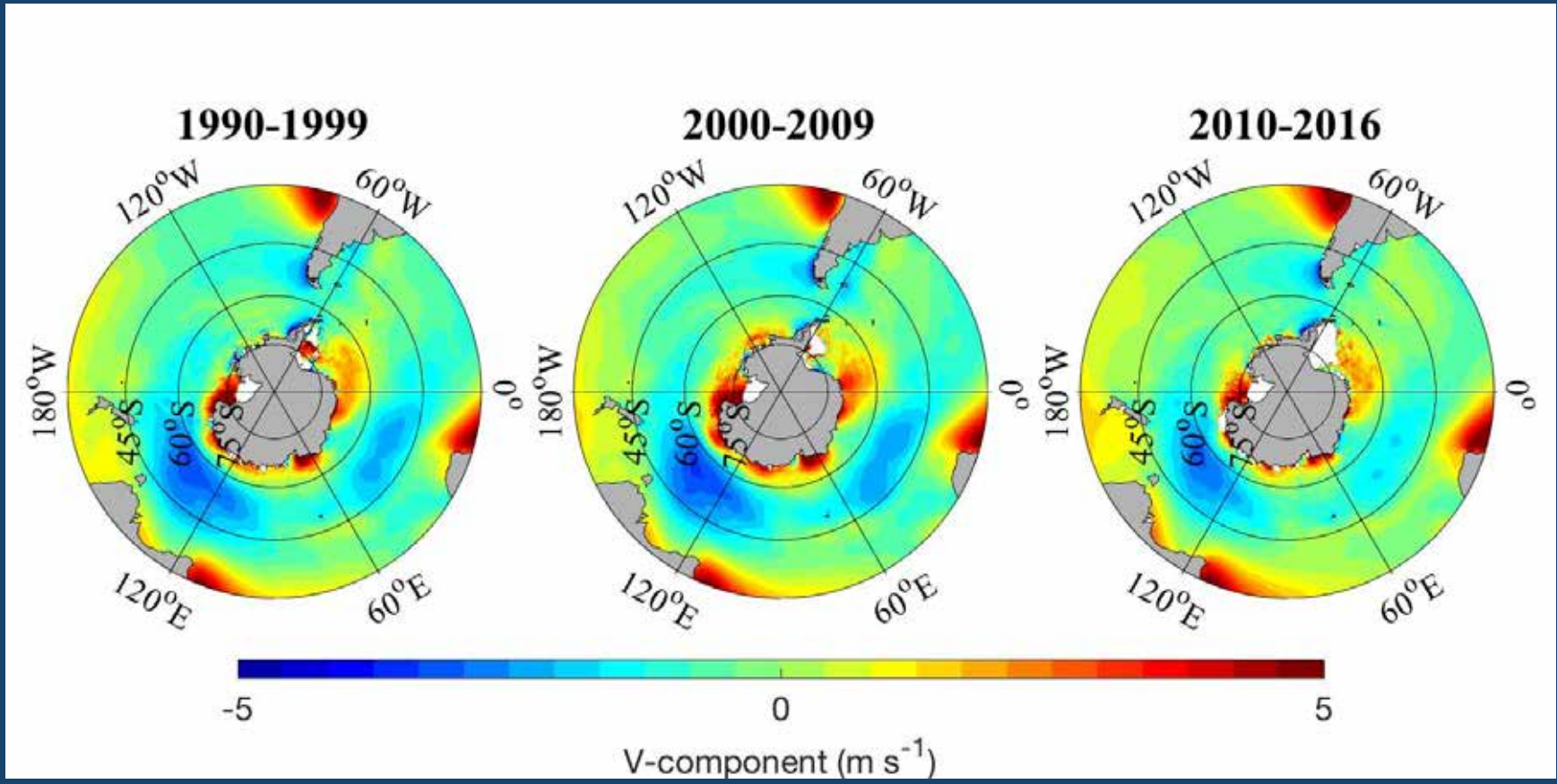
NOAA's blended wind product 1988-2016

Southern Ocean - Winds



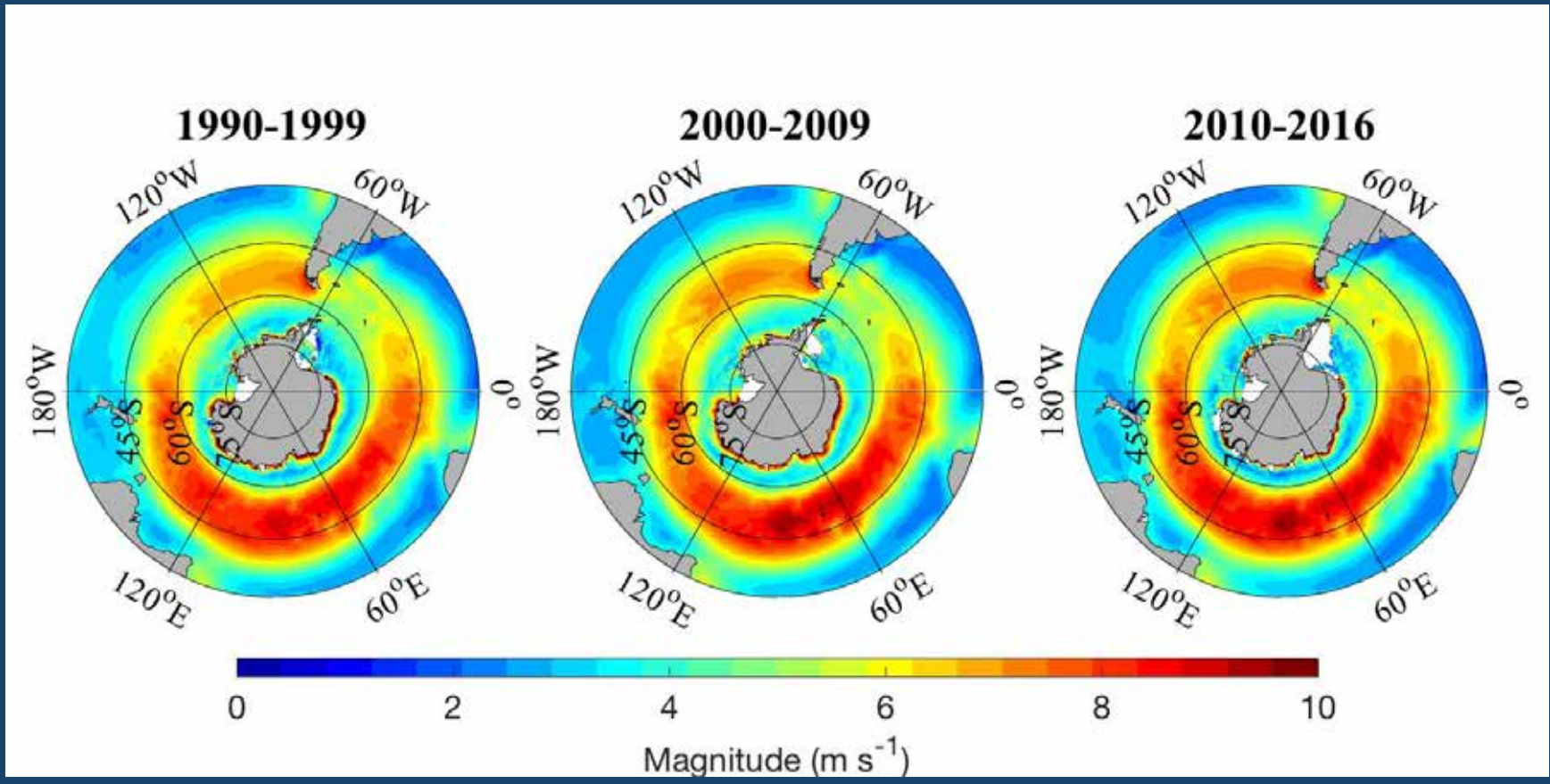
- Most noticeable changes in ACC and Indian Ocean basin
- Decreasing westward winds along the Antarctic coast
- Most noticeable change in recent decade

Southern Ocean - Winds



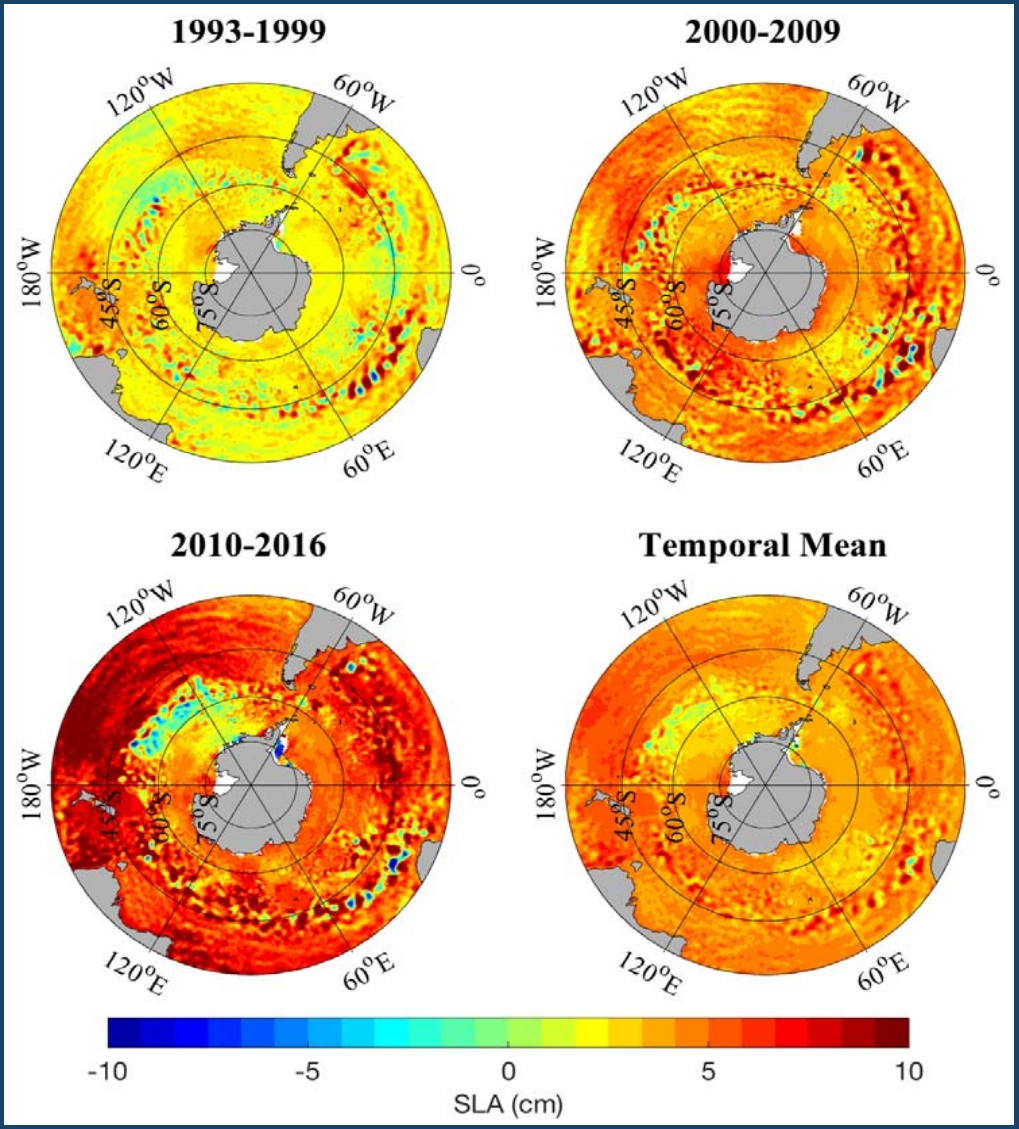
- Decreasing southward component in the Indian basin ACC
- Decreasing northward component along the Antarctic coast

Southern Ocean - Winds



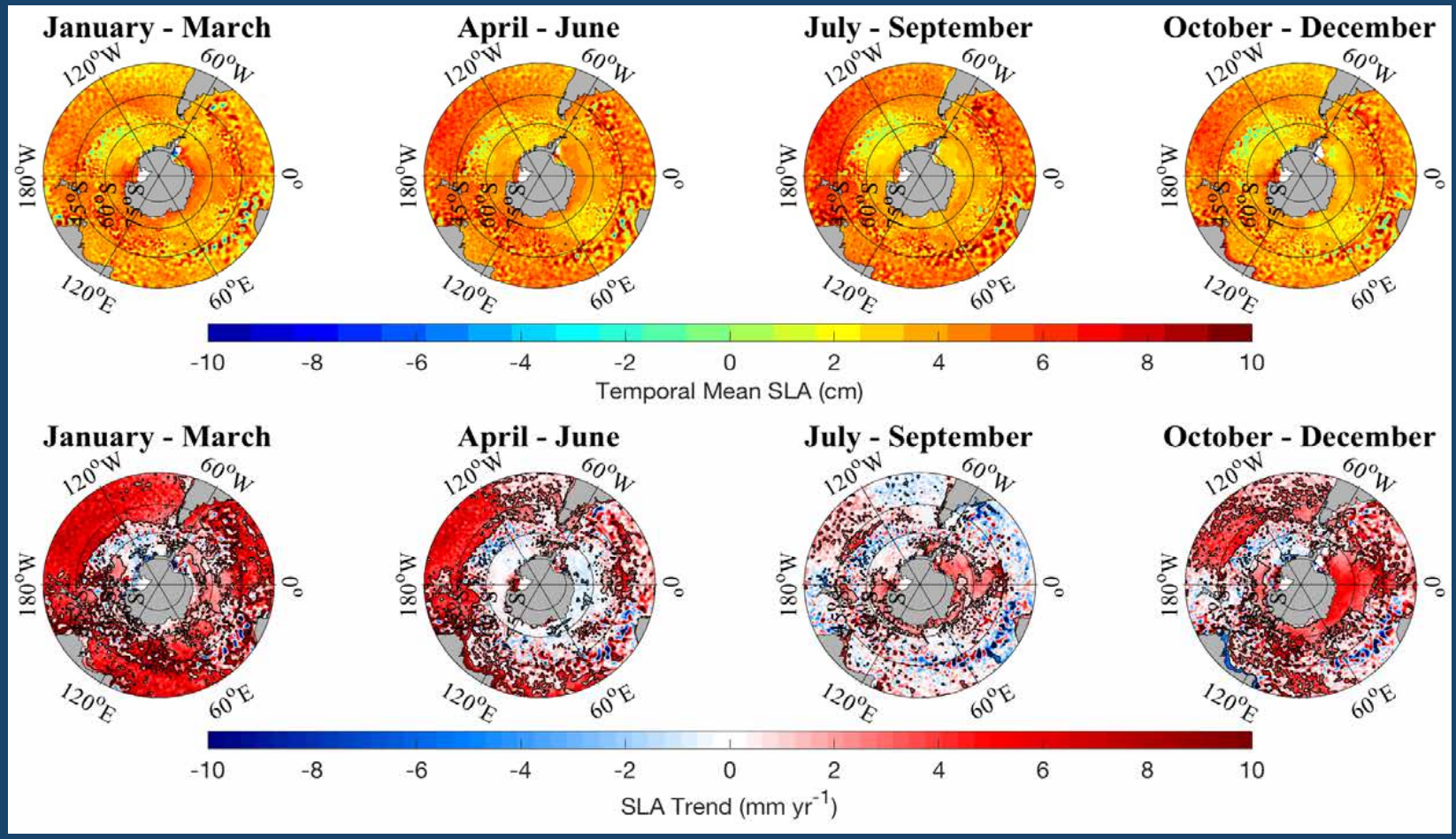
- Largest magnitude in the SO are within the ACC region
- Increasing magnitude in the ACC and mid-latitudes of the SO
- The Antarctic Circumpolar Current (ACC) flows to east as a result of the strong westerly winds within the SO region.

Southern Ocean – Sea Level Changes



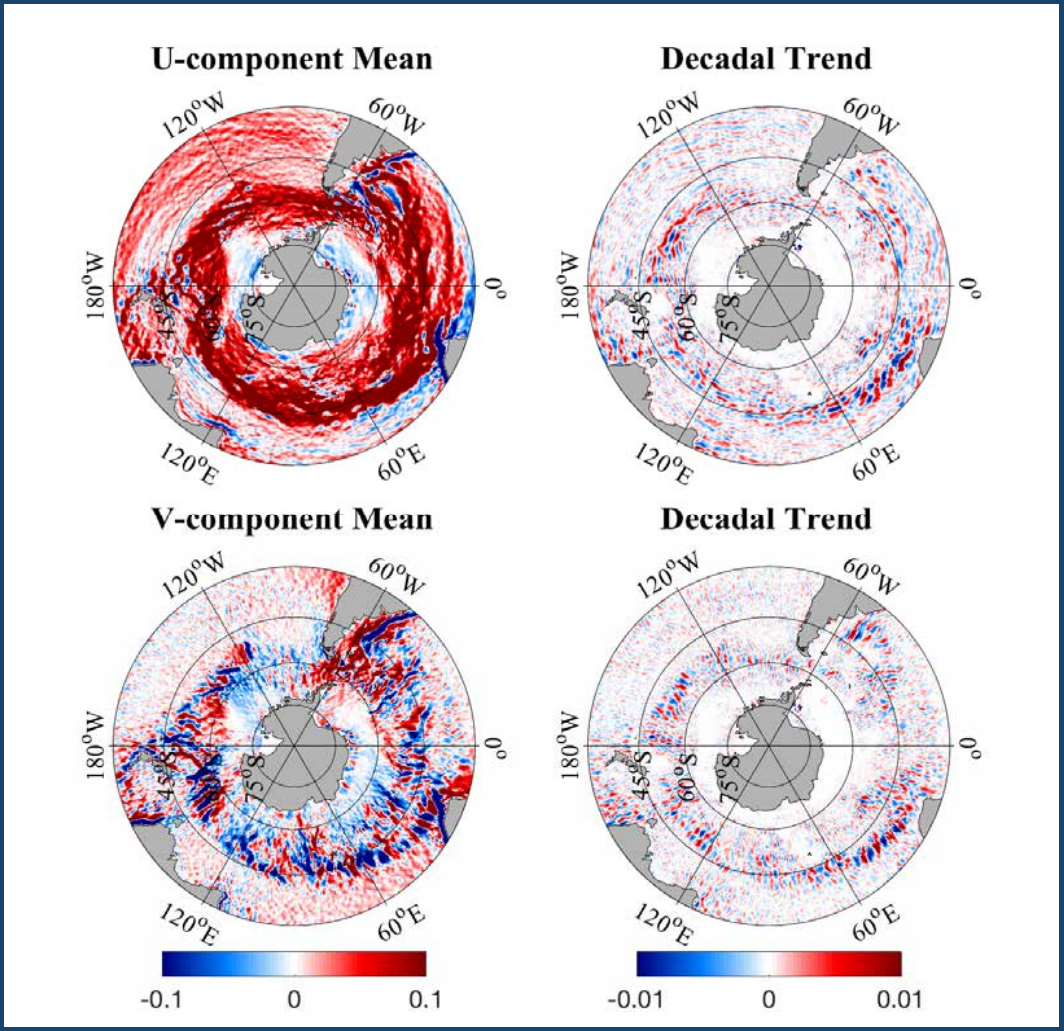
- Sea level anomaly (SLA) decadal changes show increasing sea level between the 1990's through 2016
- Decreasing SLA between 50°-60° S in the Pacific basin and within the Agulhas region

Southern Ocean – Sea Level Changes



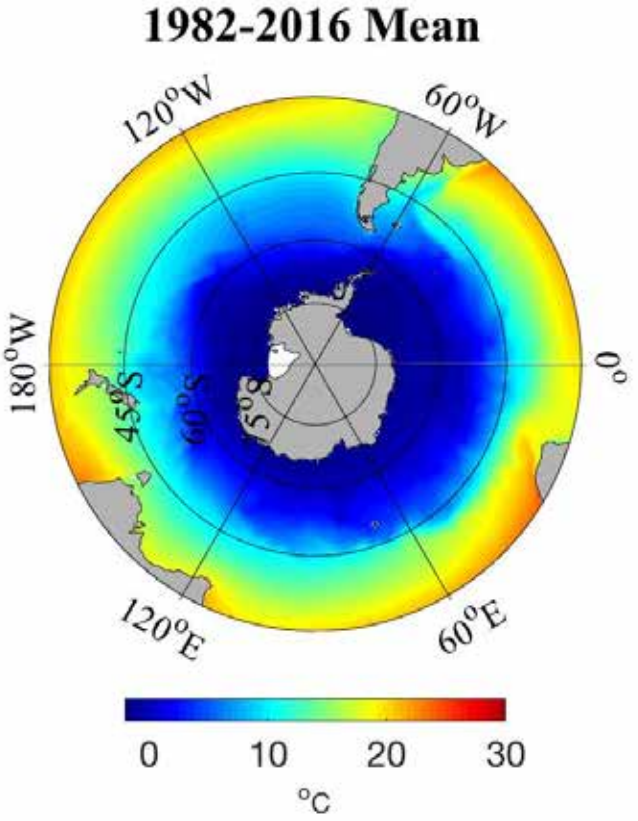
- Seasonal mean and linear trends in SLA between 1993 – 2016
- Largest trends from January to March Increasing SLA
- Smallest trends from July to September

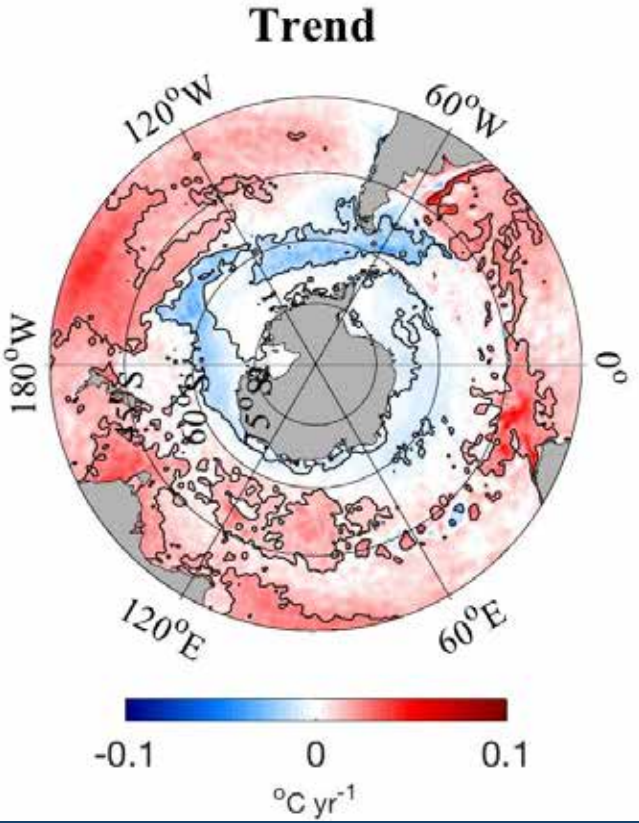
Southern Ocean – Surface Currents



- Strong surface currents within the ACC (both zonal and meridional)
- The shift in westerlies and increasing AAO are linked to restructuring the ACC fronts driving the ACC southward

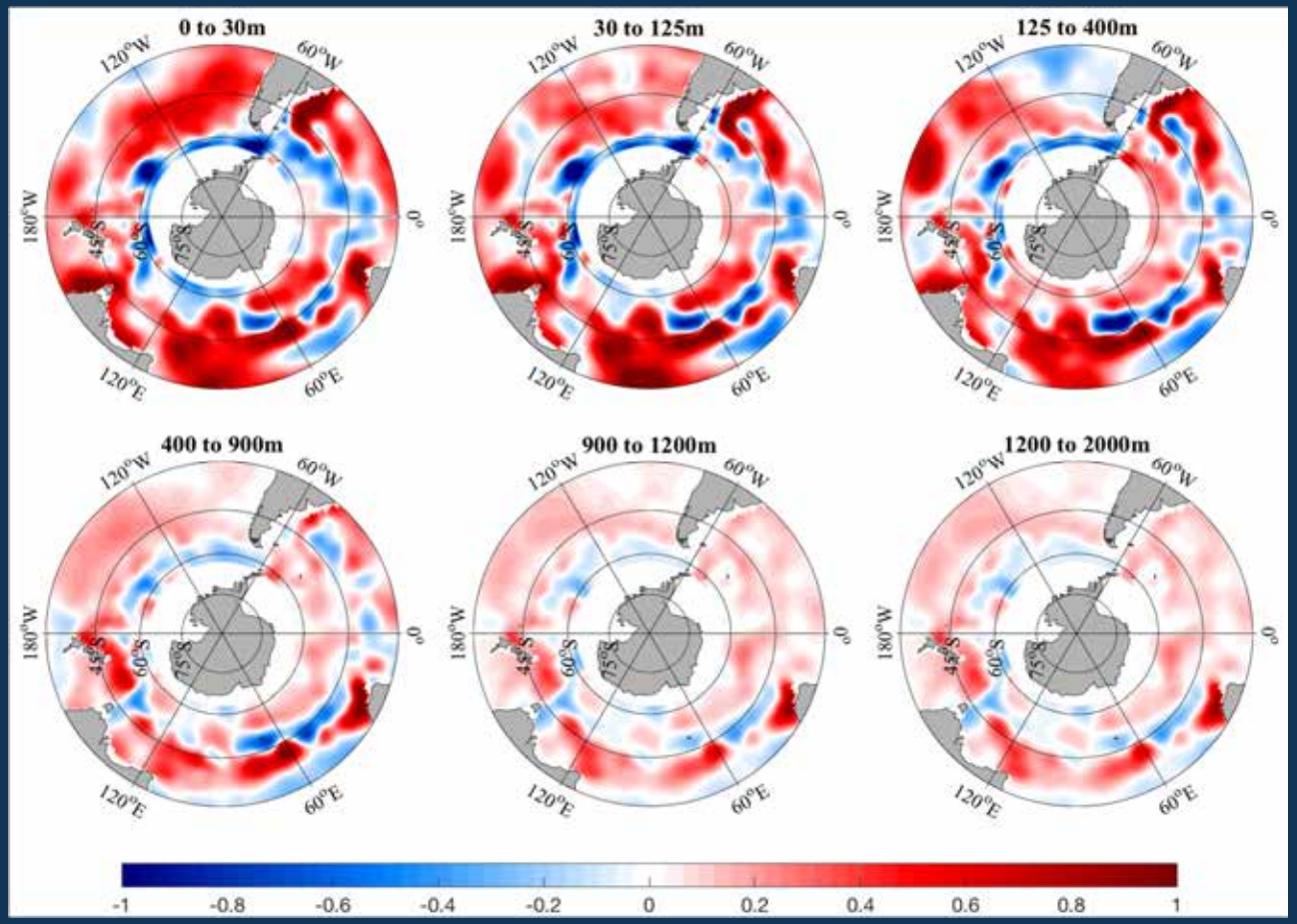
Southern Ocean – Sea Surface Temperature





- Sea surface temperatures (SST) can approach -2° C
- Decreasing SST along the Antarctic coast
- Increasing SST north of the ACC

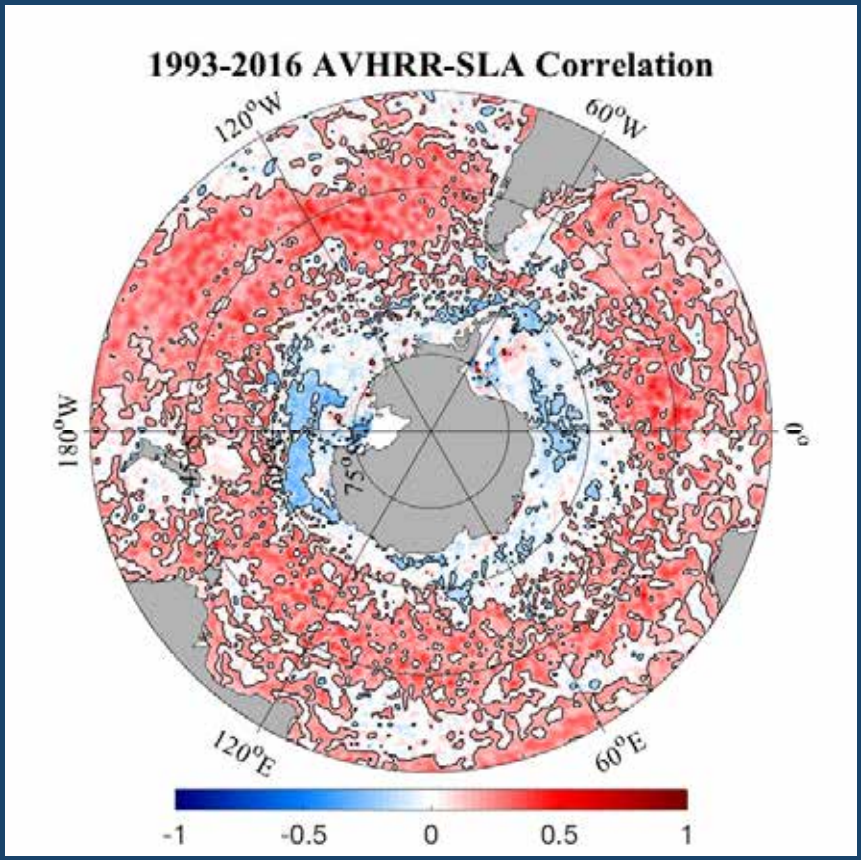
Southern Ocean Warming



The linear-trend of mean temperature (°C dec^{-1}) derived from 2005-2016 Argo data.

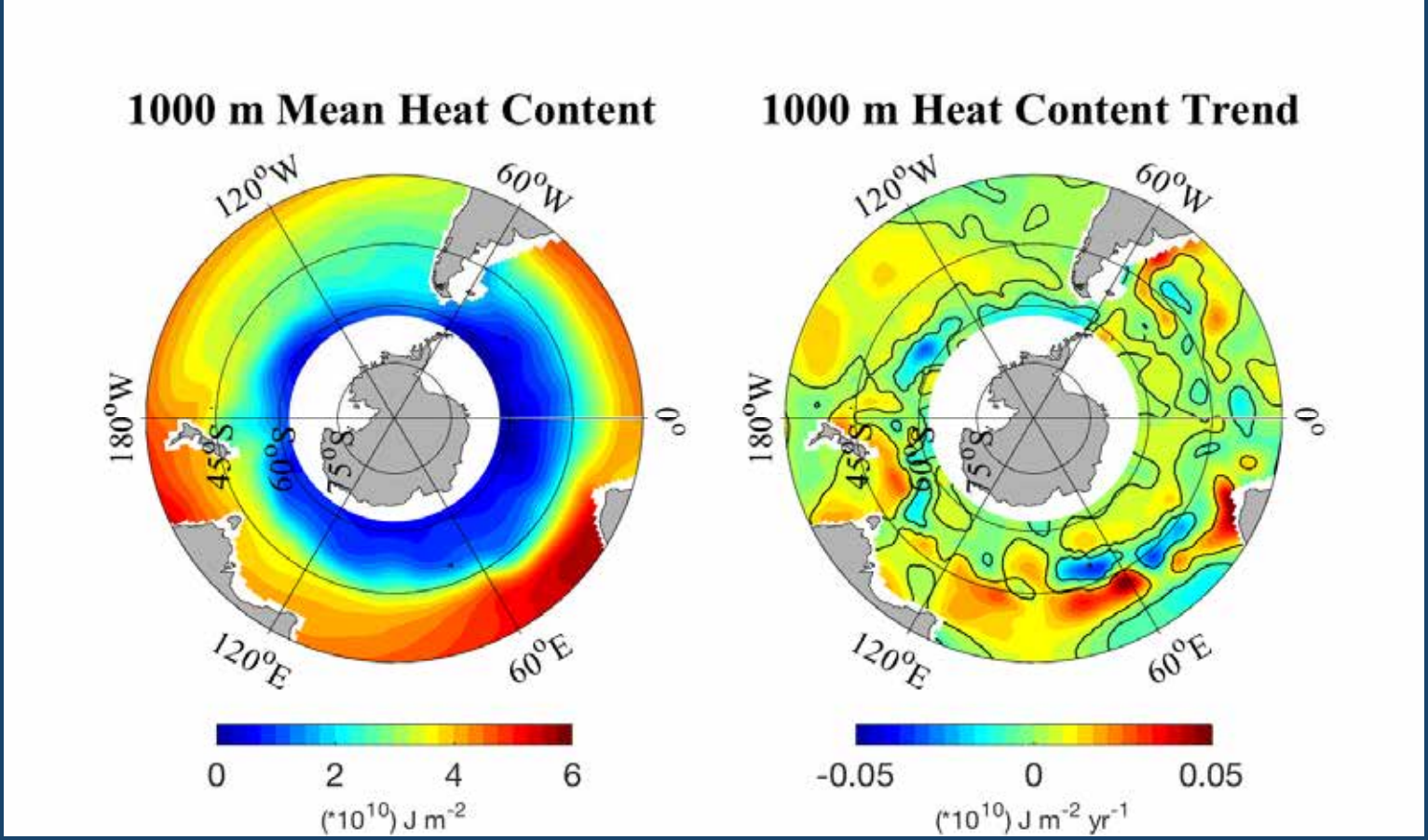
- Spatial linear-trend of Argo temperature
  - 12-year trends calculated in (°C dec^{-1})
- Warming pattern noticeable within much of the SO
- Much of the Antarctic coast suggests decreasing temperatures
- Within the deep waters, largest magnitude in trends occur within the Indian basin

Southern Ocean – SST & SLA



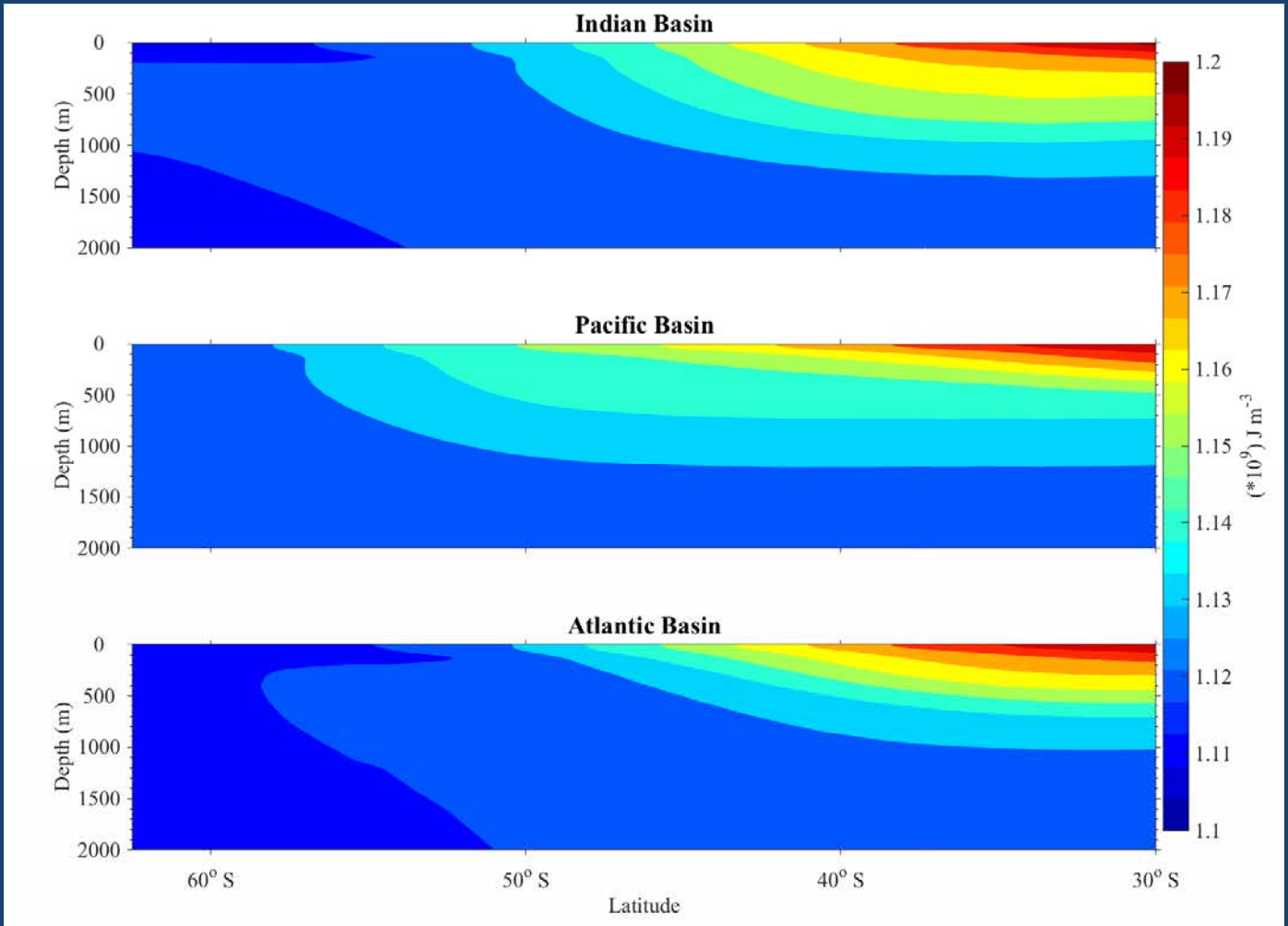
- Strong correlations between SST and SLA (Standardized by monthly anomalies)
- In regions of decreasing temperature, SLA decreases
- Regions of increasing temperatures, SLA increases

Southern Ocean – Heat Content



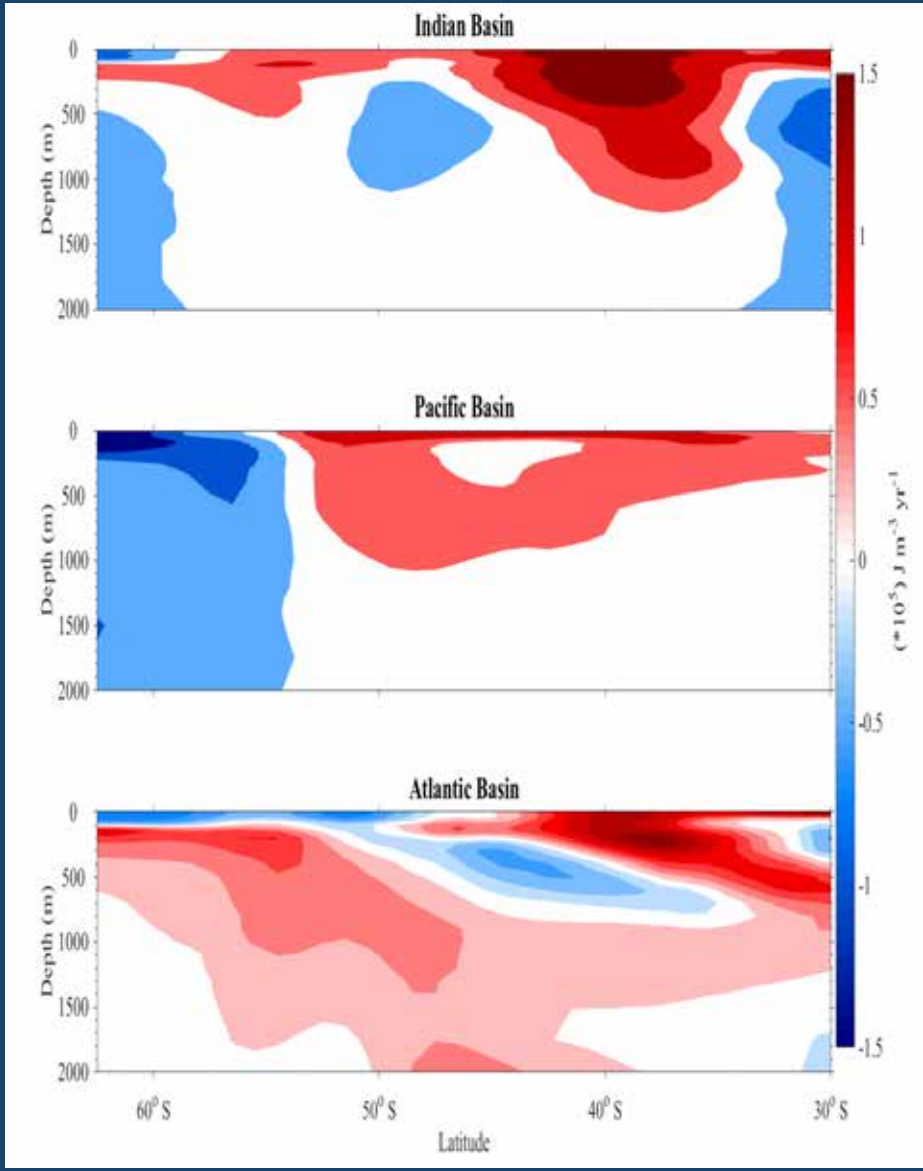
- Using Argo 2005-2016
- Increasing heat content north of the ACC
- Decreasing heat content trends in the Pacific basin and the Agulhas retroflection region

Southern Ocean – Heat Content



Steep gradient along the ACC- Result of Ekman pumping and tilted isopycnals

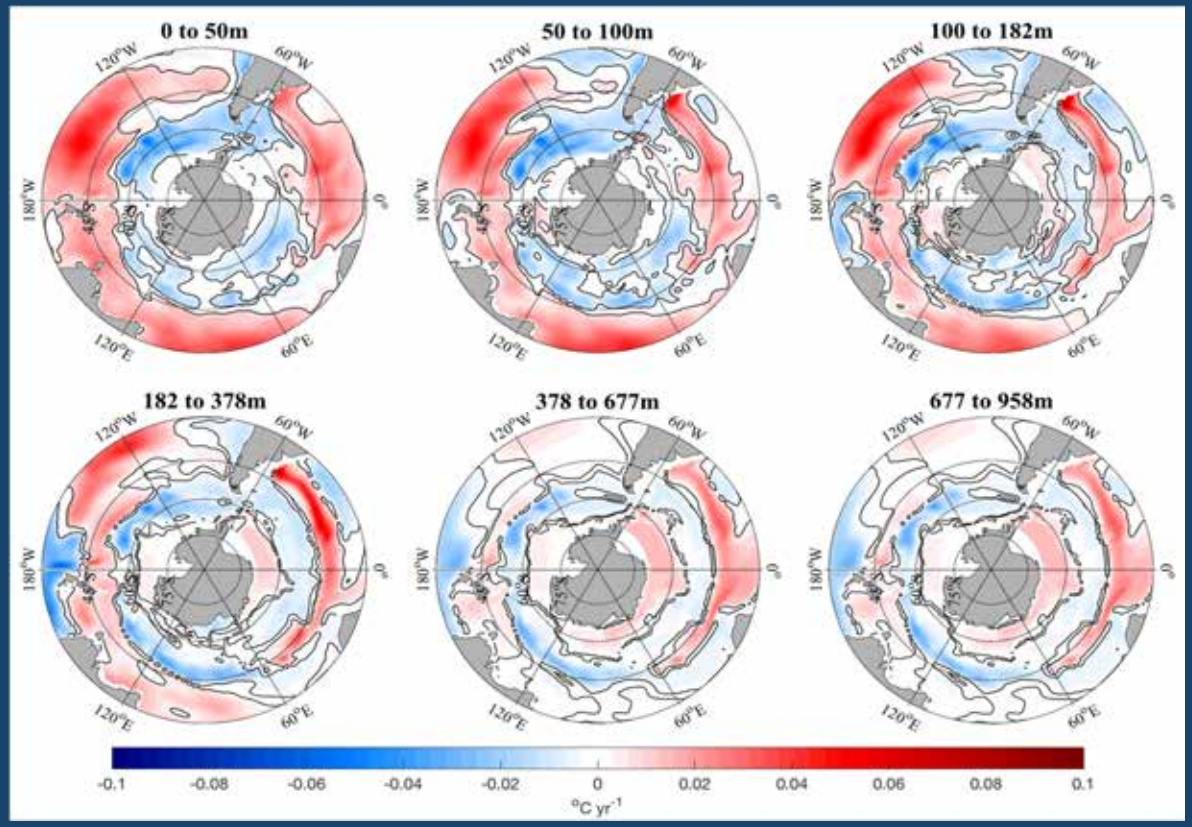
Southern Ocean – Yearly Trend Heat Content



- More Heat Content in the Indian Basin
- Surface and subsurface cooling in the Pacific basin
- Surface cooling in the Atlantic and Indian basins along the Antarctic coast
  - Subsurface warming (more noticeable in the Atlantic)
- Surface warming trends between 30°-55° S
  - Subsurface trends in these regions likely related to shift in westerlies

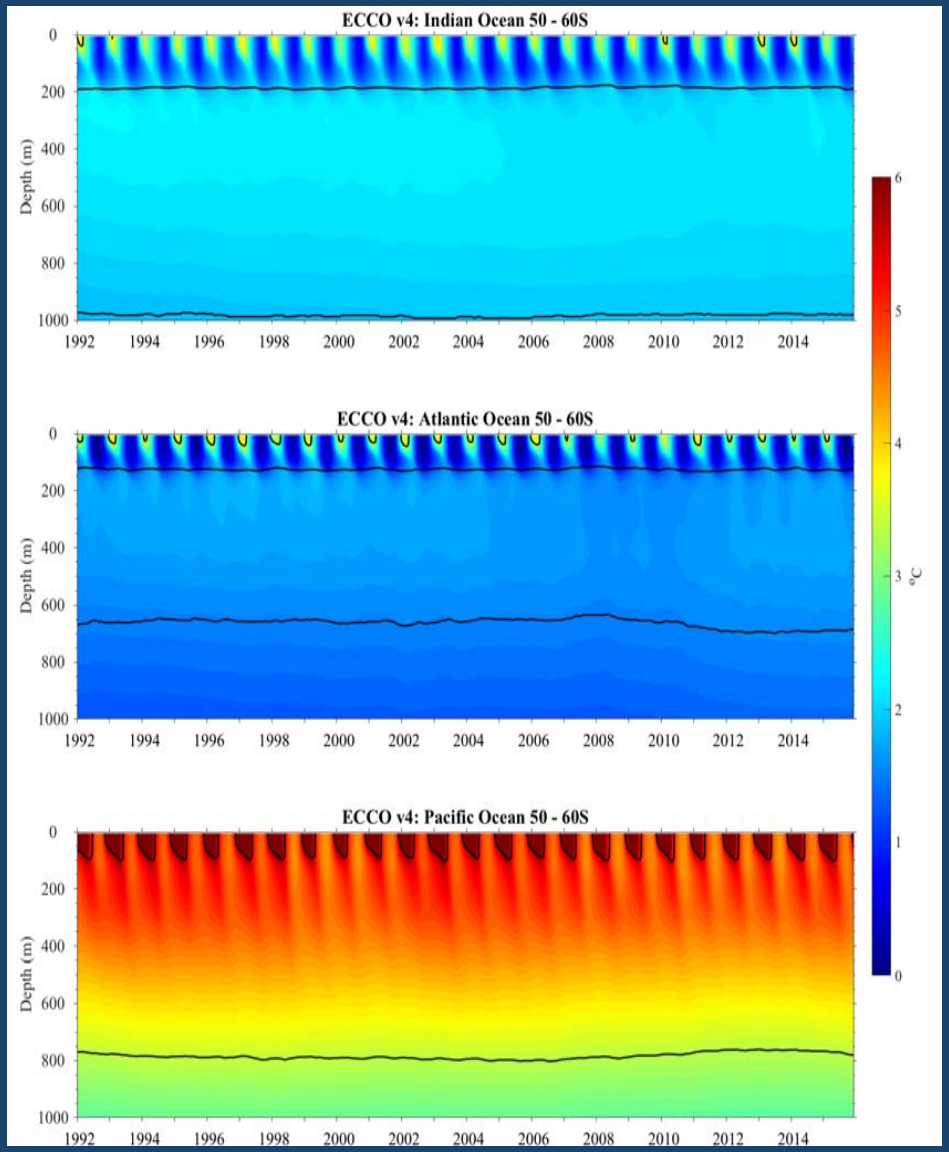
Southern Ocean – ECCO Temperature Trends

Estimating the Circulation & Climate of the Ocean (EEO)



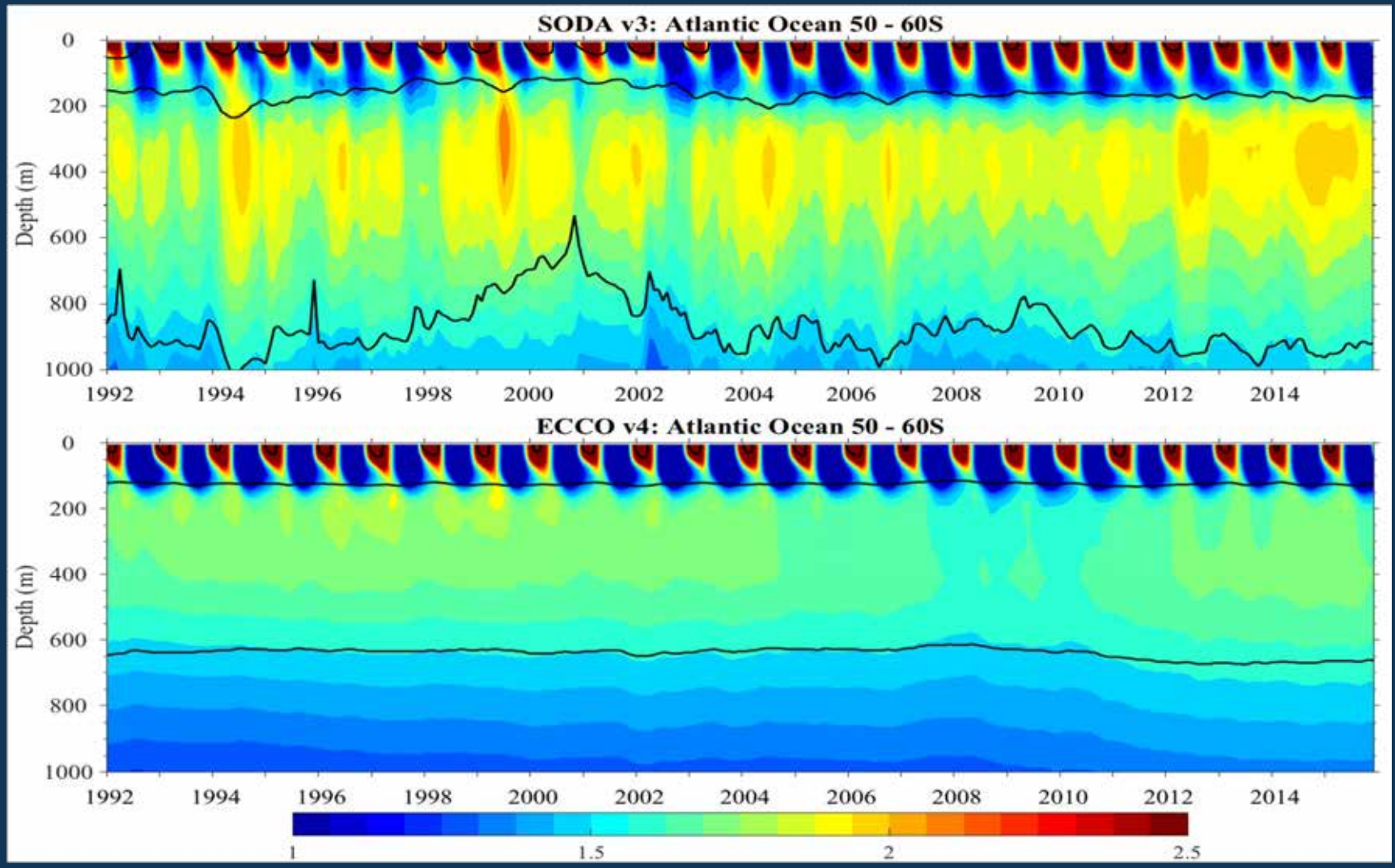
- ECCO v4 (1992-2015) depth-layered mean linear temperature trends (°C yr^{-1}) in the SO
- Similar to Argo temperature trends
- Warming north of the ACC
- Surface cooling south of the ACC
  - Sub-surface warming along the Antarctic coast in the Indian and Atlantic basins
  - Large portion of the Pacific basin is decreasing temperature within the surface 1000m

Southern Ocean – ECCO Temperature Trends



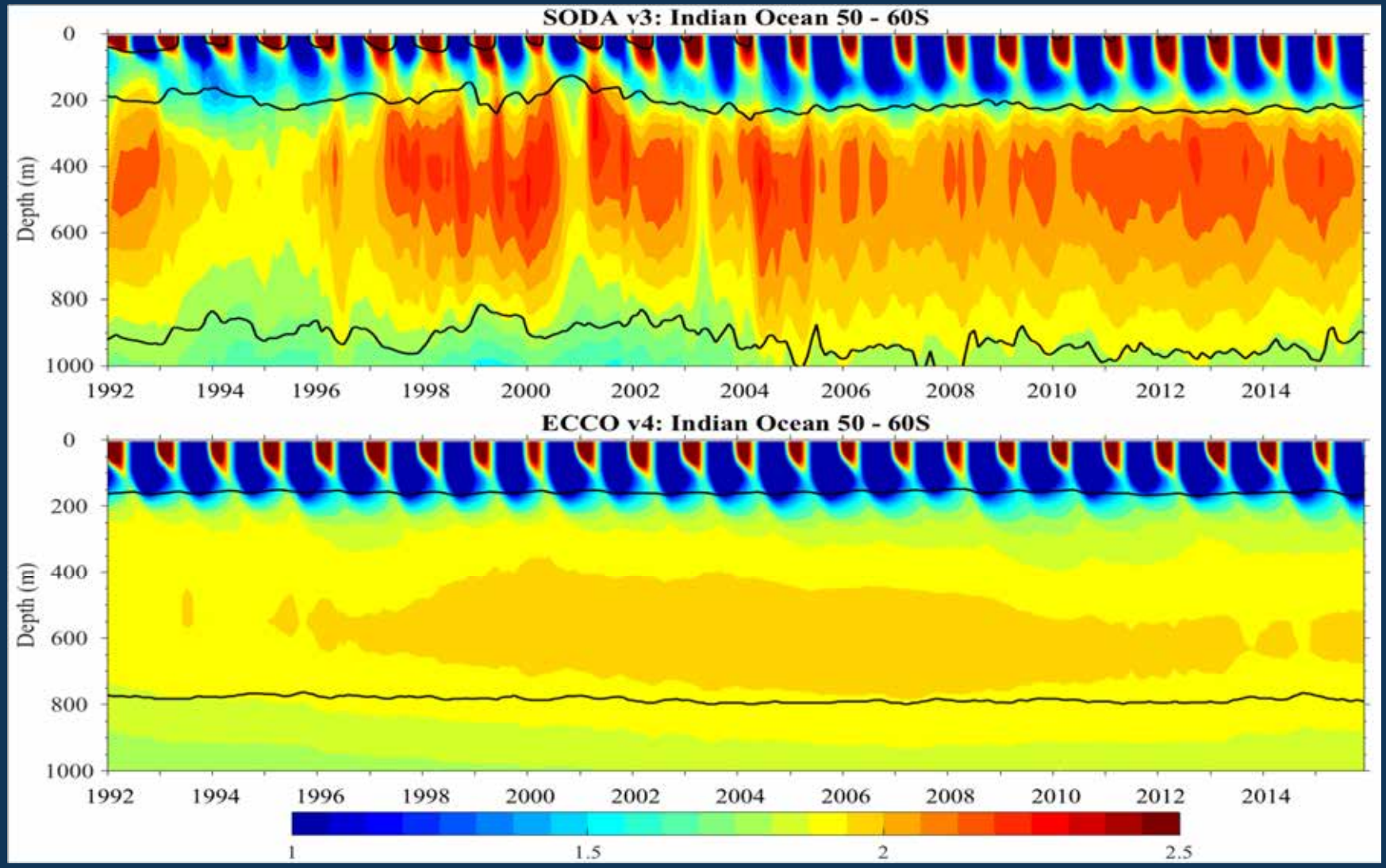
- The ECCO v4 (1992-2015) spatial mean temperature (° C) in the Atlantic, Indian, and Pacific basins averaged between 50°-60° S. Black lines are mean 27.0, 27.6, and 28.0 kg m^{-3} neutral density surfaces.
- ECCO notes increasing temperature trend in the Indian and Atlantic basins, decreasing temperature trend in the Pacific

Deep Ocean Warming in the Southern Ocean



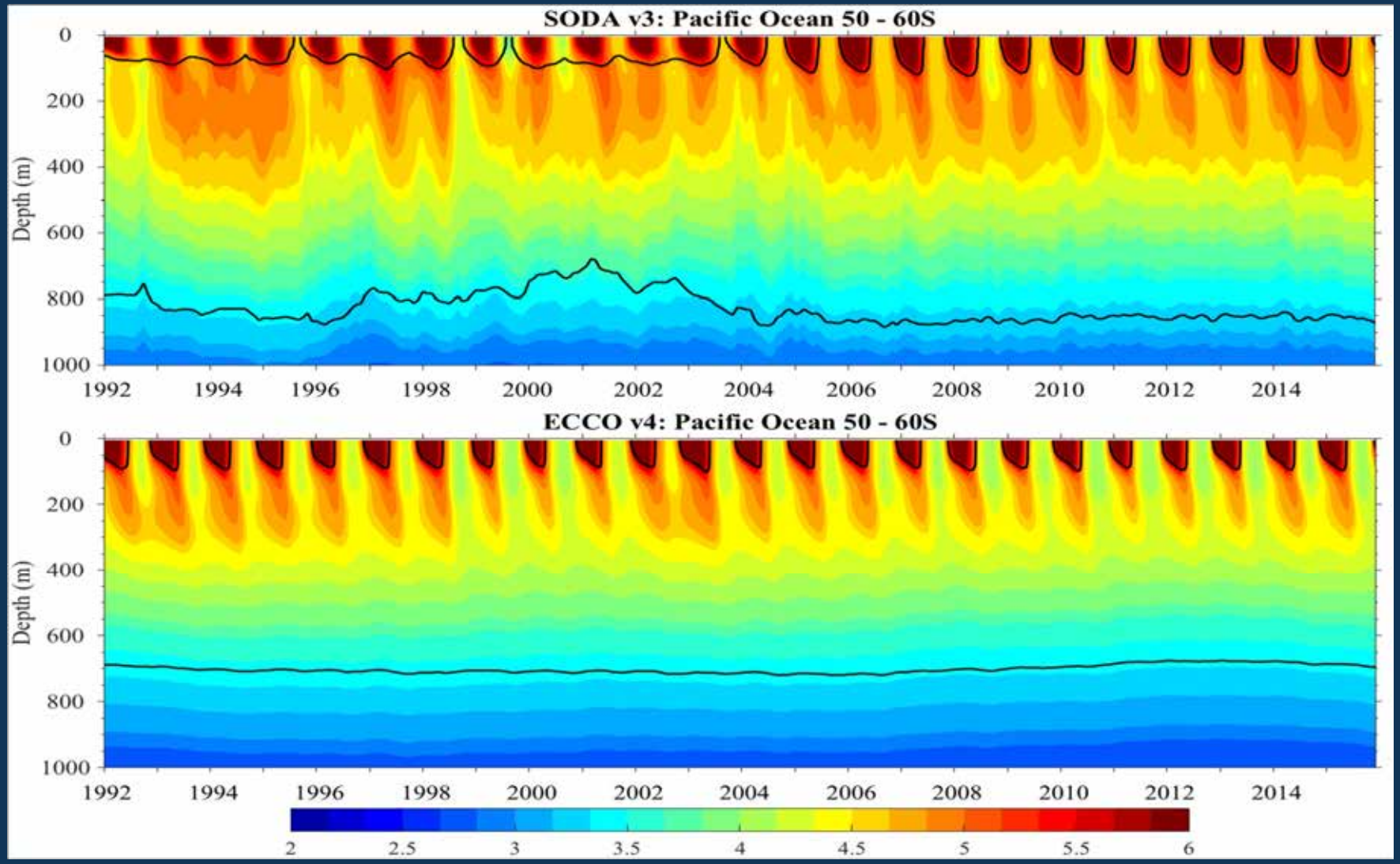
The 1992-2015 mean temperature (° C) for SODA v3 and ECCO v4 in the Atlantic basin averaged between 50°-60° S. Black lines are mean 27.0, 27.6, and 28.0 kg m^{-3} neutral density surfaces.

Deep Ocean Warming in the Southern Ocean



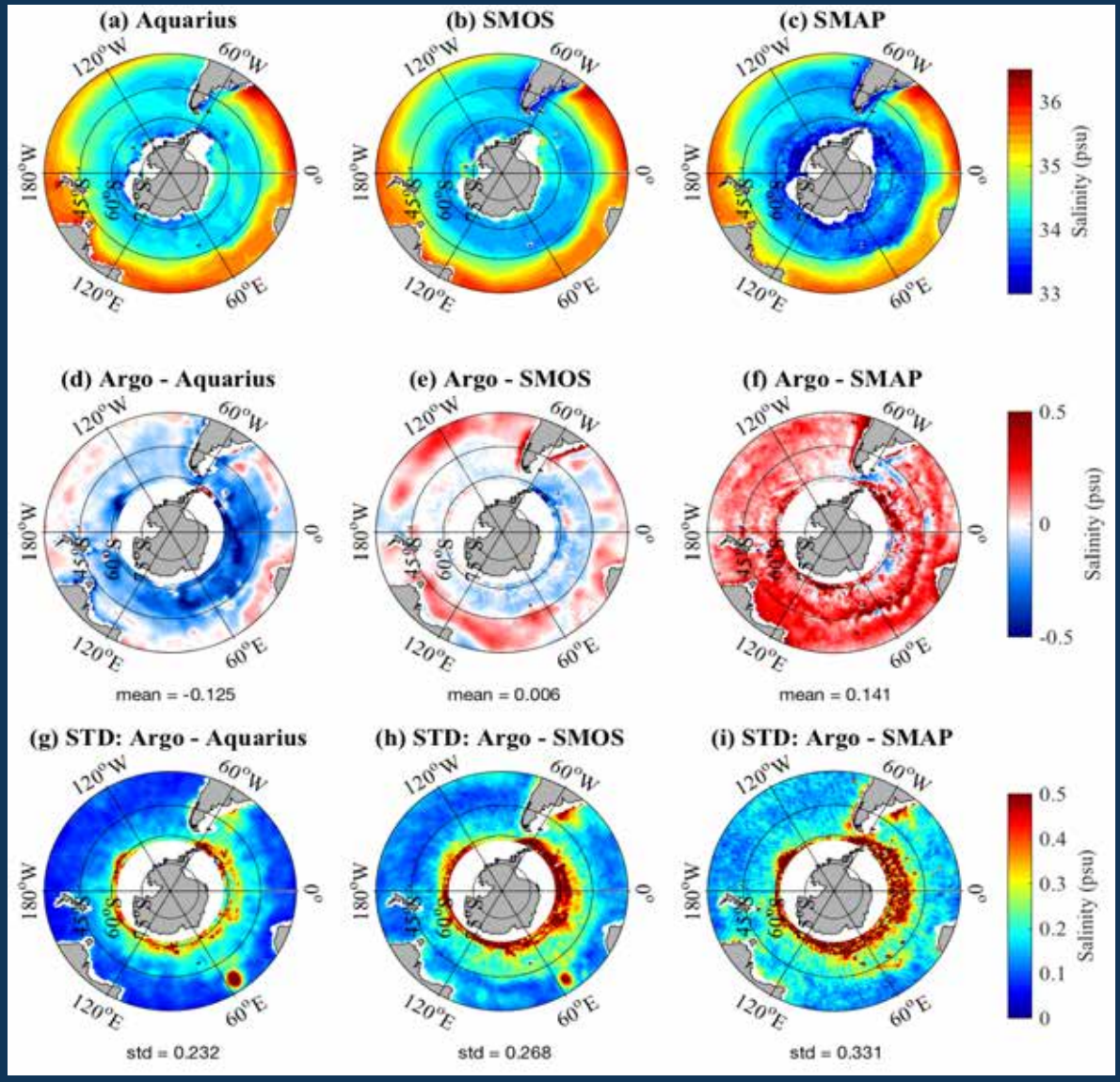
The 1992-2015 mean temperature (° C) for SODA v3 and ECCO v4 in the Indian basin averaged between 50°-60° S. Black lines are mean 27.0, 27.6, and 28.0 kg m^{-3} neutral density surfaces.

Deep Ocean Warming in the Southern Ocean

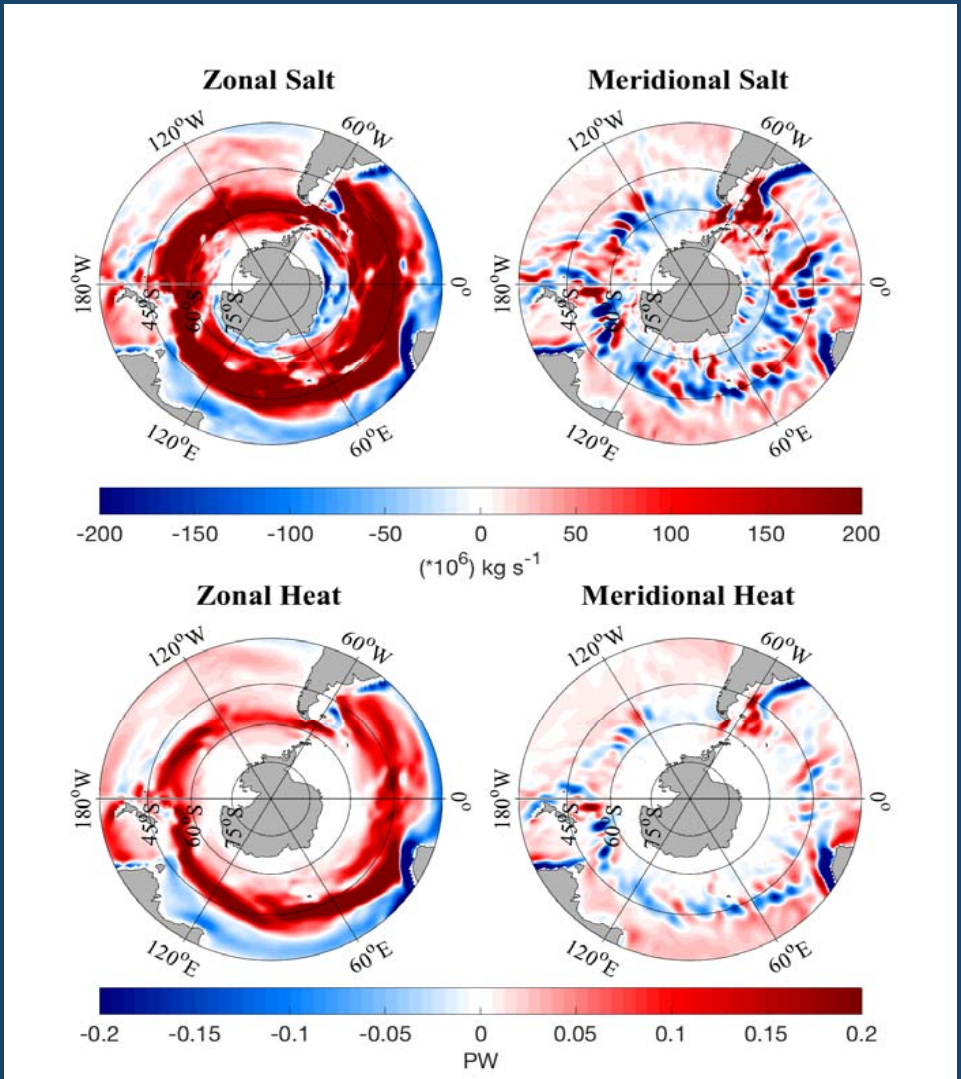


The 1992-2015 mean temperature (° C) for SODA v3 and ECCO v4 in the Pacific basin averaged between 50°-60° S. Black lines are mean 27.0, 27.6, and 28.0 kg m^{-3} neutral density surfaces.

Southern Ocean – Salinity



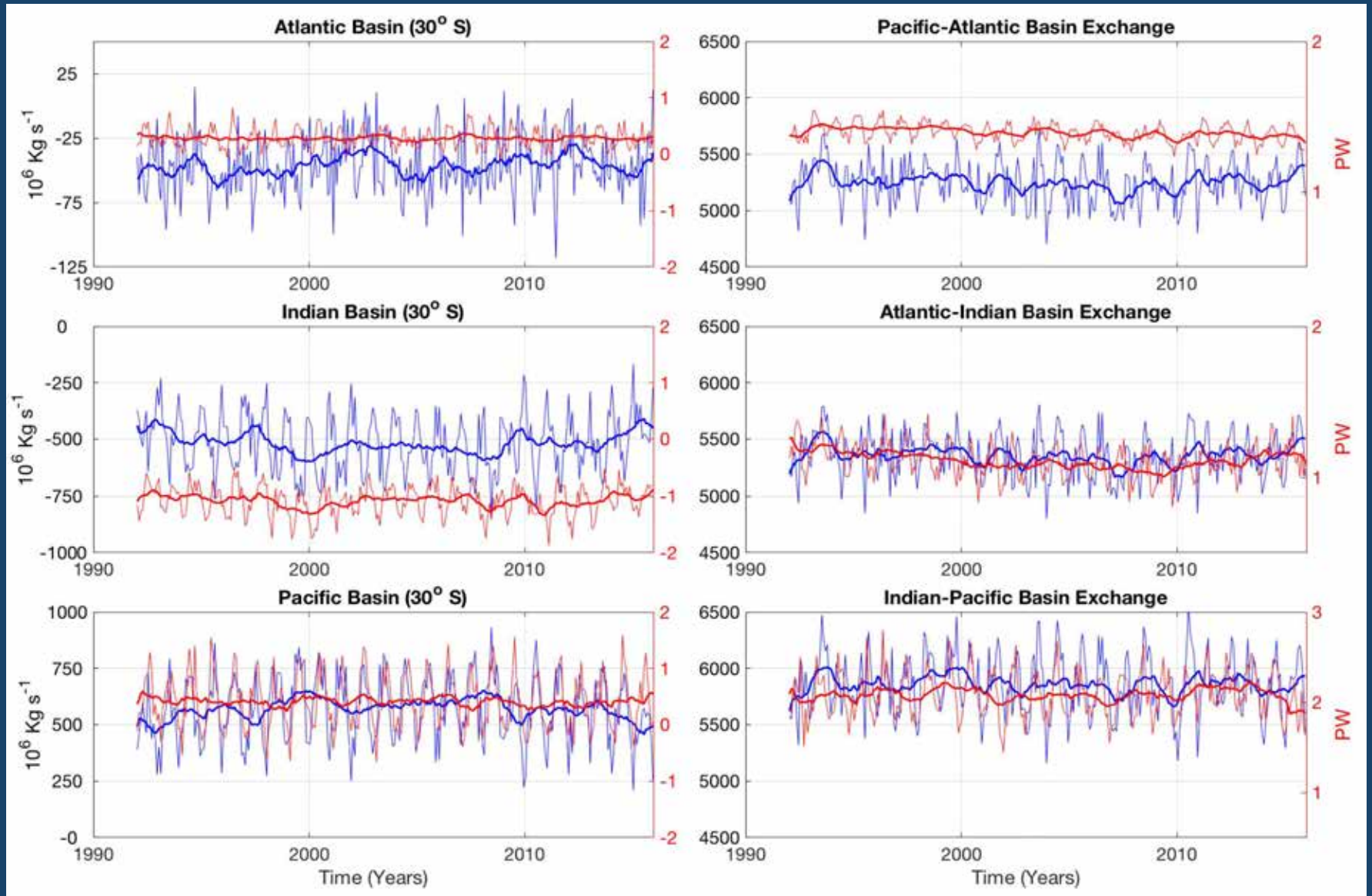
Southern Ocean – Salt & Heat Transports



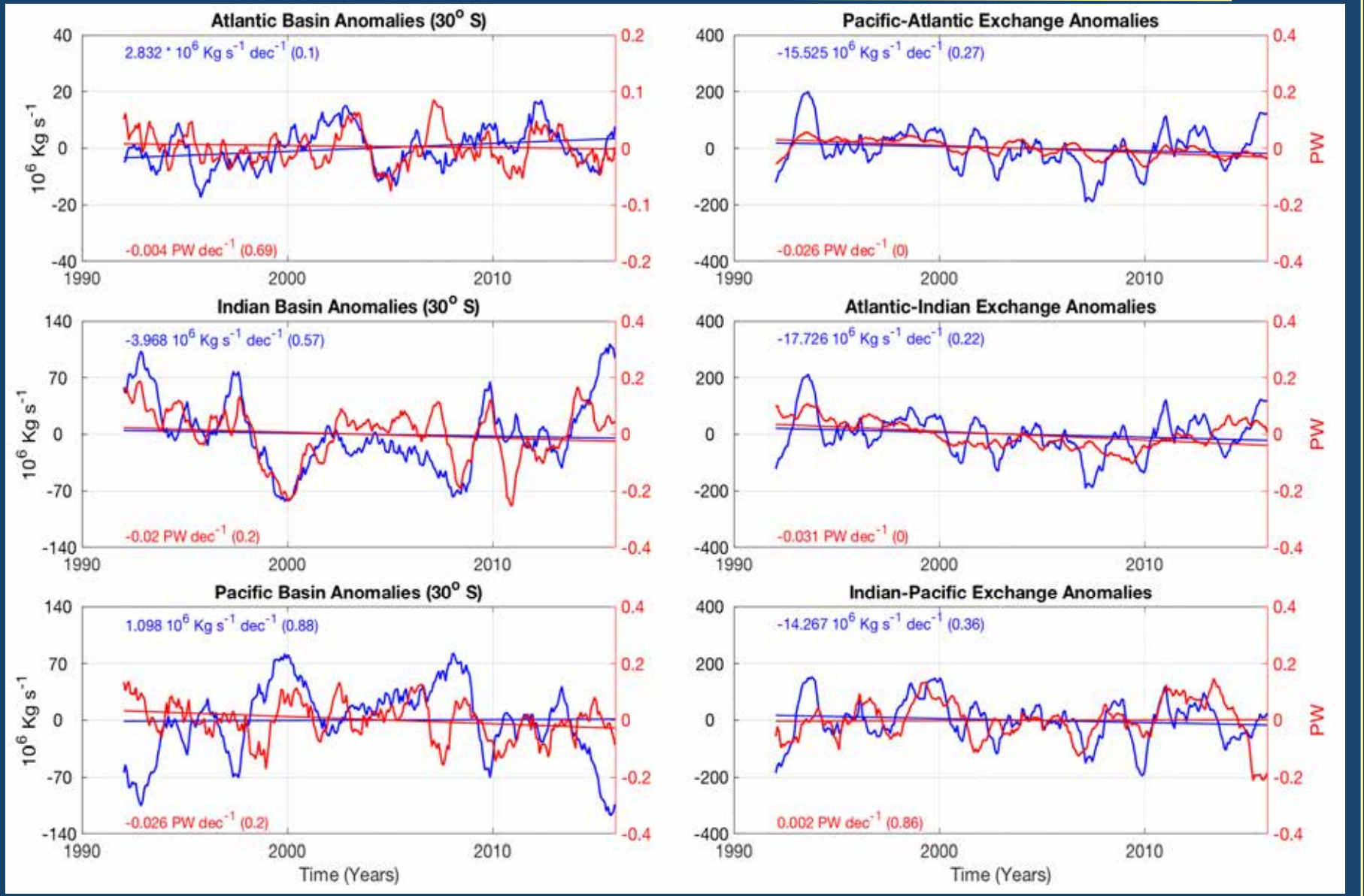
- Mean heat transports are northward at 30S in the Atlantic and Pacific basins
- Net input of salt and heat transports by the Indian basin at 30S
- Strong zonal transports within the ACC

ECCO v4 (1992-2015) temporal mean salt (10^6 kg s^{-1}) and heat (PW) transports for the SO (Depth Integrated to 6000m)

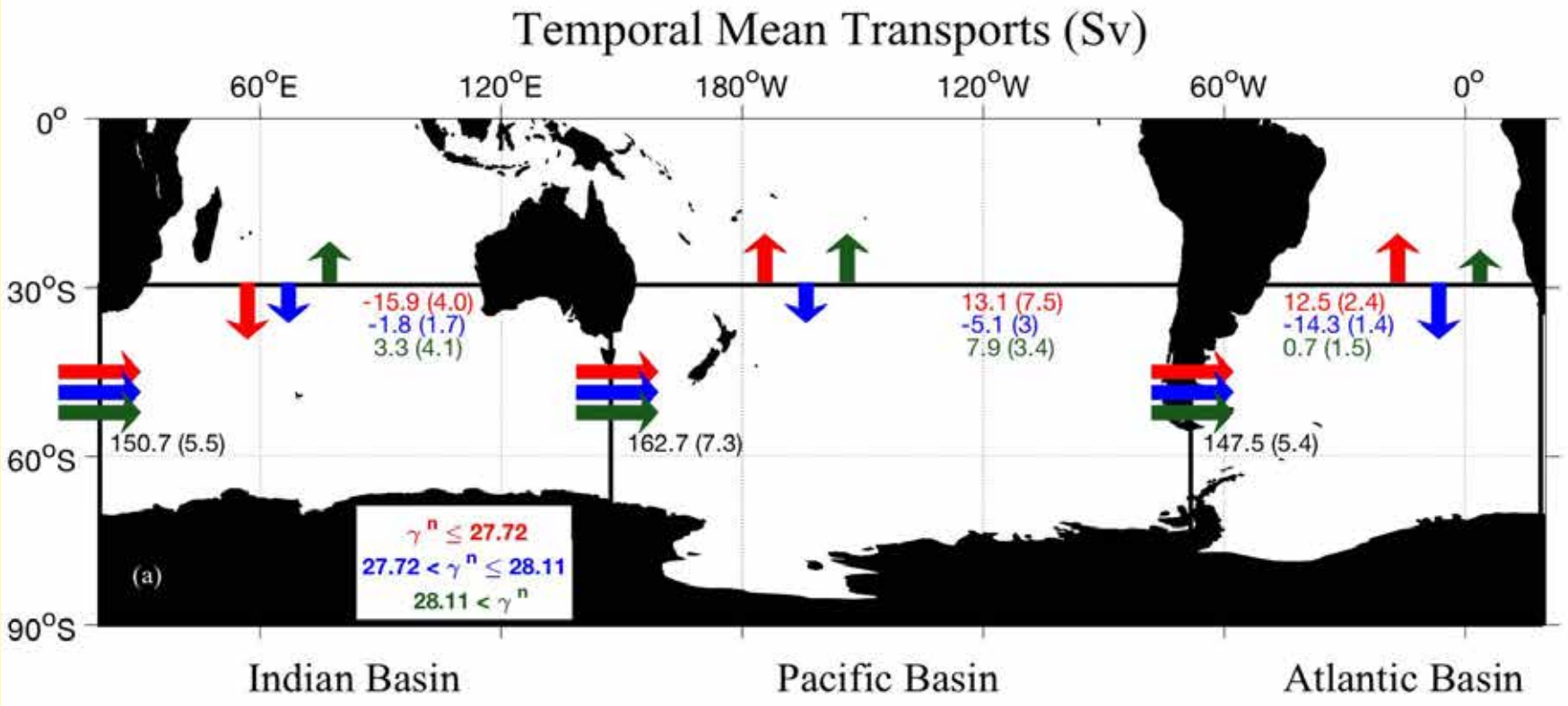
Depth integrated Salt & Heat Transports



Depth integrated Salt & Heat Transports anomalies

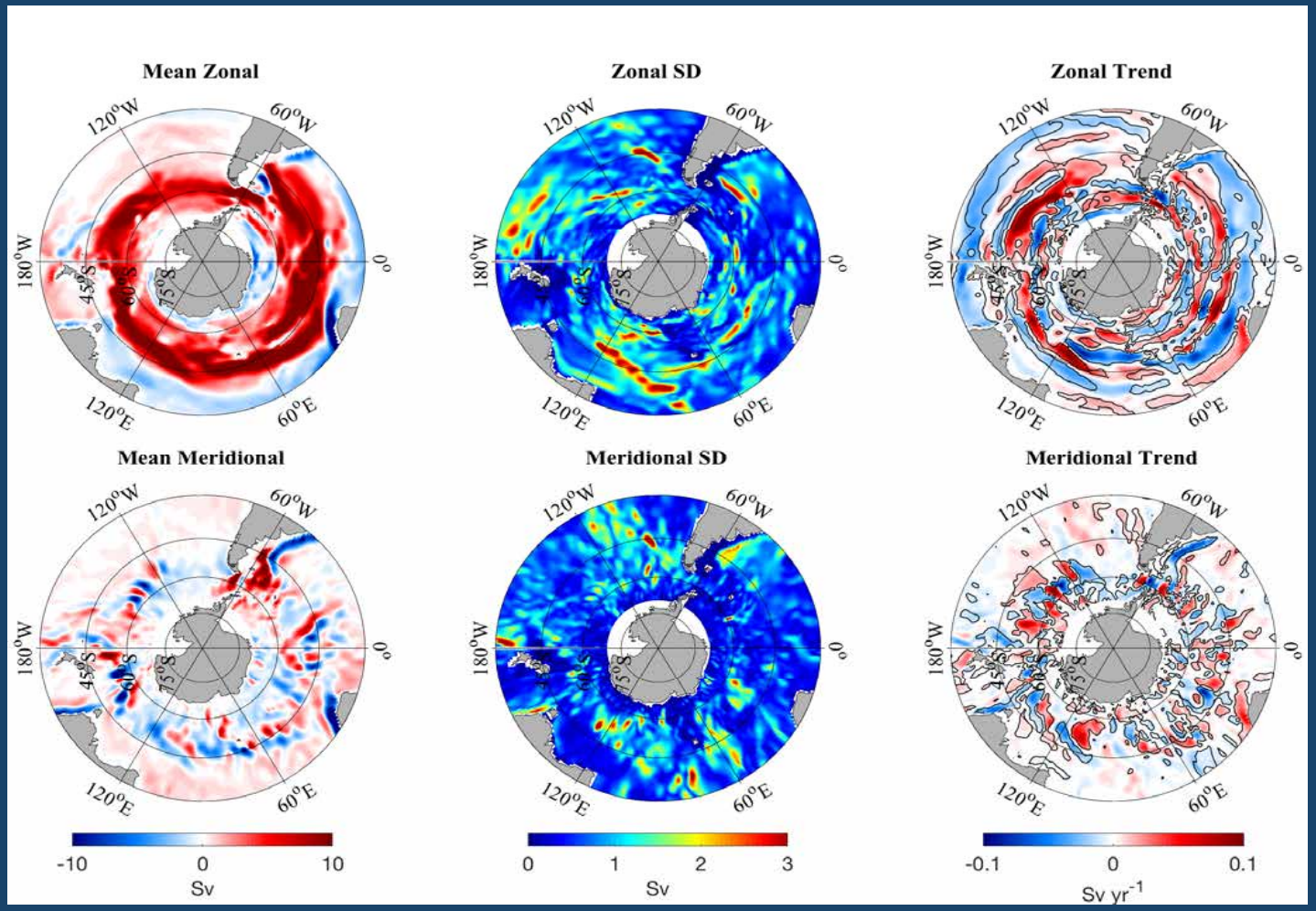


Depth Integrated Volume Transports



ECCO's 24 year mean depth integrated volume (Sv) transports and standard deviations (in parenthesis) across each of the basins. Red ($\gamma^n \leq 27.72$ kg m^{-3}) represents the surface and mode waters, blue (27.72 kg m^{-3} < $\gamma^n \leq 28.11$ kg m^{-3}) the upper circumpolar deep waters, and green ($\gamma^n > 28.11$ kg m^{-3}) the bottom waters.

Depth Integrated Volume Transports



ECCO (1992-2015) temporal mean (Sv), standard deviation (SD; Sv), and linear trend (Sv yr^{-1}) of zonal and meridional depth-integrated volume transports for the Southern Ocean. The linear trends significant under an alpha of 0.05 are contoured in black.

Summary

- Magnitude of winds are increasing and shifting southward
- Significant sea level rise in the SO
  - Southern Pacific has decreasing SLA
  - Largest change in austral summer
- Depth-integrated volume transports are correlated to AAO
  - Zonal transports are declining magnitude despite increasing winds and southward shift
- Surface Cooling and warming of the deep-ocean has potential impact on the thermohaline circulation
- Southern Ocean in Surface Decadal scale freshening
- Significant increase in magnitude of zonal transports in the Antarctic Circumpolar Current (ACC)

Future Southern Ocean

- Warmer, more precipitation
- More stratified (less nutrient input)
- Weaker overturning circulation
- “Saturation” of carbon sink
- More acidic (ecosystem impact)
- Increased melt of floating glacial ice, faster sea-level rise
- Less sea ice
- Southward shift of ocean currents