“Atmosphere-ocean interactions and dynamic response of the Southern Ocean to climate variability and trends”.

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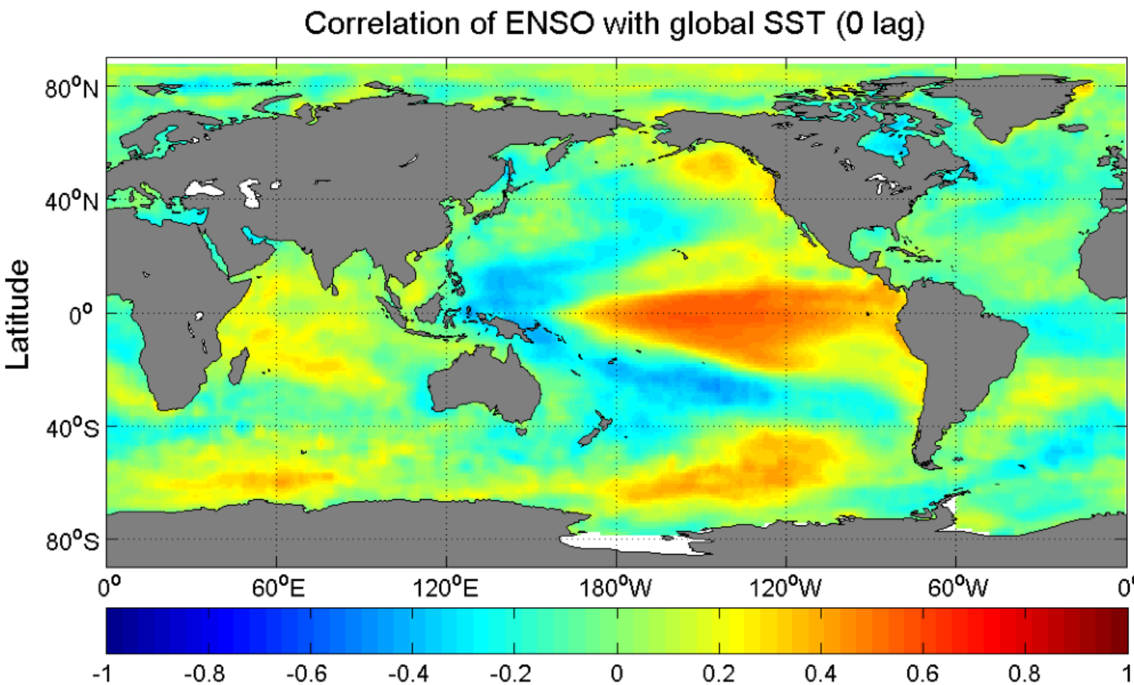
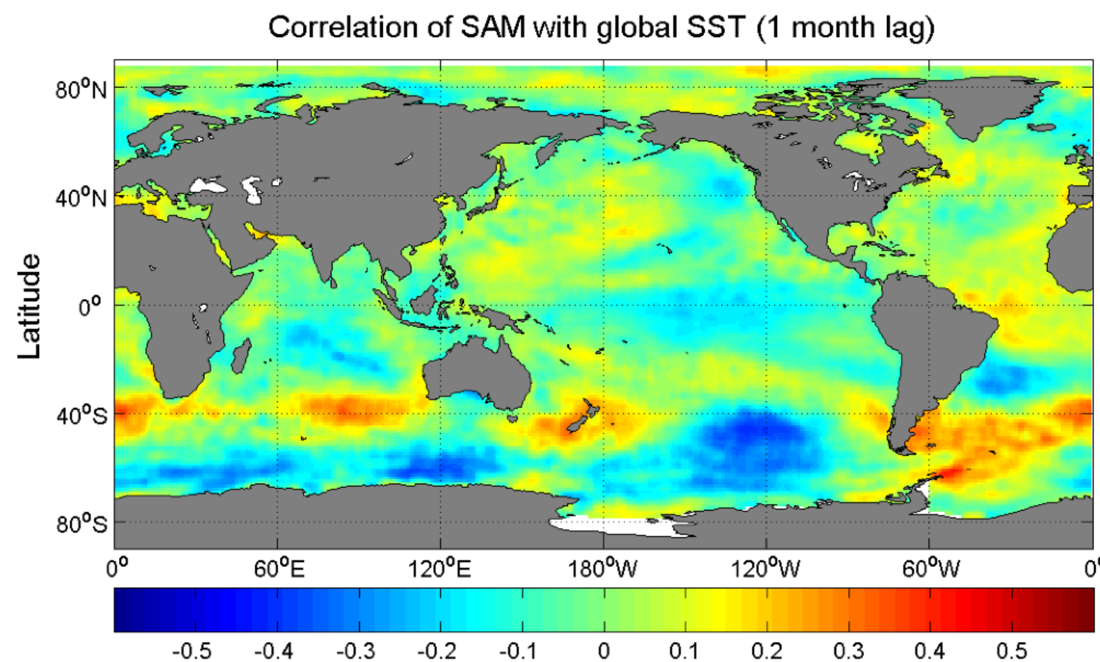
Structure

- Preliminary random thoughts
- Brief examples demonstrating state of knowledge (or lack thereof):-
  - Response of Southern Ocean properties
    - Surface and subsurface (but leaving circumpolar stuff)
  - Response of Southern Ocean circulation
    - Horizontal and vertical
- What are the key things we don't know, but might want to?



Start with clear, well-known examples of Southern Ocean response to climatic forcing.

(Near-)instantaneously, both ENSO and SAM have characteristic footprints in the Southern Ocean SSTs …



Sea ice concentration responses strongly linked to SST response (see also Kwok & Comiso, Stammerjohn etc)

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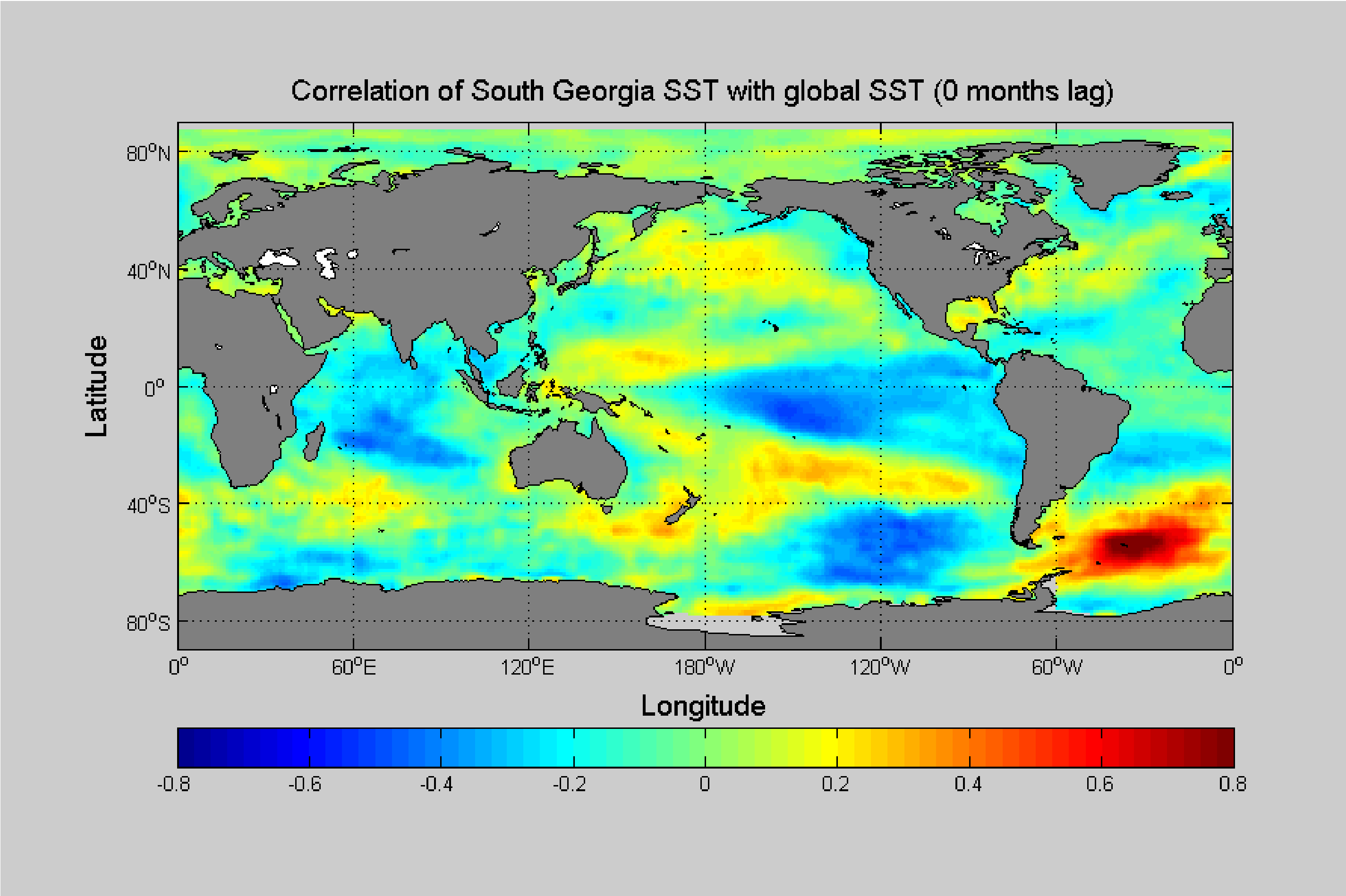
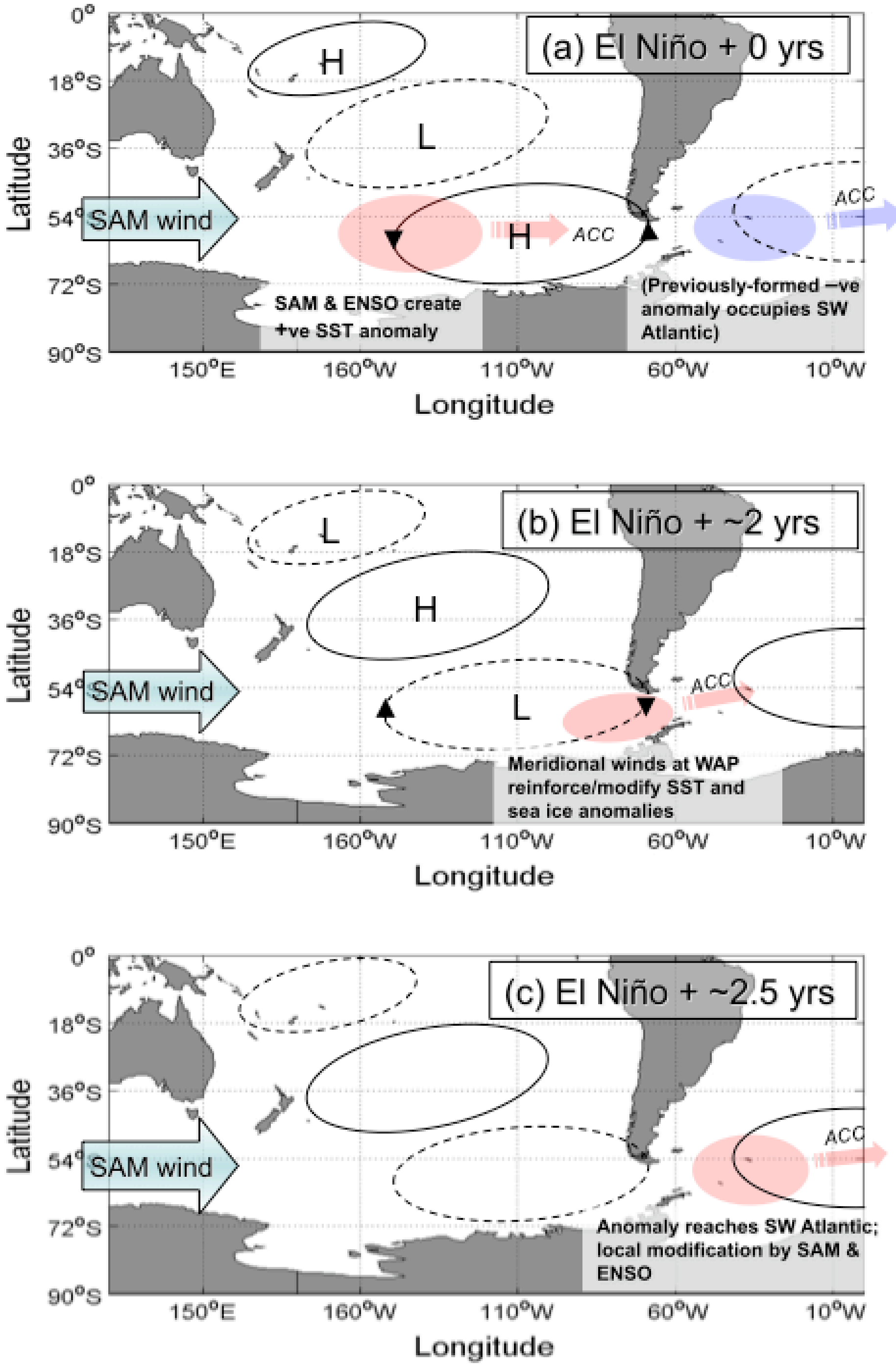
So, problem solved then? Sadly not…



Example of South Georgia – ecosystems driver.

Air-sea-ice interaction combines with advection to control evolution of SST fields (e.g. Verdy and Marshall)

At zero lag, both SAM and ENSO signals can be seen (the latter most clearly).
Note "stalling" of advection in southeast Pacific, and the timescale for transition



"Simplified" representation of South Georgia case!

This relates to the satellite era - what about other eras? Does variability in ENSO periodicity explain presence and absence of a resonant signal?

Note that this depiction is the canonical response to ENSO and SAM – but all El Niños are different, especially in their high latitude impact. Why, and how do we improve predictability of Southern Ocean response?

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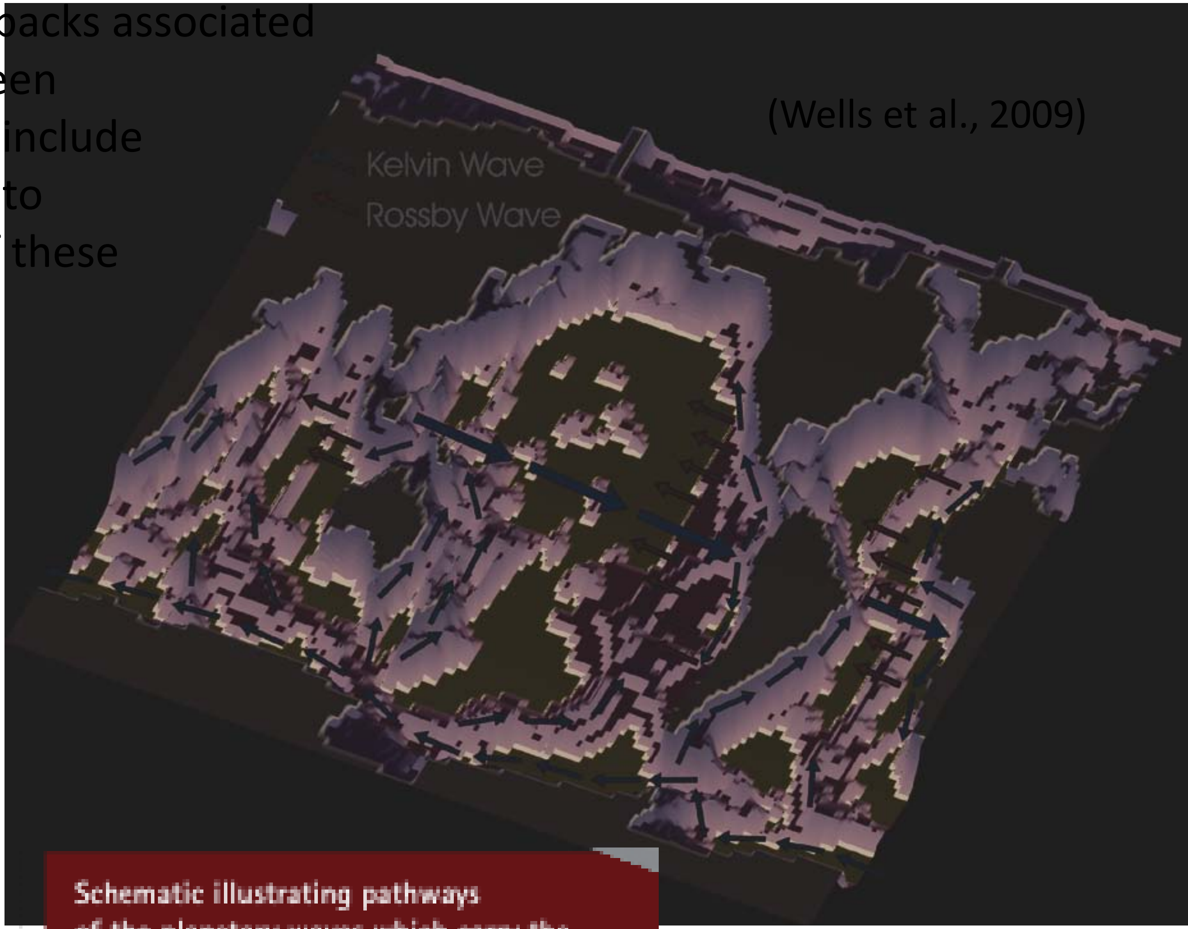
Southern Ocean doesn't just receive and move signals – it also feeds back to the atmosphere e.g. SAM feedback; Marshall and Connelly, Sengupta and England etc.

Not just limited to SAM…

Important to understand the feedbacks associated with these, both within and between different climate modes. Need to include these processes in models if want to predict the long-term evolution of these modes, and their impacts on the Southern Ocean.

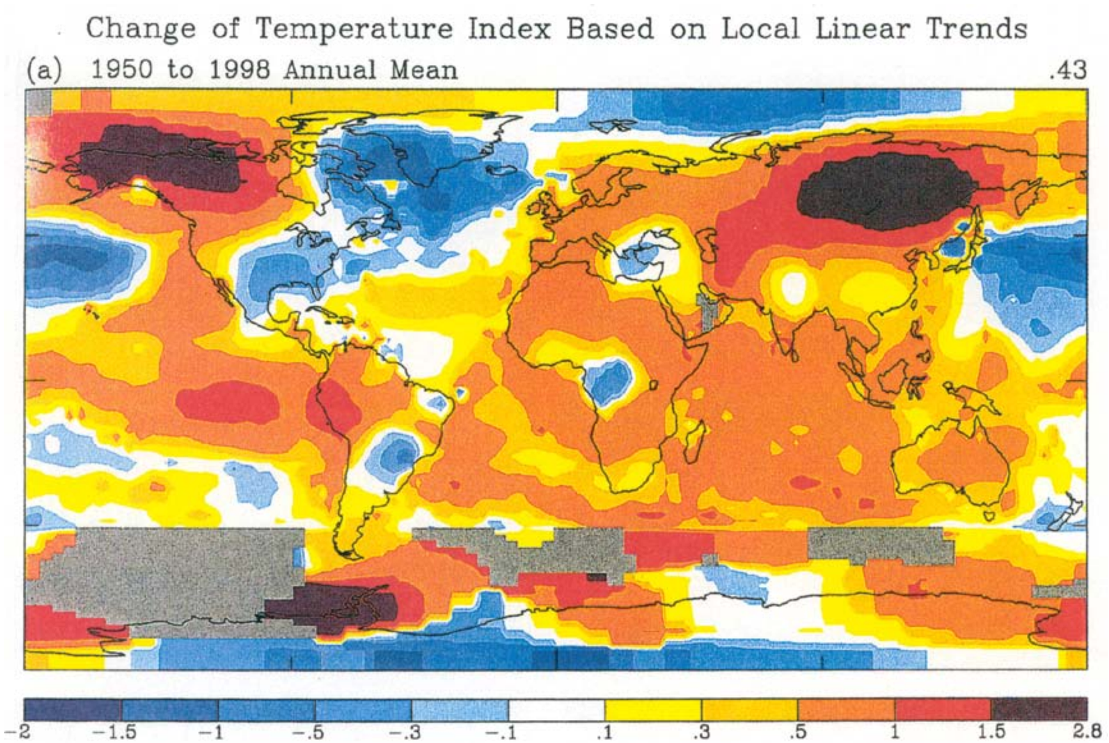
Is it enough to study ENSO (or SAM, or whatever) on its own? Where will the predictive skill come from?

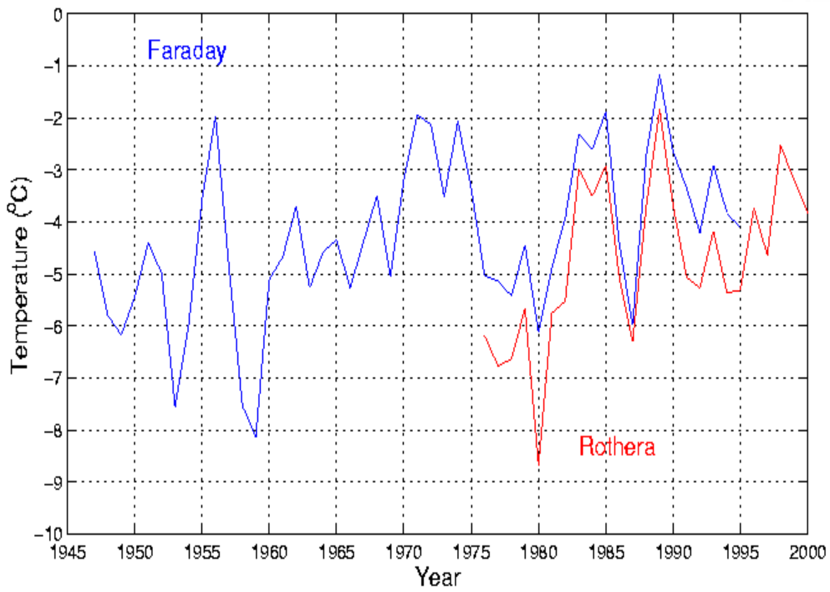


(Wells et al., 2009)

Schematic illustrating pathways of the planetary waves which carry the teleconnection signal away from Antarctica

Example of rapid regional change in the Southern Ocean….





Western Peninsula/Bellingshausen Sea

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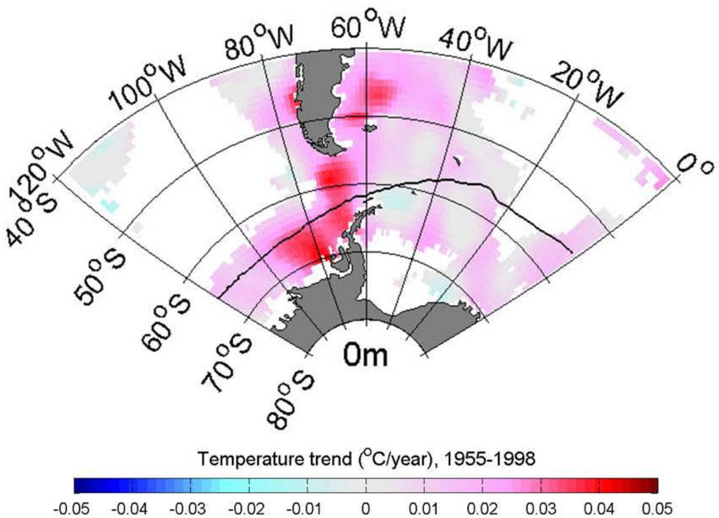
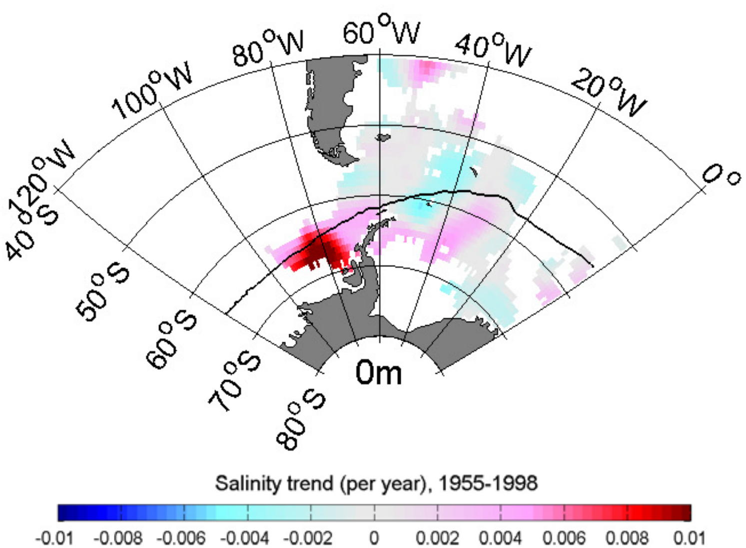
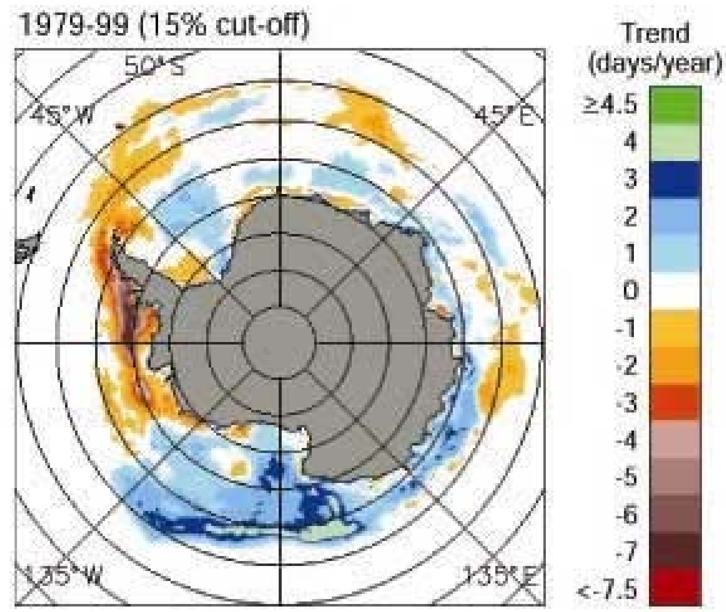
Ocean is warming strongly in the near-surface layers, but also becoming more saline…



(Meredith & King, 2005)



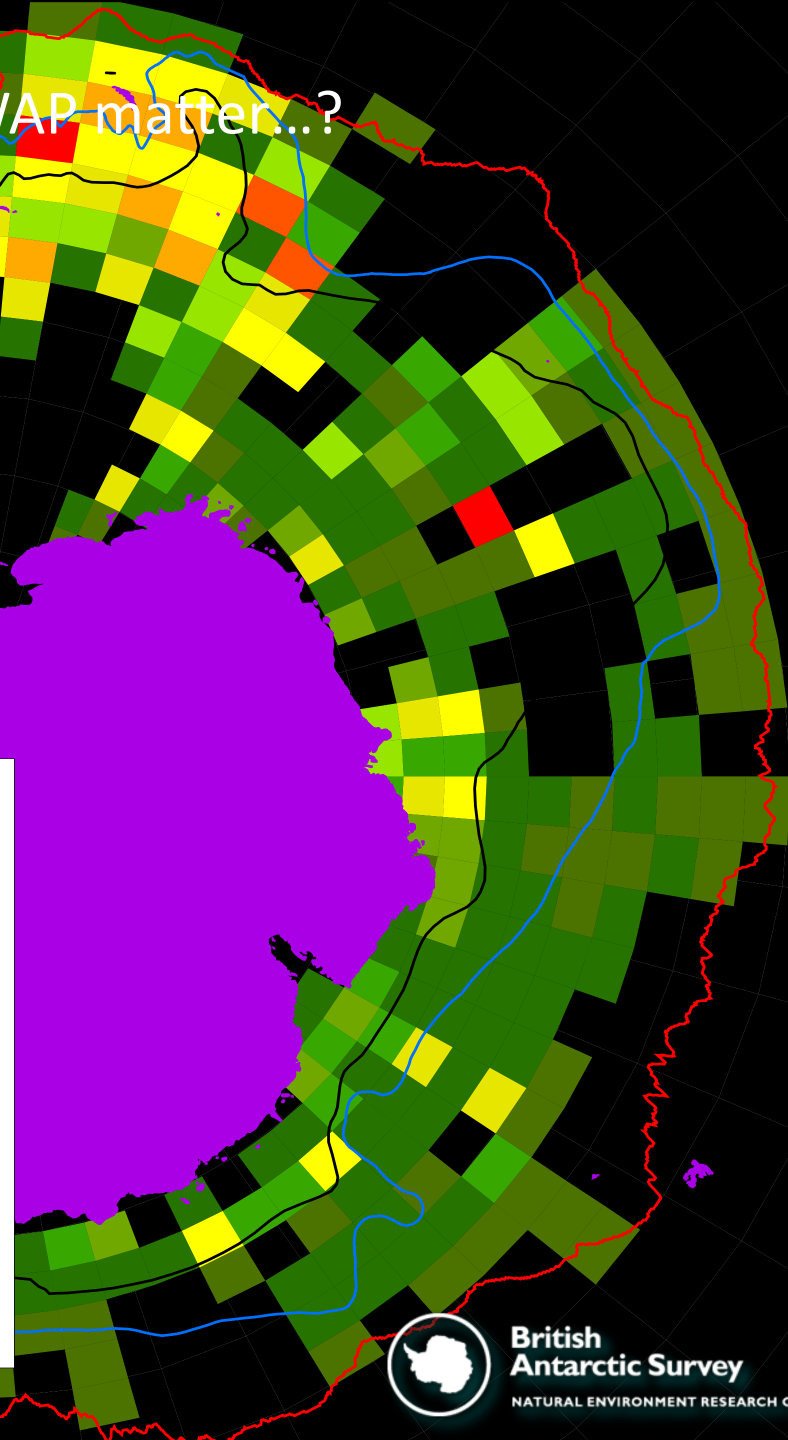


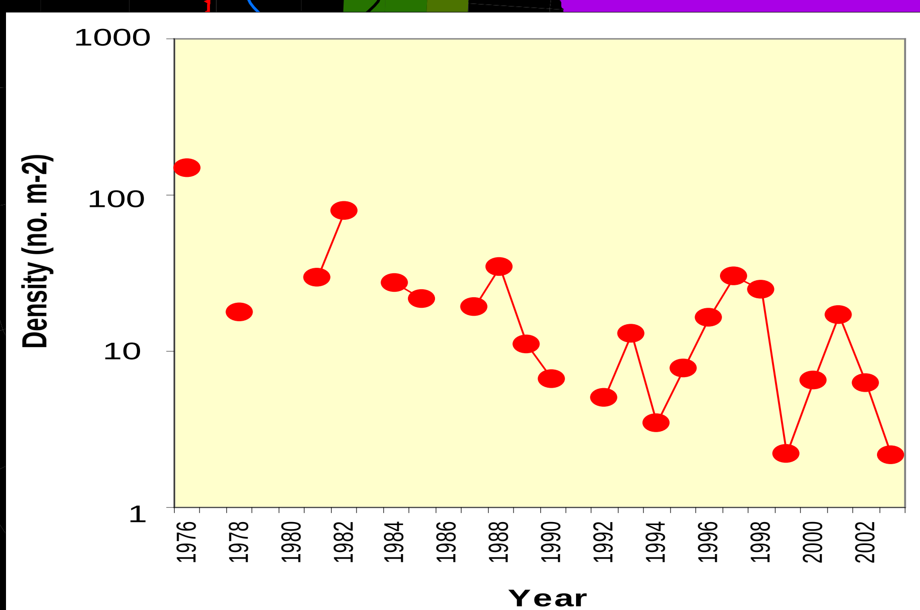
Cause appears to be atmospheric-induced reduction in ice production, combined with seasonal bias in sampling…

… but both T and S trends are positive feedbacks, acting to sustain and enhance the atmospheric & cryospheric change.

Why does ocean warming at the WAP matter…?

Lots of reasons, one of which is the relative abundance of krill, and their recent decline in numbers… could be due (at least in part) to physical processes such as loss of sea ice and ocean warming





Atkinson et al., *Nature*, 2004

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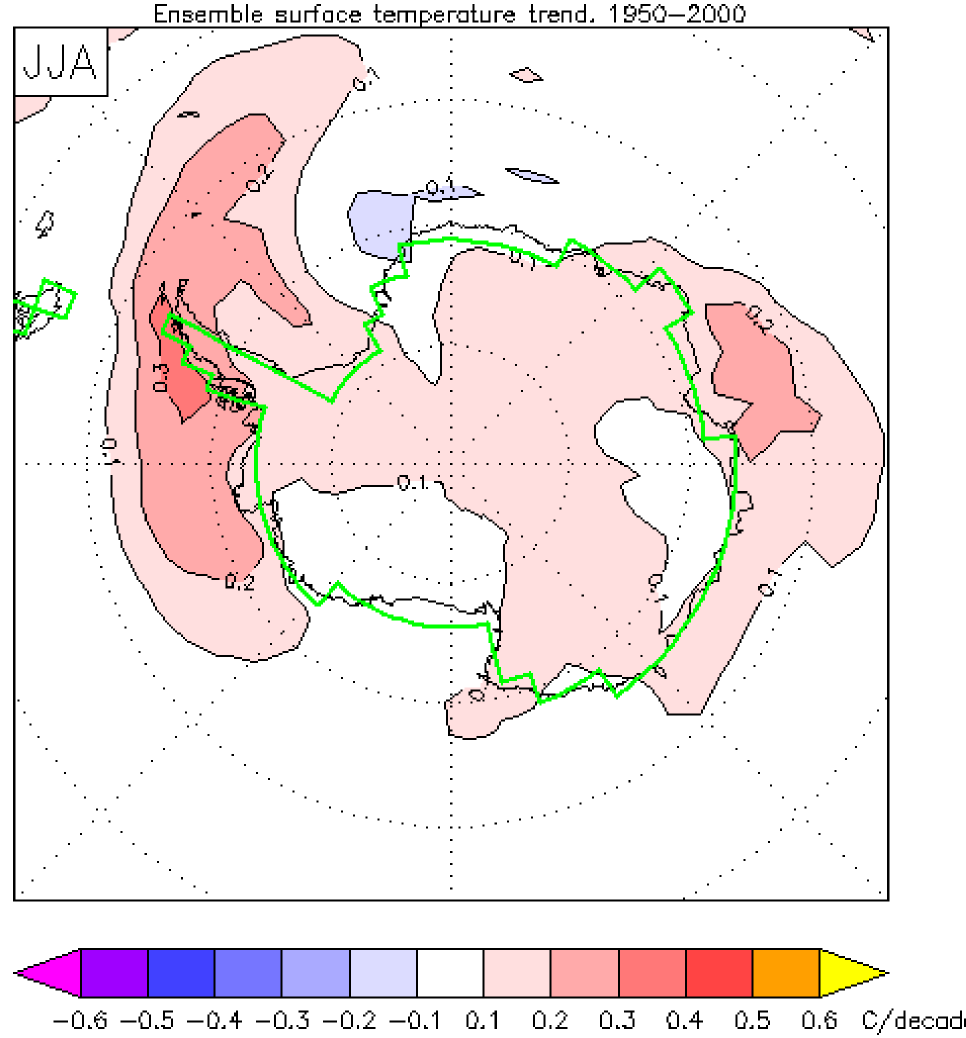
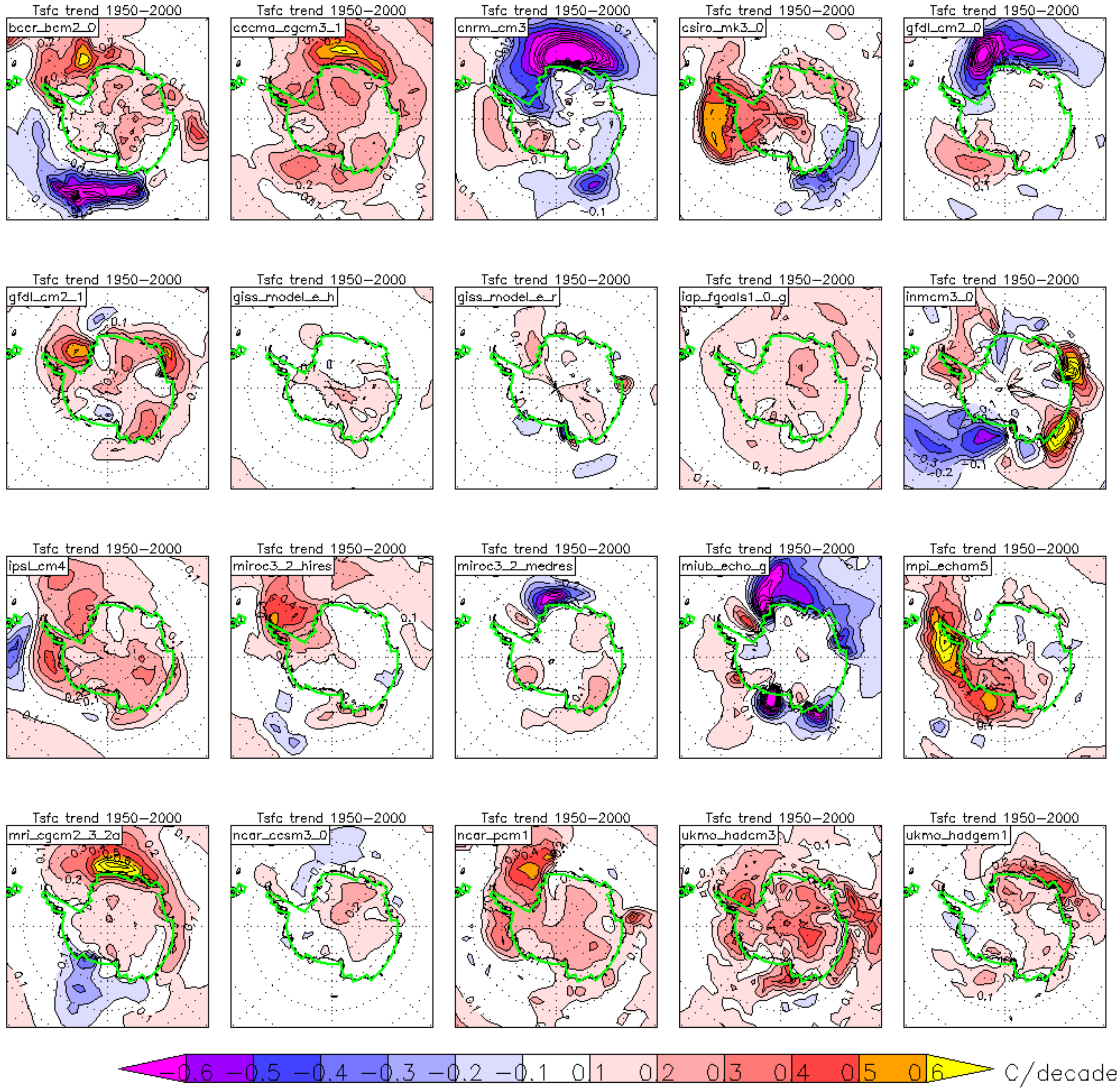
Can IPCC-class climate models reproduce the observed warming…?

- Weighted ensemble mean surface temperature trend: last 50 years
- Strongest warming is west of Peninsula; in qualitative agreement with observations.
- Magnitude is less than observed.



Bracegirdle et al., 2007

Weighted ensemble averages over a large inter-model spread.



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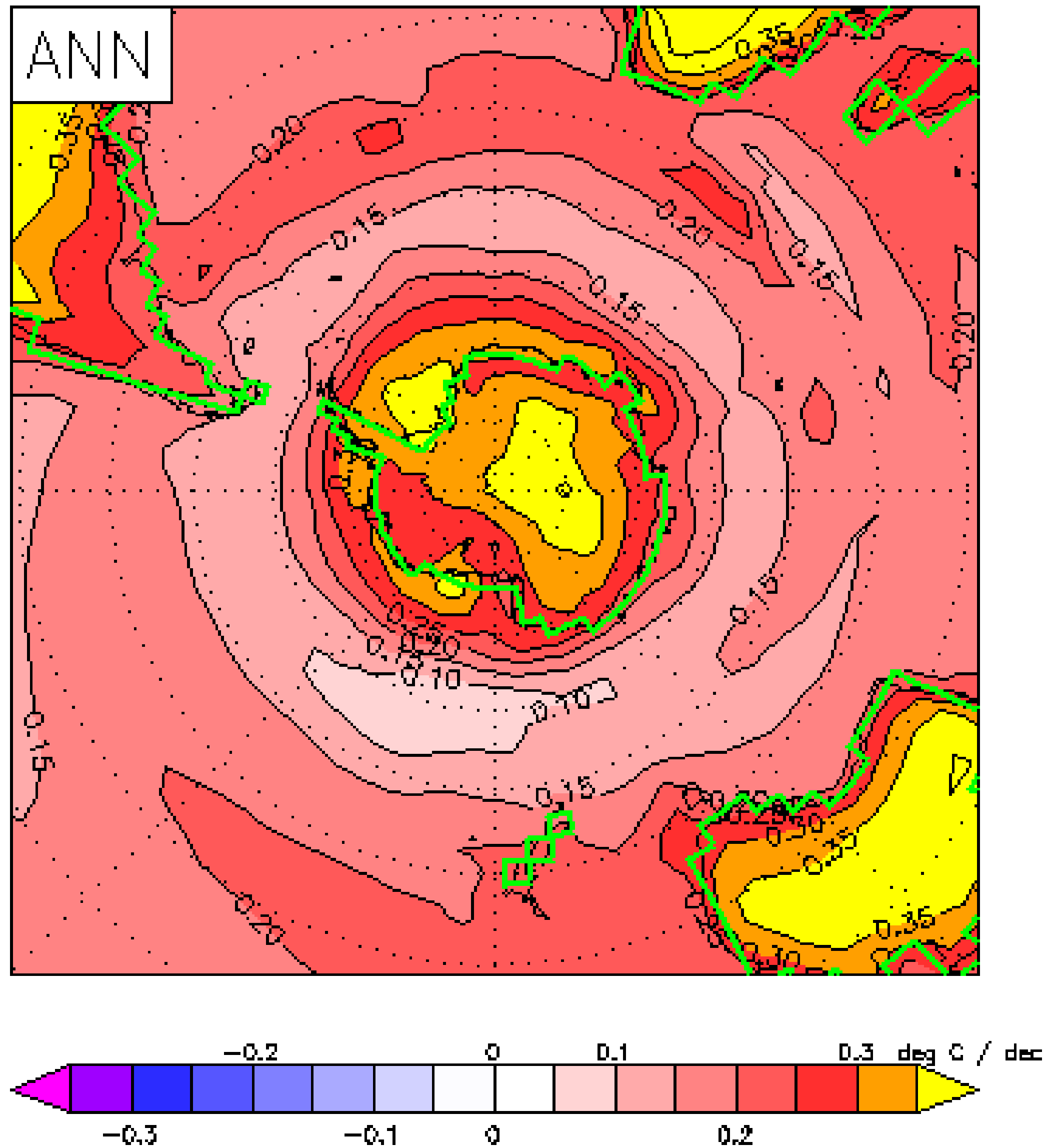
IPCC model-based prediction for next 100 years

- Weighted ensemble predicts a significant increase in surface temperature, over land masses especially, but also over the ocean
- Weddell and Ross Seas (bottom water formation regions) show strong warming.
- Sea ice extent shows strong circumpolar retreat; ~25%
- Major impacts on e.g. stratification.
- None of the IPCC models have eddy resolving oceans
- Weighting was done on the basis of atmospheric (not oceanographic data). Not enough ocean data available.
- Sign of change is believable, and consistent with GHG forcing. But pattern, and magnitude?



Bracegirdle et al., 2007

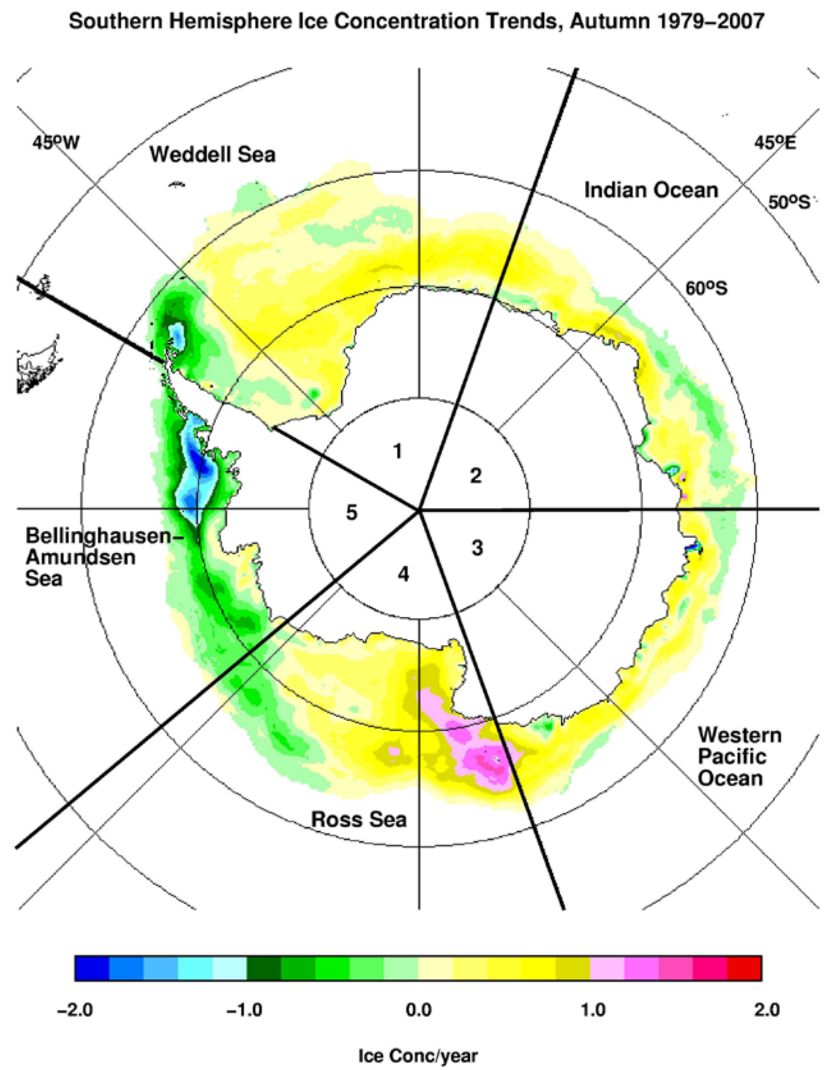
Future of sea ice?

Circumpolar Antarctic sea ice extent has been increasing at a small, but significant, rate (c.f. Arctic).

This increase is driven strongly by increases in the Ross Sea, associated with strengthening southerly winds. These have been attributed to ozone depletion, and intensification of the SAM (Turner et al., 2009).

Different anthropogenic drivers affect sea ice differently, and on different timescales.

When will sea ice start decreasing?



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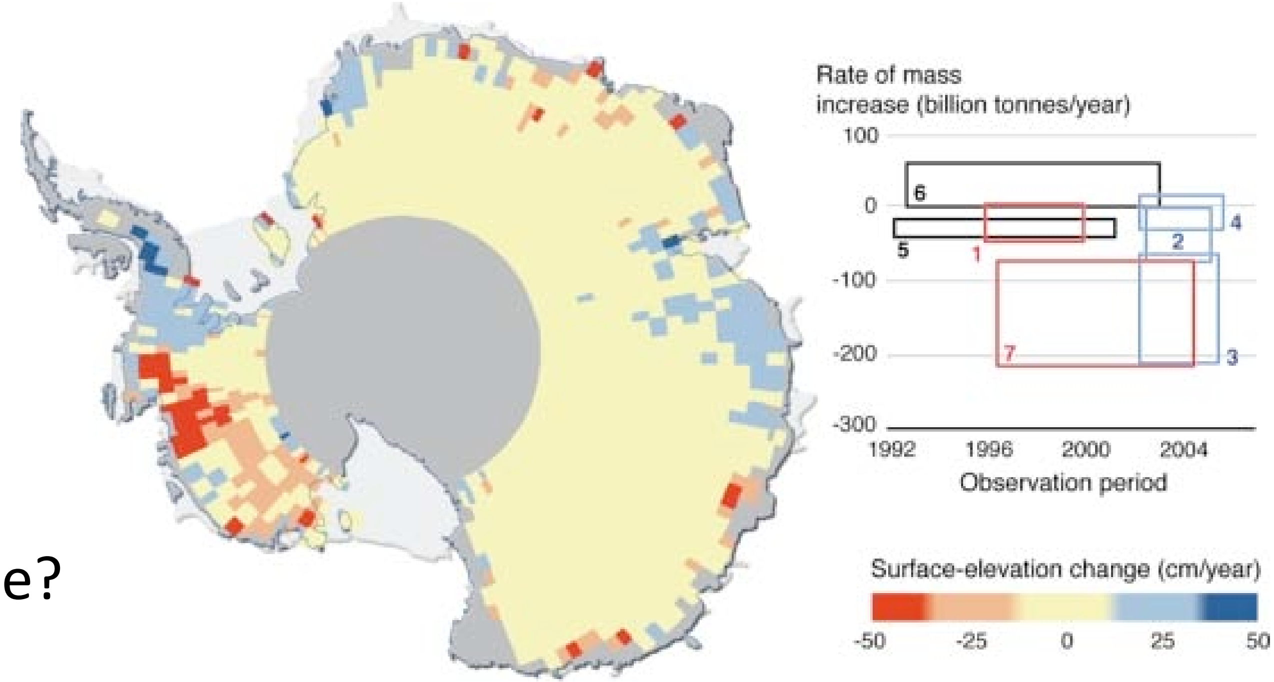
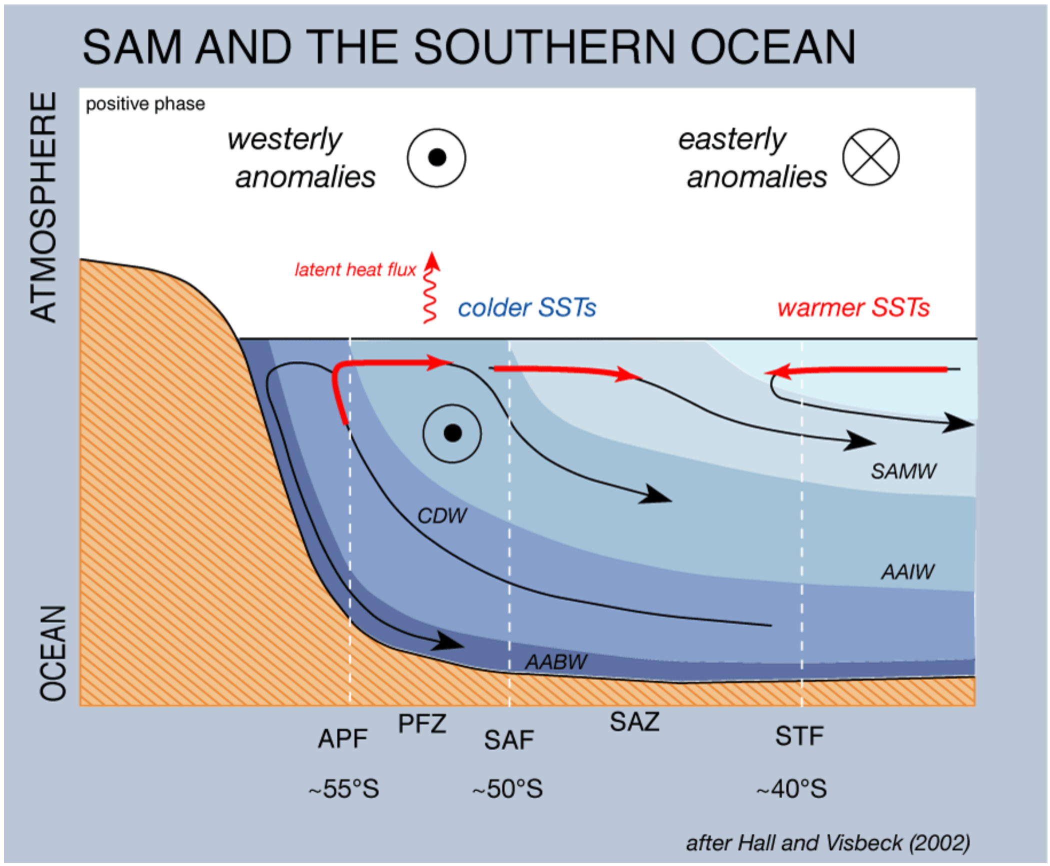


Future of glacial ice?

- Glacial ice changes are likely to be increasingly important in future
- Parts of west Antarctica (e.g. Pine Island) are melting rapidly, with significant freshwater release to ocean (hence AABW freshening in Ross Sea?)
- Will affect stratification, freezing point, micronutrient levels etc.
- SAM trend has been implicated, via increase in upwelling/temperature of CDW onto the shelf and into the ice shelf cavities
- Much remains to be done in terms of understanding and parameterising fluxes, melting, freezing in “warm” sector ice shelves
- Need to couple ice sheet/ice shelf models to ocean models? e.g. ICOM?

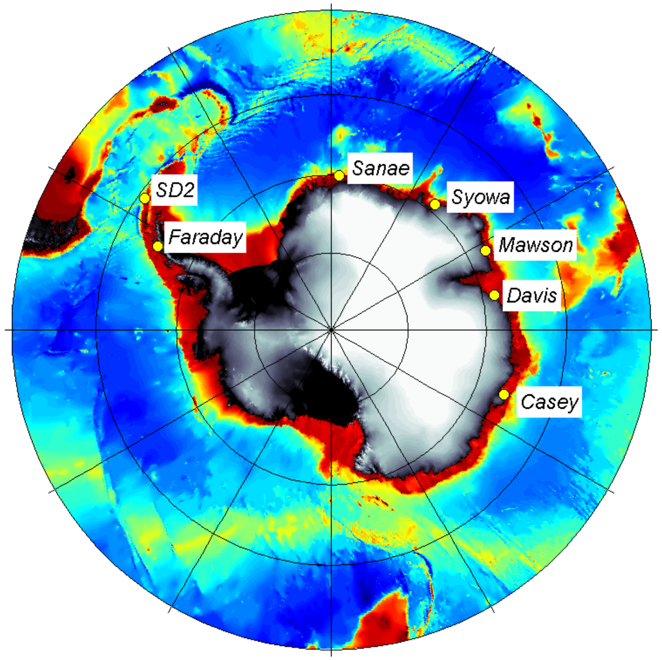
Southern Ocean circulation response to a positive change in the SAM …



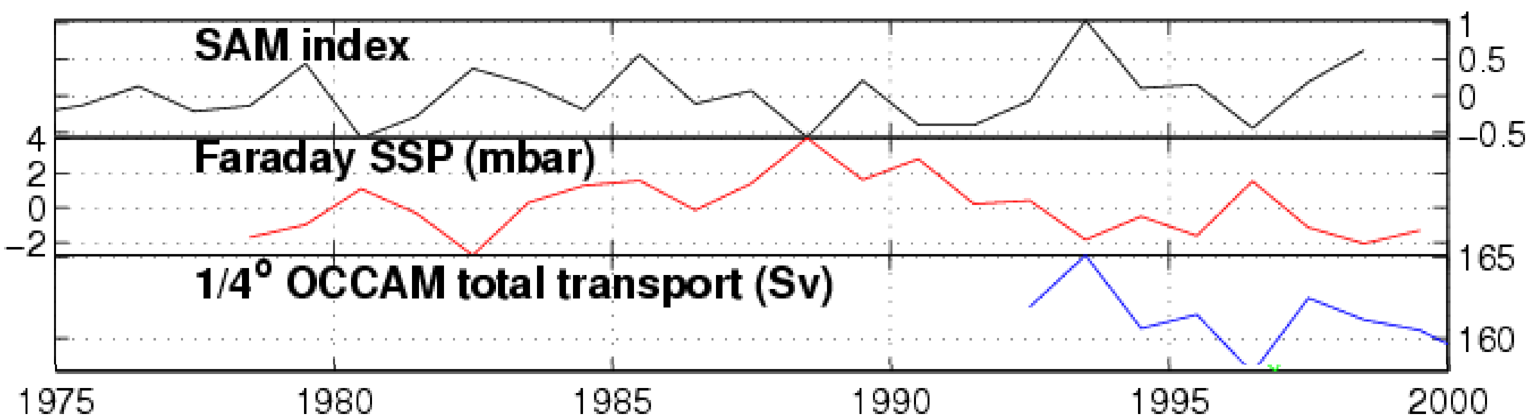
Impacts also on stratification, CO_2 fluxes, primary production etc

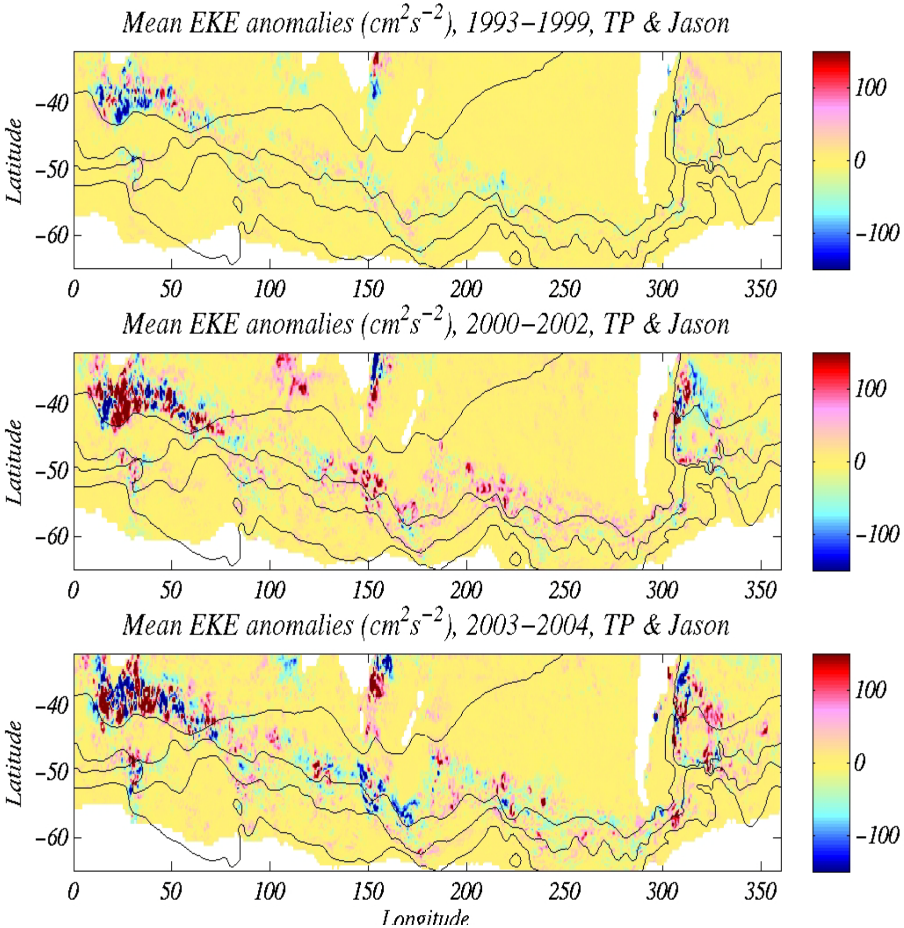
But was derived from a coarse-resolution climate model - does the observational evidence support this picture?

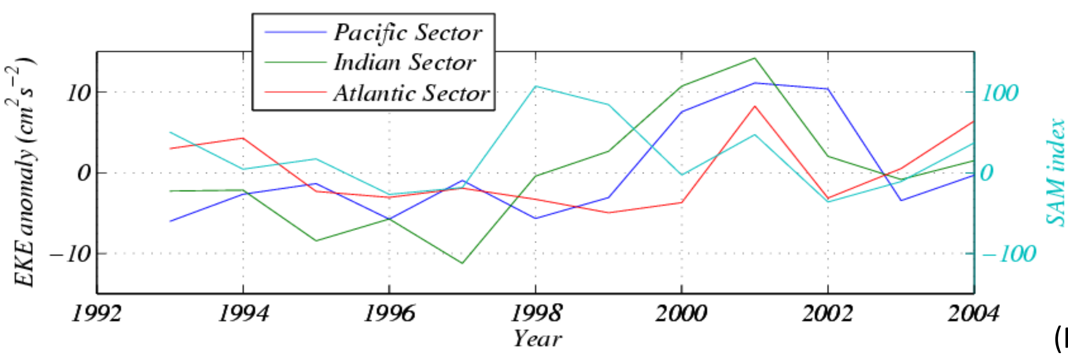
How do we monitor changes in horizontal circulation anyway?



- Lots of different ways of monitoring interannual changes in transport, most of which don't work…
- One of the few that does work is to use measurements of sea level (CTD/XBT sections etc badly aliassed)
- ACC transport *does* change on these timescales in response to winds, with little lag – but response is <u>small</u>.

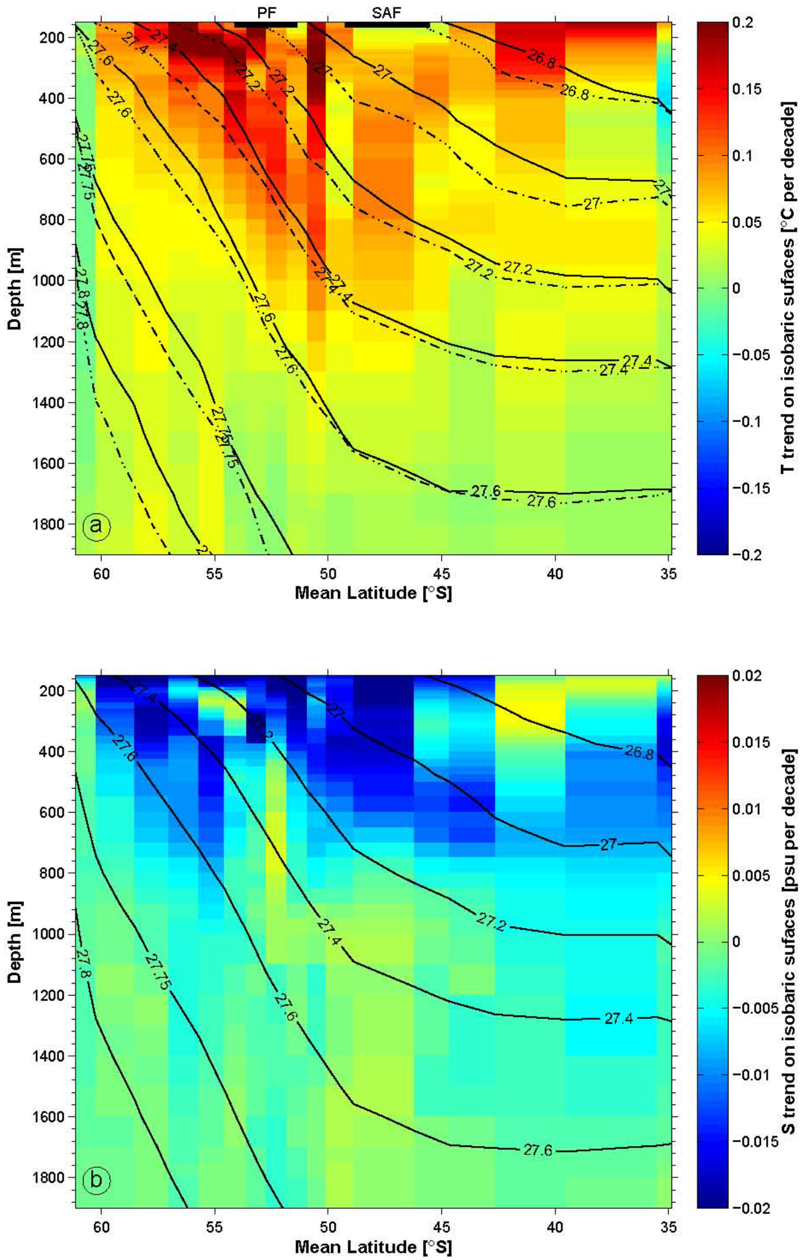






- Why so little change in transport on interannual timescales?
- One theory is that energy is cascaded from mean flow to mesoscales, e.g. Hallberg and Gnanadesikan
- Supported by observations of Eddy Kinetic Energy from altimetry, with a 2-3 year lag between peak ACC flow and peak eddy activity.

(Meredith and Hogg, 2006)



This was invoked by Böning et al. (2008) to explain the apparent invariance in isopycnal tilt (i.e. transport) accompanying the temperature and salinity changes in the Southern Ocean on decadal timescales.

It was also argued that the overturning is invariant w.r.t. winds, for the same reason - is this the only interpretation? Why should an increase in the wind-driven overturning be compensated exactly by an opposing increase in the eddy-driven circulation, especially if they have different spatial patterns & different lags?

Why does relative horizontal invariance necessarily imply relative invariance in overturning?

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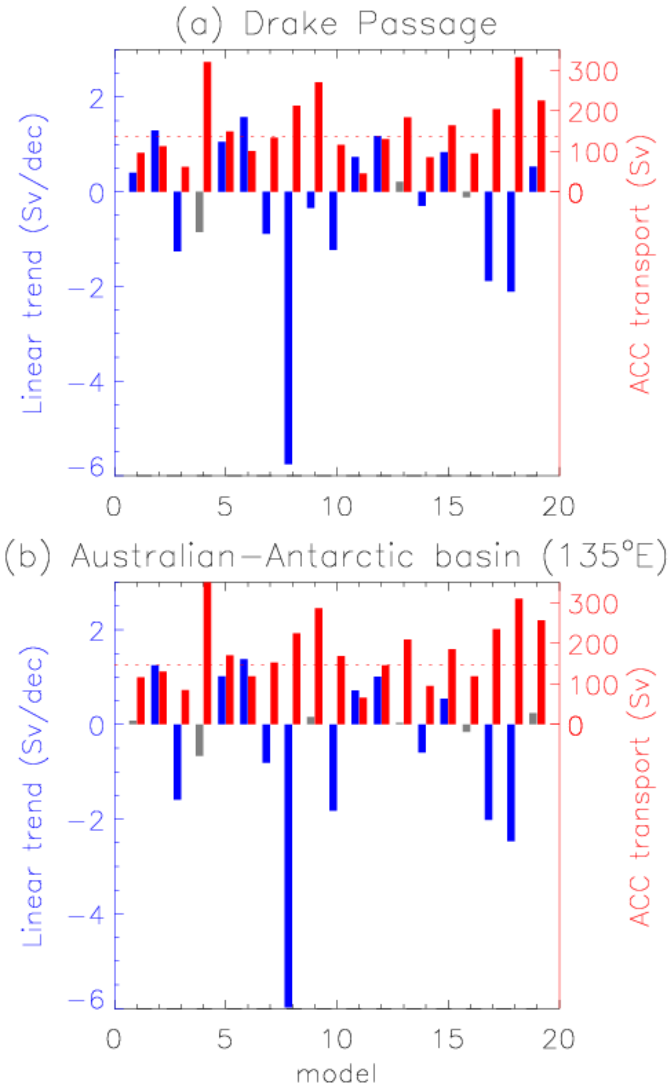
What about climate model response to SAM trend?



(Wang and Meredith, 2009)

- IPCC-class models show a huge range in mean ACC transports
- Also a huge range in the response of the ACC transport to strengthening winds
- Many even show a deceleration, for reasons not yet fully determined

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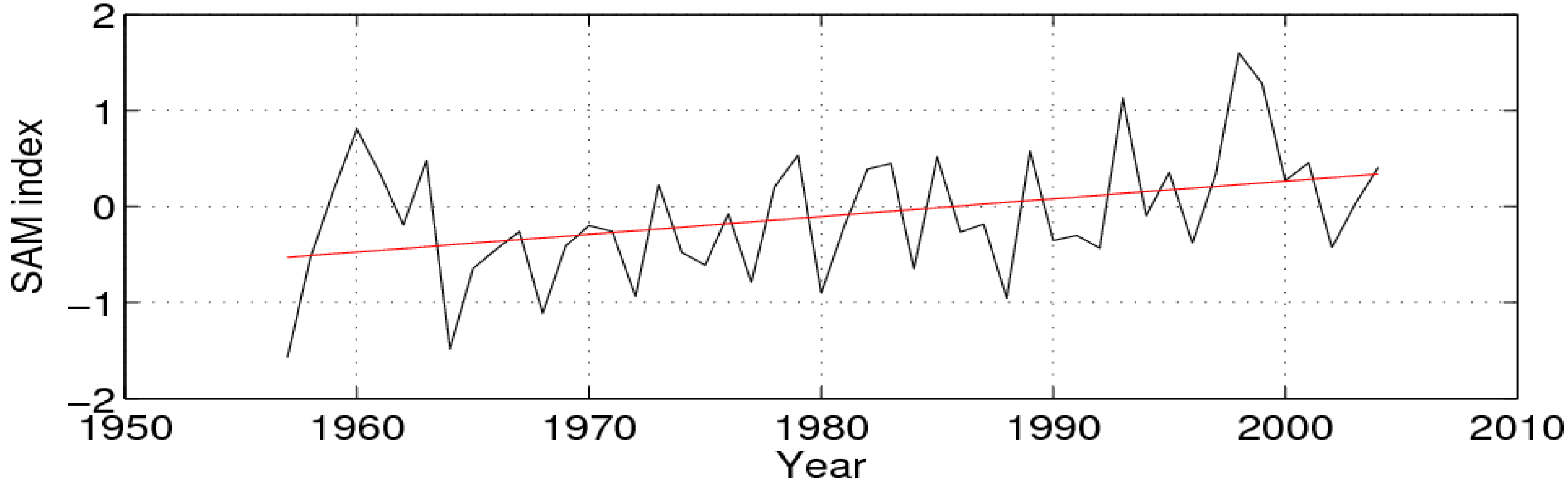
Need to assess models against observations – do these show a decadal increase in ACC transport?



- Hard to say, because we don't really have a way of directly monitoring trends in ACC transport (one possible exception)
- On interannual timescales, a change in SAM index of 1 gives a change in ACC transport of around 6 Sv…
- If same relationship holds true for longer timescales (?), acceleration in ACC due to trend in SAM would be small compared to aliassing and measurement error in CTD sections etc.
- Observations therefore do not support or refute - but any past change in transport is likely to be small. (The future?)

Things we don't know (but might want to)

- Is the ACC transport increasing, even a little?
  - If so, how much?
  - How can we monitor such trends in transport? CPIES array? Cable across Drake Passage?
  - What are impacts on ecosystems via e.g. advection of biologically-active material?
- Is overturning in the Southern Ocean increasing?
  - What drives and controls the overturning anyway?
    - Diabatic versus adiabatic processes - DIMES to answer?
    - How to represent (better) in climate models?
    - How responds to changing forcing?
  - How do we monitor overturning in the Southern Ocean?
    - Needed for assessment/weighting of models. Three RAPID arrays?
- Is the eddy field in the Southern Ocean becoming more energetic?
  - If so, what is this doing to SST? Dispersion of biological material? Upwelling, nutrients, carbon, predators?
  - If not, where is the energy going? Internal waves? Back to the mean flow? What would this do mixing/overturning?
- When will the westerly winds start slackening, and what impact will this have?
  - Will there be hysteresis in the ACC response? In the eddy field response, and temperatures? What will this do to the SAM?
  - Will the Southern Ocean relax to a different physical state? Biological state (presumably it must?)
- Have the subpolar gyres been intensifying, and will this continue?
  - What would this do to meridional heat flux, supply of CDW to shelves, ice production, AABW production, ice shelf stability, subpolar ecosystems?
  - How can we monitor this?

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Things we don’t know (but might want to)

- How will SAM, ENSO, and other modes evolve in the future?
  - What role will feedbacks involving the Southern Ocean play in this, including to equatorial regions?
  - How will the different modes interact? Studying in isolation is important, but will only get us so far…
  - What are the anthropogenic effects?
  - What will be the impacts on SST, sea ice, glacial ice, stratification, 1° production etc?
  - When will the present increase of sea ice extent in Southern Ocean reverse?
- How do we improve predictability of Southern Ocean response to coupled modes and decadal trends?
  - e.g. why do sometimes very similar El Niños have very different high latitude expressions?
- How do we include the influence of ice shelves and ice sheets in ocean and ecosystem analyses/models?
  - Likely to be important on longer timescales
  - Coupled ice sheet/ocean models?
- How do we obtain the ocean data with which to evaluate/weight climate models?
  - Will SOOS do this?
  - How will data density/distribution be prioritised?
- How do we better represent Southern Ocean processes in century-scale climate models?
  - Eddies/submesoscales likely to be fundamentally important; topography, convective processes
    - Moore’s law?
    - Nesting of “key” areas? (How defined? Physically? Biologically?)
    - Adaptive grids? e.g. ICOM?

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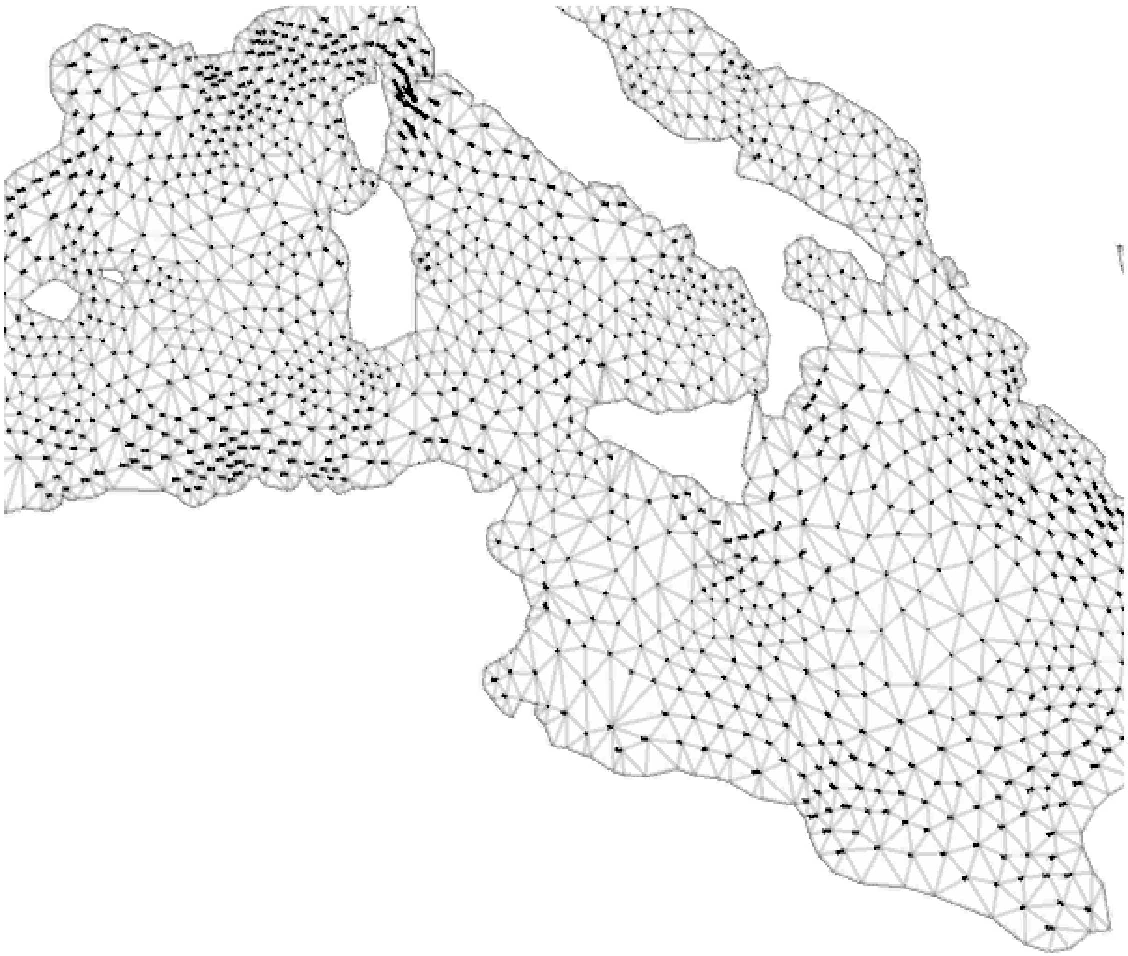
Mediterranean model, with horizontal adaptive grid



(courtesy of Imperial College, London)

Global scale possible.

Vertical adaptive grid could better represent deep convective and water mass formation.

Biogeochemical components in progress. Other ecosystems components?

Inclusion in climate models?

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So – far more questions than answers, but thank you for listening…

… and I hope you found it interesting anyway.

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