Global changes of the hydrological cycle and ocean renewal inferred from ocean salinity, temperature and oxygen data

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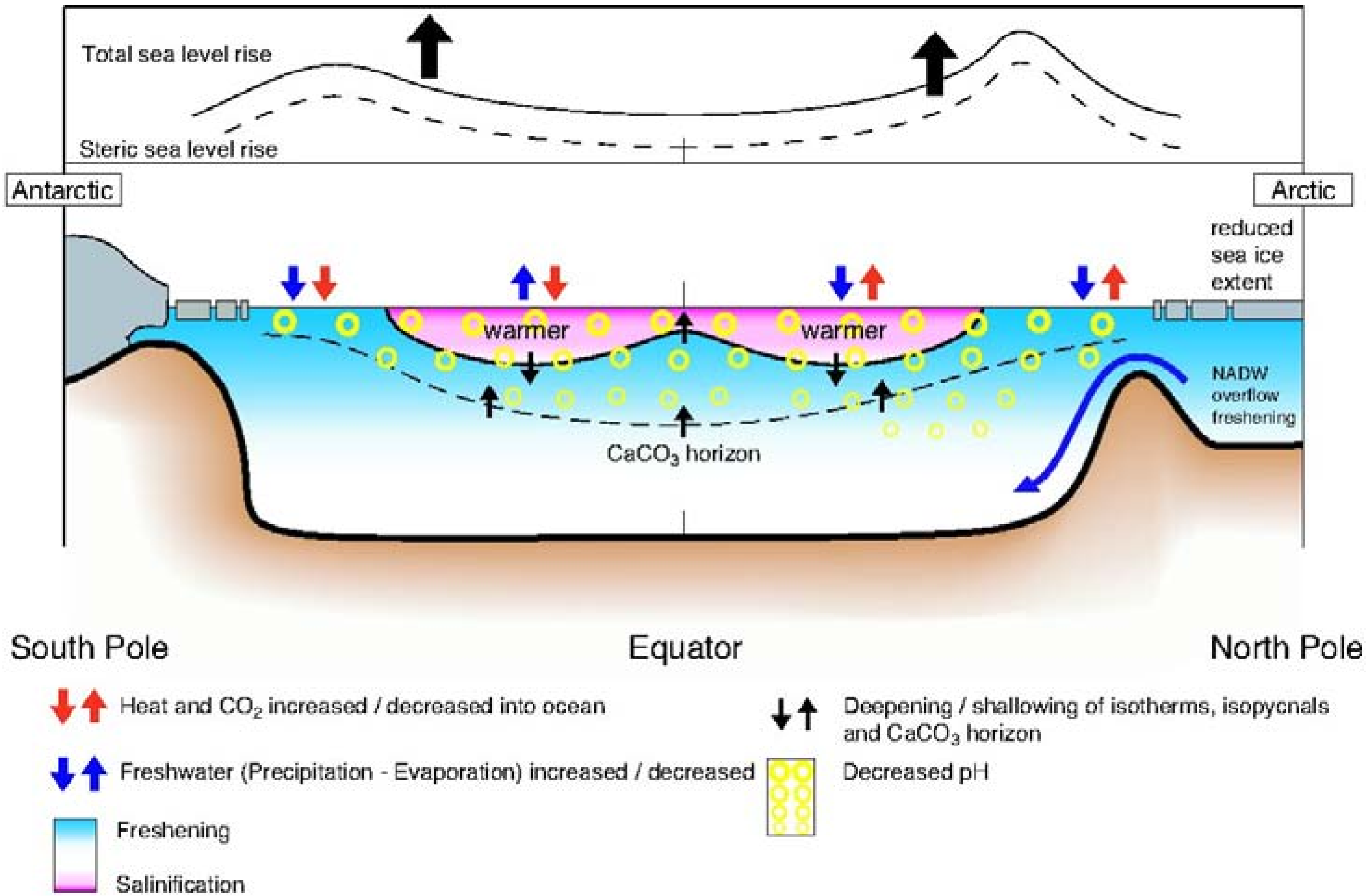
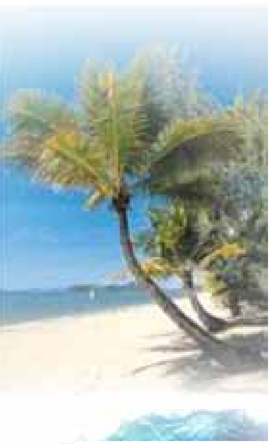
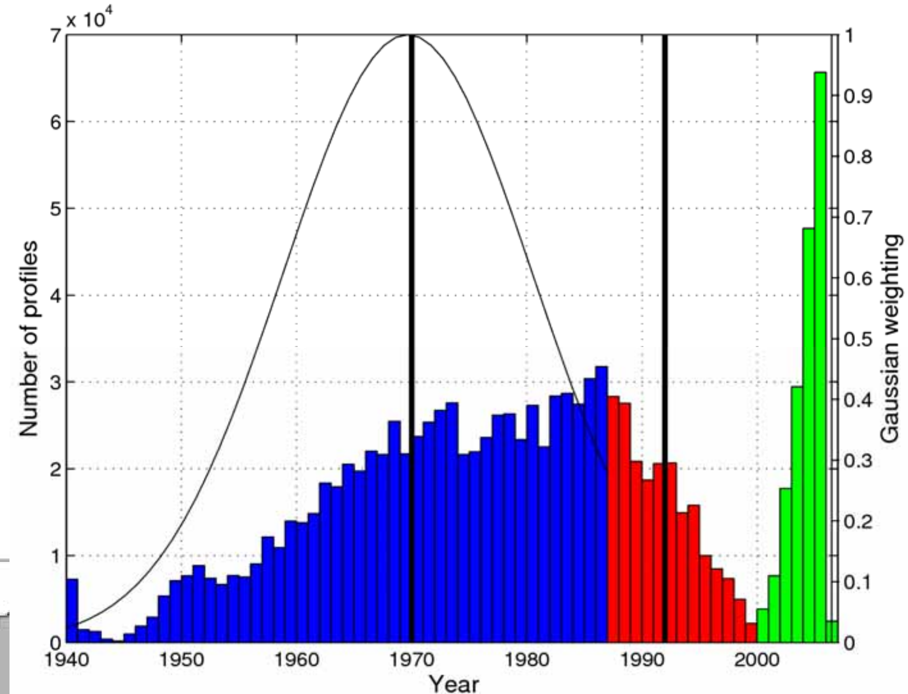
IPCC AR4 Synthesis

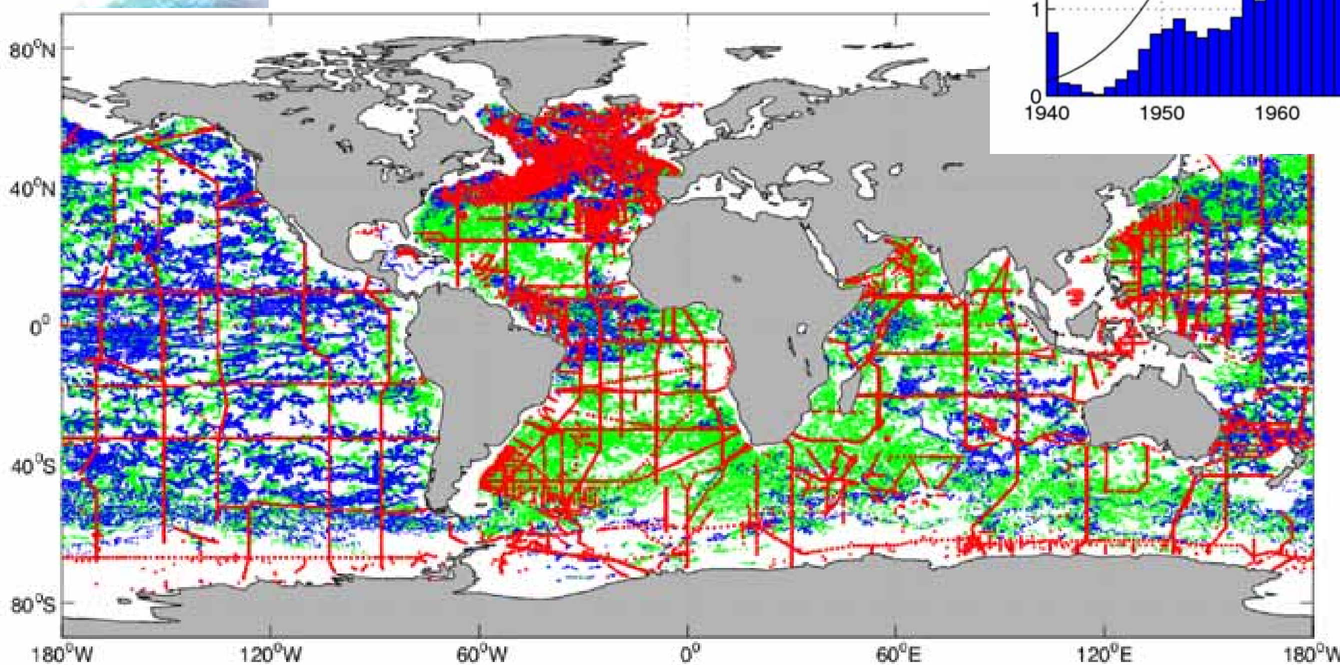


Data Distributions



Methods
- Interpolated WOCE
- Used adaptive
- Blue water

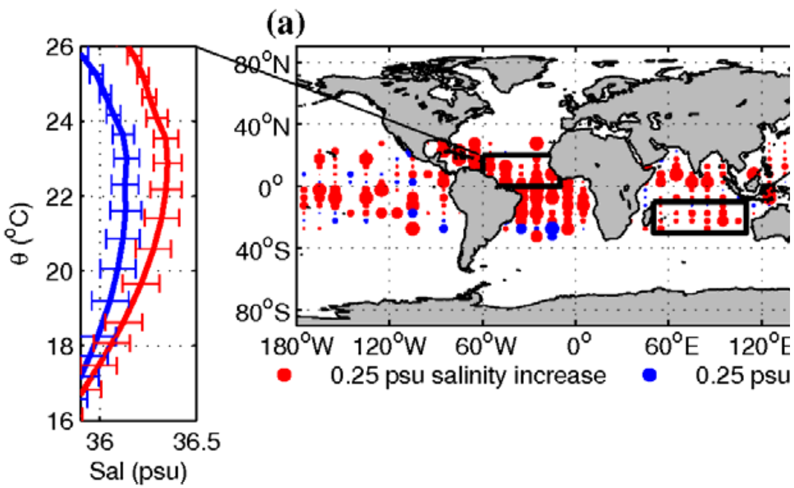


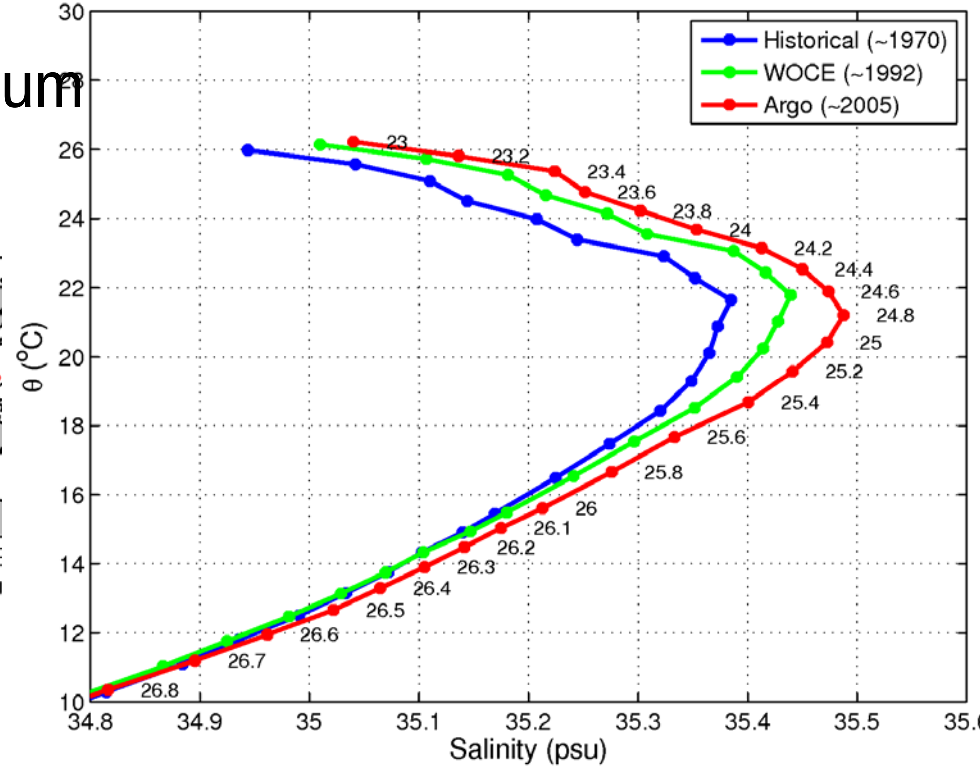


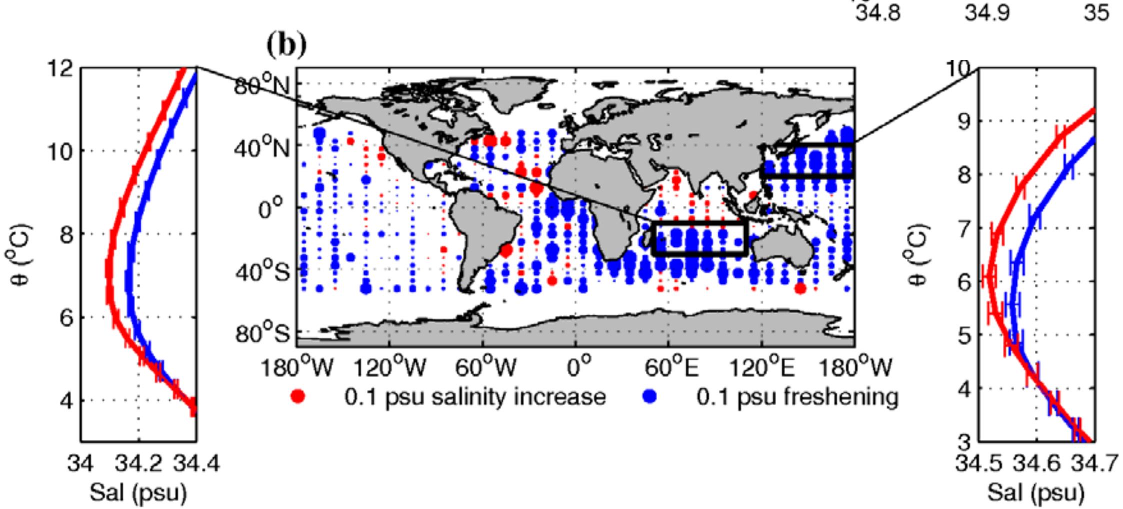
Database
- WOCE (Red)
- Profiles (Blue)
- ARGO (Green)

Water Mass change

Shallow salinity maximum

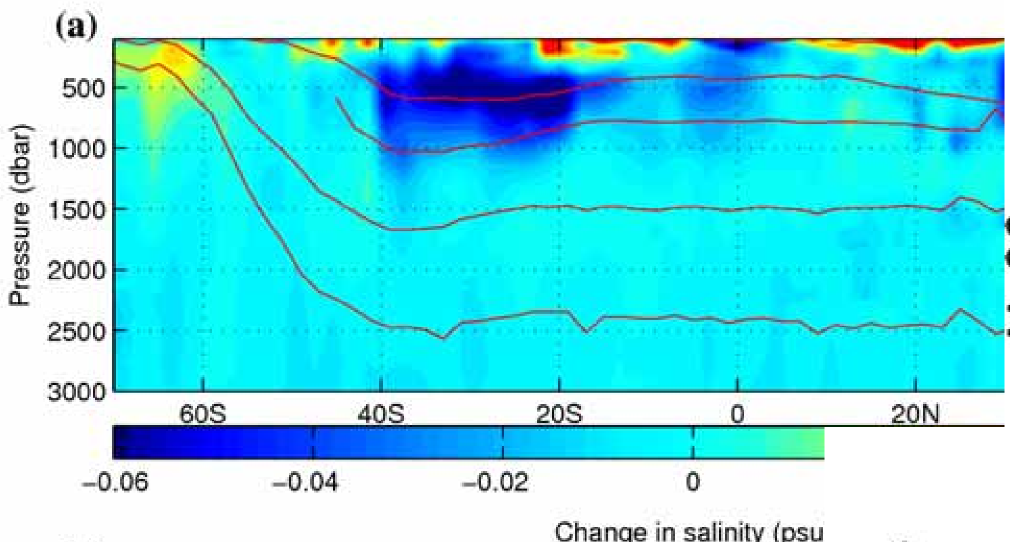


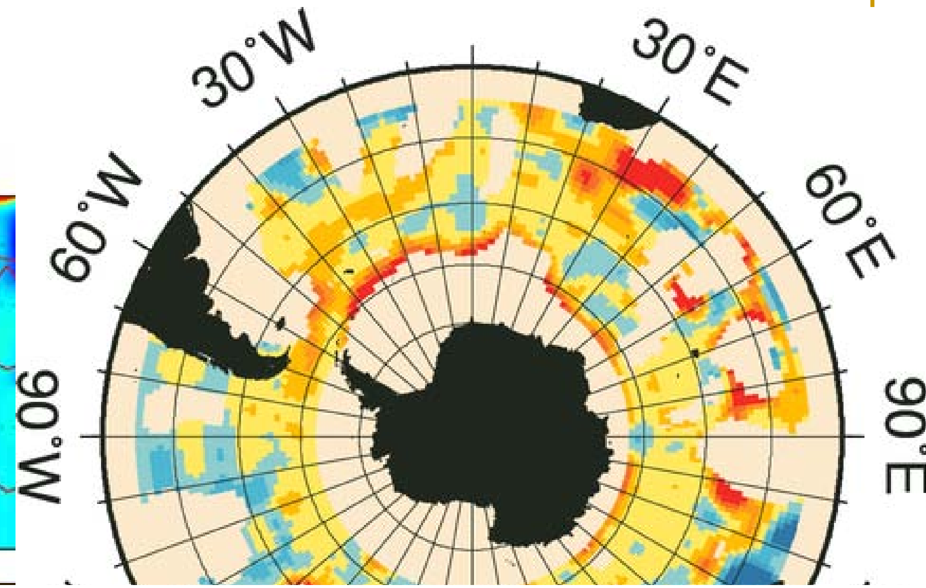


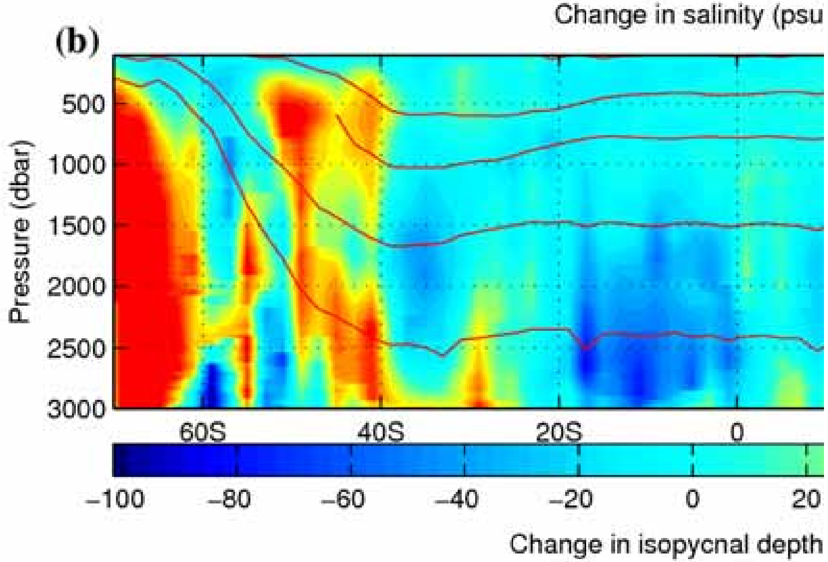


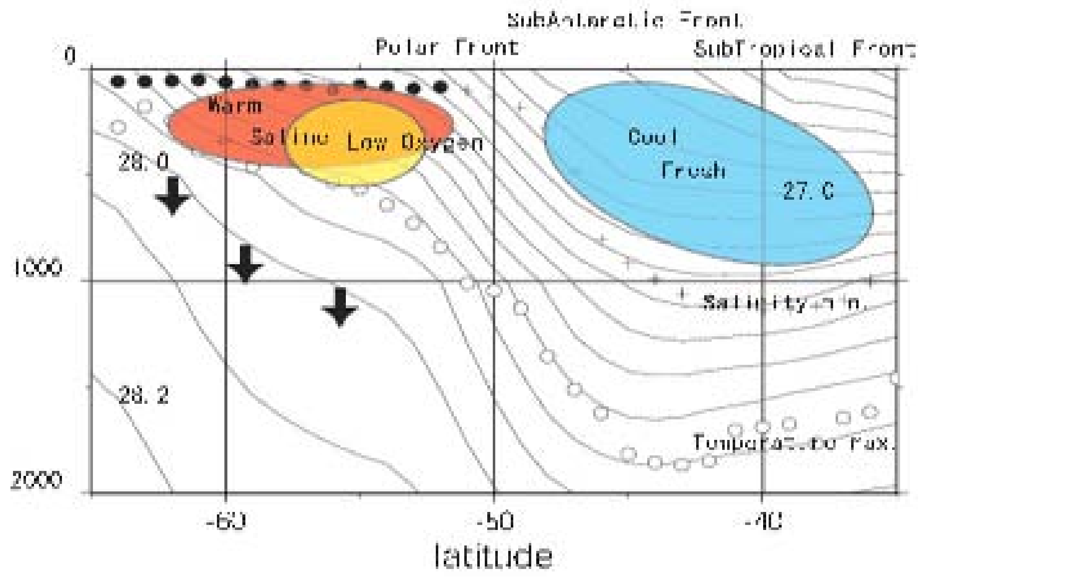
Salinity Minimum

Zonally averaged changes

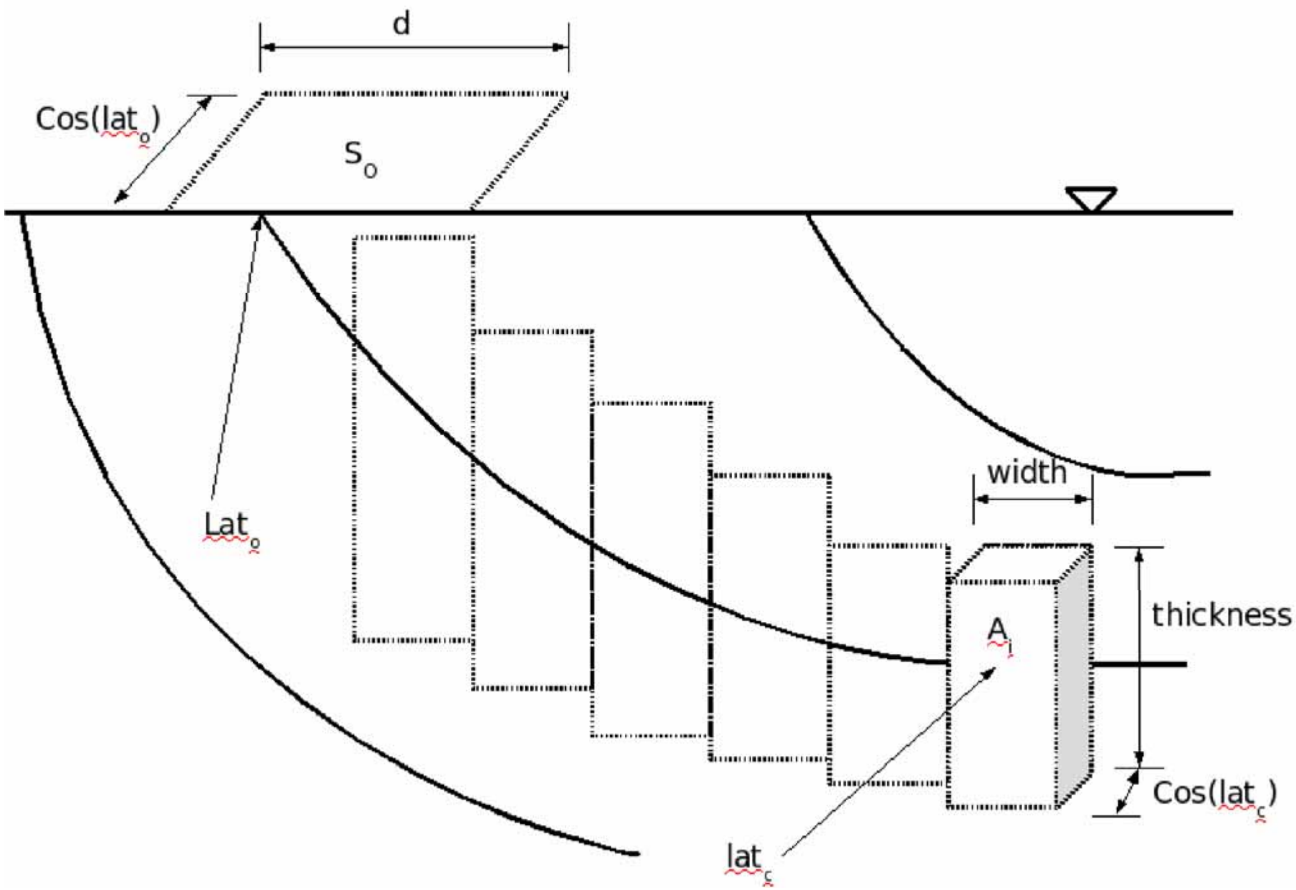




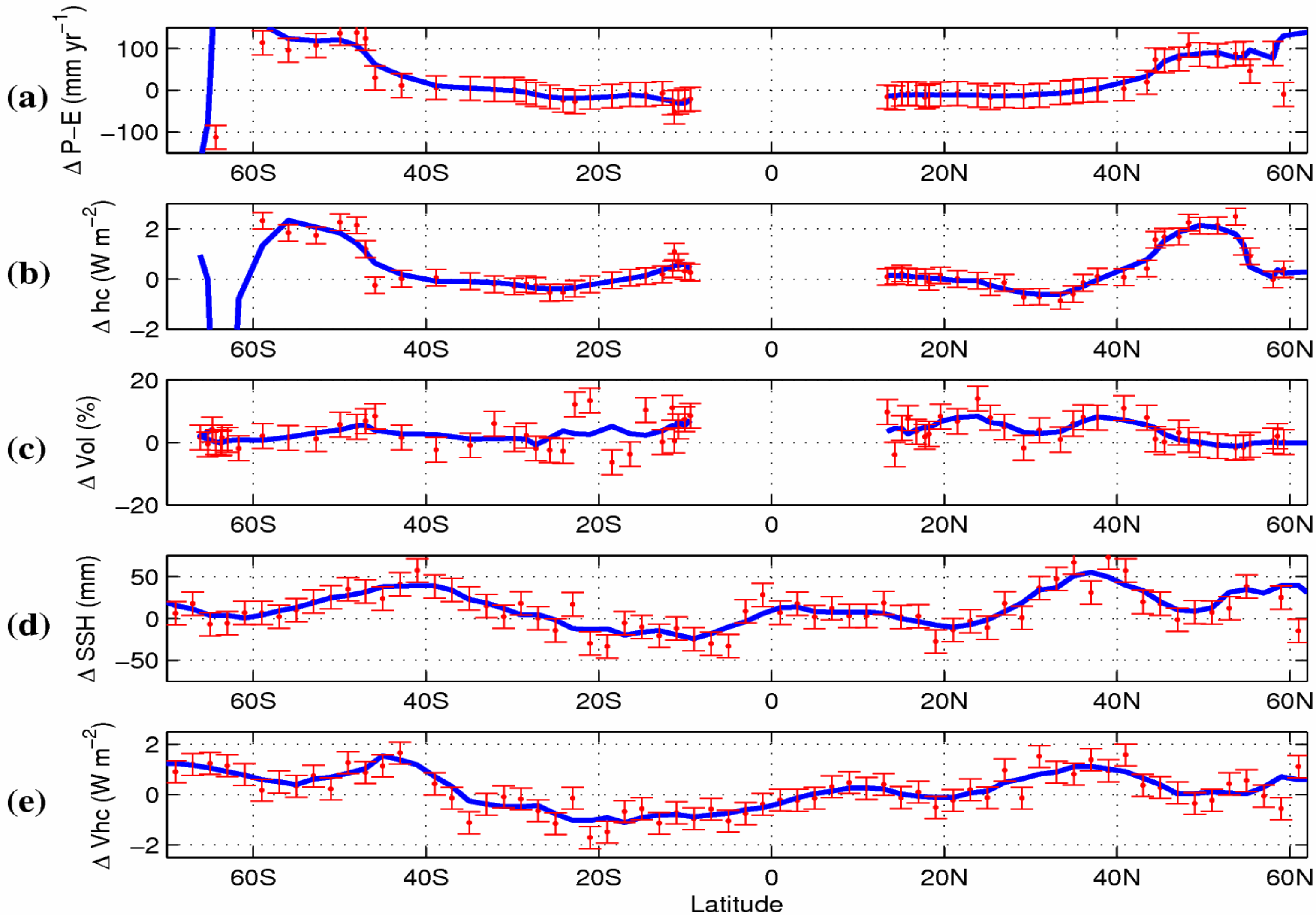




Apparent surface fluxes



Apparent surface fluxes

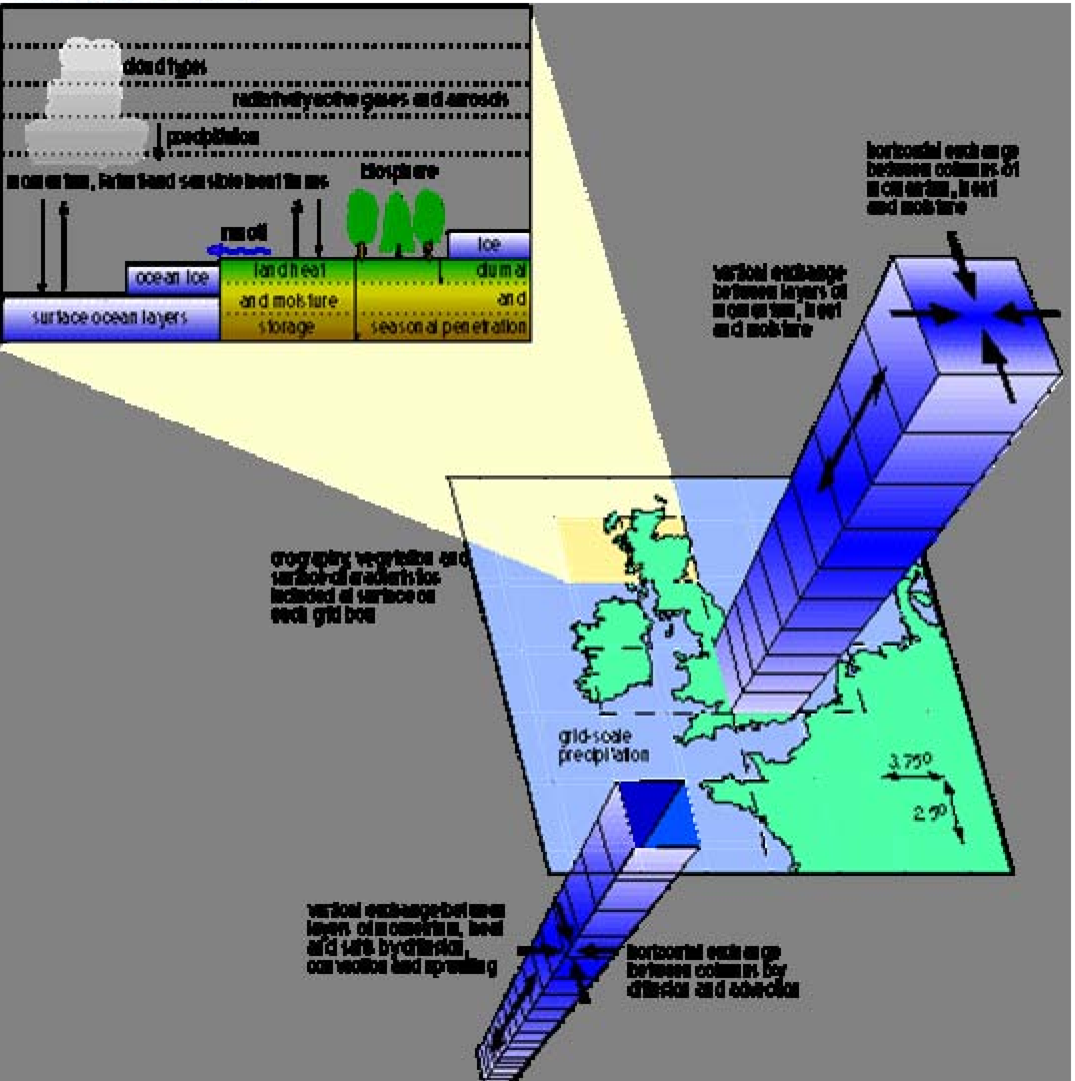


P-E

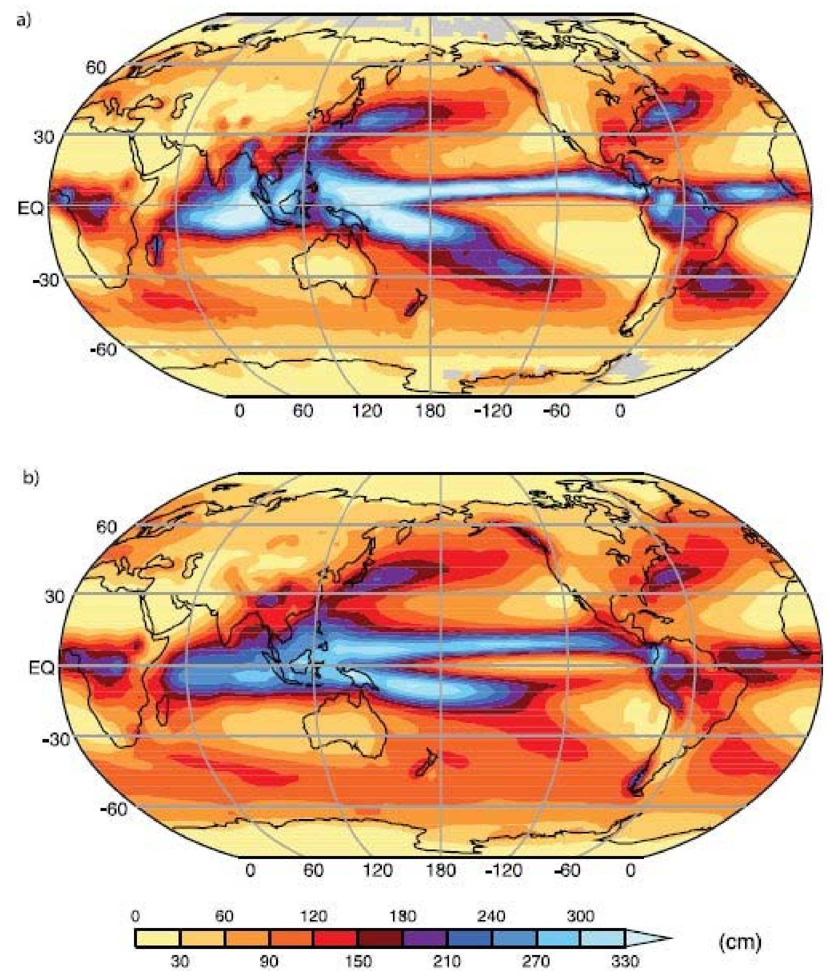
Heat

Volume

Climate models, essential to hypothesis testing

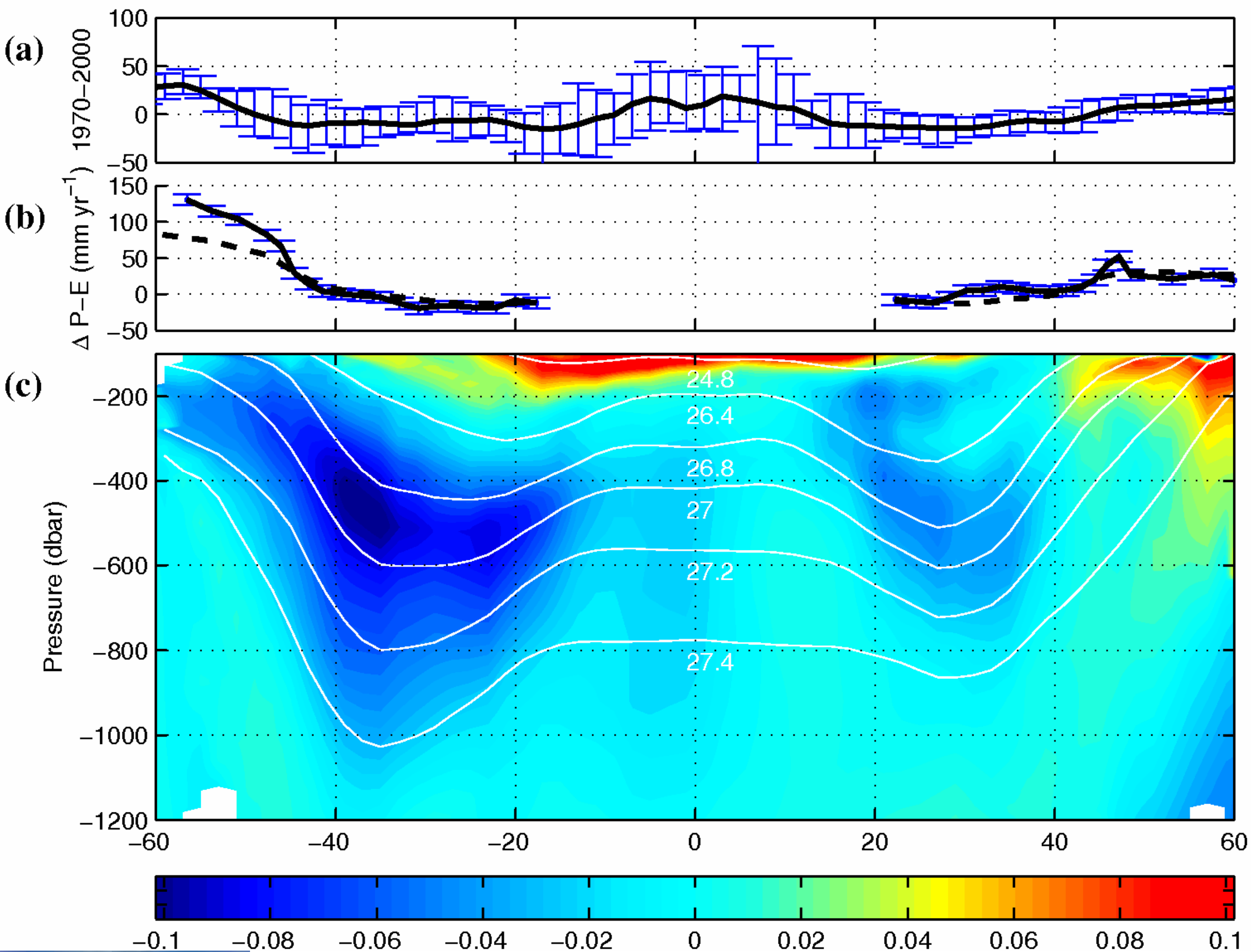


Observations 1980-2000



Mean Model 1980-2000

Comparison with models

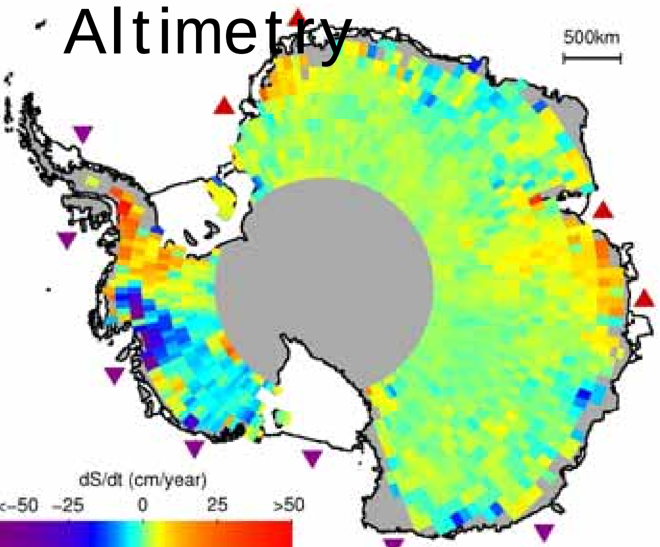


IPCC models 1970-2000

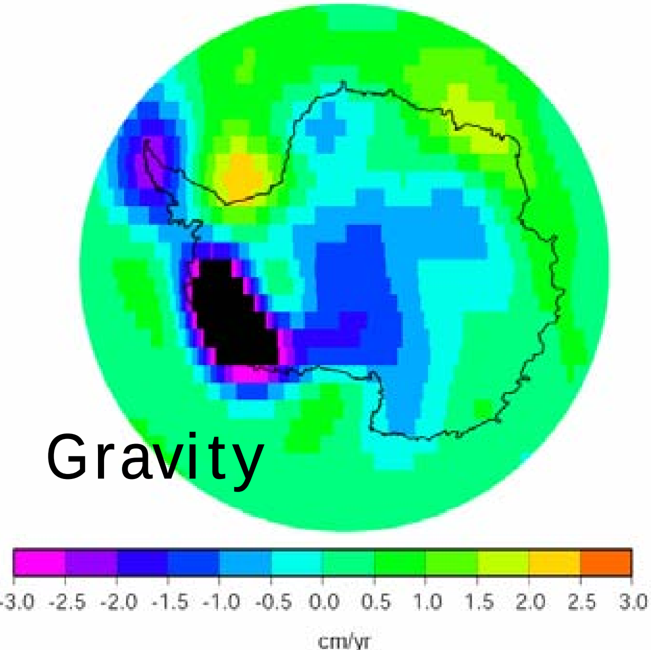
Estimated P-E

+16±6% in S. Ocean
+ 7±4% in N.H
- 3±2% in S.T. gyres

Excess P-E near Antarctica?



Rate of mass change between April, 2002 and June, 2007.



Antarctica is loosing mass

- 0.14 ± 0.41 mm yr-1 SLE, 1961-2003
- 0.21 ± 0.35 mm yr-1 SLE, 1991-2003
- ~0.4 ± 0.35 mm yr-1 SLE,2002-2007

Wahr and Velicogna 2007.

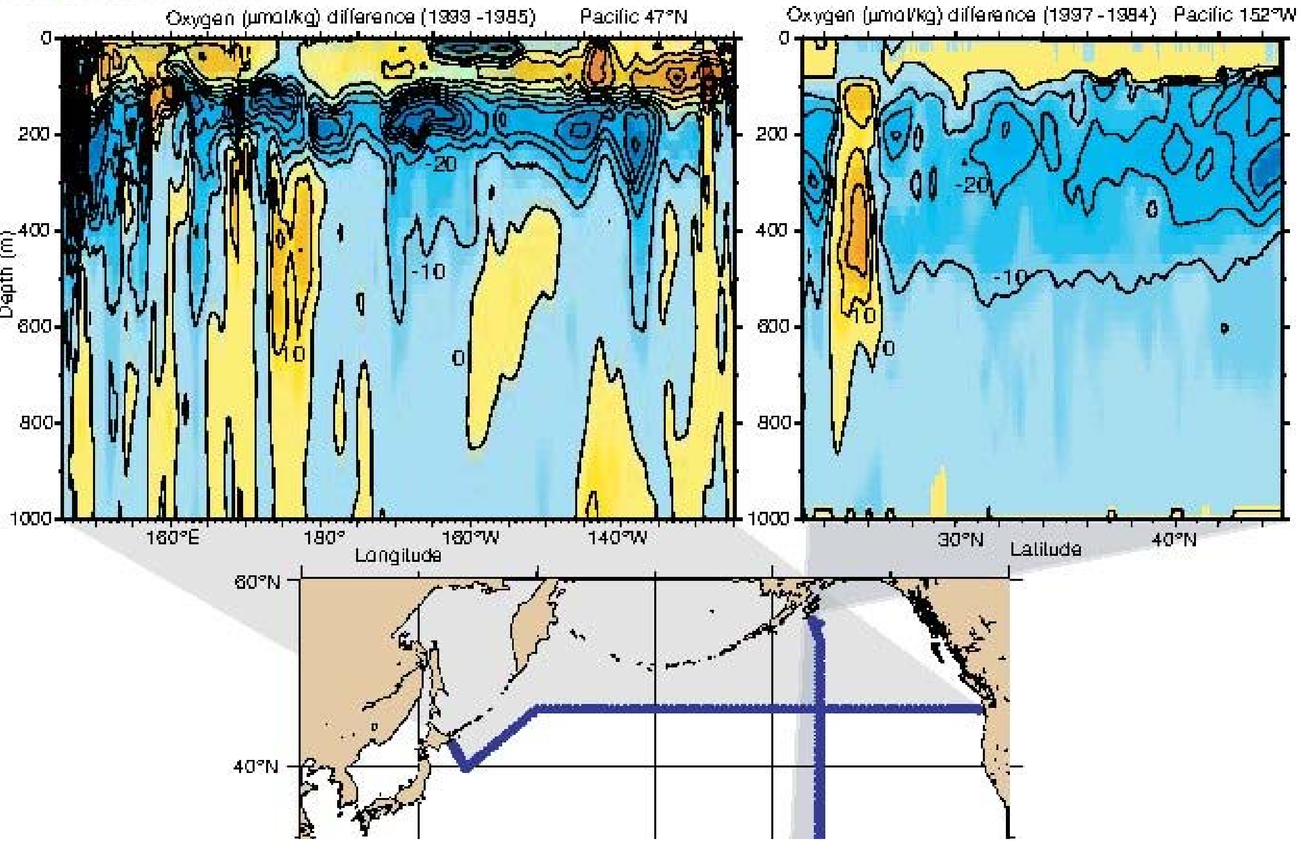
Increasing evidence of melt

- Jacobs 2001, Rintoul 2006,
- Aoki et al 2005

Melt of ice shelves?

- <5% over 30 to get extra 50 mm.yr^{-1}
- no sea-level rise
- negligible gravity signal
- consistent with ocean melt
- 700 years at ~50mm.yr^{-1}

Is ocean renewal changing?

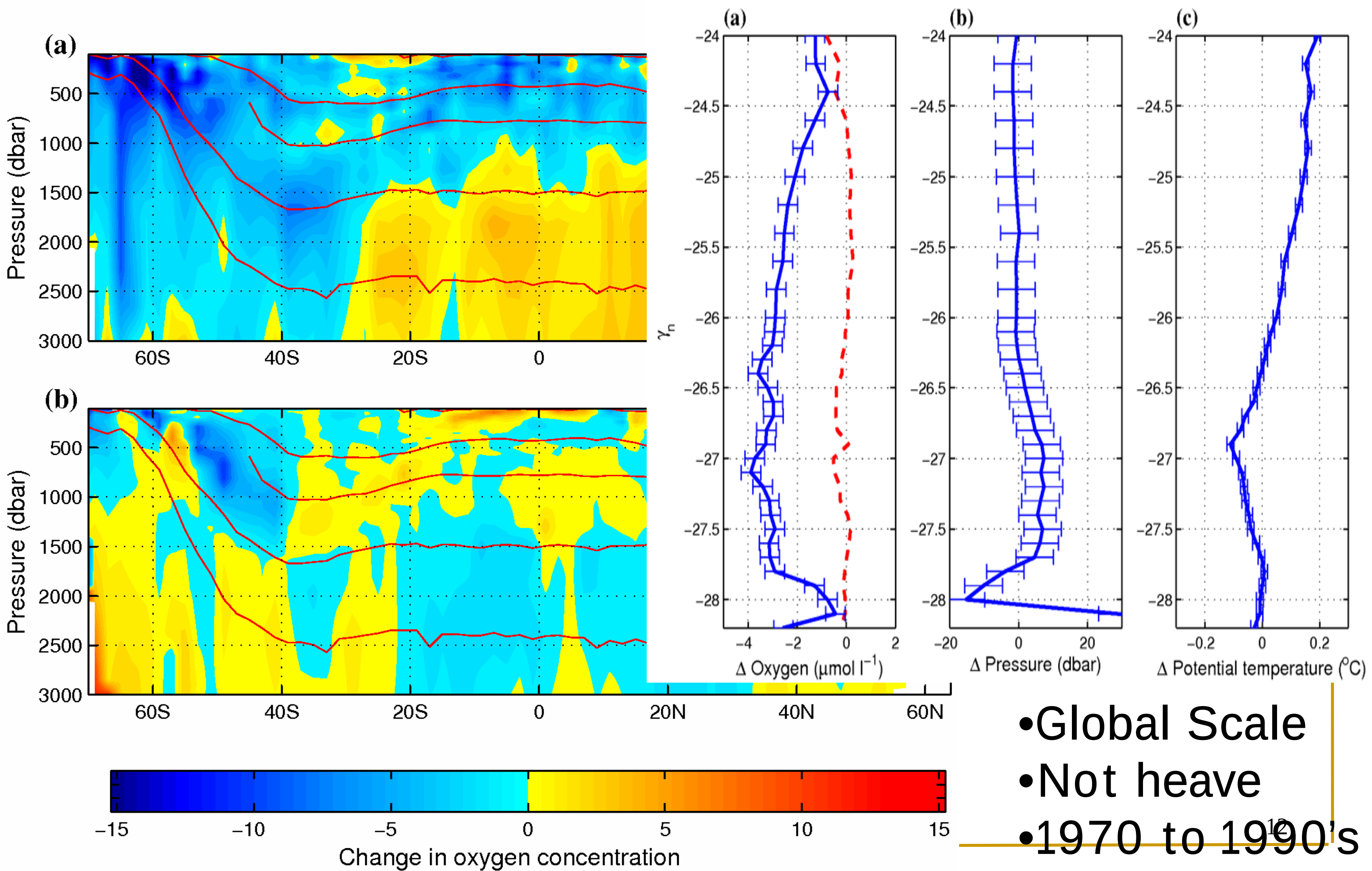


- Decrease surf. Buoyancy
- Changing stratification
- Carbon cycle

Table 5.1. Fraction of CO_2 emissions taken up by the ocean for different time periods.

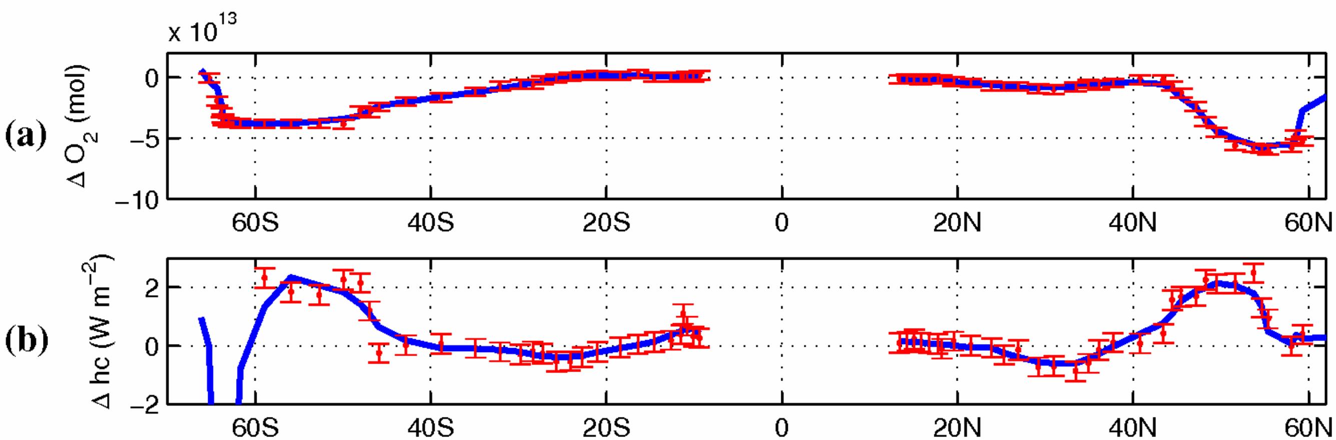
Time Period	Oceanic Increase (GtC)	Net CO_2 Emissions[a] (GtC)	Uptake Fraction	Reference
1750–1994	118 ± 19	283 ± 19	0.42 ± 0.07	Sabine et al., 2004a
1980–2005[b]	53 ± 9	143± 10	0.37 ± 0.07	Chapter 7[c]

Zonal oxygen changes



- Global Scale
- Not heave
- 1970 to 1990's

Apparent surface fluxes



Oxygen flux

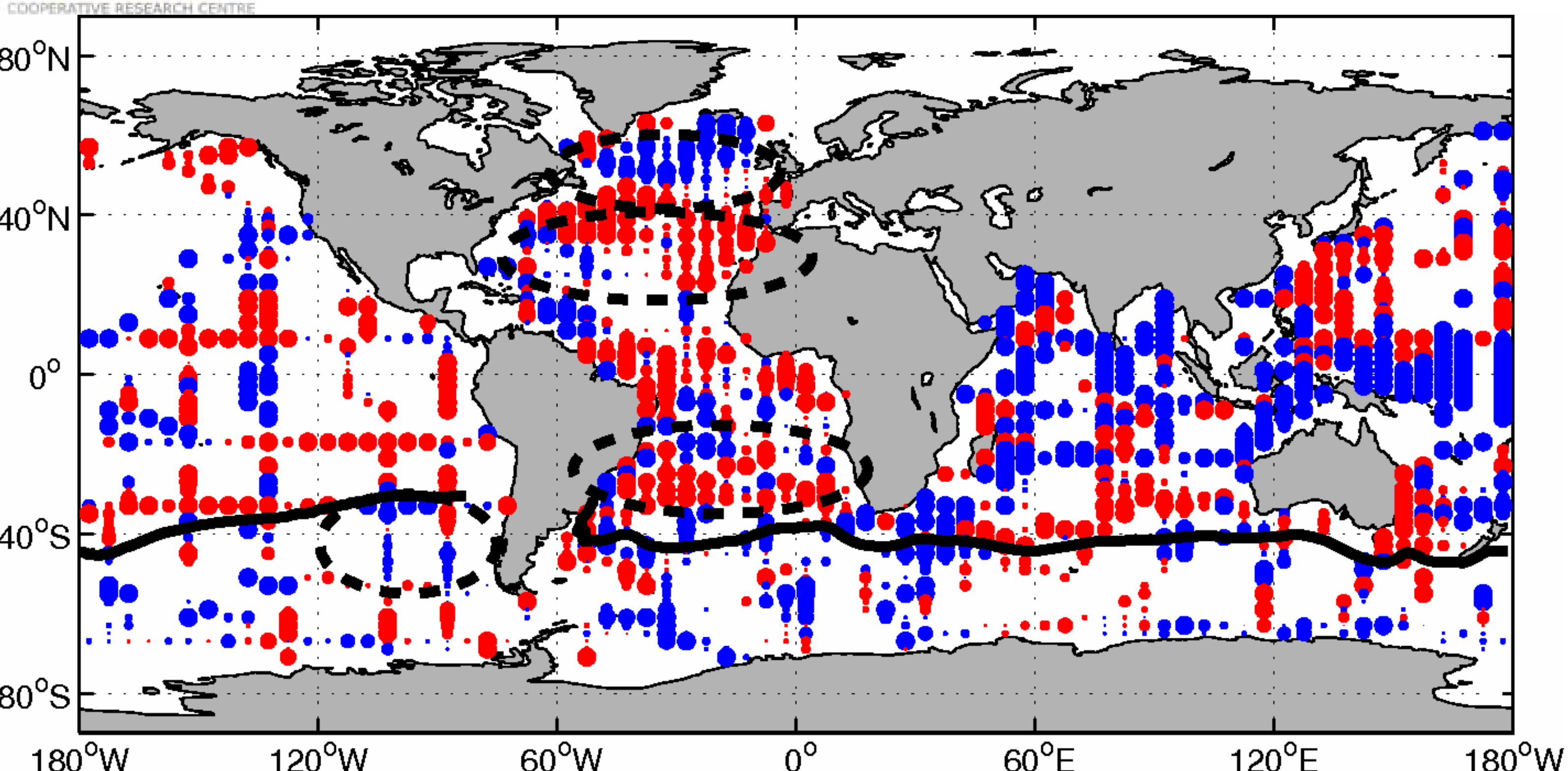
Heat flux

- Decrease 1.8+-0.9 μmol.l^{-1}
- Equivalent to ~1% decrease
- Equivalent flux
    - 0.6+-0.3 10^{14} mol.yr^{-1}
    - 0.2 to 0.7 10^{14} mol.yr^{-1} in the literature (eg Keeling and Garcia 2002)

Implications:

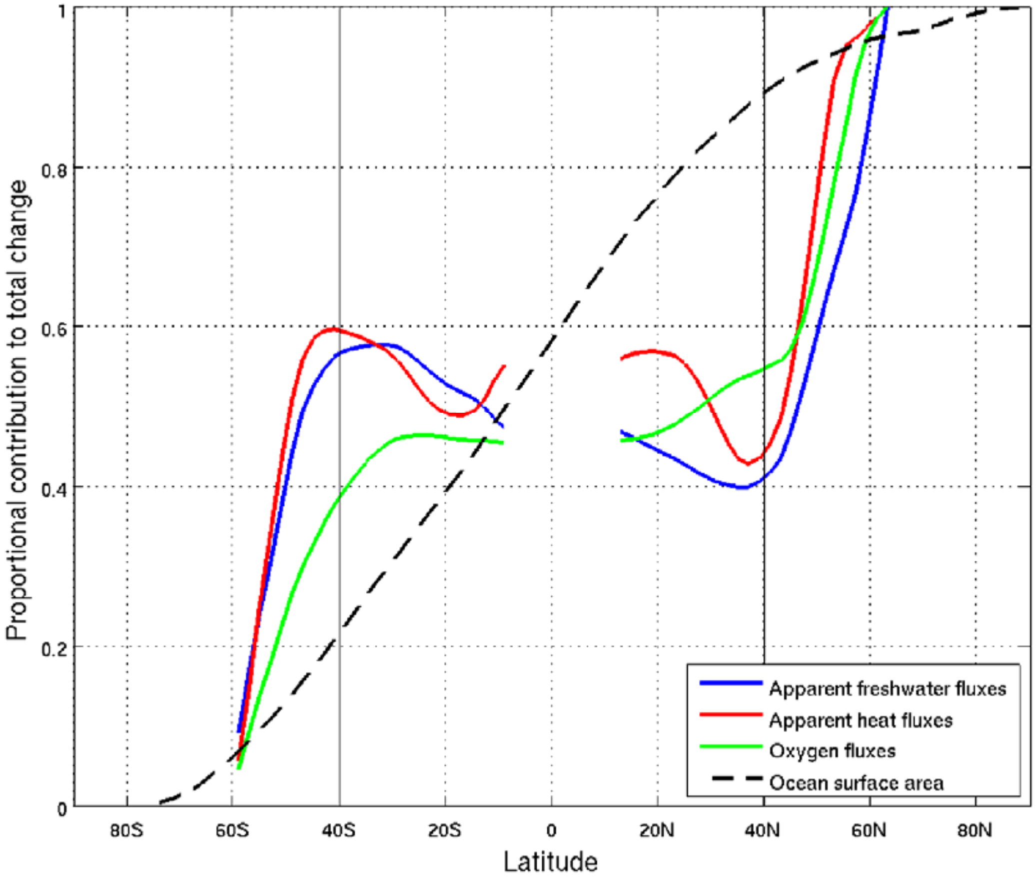
- Reduce O2 exchange with atmosphere
- Reduced water mass ventilation in the subduction

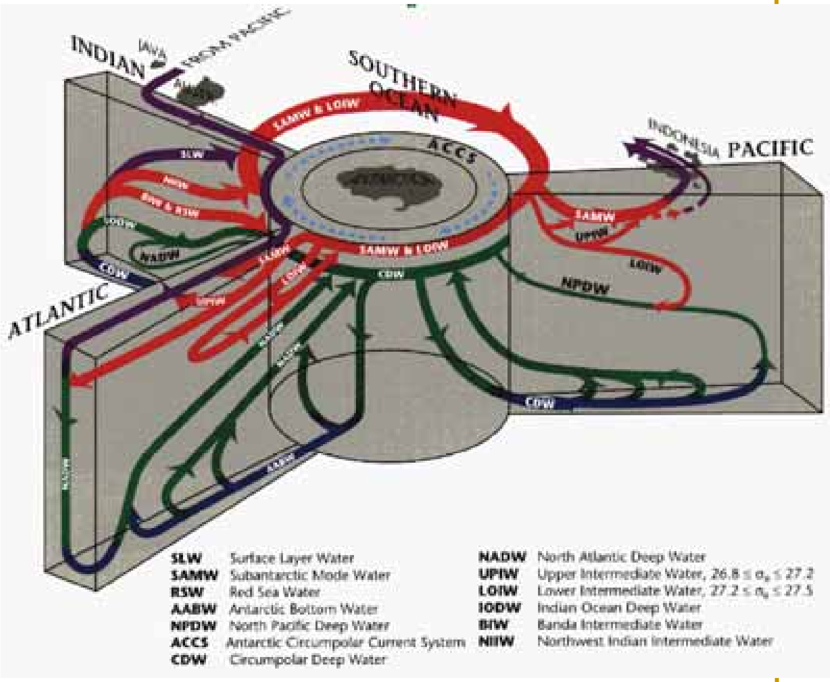
Winds or buoyancy?



$$S_{ann} = \frac{1}{T_{yr}\,\rho\,g} \int \frac{B_{net}}{h\,Q_b}\,dt$$

High latitudes processes and symmetry



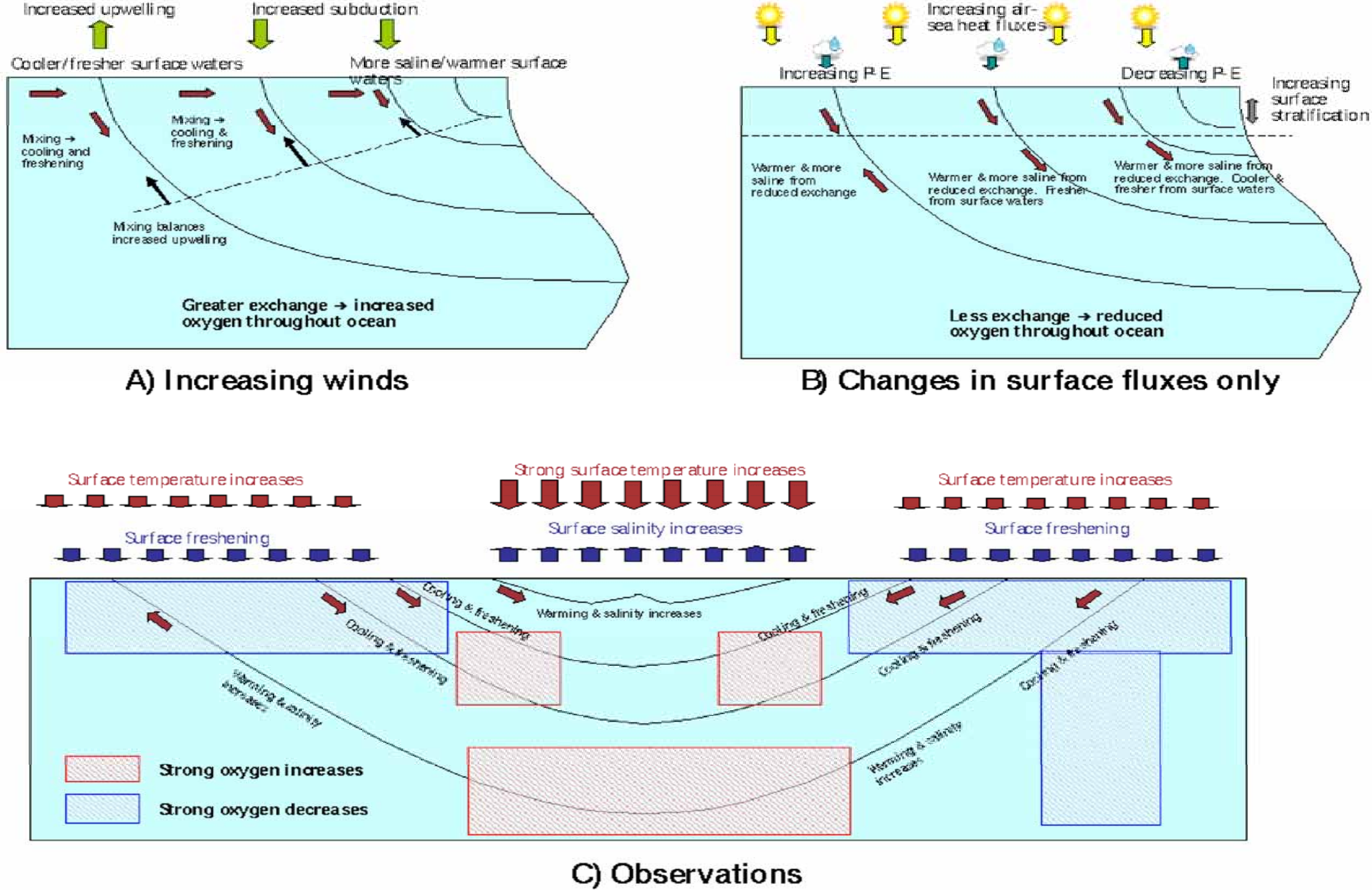


- High Latitudes large impact on storage changes
- Zonal averages similar in both hemispheres

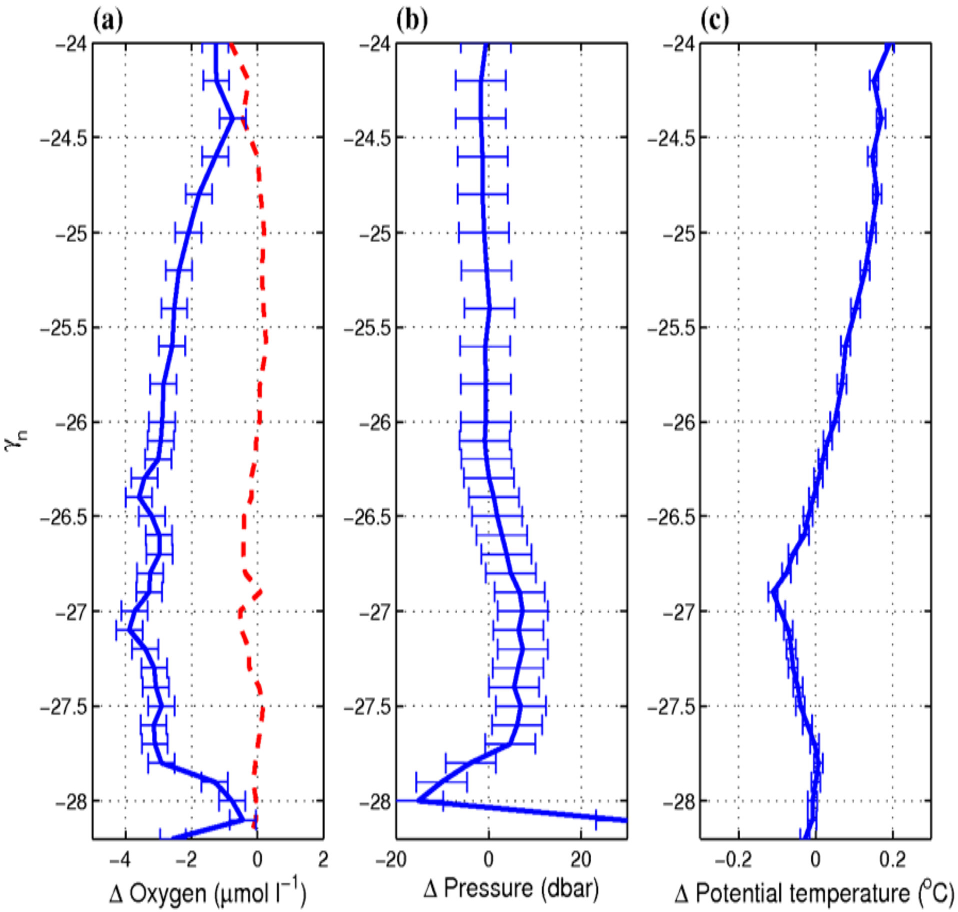
Conclusions

- Changing freshwater fluxes
  - Plausibly attributable climate change
  - Evidence of increased melt of Antarctic ice
  - Acceleration of hydrological cycle
- Striking global scale oxygen changes
  - Evidenced for reduced ocean exchange
  - Weakening of the global overturning circula

Interpretation



Global Oxygen Changes



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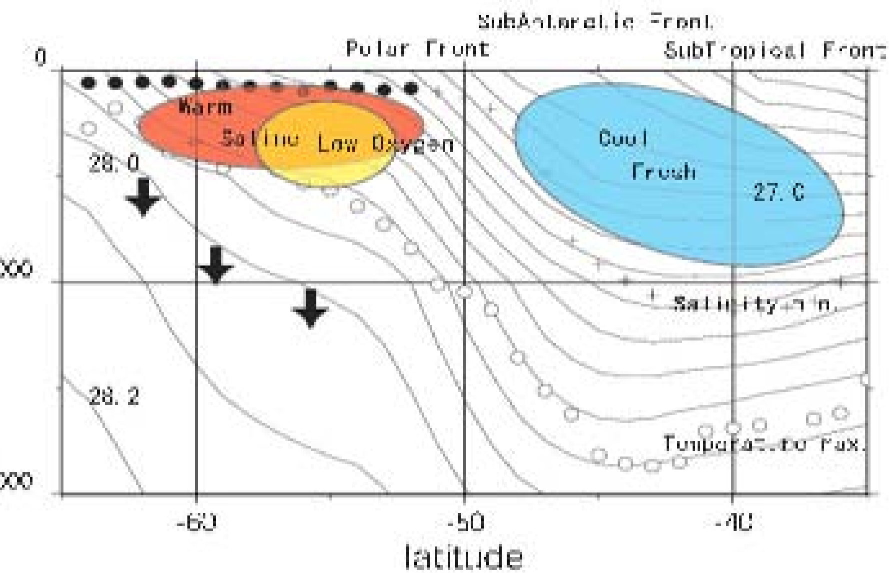
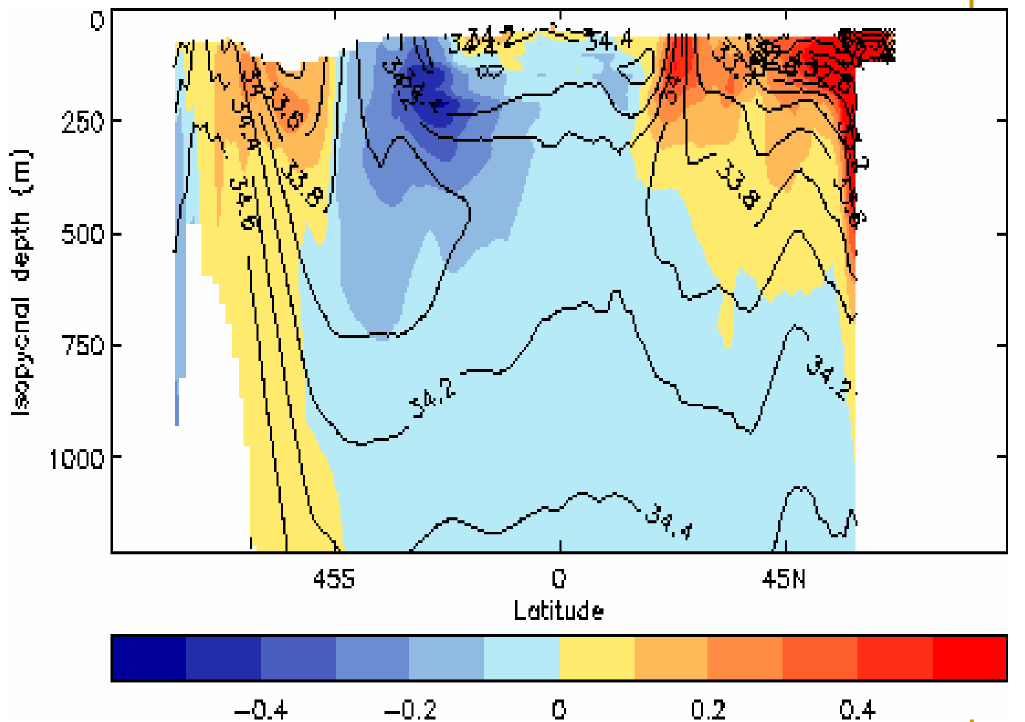
More evidence



Aoki et al, 2005

1960’s to 1990’s
30E to 180

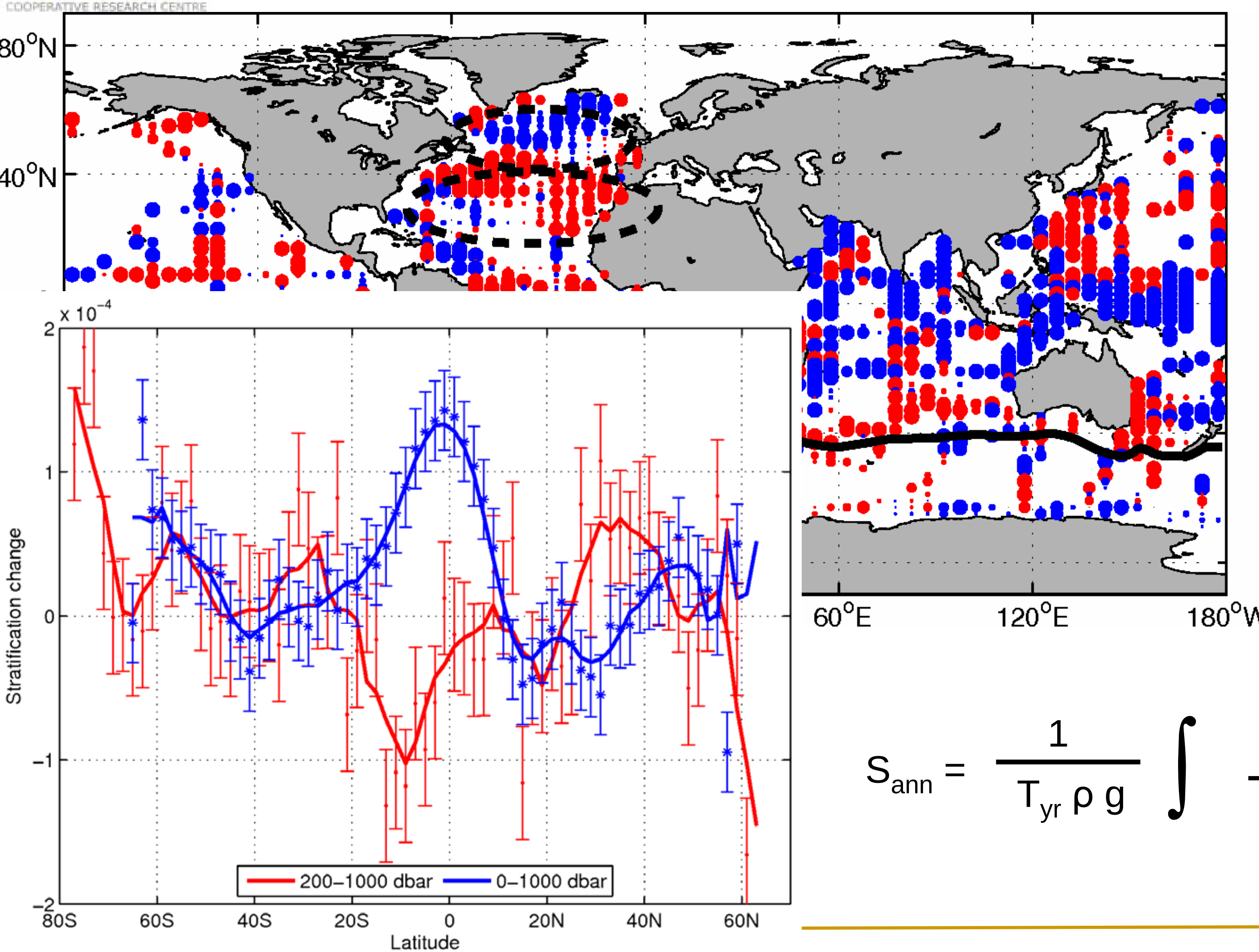


HadCM3 1990's- 1960's

Banks and Bindoff, 2003

Climate Differences

Winds or buoyancy?



$$S_{ann} = \frac{1}{T_{yr}\,\rho\, g} \int \frac{B_{net}}{h\, Q_b}\, dt$$

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Consequence of ocean acidity and renewal change

- Impacts on organisms that have calcareous shells (in particular aragonite)
- Coral reefs
- Changes in upwelling

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Warming of the Southern Ocean

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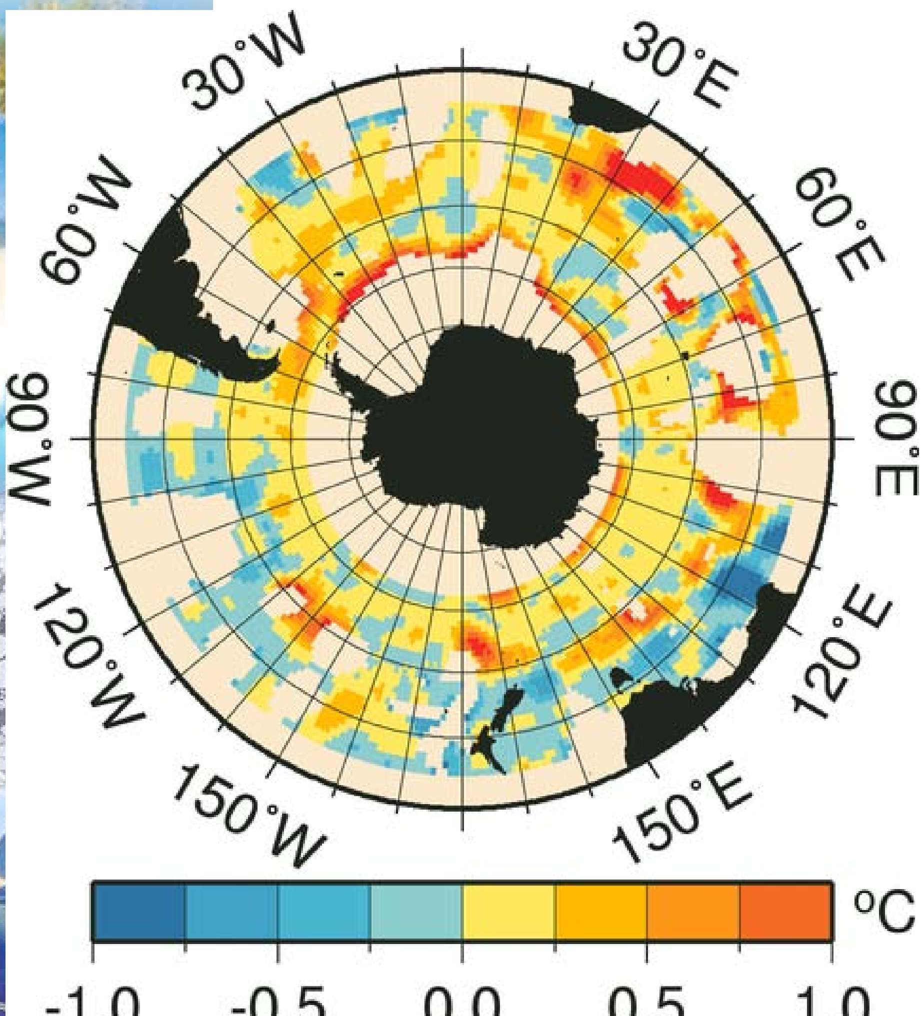
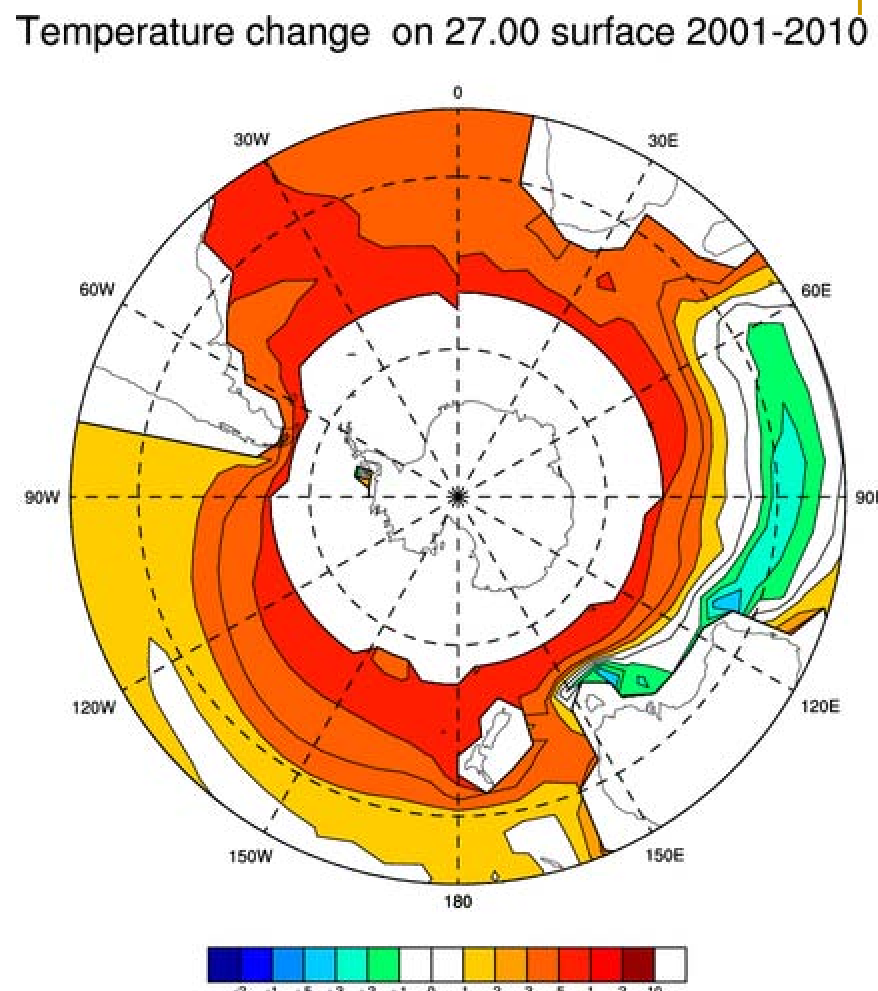
Observations (Gille)

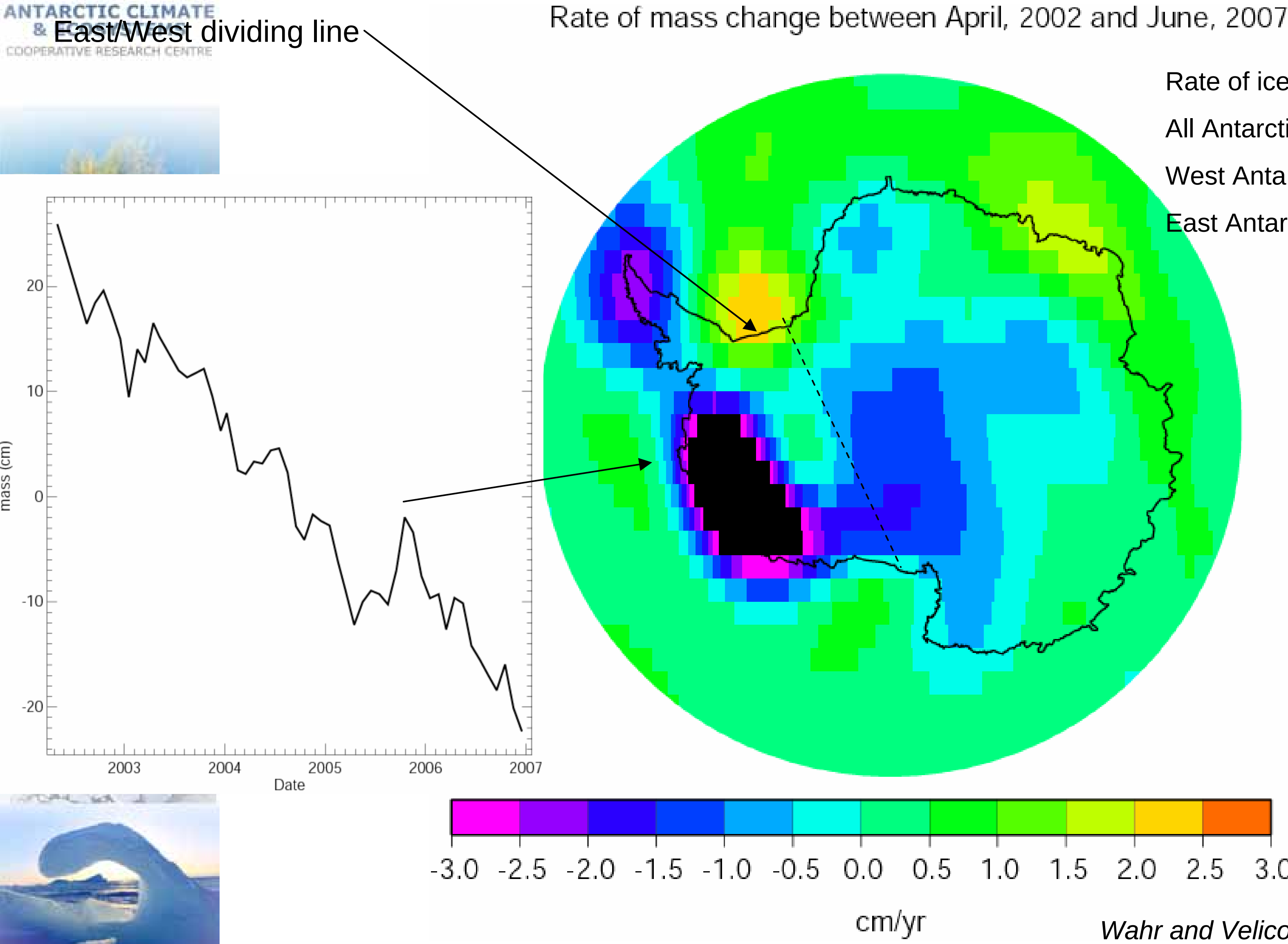
Model





O'Farrell + Budd, in prep

Antarctic Ice Mass Loss from GRACE



Rate of ice volume change:

All Antarctica: -149 km^3/yr

West Antarctica: -115 km^3/yr

East Antarctica: -23 km^3/yr

Wahr and Velicogna, 2007

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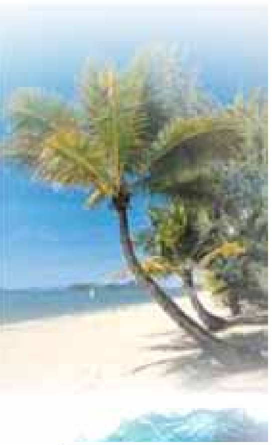
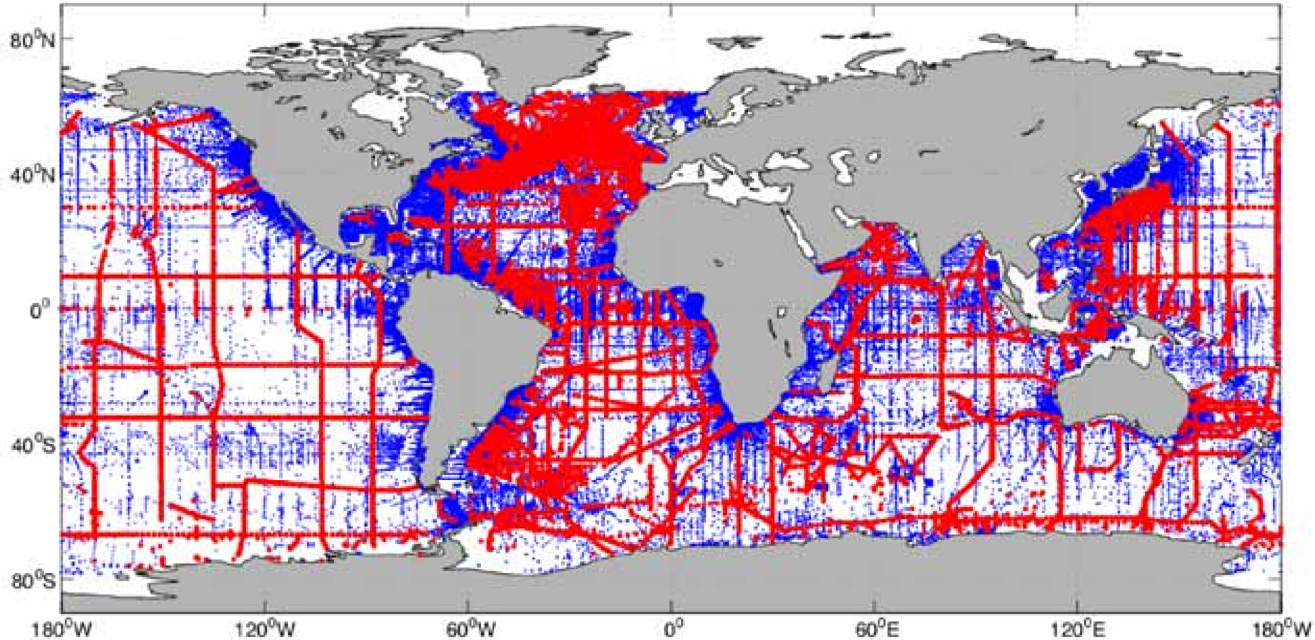
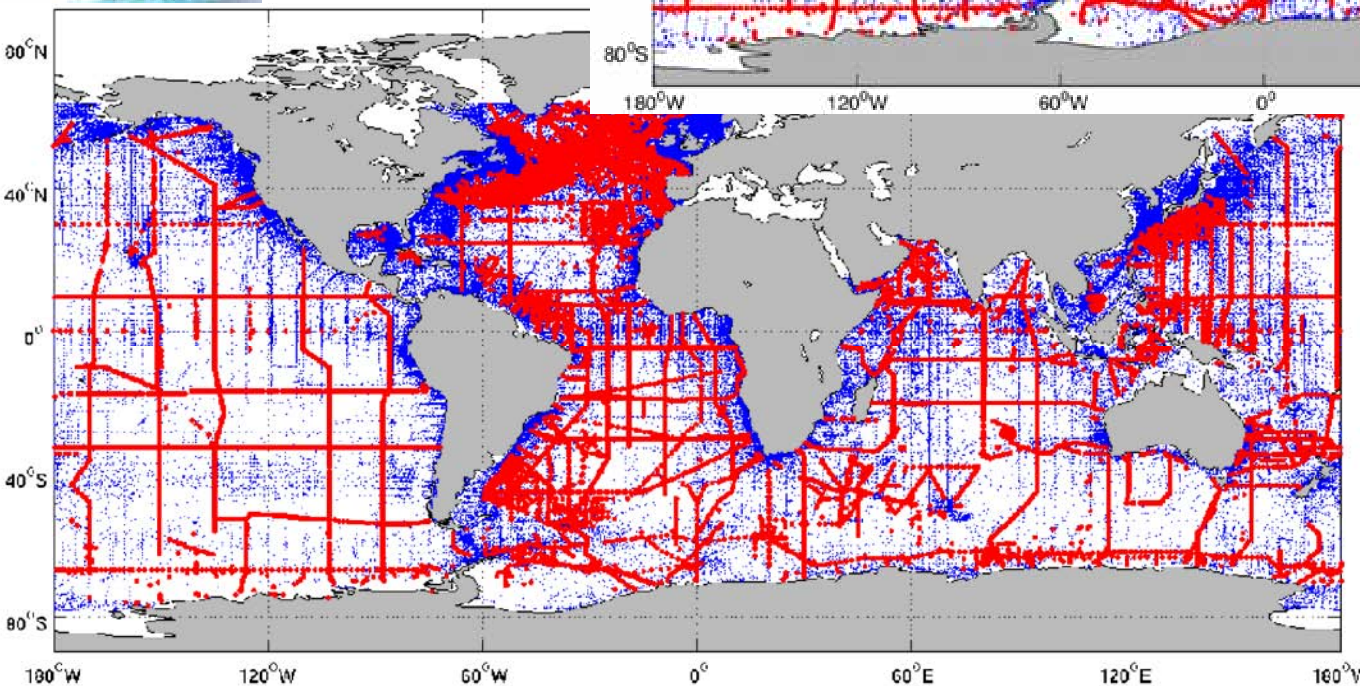


Data Distribution: profile data

Oxygen

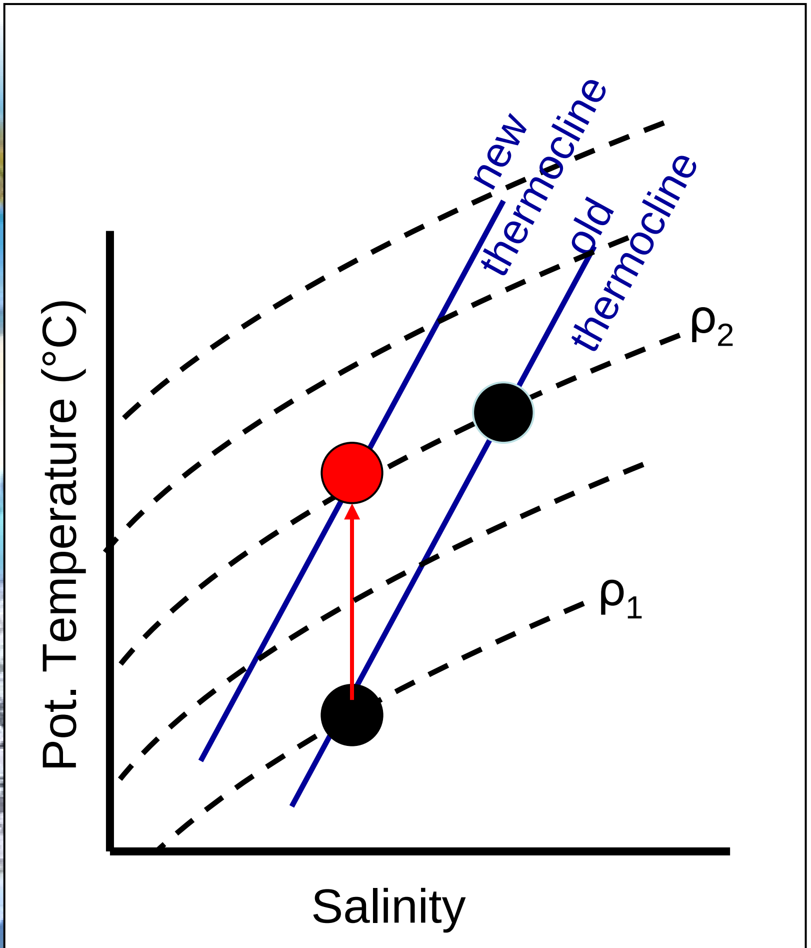




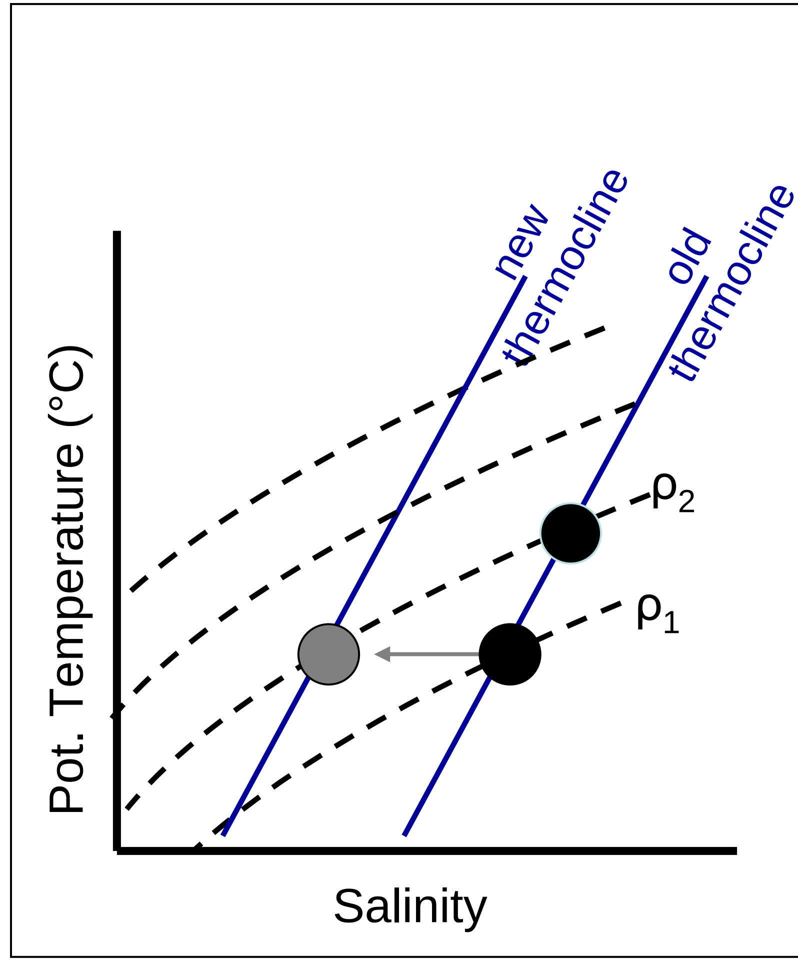
Temperature
and salinity

Changes on neutral surfaces

(See: Bindoff & McDougall, 1994, 2000)

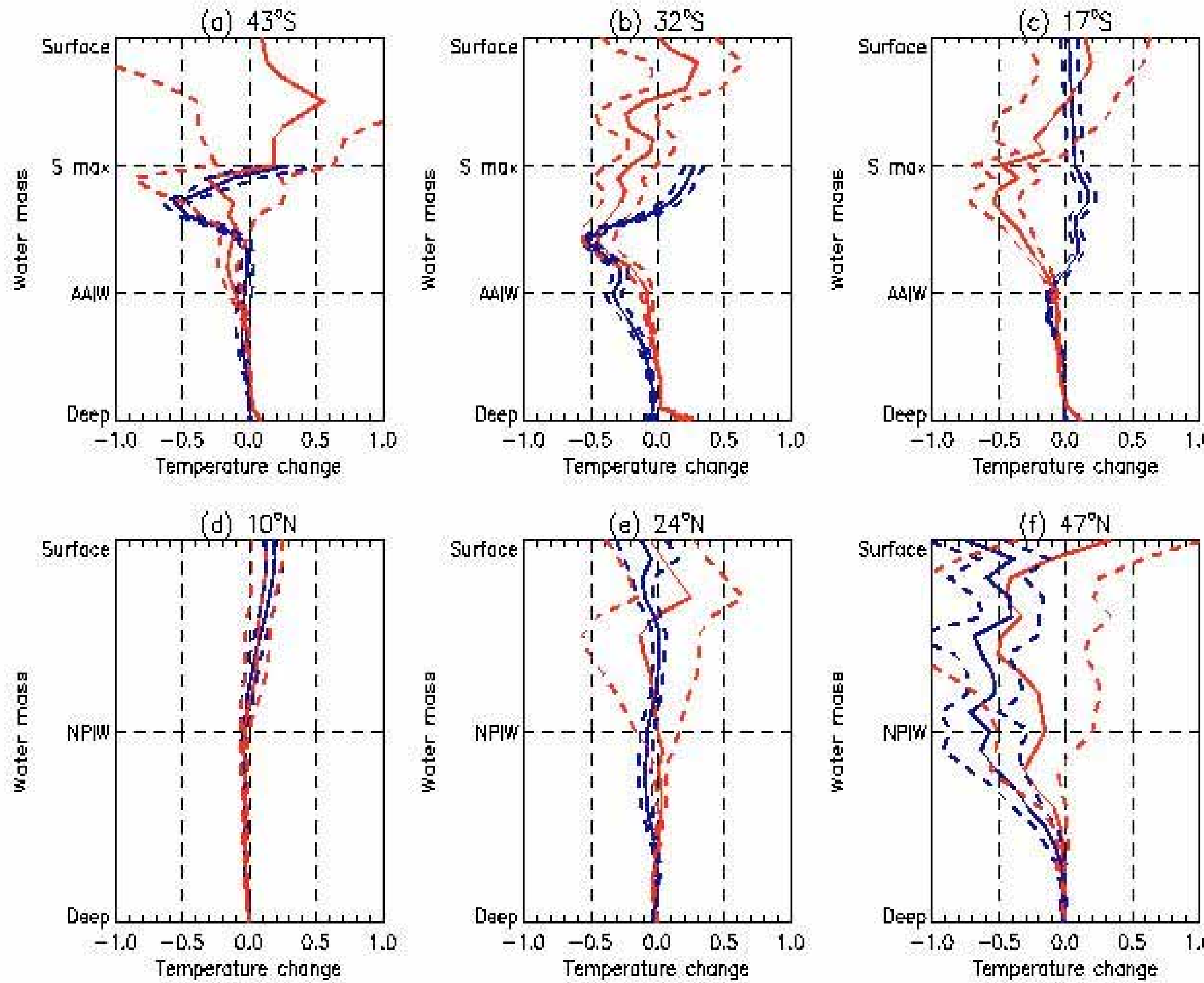


Pure warming

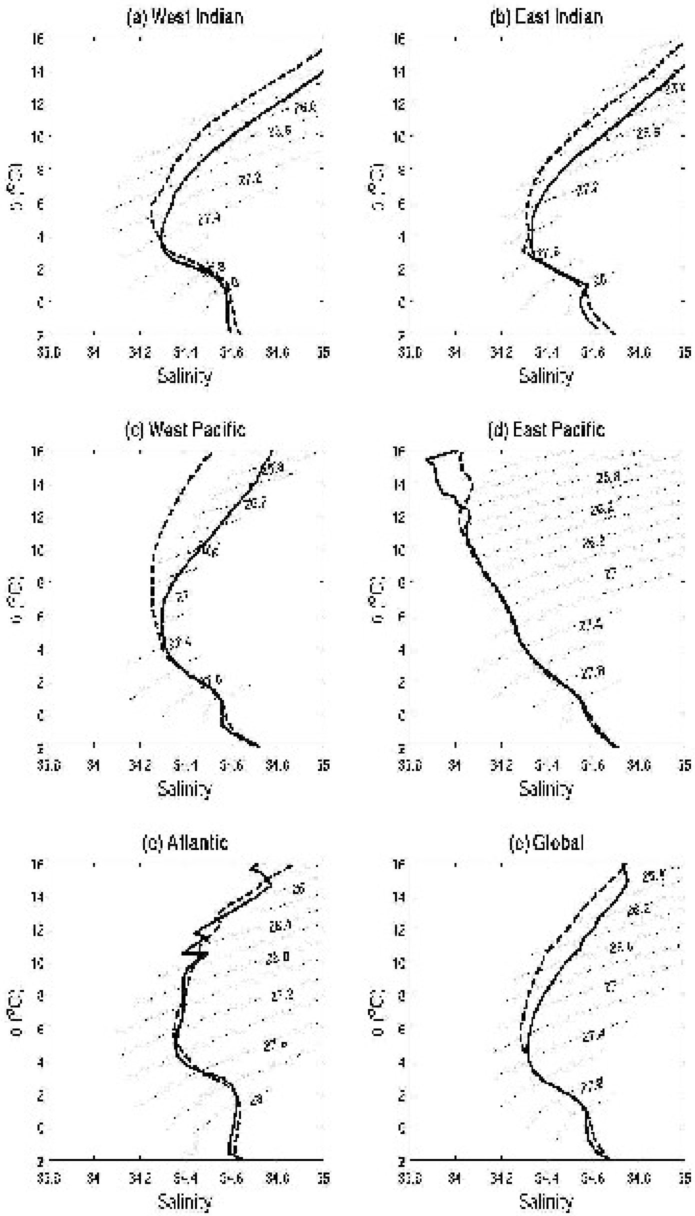


Pure freshening

Comparison with HADC[illegible]



Comparison with CSIRO Mk3 Model



2090’s minus 1950’s

Downes et al, inprep.

ace CRC
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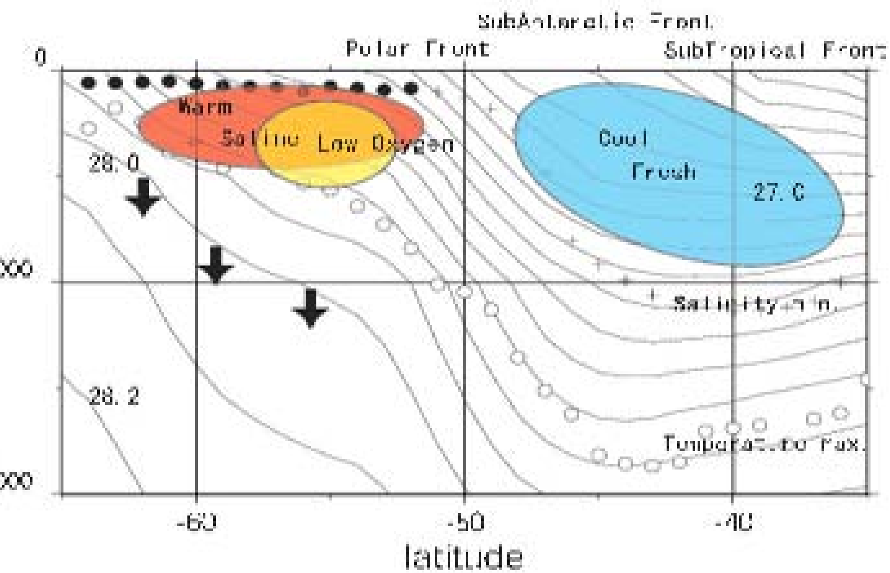
More evidence



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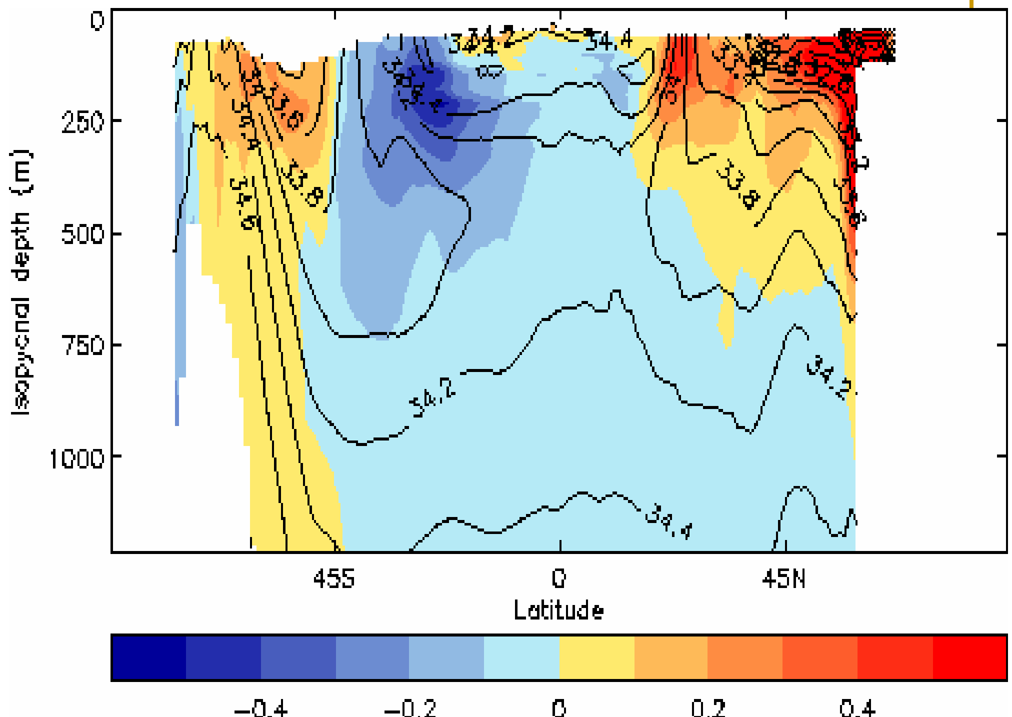
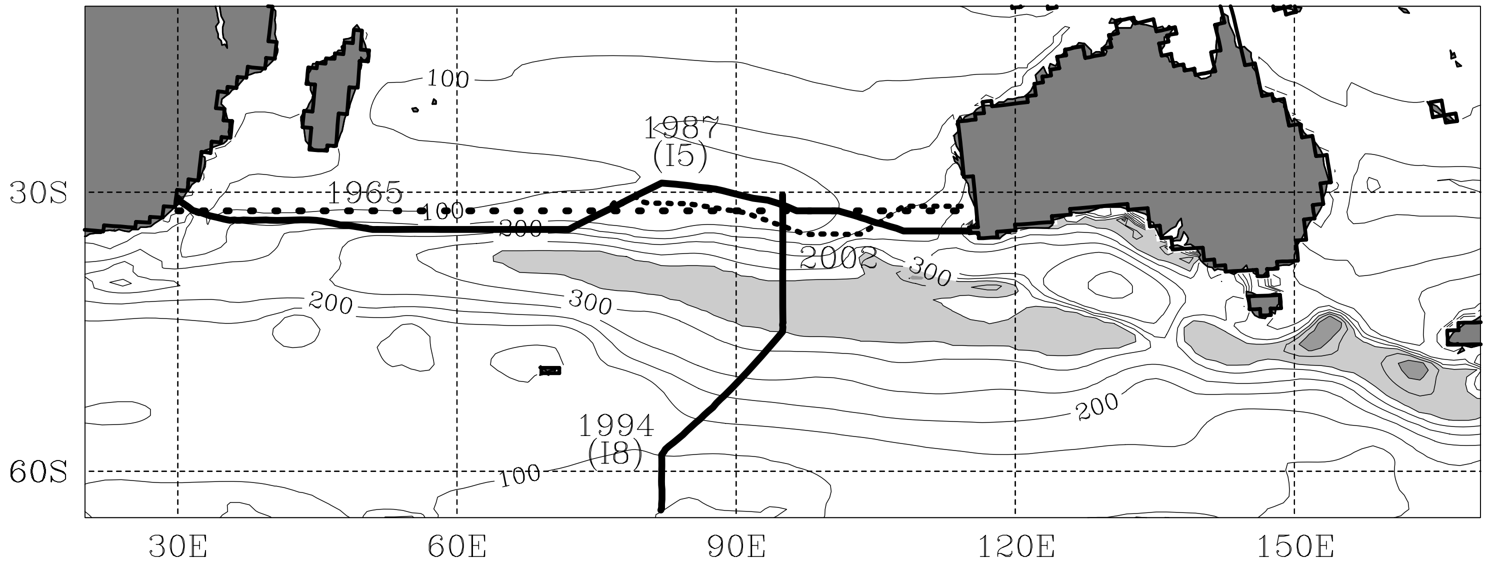


HadCM3 1990's- 1960's

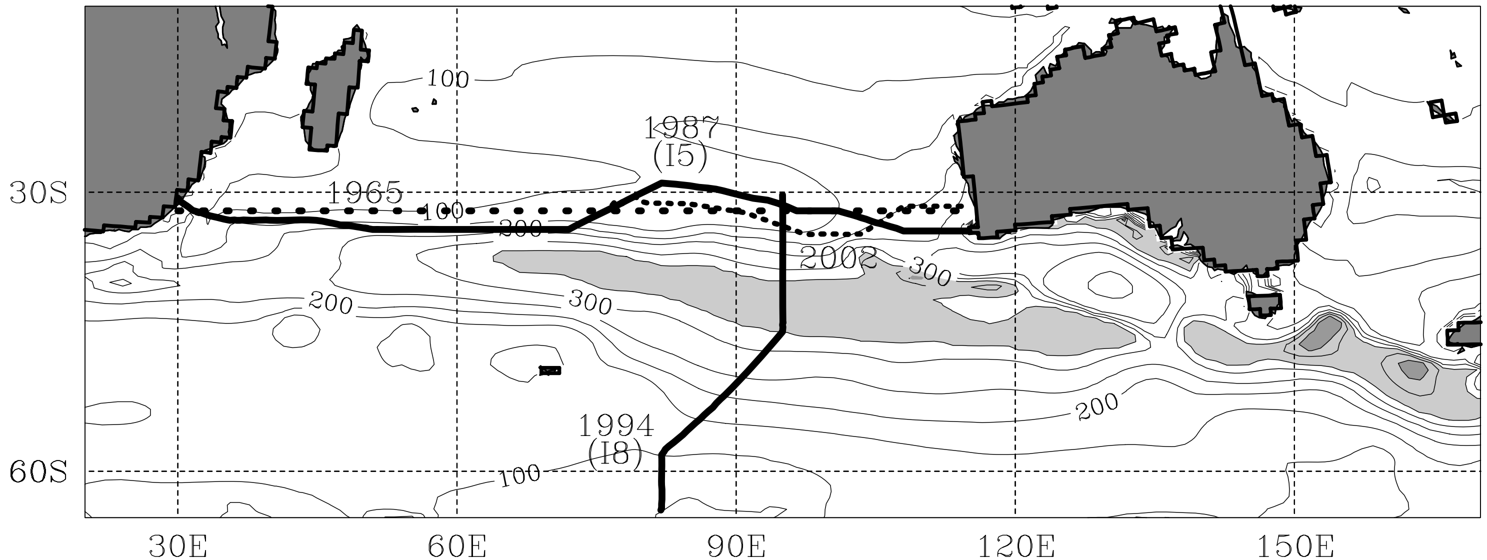
Banks and Bindoff, 2003

Decadal variability



Decadal variability

Mixed layer depths and section lines



•Bryden et al., 2003, McDonagh et al. 2005

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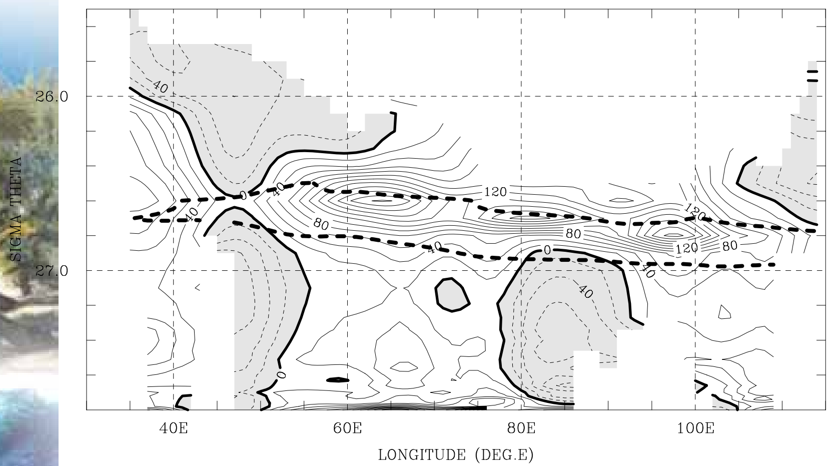
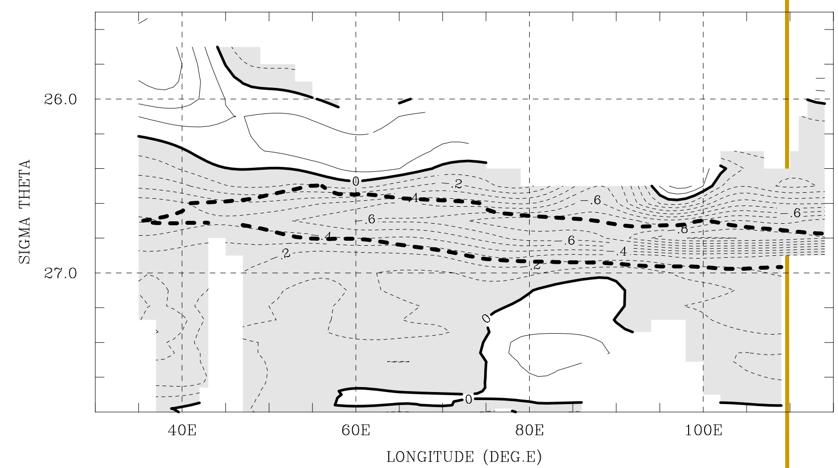
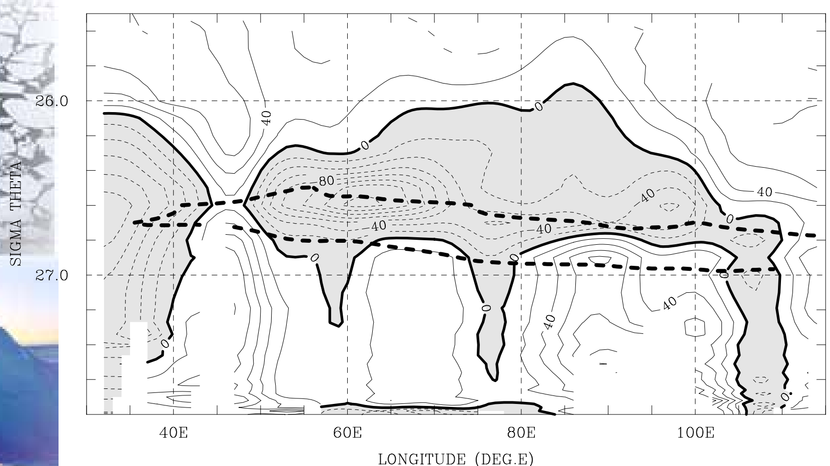
1965-1987 Observed depth



1965-1987 Observed temp.



1987-2002 Observed depth



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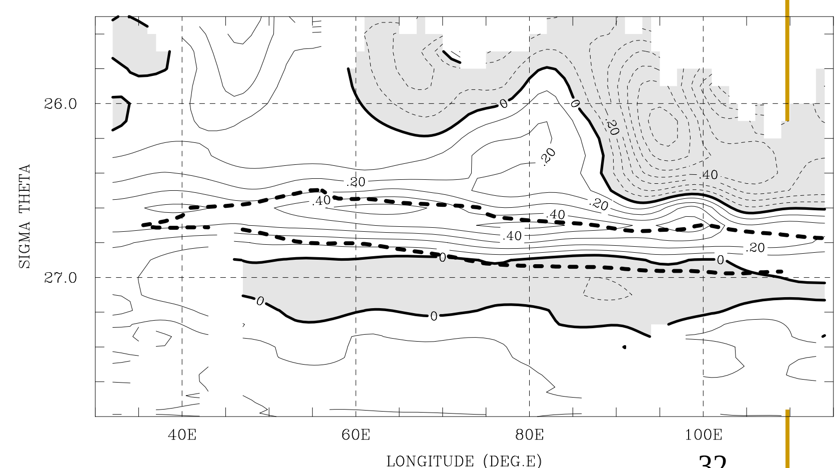
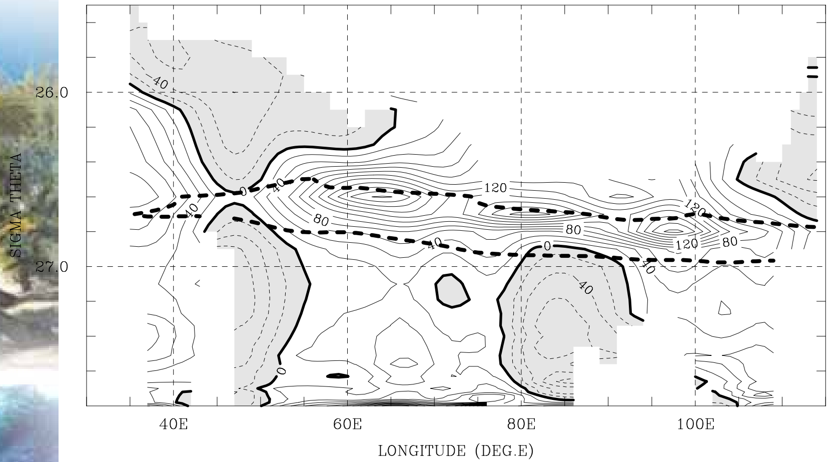


Observations

1965-1987 Observed depth



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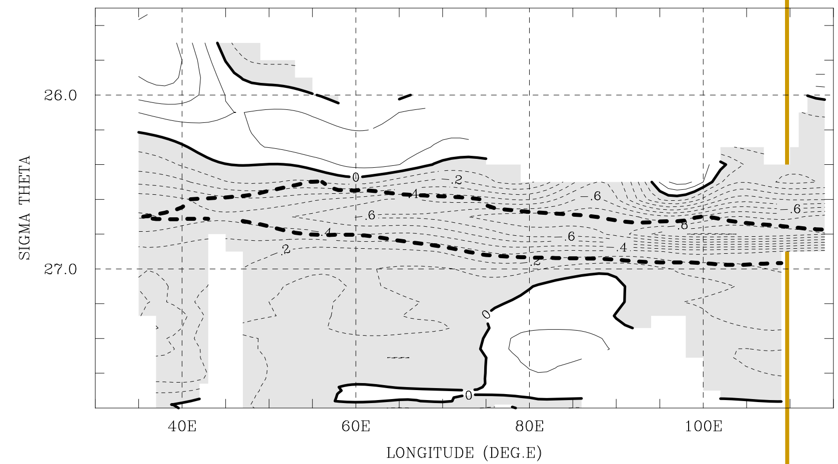

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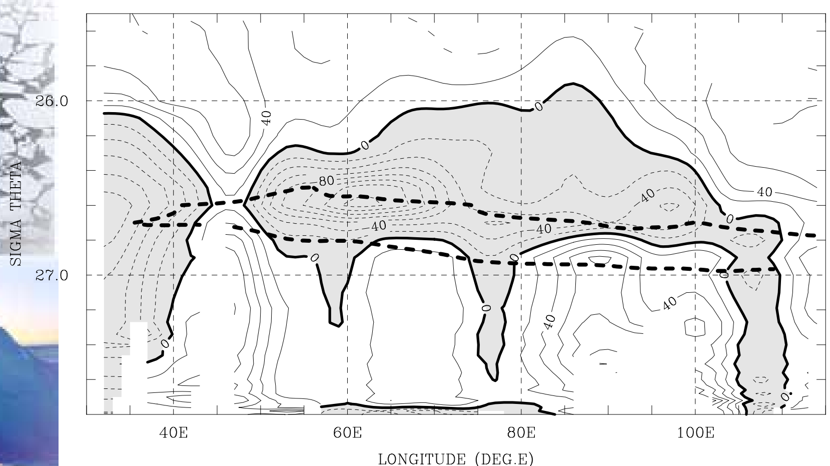

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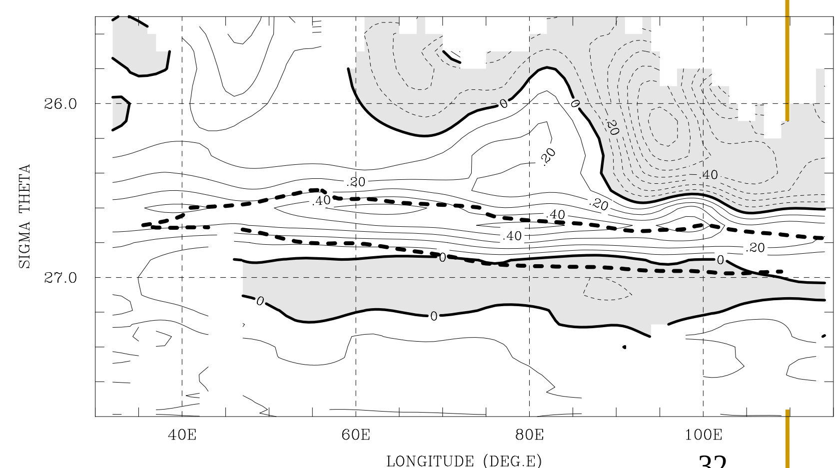

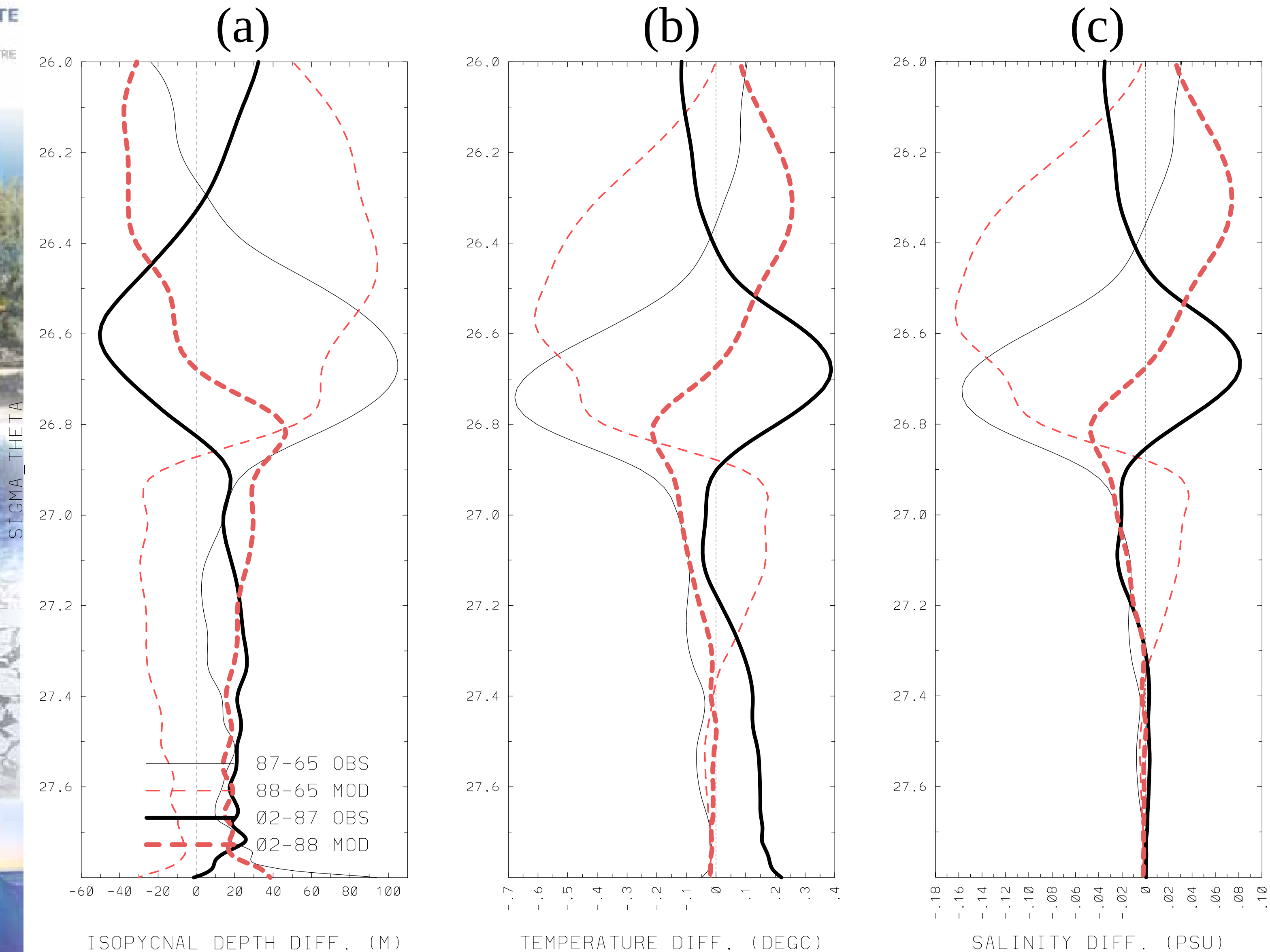

(a)
(b)
(c)
SIGMA_THETA
87-65 OBS
88-65 MOD
Ø2-87 OBS
Ø2-88 MOD
ISOPYCNAL DEPTH DIFF. (M)
TEMPERATURE DIFF. (DEGC)
SALINITY DIFF. (PSU)

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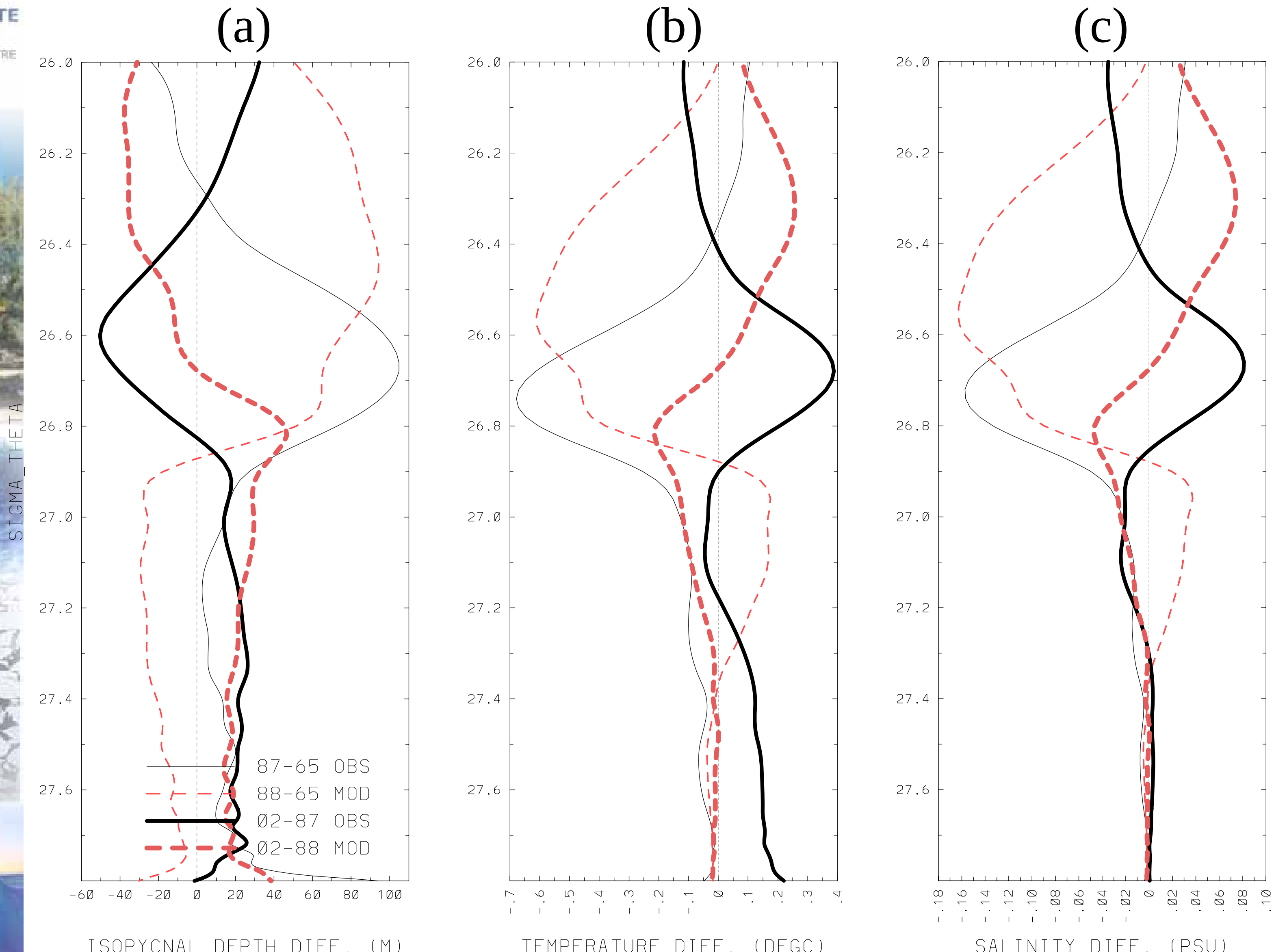
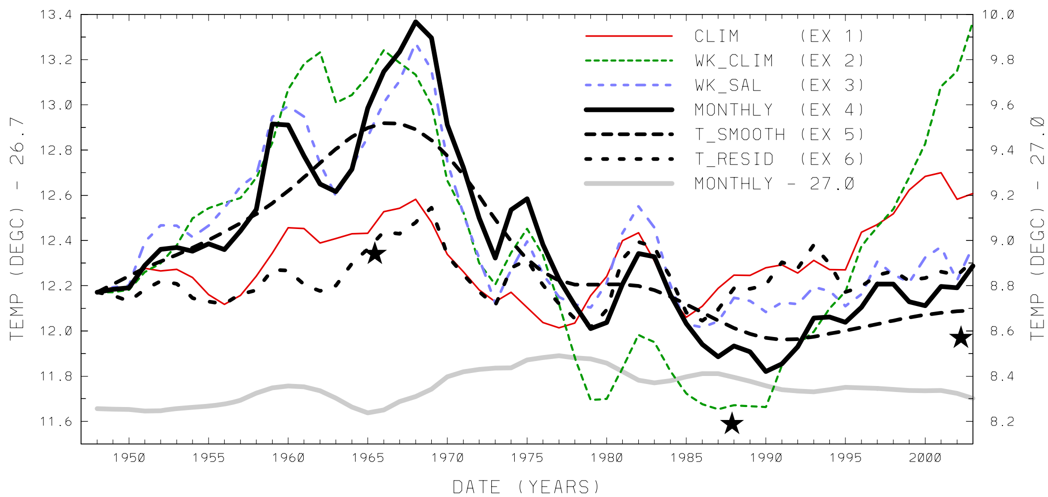
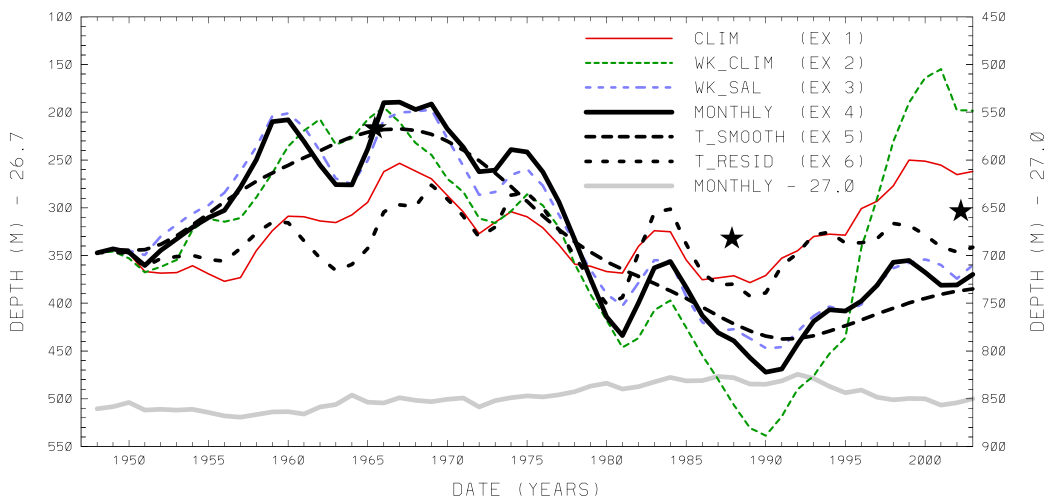
Zonally averaged differences on density surfaces



Temperature

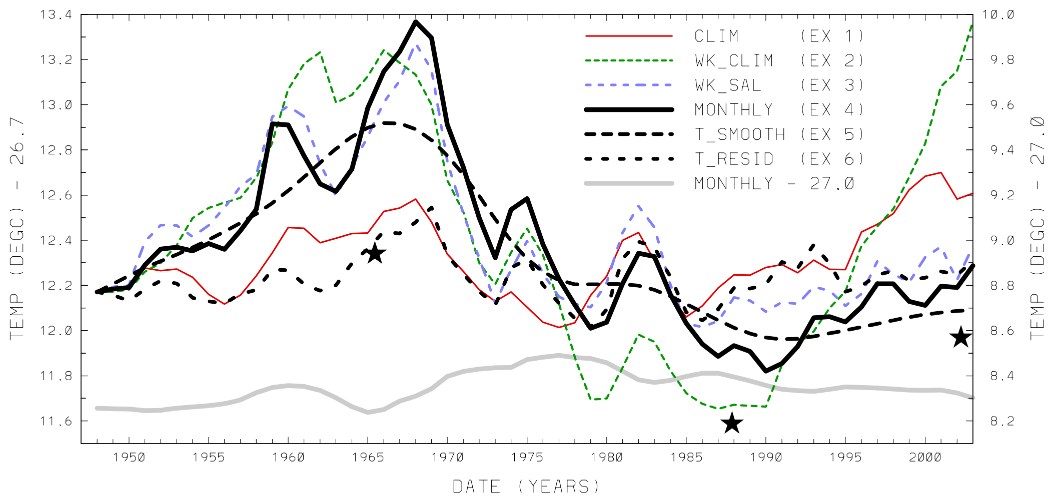


Isopycnal depth



Time series of zonal averages at sigmat=26.7

Temperature



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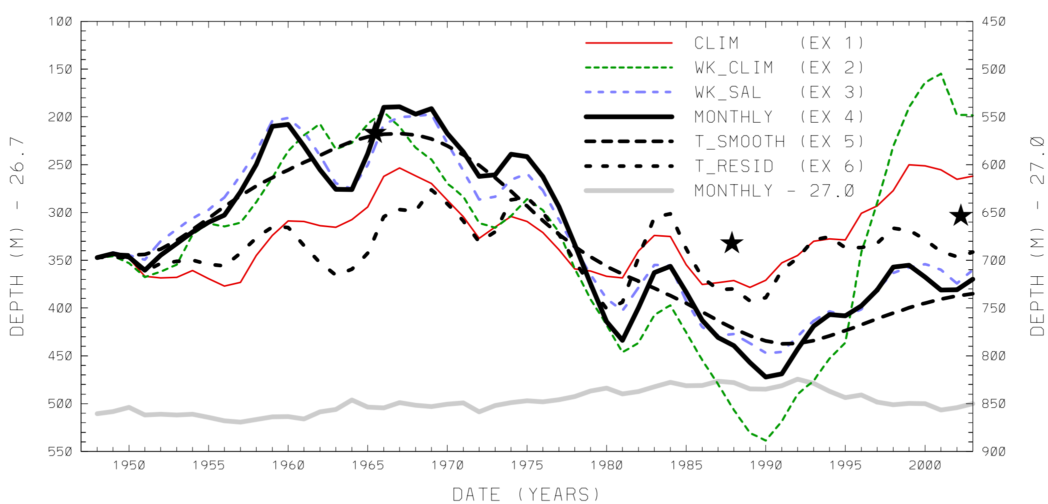
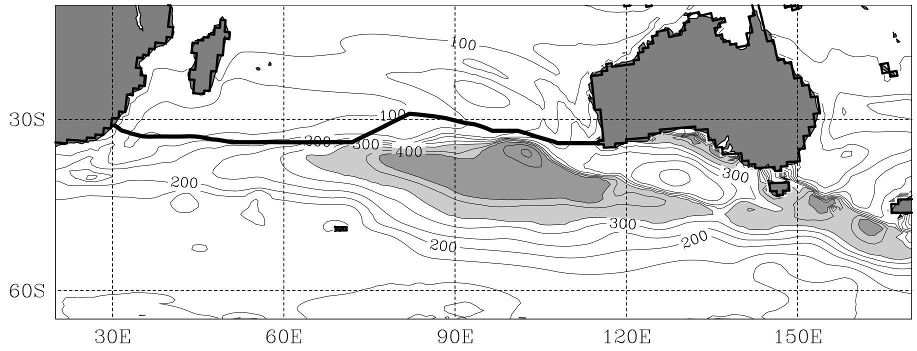
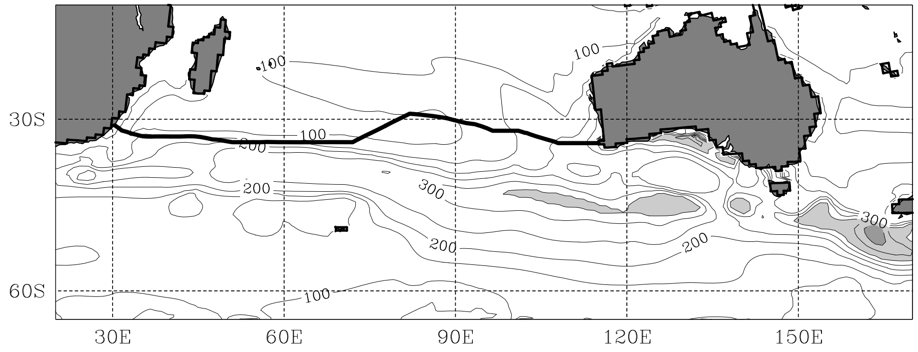


Sep. 1965

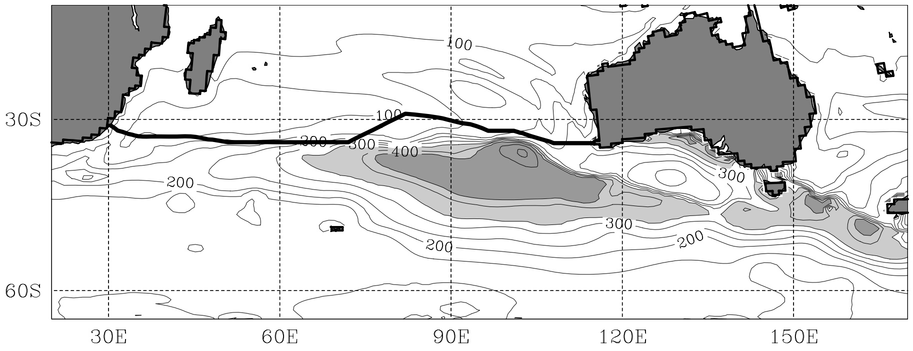


Sep. 1987

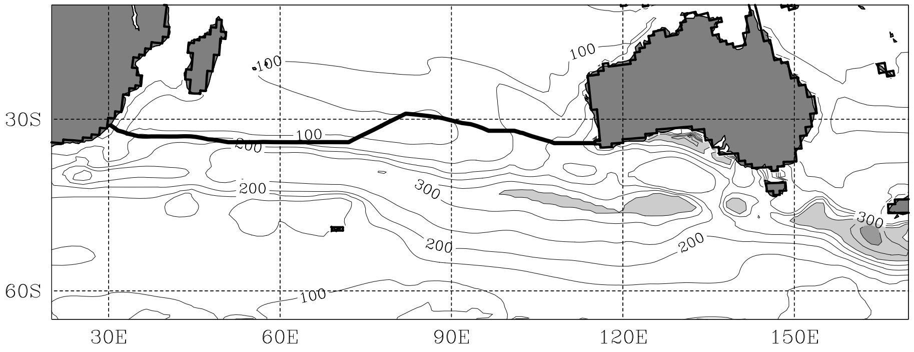


Extremes of modelled mixed layer development

Sep. 1965



Sep. 1987



Message: the water mass variations related

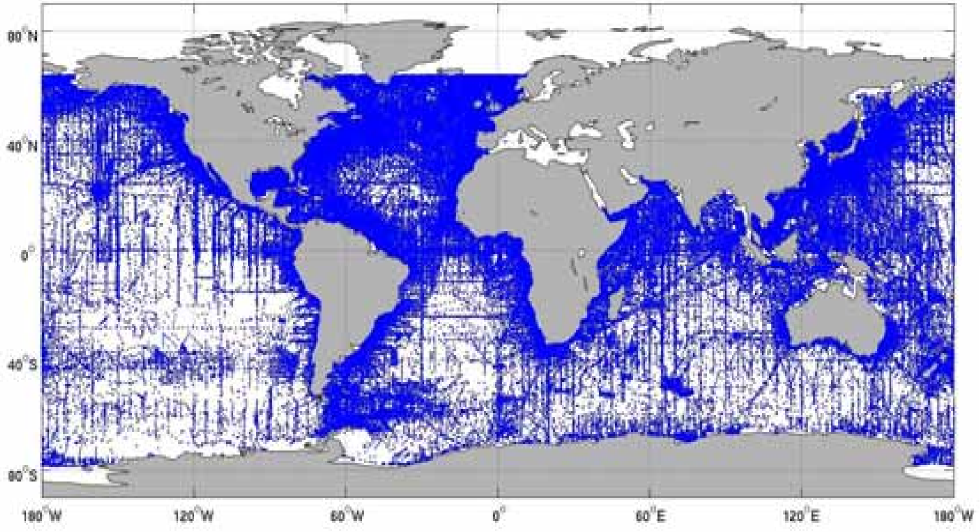
Mixed layer thickness changes

Murray et al. 2007

Climate Differences

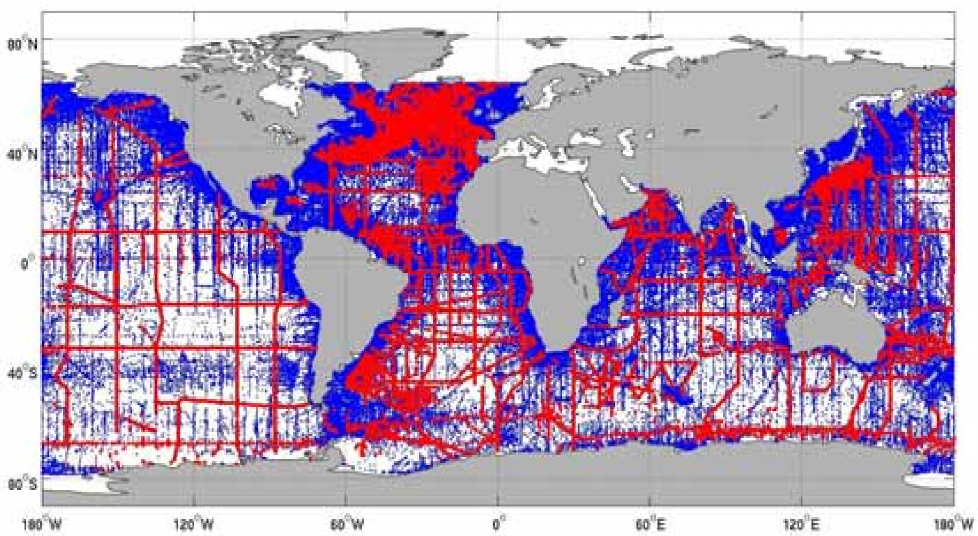
Mawson Harbour, Antarctica

Data and method



1. Convert Hydrobase2 from pressure to density levels
2. Optimally interpolate 800,000 pre-1988 profiles to 40,000 post-1988 locations

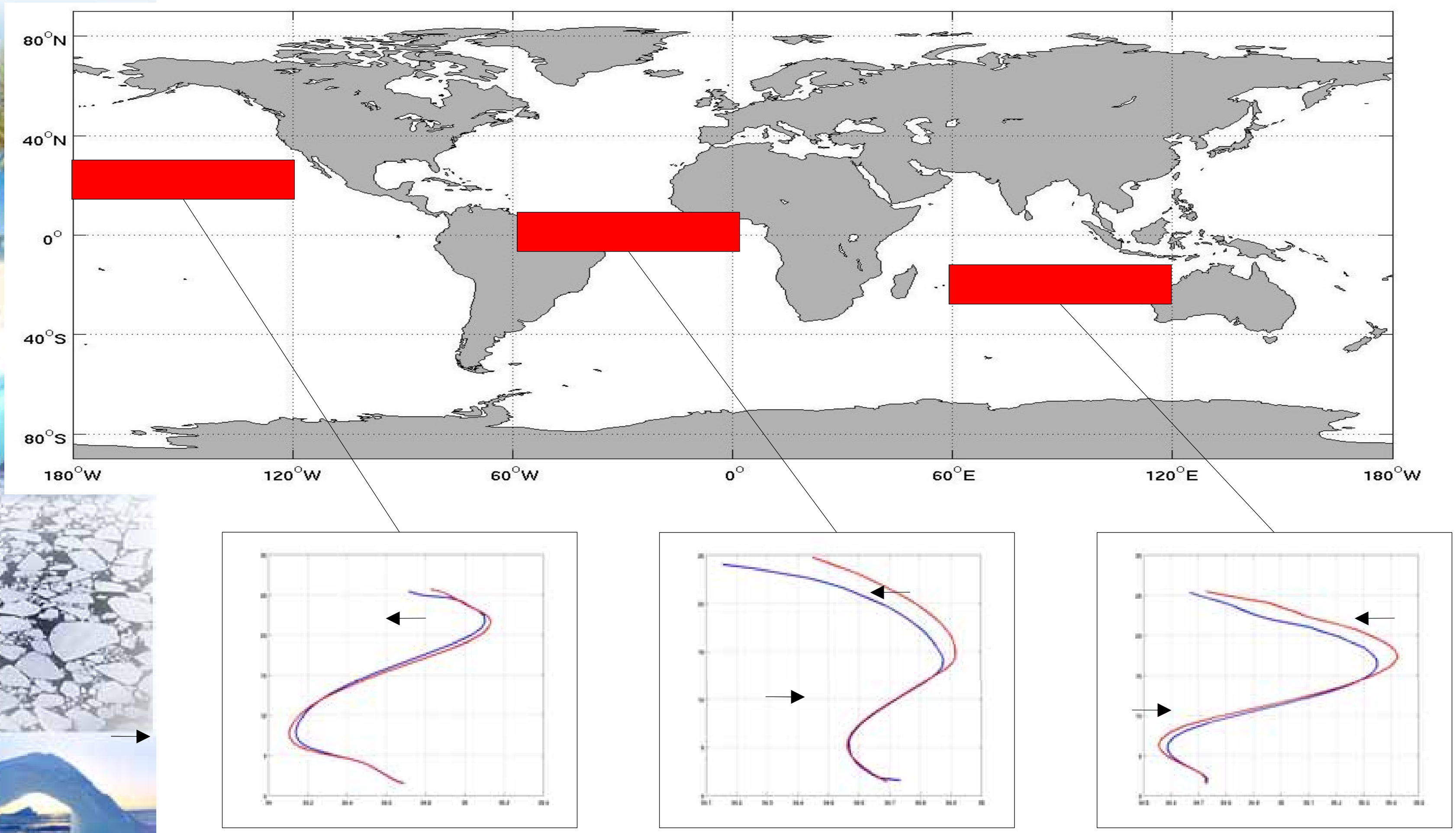
Data and method



1. **Convert Hydrobase2 from pressure to density levels**
2. **Optimally interpolate 800,000 pre-1988 profiles to 40,000 post-1988 locations**
3. **Directly compare 1970 with the early 1990s using a 'snapshot' approach**

Helm et al., inprep

Regional T-S changes



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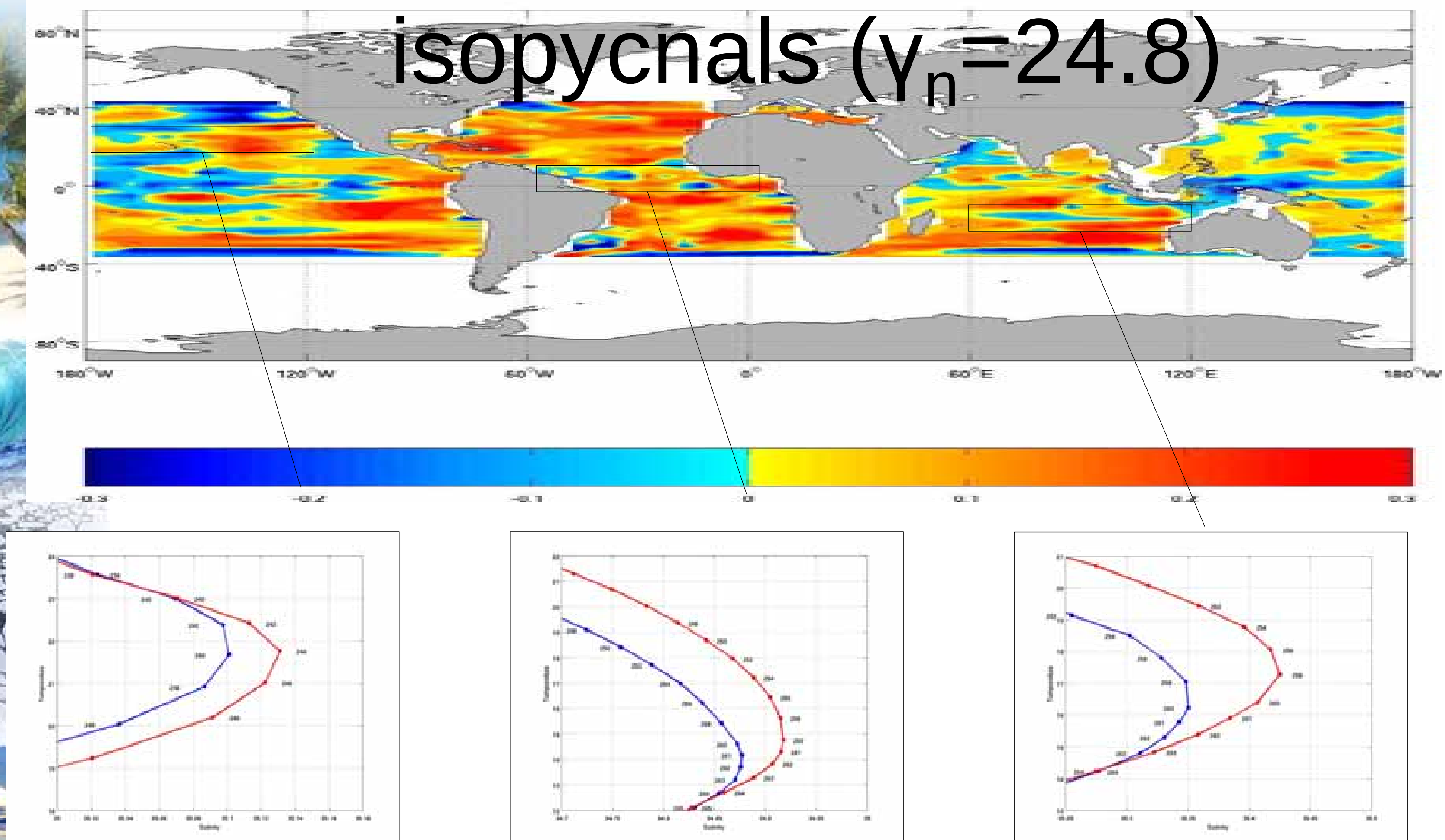
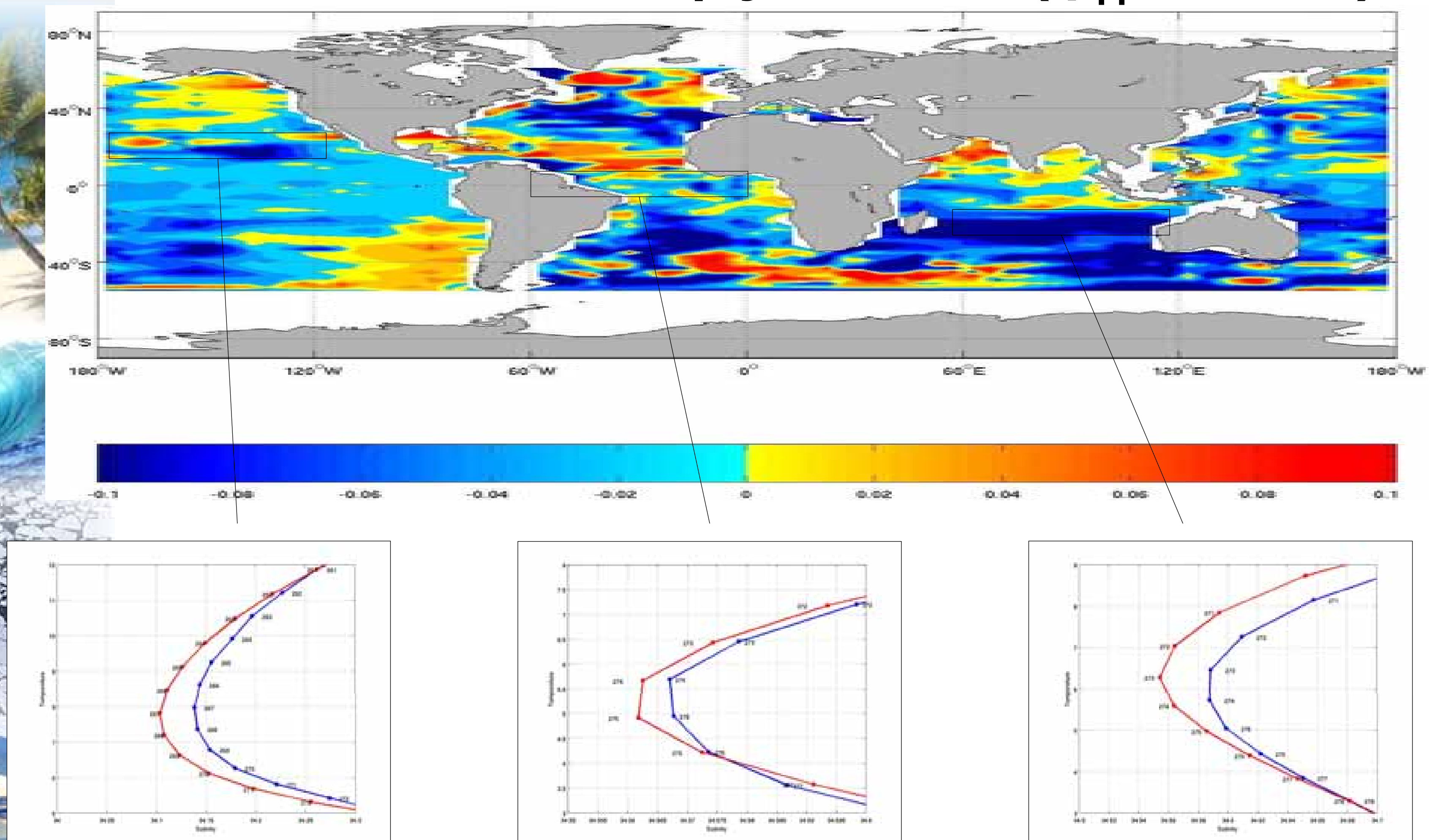
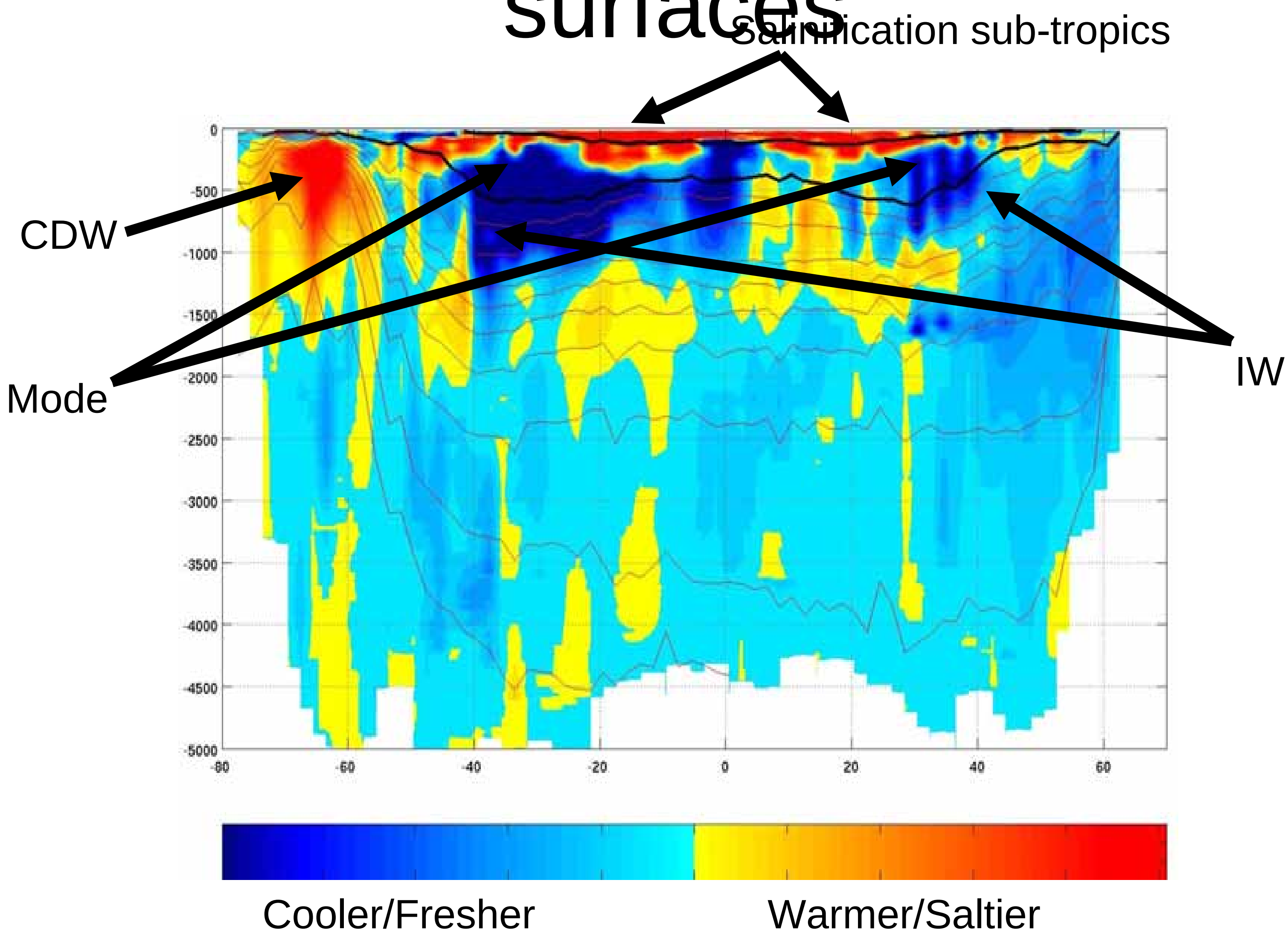
Salinity increases in thermocline water on isopycnals (γ_n=24.8)



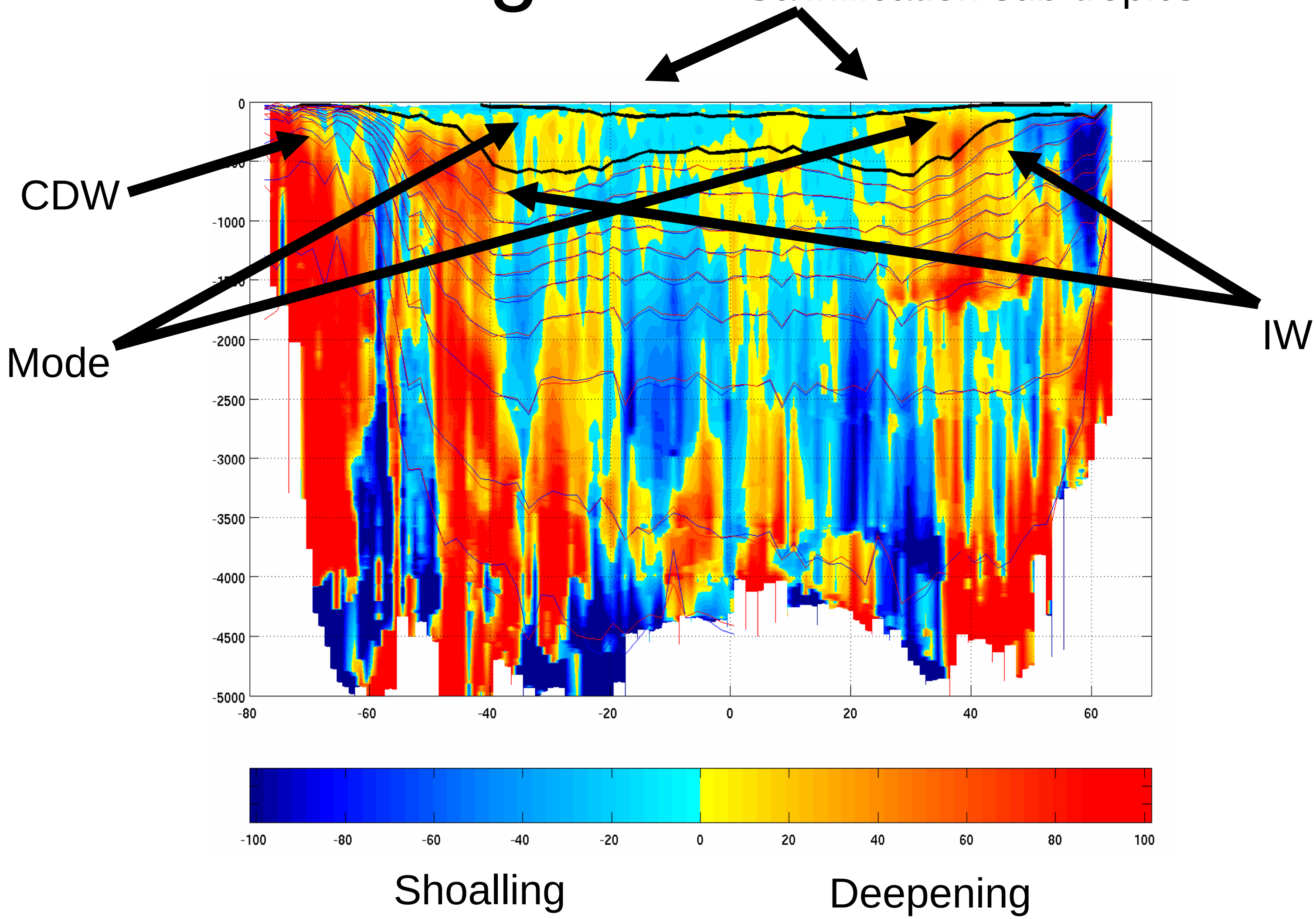
Freshening of intermediate water on isopycnals (γ_n=27.0)



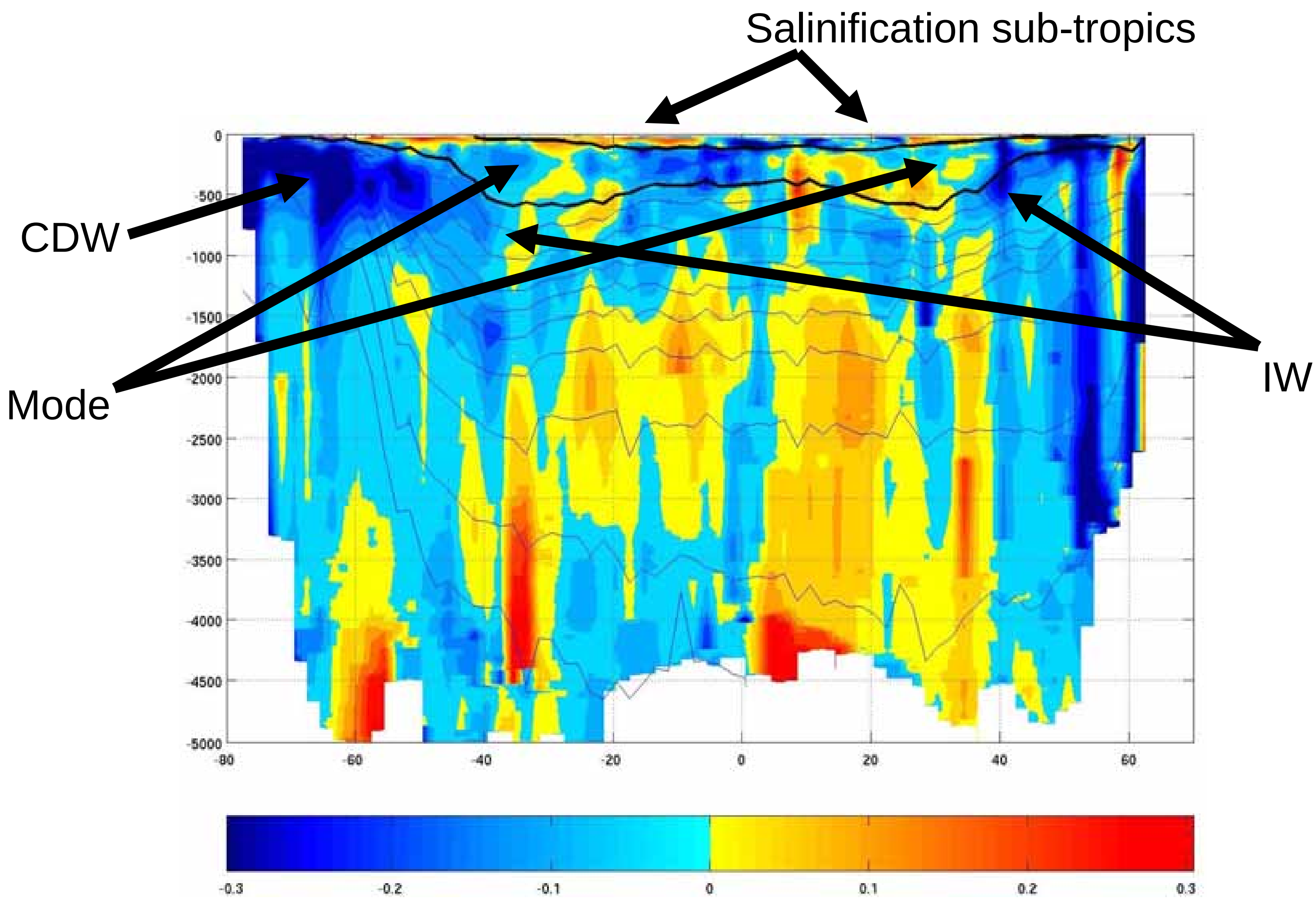
Zonal changes on density surfaces



Deeping of isopynals in mid to high latitudes



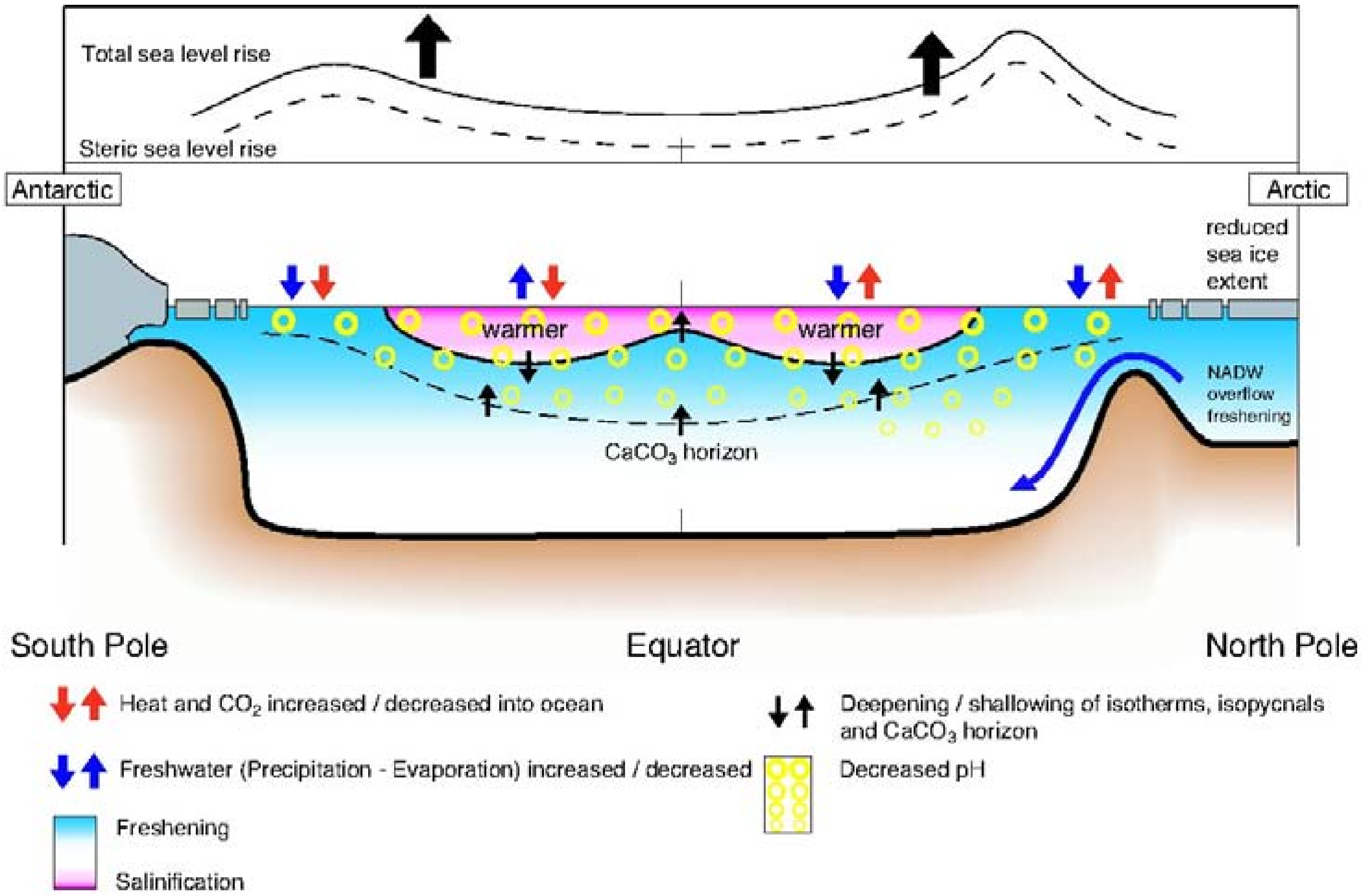
Global oxygen decreases



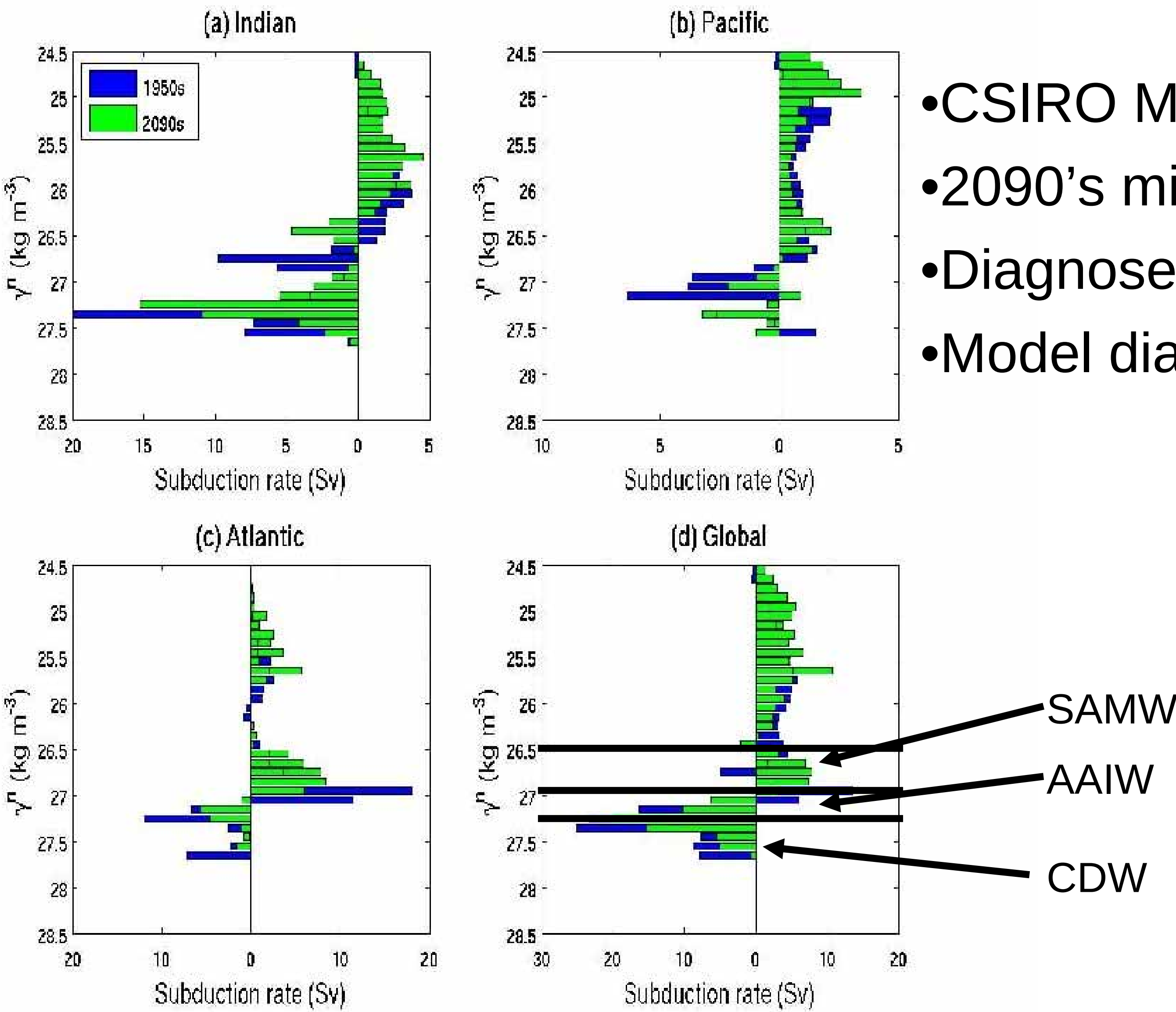
Key findings 1970's to 1990's

- On neutral density surfaces:
  - Globally coherent temperature/salinity changes
  - Warming/increasing salinity of upper thermocline waters
  - Cooling/freshening of mode and intermediate waters
  - Oxygen decrease in upper thermocline, mode, intermediate waters and CDW
  - Largest changes occurred in the

Summary

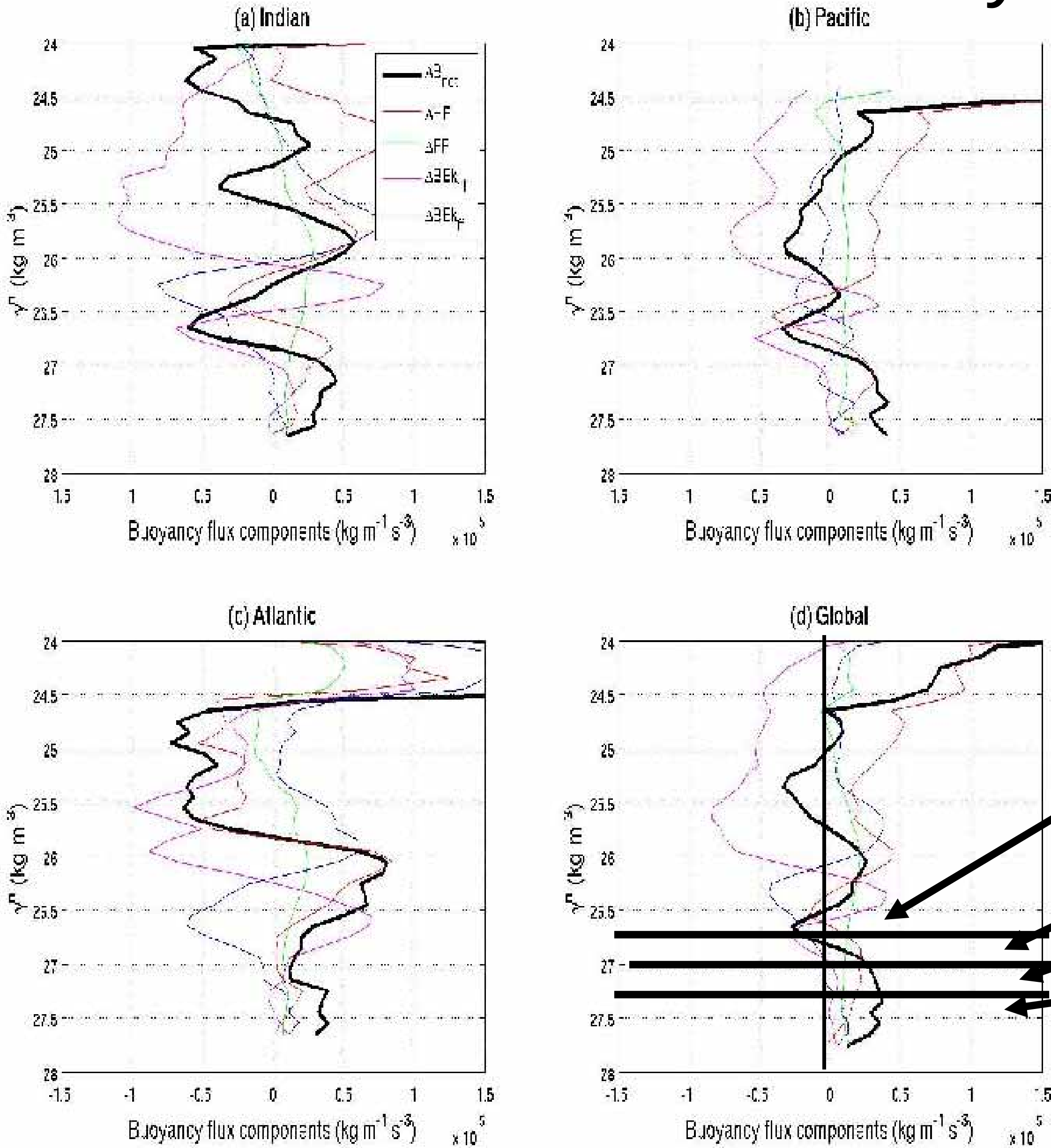

Total sea level rise
Steric sea level rise
Antarctic
Arctic
reduced sea ice extent
warmer
warmer
NADW overflow freshening
$CaCO_3$ horizon
South Pole
Equator
North Pole
Heat and CO_2 increased / decreased into ocean
Freshwater (Precipitation - Evaporation) increased / decreased
Freshening
Salinification
Deepening / shallowing of isotherms, isopycnals and $CaCO_3$ horizon
Decreased pH

Subduction Changes



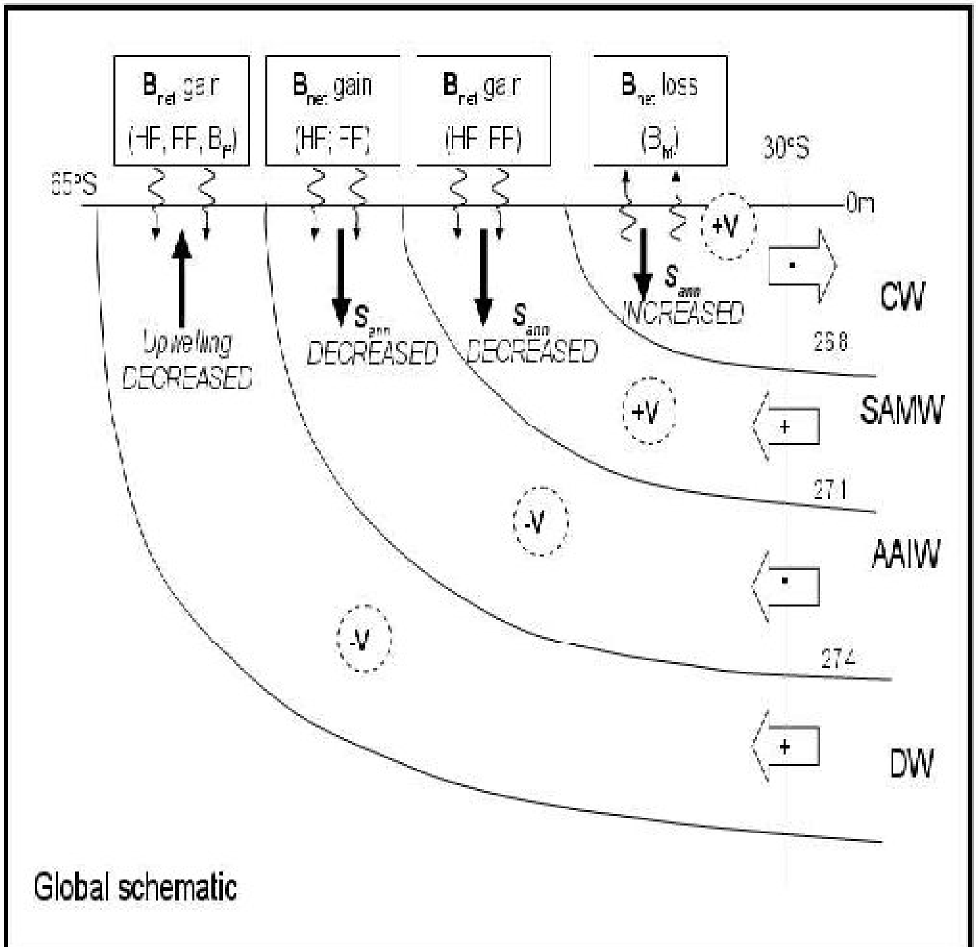
- CSIRO Mk3
- 2090's minus 1950's
- Diagnosed using MNW
- Model diagnostics

Buoyancy Changes



- CSIRO Mk3
- 2090's minus 1950's
- Diagnosed using MNW
- Model diagnostics

Schematic of changes…



CSIRO MK3 model

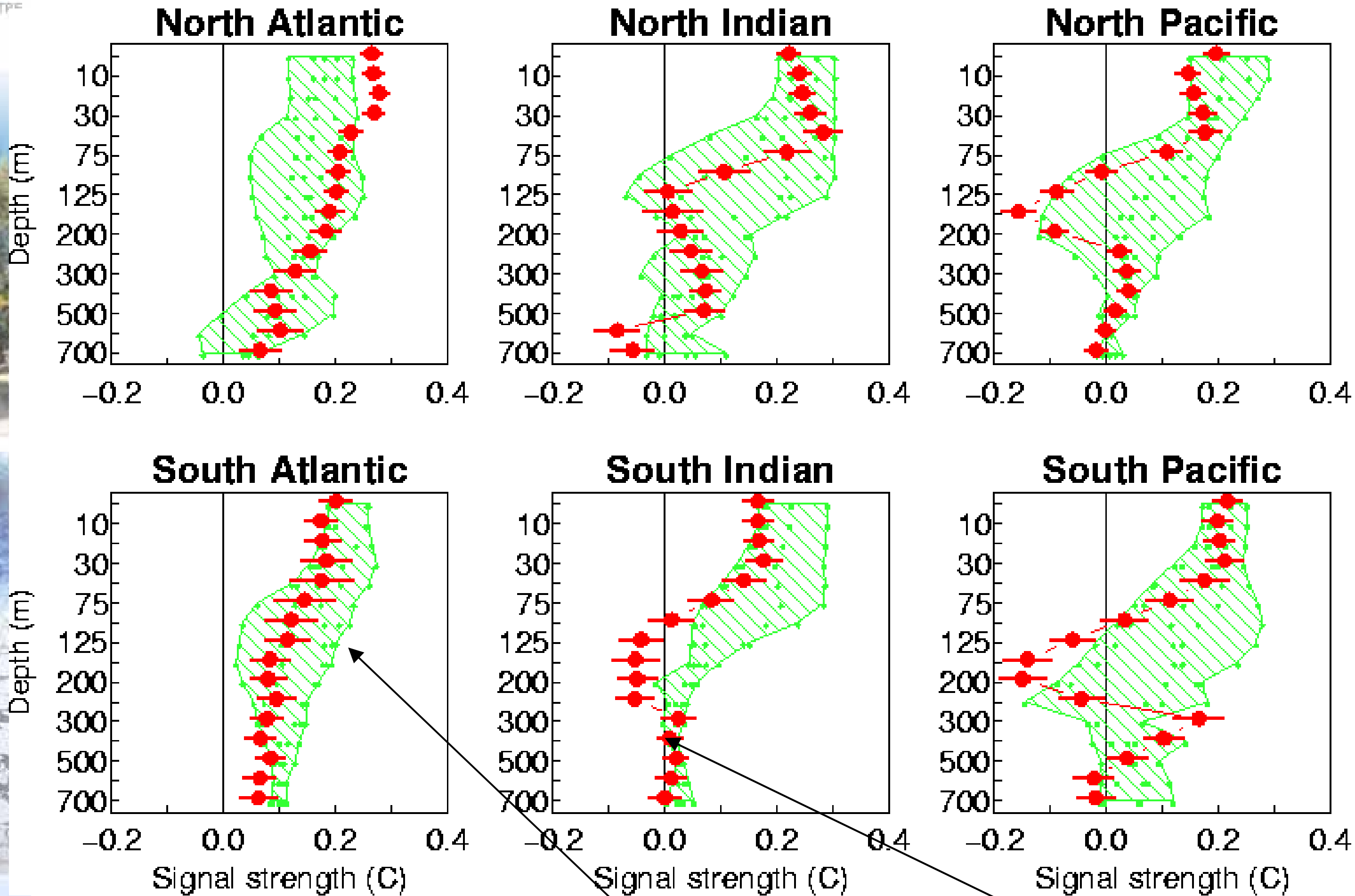
2090's to 1950's

Process that matter:

- CW Increased subduction,decreased buoyancy
- SAMW Decreased subduction, Decreased HF and FF
- AAIW Decreased subduction, HF and FF
- CDW Decreased entrainment, increased HF,FF

Detection

Parallel Climate Model



ACC Simulations

Observations

Barnett et al. Science 2005

Implications of Climate Differences (1)

- **Patterns are global, coherent, consistent with earlier work.**
- **Salinity changes suggest**
  - **increased “evapouration” in sub-tropics,**
  - **increased “precipitation” at high latitudes,**
  - **and increased strength in hydrological cycle.**
- **CDW warmed and lower in oxygen**
  - **Lower renewal rates, decreased ventilation (even though winds are stronger)**

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Climate Differences (Conclusions) (2)

- **AABW now fresher (Aoki et al, 2005)**
- **Observations are qualitatively same as climate change mode in CSIRO Mk3 model (and HadCM3)**
- **Natural variability, aliasing cannot be ignored**
  - Heat content in 2004 and 2005

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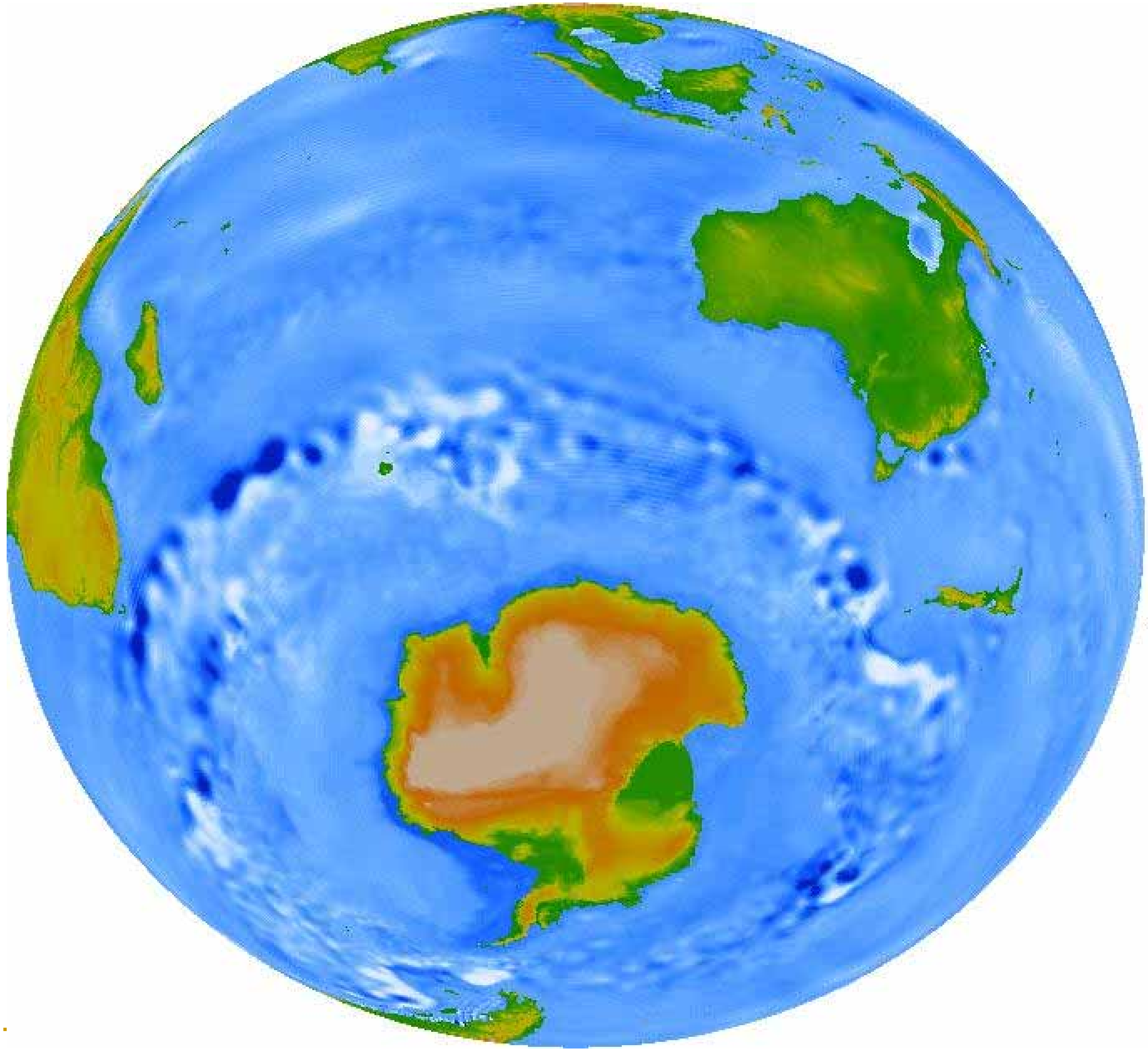
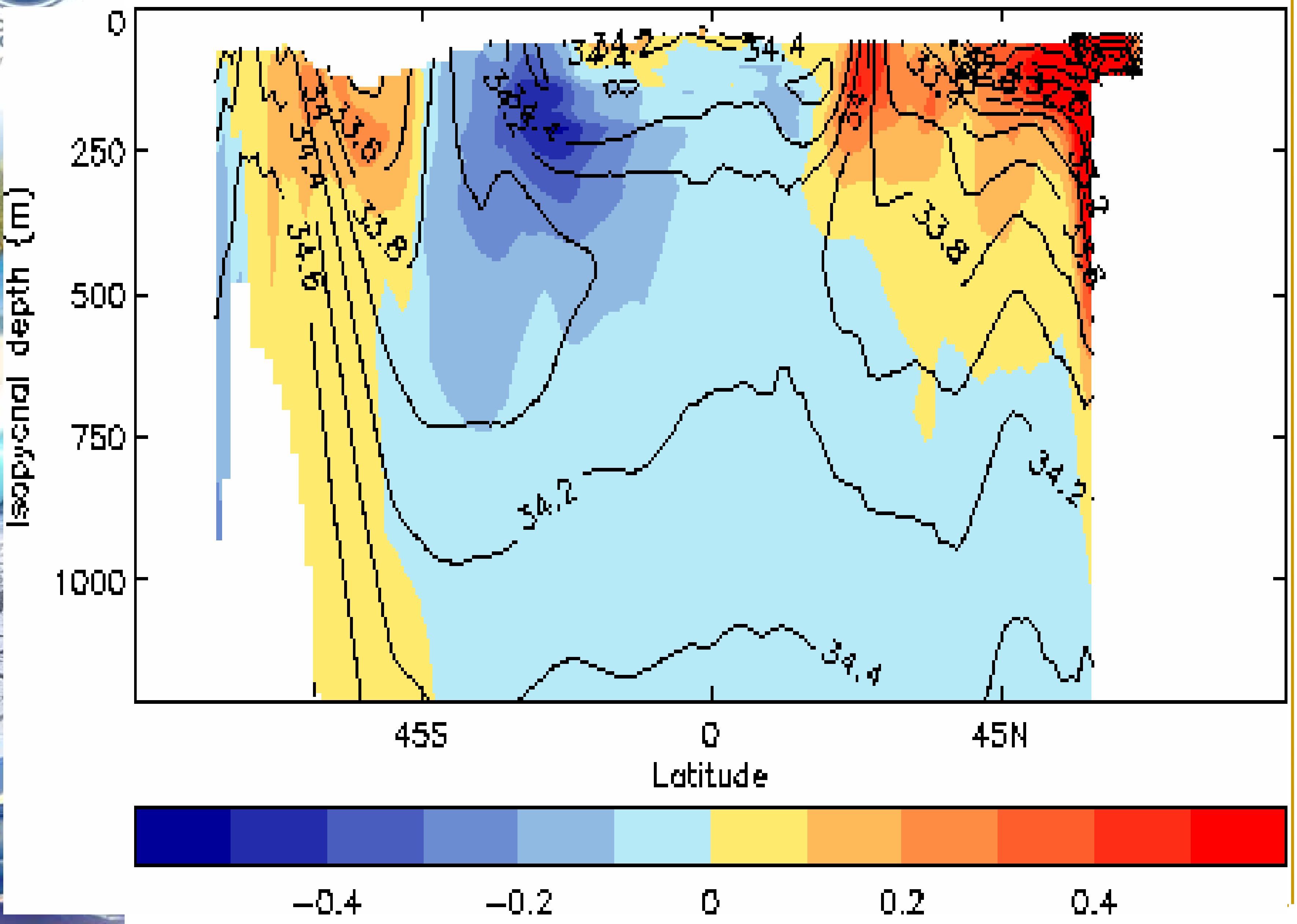
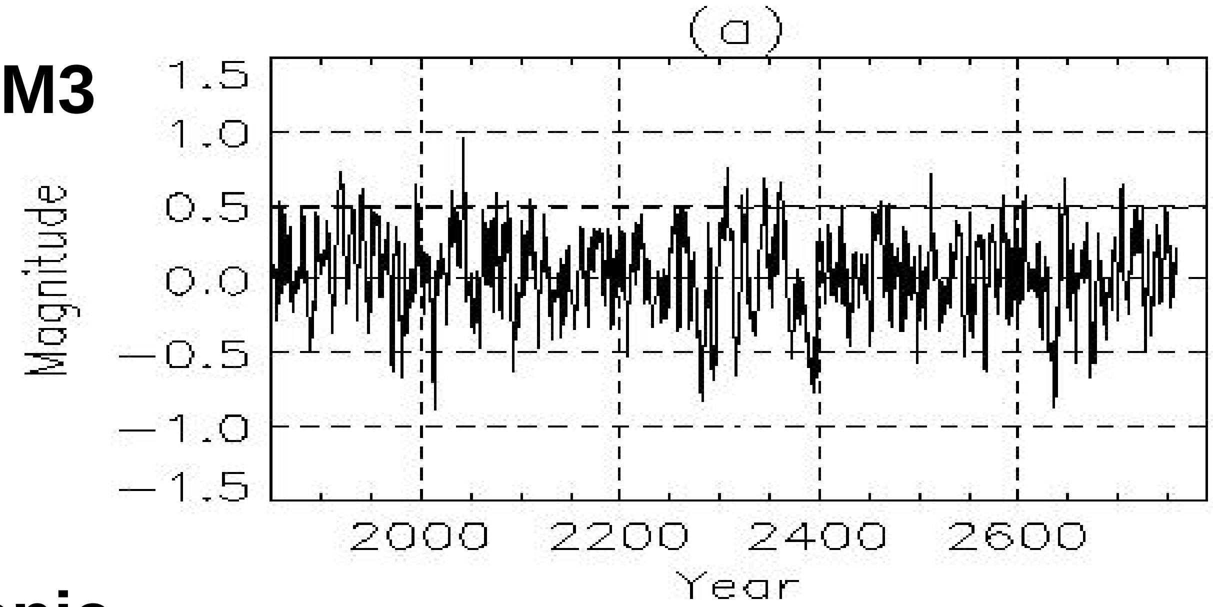
Thanks..



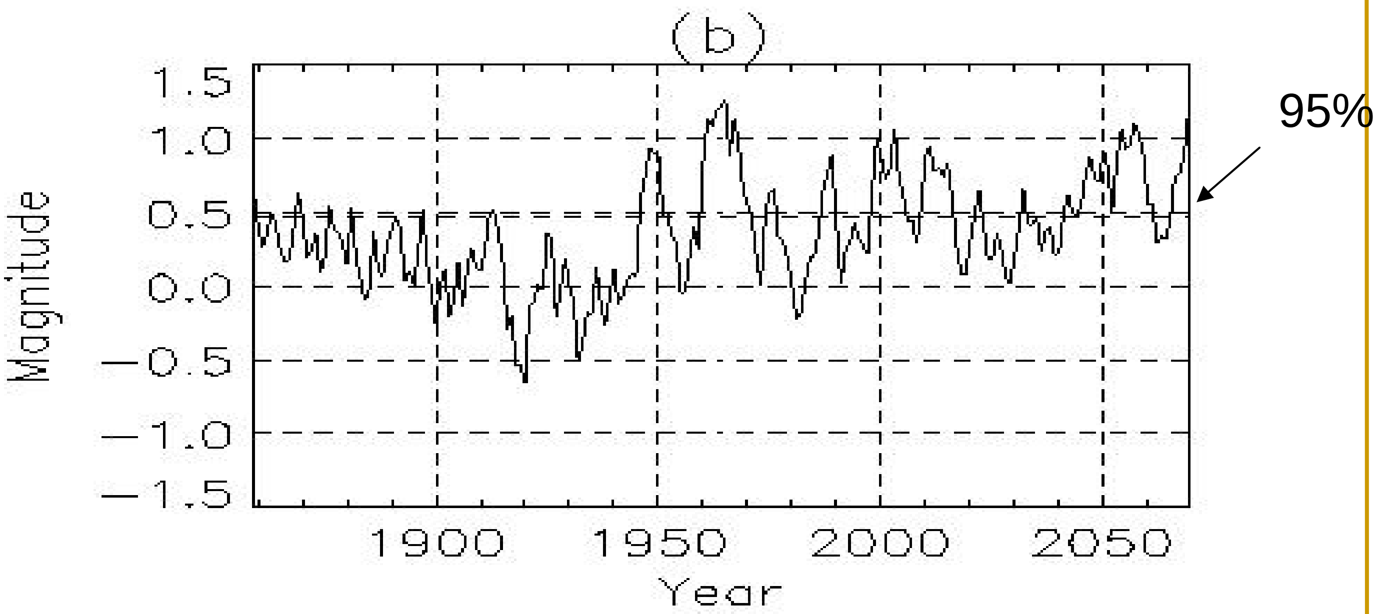
HadCM3 1990's- 1960's



Control HadCM3



Anthropogenic simulation HadCM3



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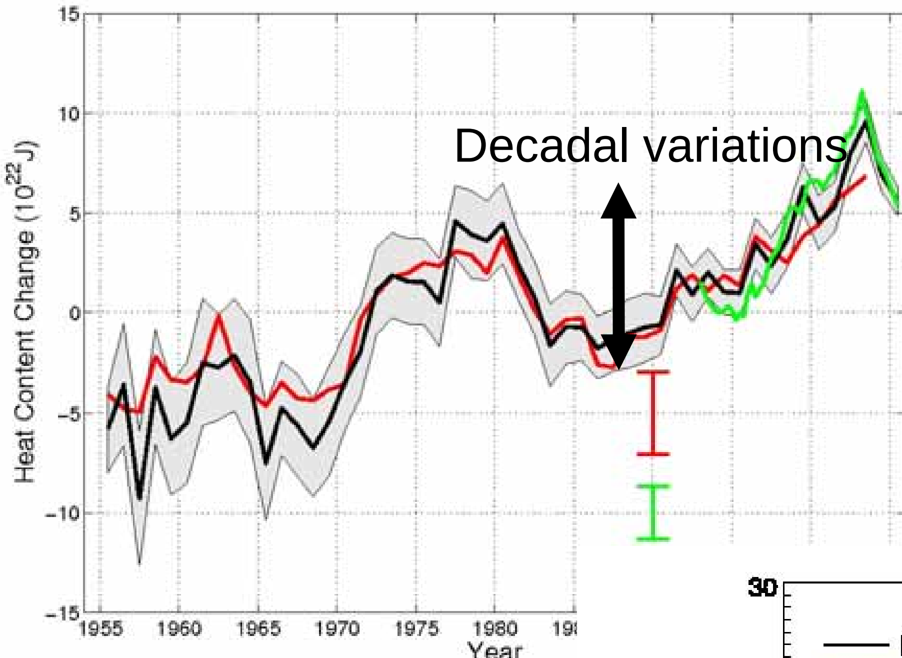
Science Questions

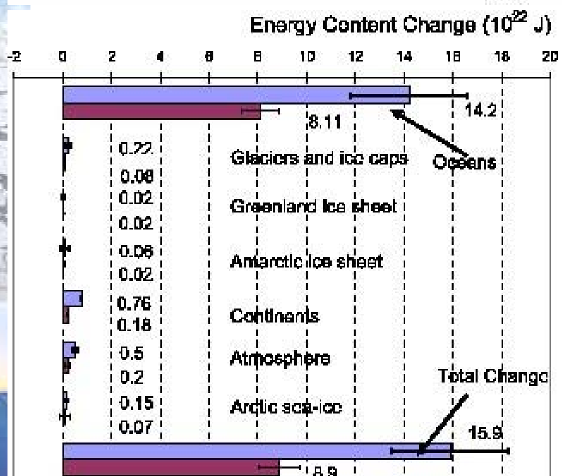
- Global heat content of the oceans and its variations
- Global observations of oxygen change in the oceans
- Global changes in sea-level and its spatial variations
- Global observations of the cryosphere and decadal variations

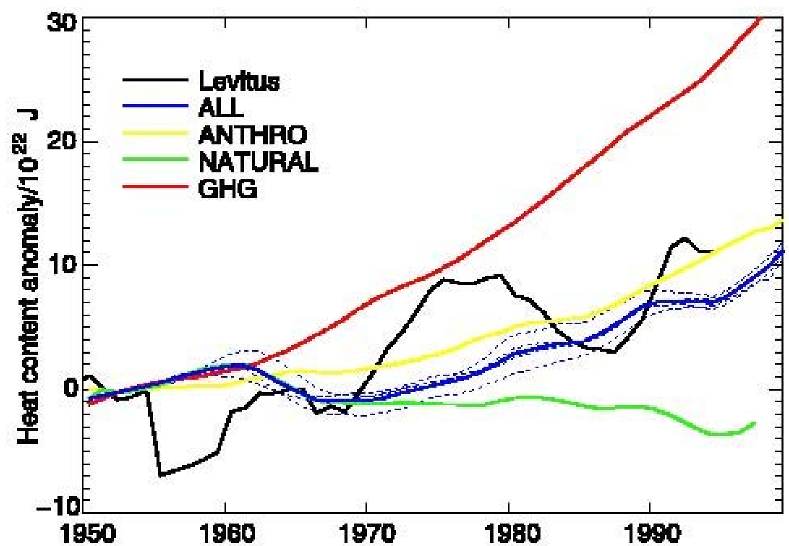
Heat Content



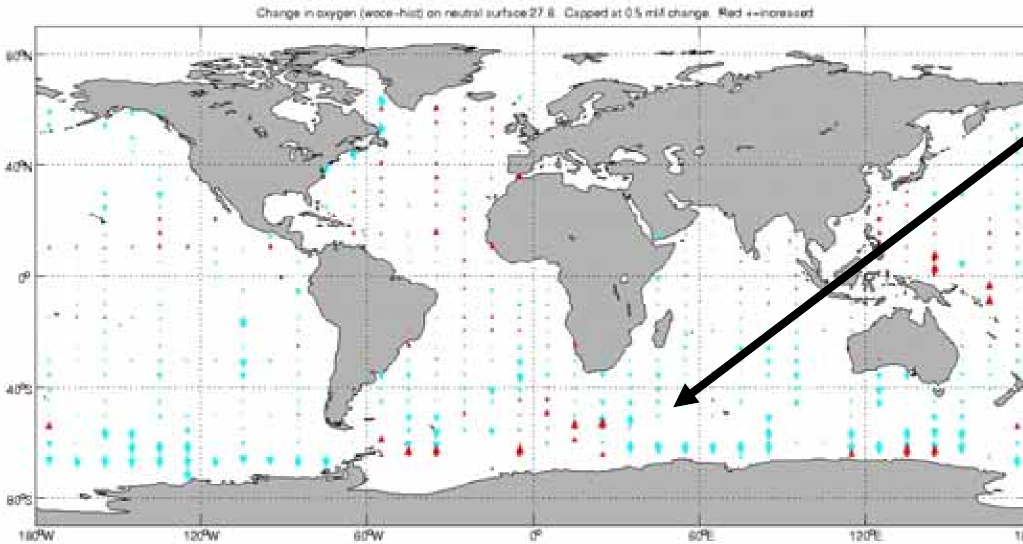
Question: why do models not simulate as much variability as seen in observations.

Gregory *et al* 2004



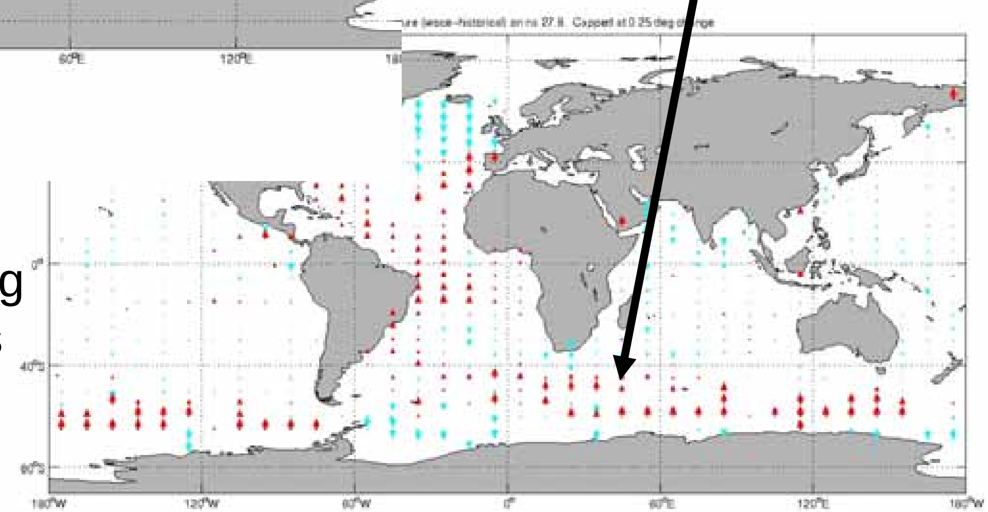


Oxygen Content Change



Oxygen change,
WOCE- historical, 27.8 ns

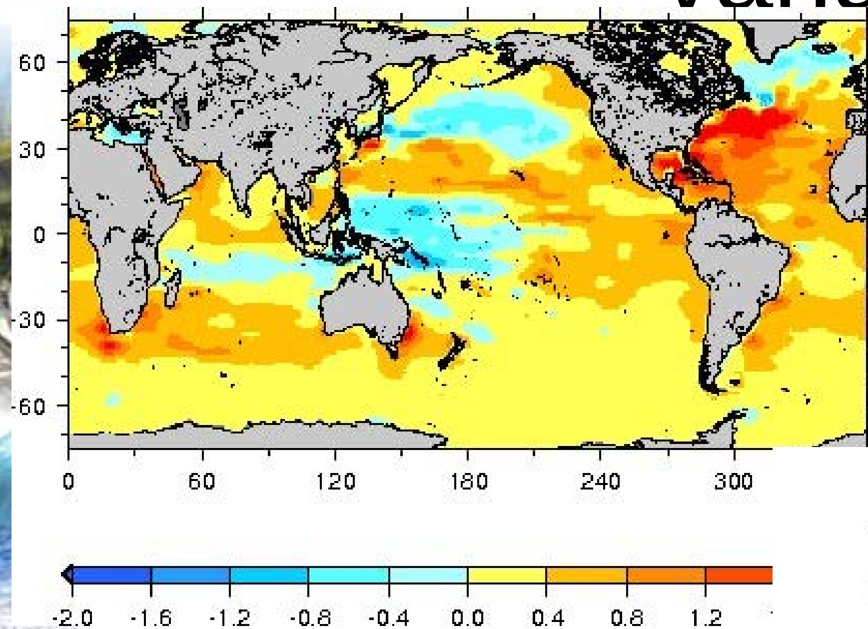
Temperature change 27.8ns



Oxygen content changing on global scales- implies ocean processes are Important, is physical or Biological?

Helm *et al*, in prep

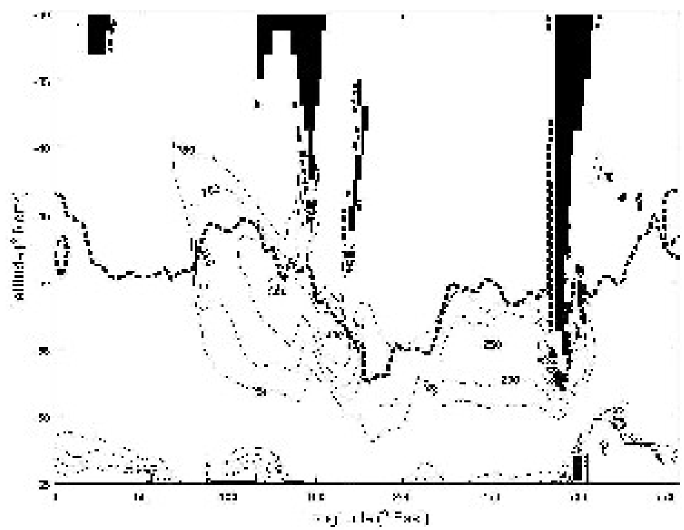
Sea-level and its spatial variations



IPCC models do not agree on spatial patterns of steric sea-level change, but do agree on SST.

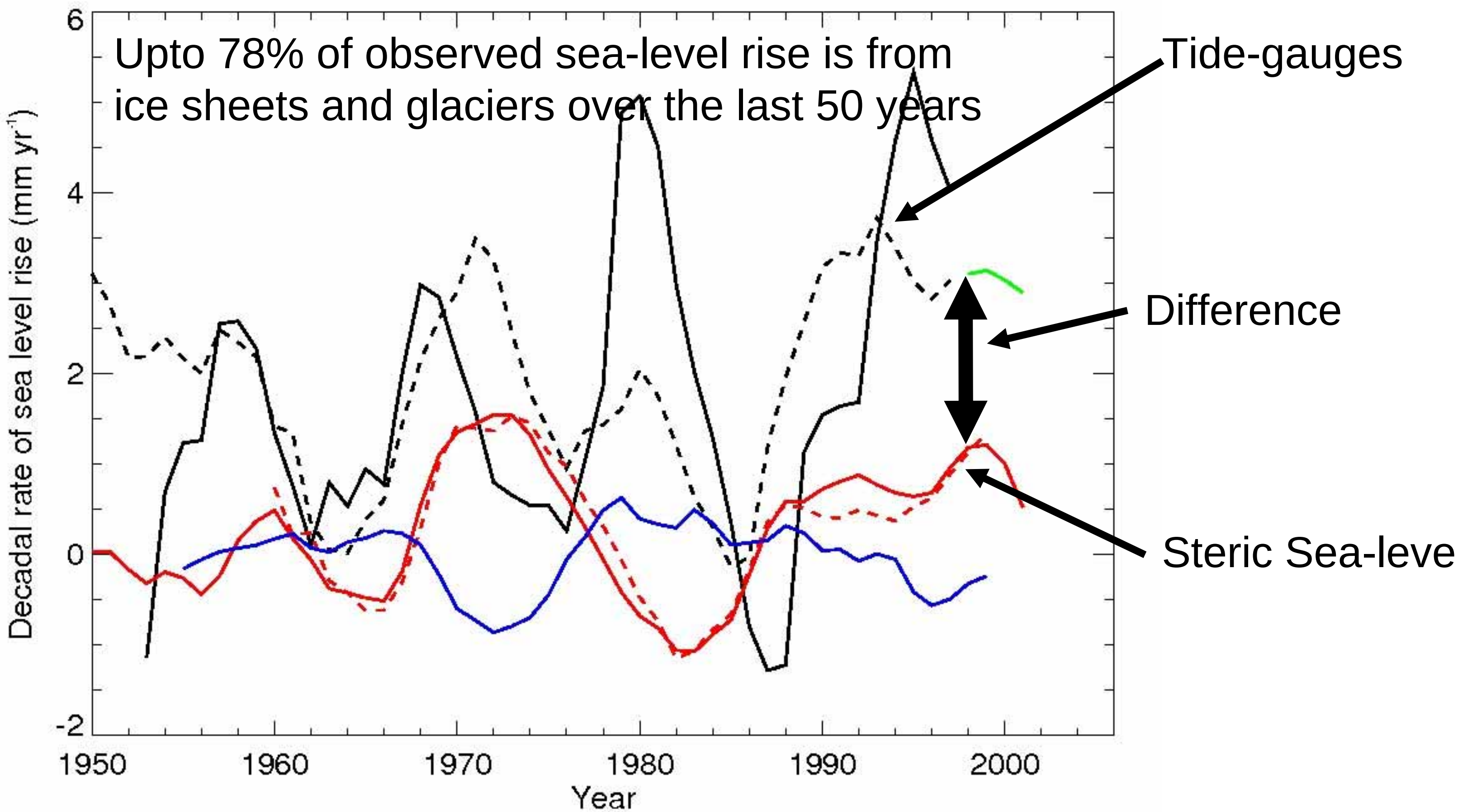
Results from TAR for sea-level.

Reasons:
- Sea level is integrative
- Subduction and ventilation not well simulated



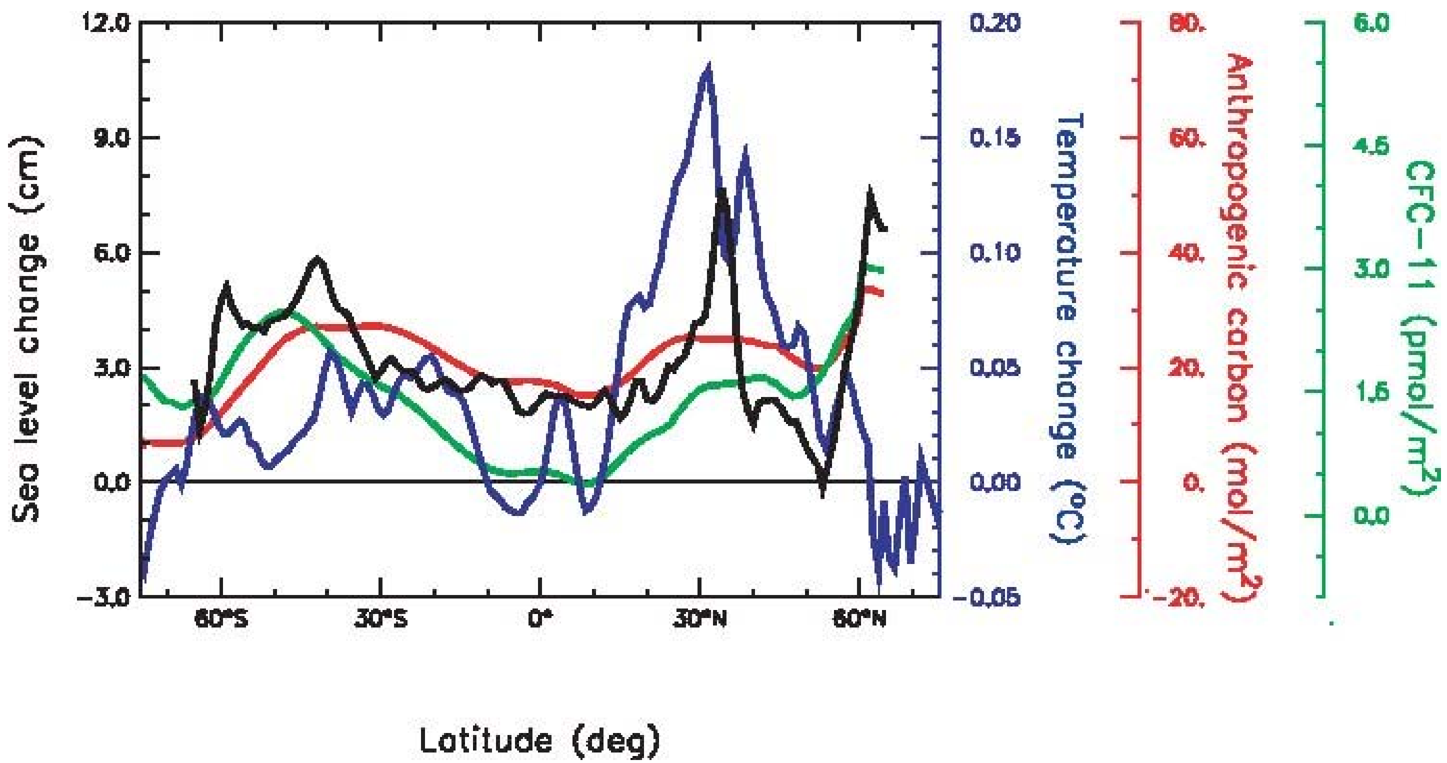
Downes *et al*, in prep

Cryosphere and decadal variations?

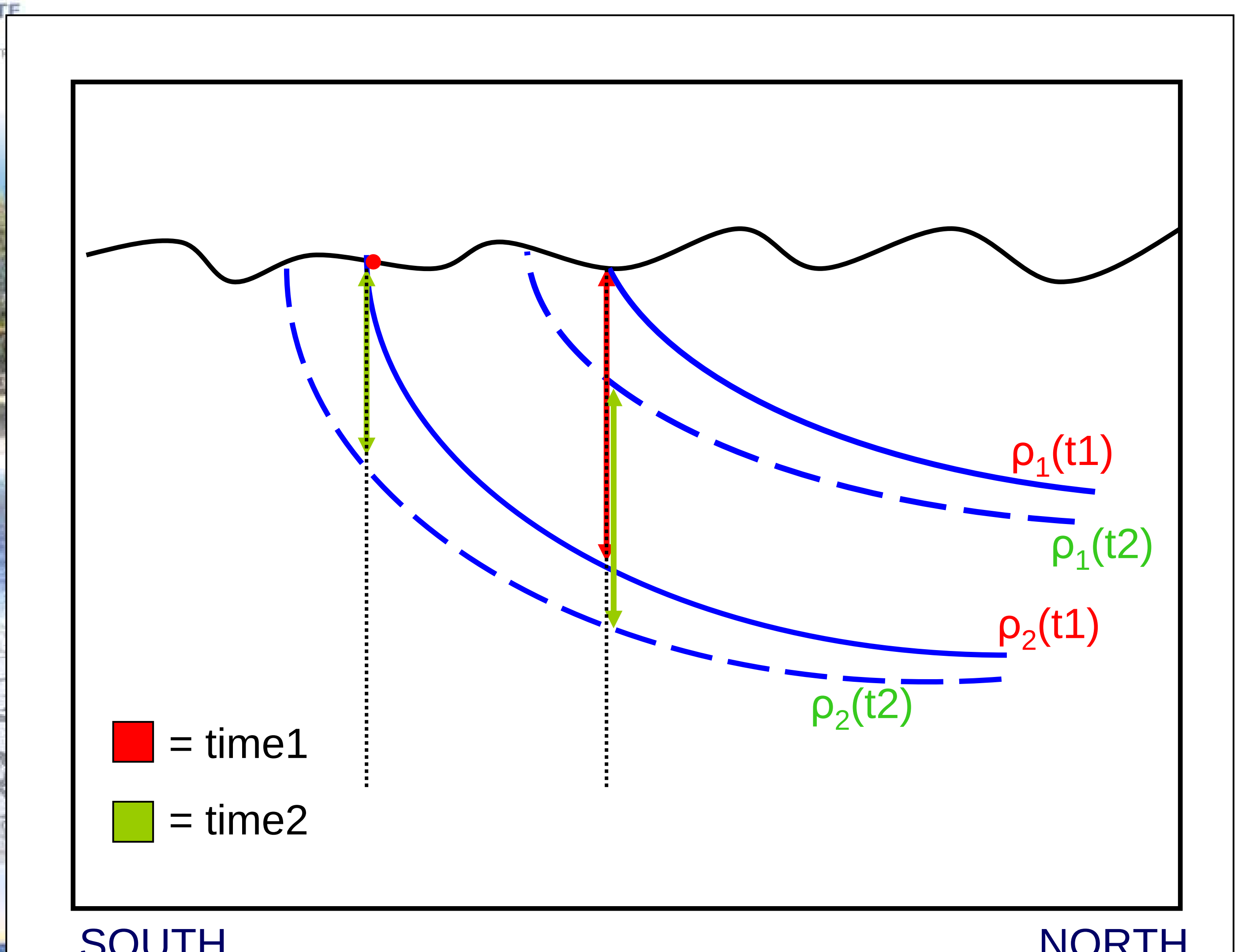


Suggest that there is decadal variations in cryospheric component to global sea-level.

Zonal averages of ocean state

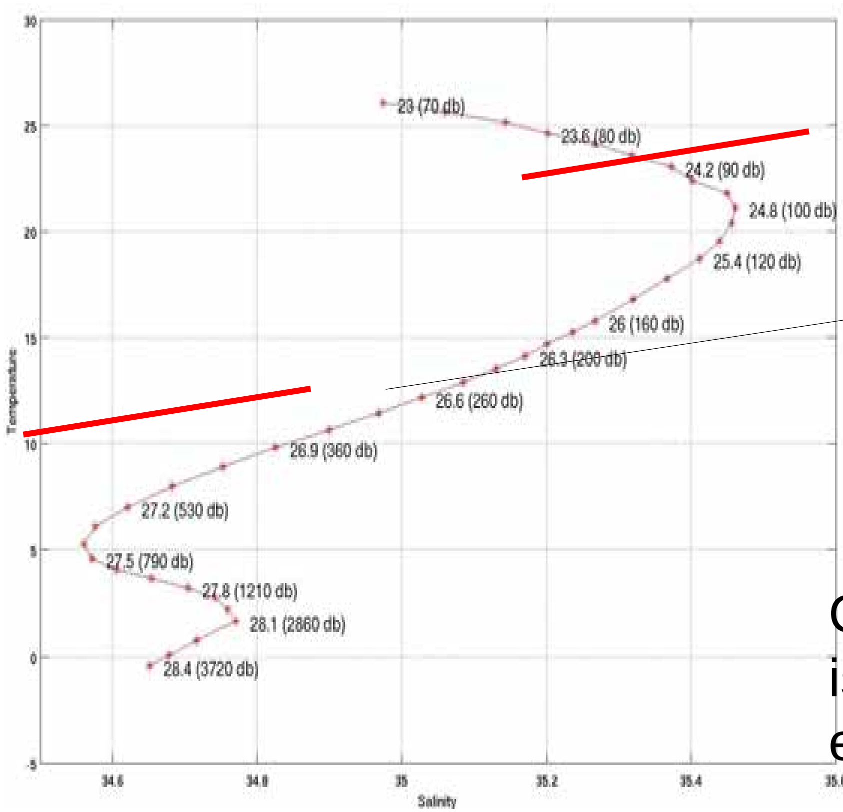


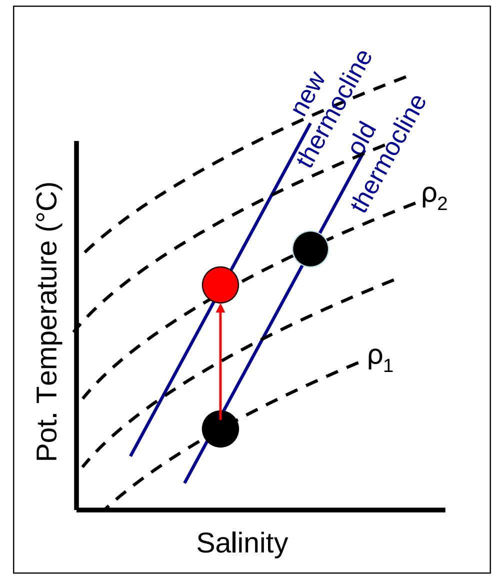
Shifting outcropping zones



$\rho_1(t1)$

Global T-S profile





Pure warming

Cooling and freshening on isopycnals may be able to be explained by 'pure warming'

See Bindoff & McDougall (1994,2000)

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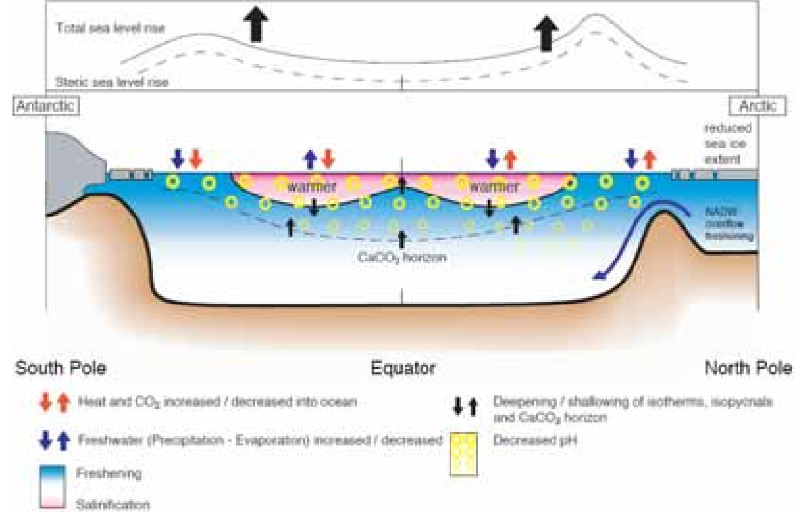
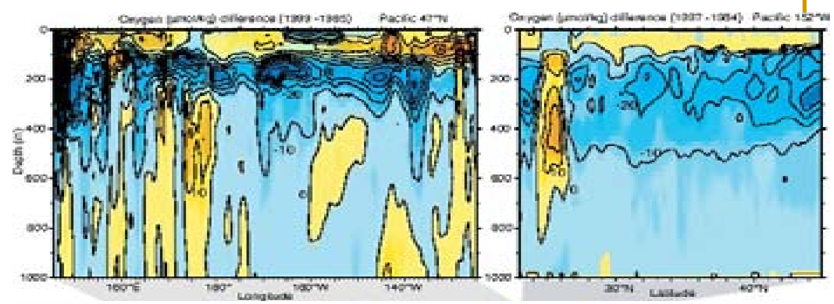
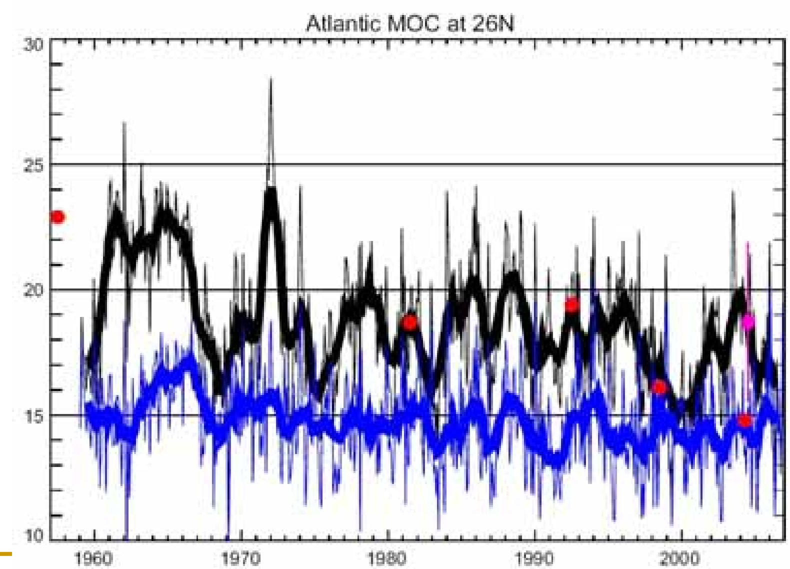
Revolution in ocean observations

Scientific questions:

- Do we understand the heat content record (and sea-level)?
- Do we understand the changes in ocean salinity?
- Is ocean carbon cycle changing?
- Is ocean ventilation changing?
- Can we detect the changes in the SO overturning cells.
- Assess ocean models (and GCM's)







Solutions

- ACCESS evaluations
  - Freshening of bottom water,
  - Change in precipitation, carbon cycle, heat content
  - Improve spatial distributions of heat, carbon
- Detection and attribution
  - Natural variations or man induced?
- Initialisation

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Three underlying issues for ocean observations and models

1. **Sustained observations (big risks)**
   - **operational capability (eg IMOS)**
   - **Insitu programs (ARGO, SOO, etc)**
2. **Timely data and model access**
   – to ensure **timely access to data** so that all may derive benefit (repository)
   – range of model outputs (eg ACCESS, IPCC/PCMDI, re-analyses like BlueLINK, ECCO, SODA)
3. **Need specialist Earth System Science Facility**

HPC, Storage, technical support for ACCESS, and managed by/on behalf of climate scientists

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Climate Change Initiative

- Enhanced and sustained climate measurements ($300 million over 5 years)
  - Ocean climate data, new ship(s), additional support ($200 million)
  - Terrestrial climate networks ($100 million)

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Climate Change Initiative

- An e-Research or Information Systems for Earth Systems Science ($30 million, 5 years)
- Specialist Earth Systems Science Facility (Service support and 100 Terraflops and data, ~$40million)

Climate Change Initiative

- Climate Challenge Projects ($40million)
  - Australia 30 year initialisation (include
  - Australia Re-analysis project
  - Australian Ocean re-analysis project (including Southern Ocean and Antarctica)
  - Australian Climate Risk Managements
- New collaborative arrangements that include researchers and government

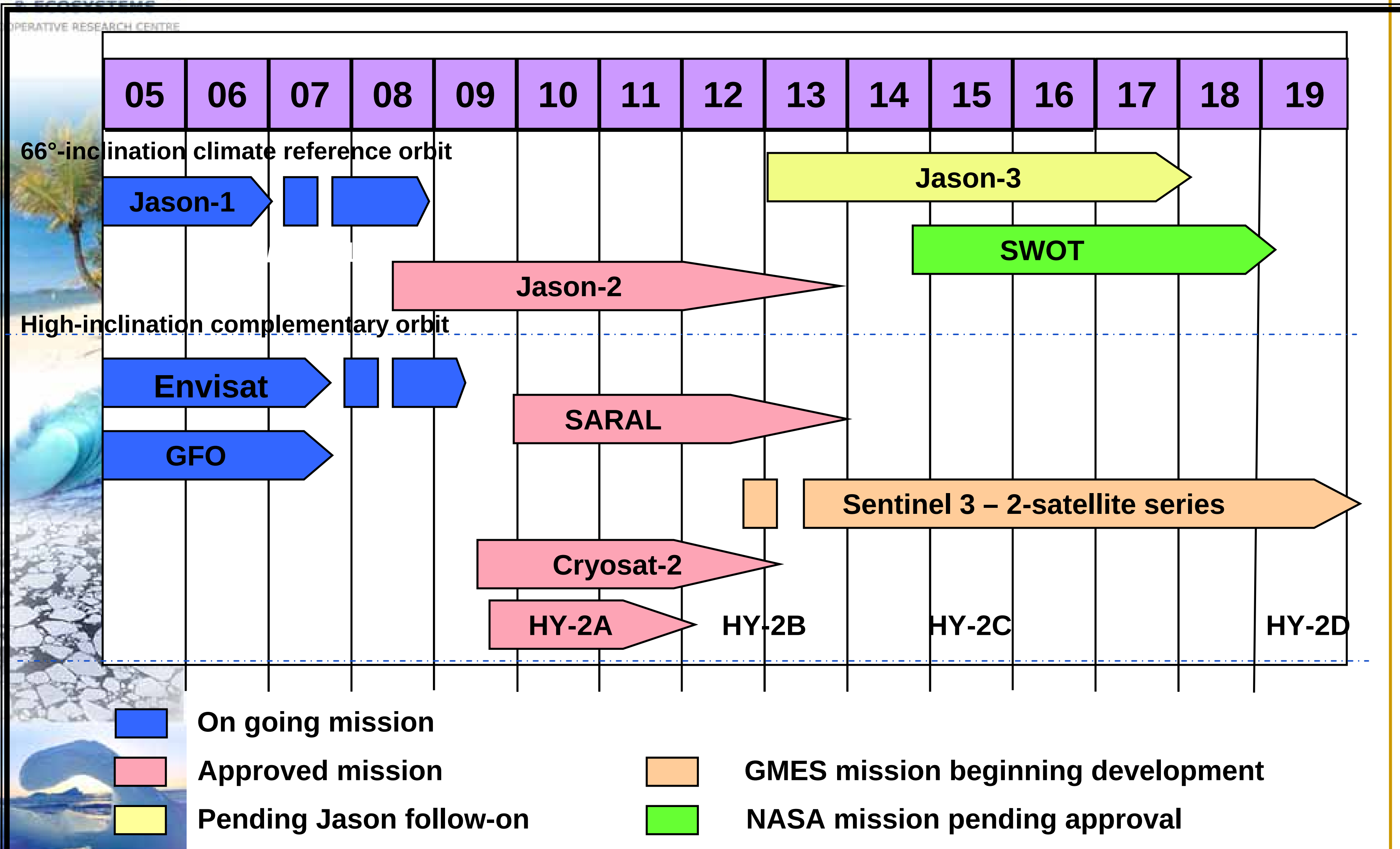
Climate Change Initiative

- Mitigation and validation service for Australian Carbon Trading Bank

Climate Change Initiative

- Enhanced and sustained climate measurements ($300 million over 5 years)
- e-Research or Information Systems for Earth Systems Science ($30 million, 5 years)
- Specialist Earth Systems Science Facility (Service support and 100 Terraflops and data, ~$40million, 5 years)
- Climate Challenge Projects ($30 million)
- Mitigation and validation service for Australian Carbon Trading Bank ($10 million)
- Budget ($310million)

Observational Risk – potential failures



Stan Wilson