Long-term warming (and freshening) trends in the Southern Ocean from Argo

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Before Argo.... How much do we know?

- What do floats and historic data together tell us about pre-Argo heat and freshwater change?
- What mechanisms account for change?
How do we assess change in T or S?

**Historic data**
- Profile data
- Isotherms
- Data too sparse to map.
- Use individual points.

**Since 2004**
- Profile data
- Isotherms
- Data comparatively dense.
- Objectively map to grid.
How do we assess change in T or S?

- Compute $T_{\text{profile}} - T_{\text{mapped Argo}}$ or $S_{\text{profile}} - S_{\text{mapped Argo}}$.

Southern Ocean warming since 1900

Historic hydrographic data minus modern Argo data, 40-60 S. (Gille et al, in prep)
Southern Ocean warming since 1900

Historic hydrographic data minus modern Argo data, 40-60 S. (Gille et al, in prep)
Southern Ocean warming since 1900

Historic hydrographic data minus modern Argo data, 50-60 S. (Gille et al, in prep)
Southern Ocean also freshening

$S_{\text{profile}} - S_{\text{mapped Argo}}$

Historic hydrographic data minus modern Argo data, 40-60 S. (Gille et al, in prep)
Mechanisms for Southern Ocean change

For full Southern Ocean (south of 40S)
- Advection (by mean flow or eddies)?
- Air-sea fluxes (heat and evaporation minus precipitation)?
What if water masses have shifted south?

Mean meridional T and S sections
Meridional shifts in water masses?

- Suppose that over time, water masses have shifted south by 1° latitude.
- Since historic sampling is variable, resulting changes in water mass properties could appear to vary in time.
Poleward shift implies warming

- 1° southward displacement.
- Watermass shift can’t be uniform with depth: observed warming surface intensified relative to hypothesized warming due to southward shift.
Poleward shift implies freshening at depth

- Southward water mass shift would account for freshening at middepth...
- ... but not freshening at surface.
Equatorward shift: freshening at surface

- Northward water mass shift would account for freshening at surface...
- ... but wouldn’t explain temperature trends at surface (or subsurface salinity trends).
Speed up of overturning circulation?

- Mid-depth water moving south; surface water moving north?
- But need surface fluxes to close temperature and salinity budgets in upper ocean.
Estimating net air-sea fluxes

Integrate in time, since year-to-year changes would yield noisy fluxes.

Integrate in depth to account for upper ocean heat content.
Suppose all warming from atmosphere is consistent with persistent $Q_{\text{net}}$ of $O(0.5 \, \text{W m}^{-2})$. 
Suppose all freshening due to E-P

- Consistent with $O(0.5) \text{ cm yr}^{-1}$ freshwater input (0.01 Sv excess flux.)
Summary/Conclusions

• Historic data minus modern Argo records indicate Southern Ocean warming throughout 20th century and freshening since 1950s.
• To explain surface and subsurface trends, invoke advection plus surface fluxes.
• Is the freshwater from precipitation or melt?