Changes in the Ventilation of the Southern Oceans, and links to Stratospheric Ozone Depletion

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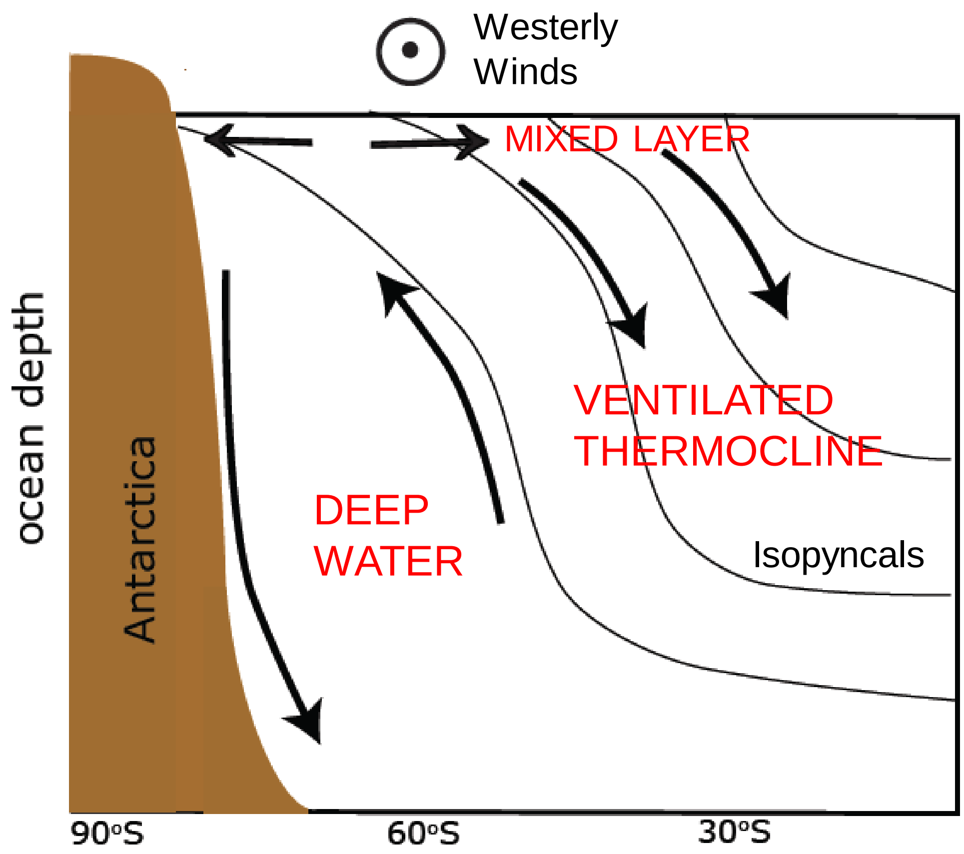
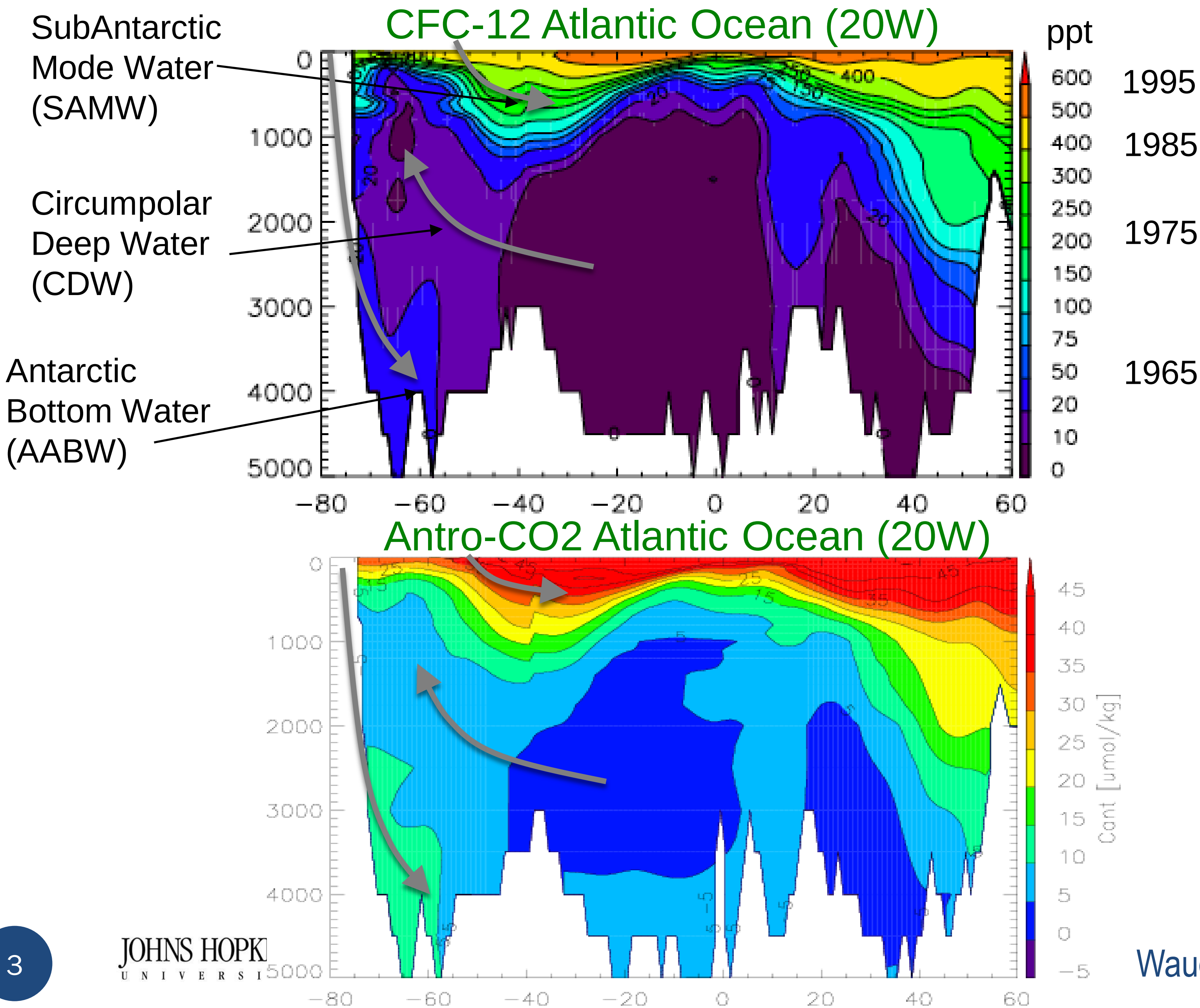
Southern Ocean Ventilation

Ocean Ventilation = Transport of surface waters into ocean interior.



CFCs and Anthropogenic CO2



Waugh et al., 2006

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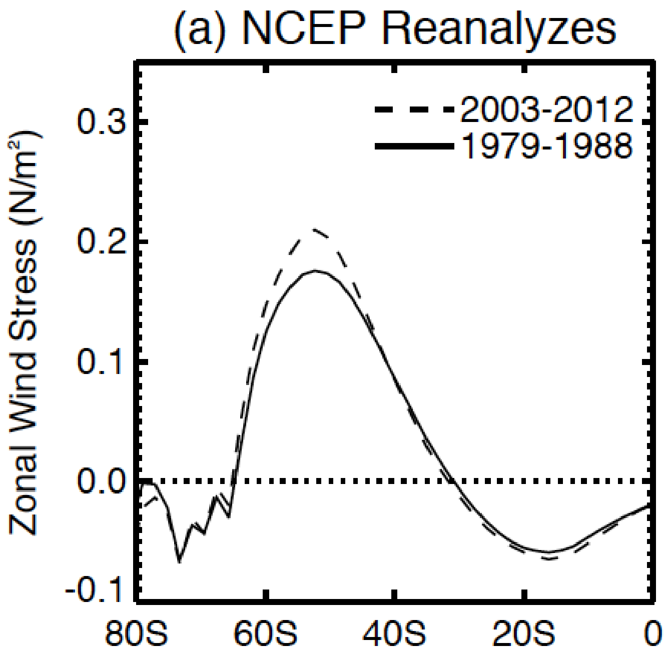
Southern Ocean Ventilation

Ventilation of southern oceans important for global climate and cycling of carbon, oxygen and nutrients.

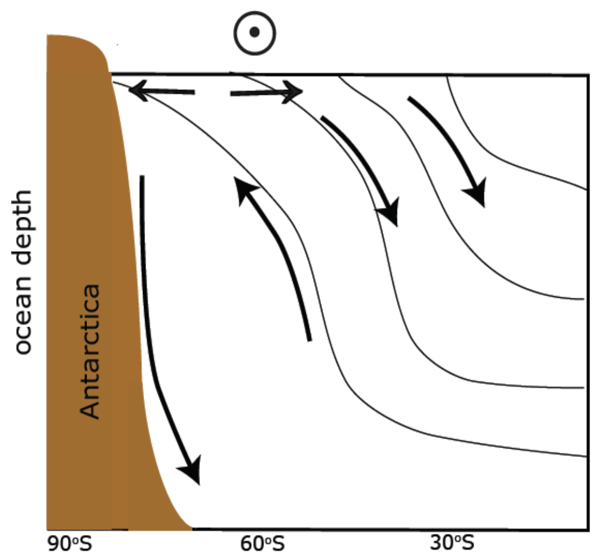
- Southern oceans have warmed at roughly twice the global rate over past few decades.
- 40% of anthropogenic carbon uptake by ocean is south of 40S.

Changes in Wind Stress

- Wind stress is important driver of the ocean circulation / ventilation.
- Observations show an increase in SH wind stress in recent decades (due mainly to ozone depletion).
- Theoretical and modeling studies indicate that this will lead to *changes in ocean circulation and ventilation*.



But some debate …



=> Examine ocean measurements of chlorofluorocarbons (CFCs)

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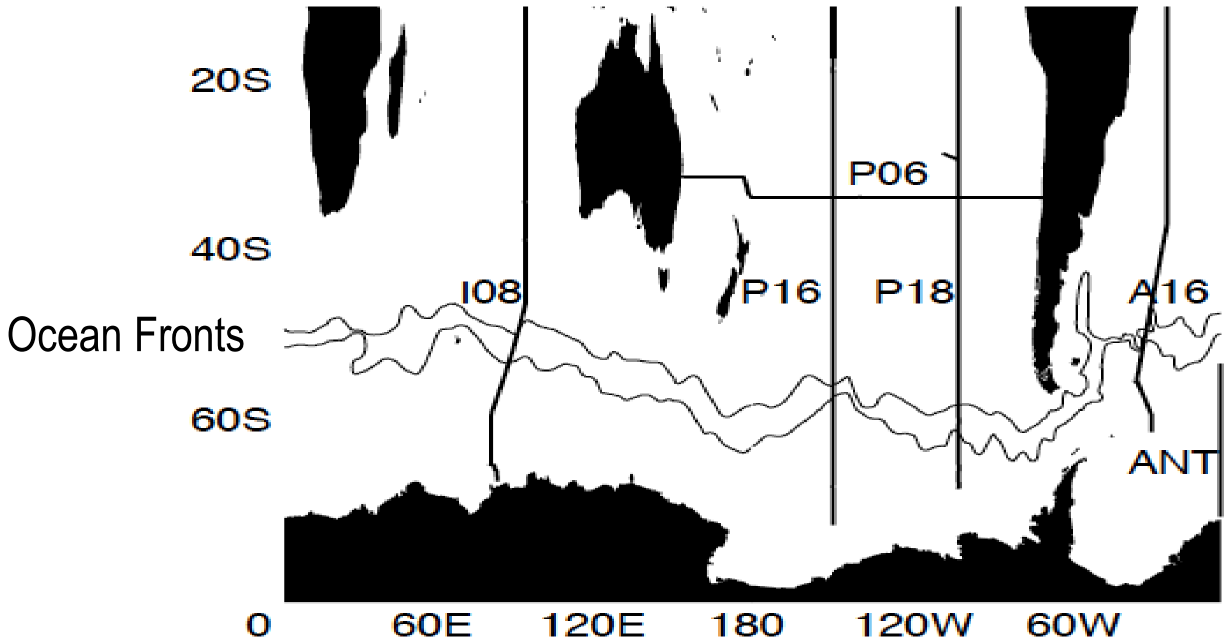
Ocean CFC Measurements

As CFCs are conserved in oceans and their atmospheric concentration increased from 1950 to 2000, repeat CFC measurements can be used to estimate changes in ocean ventilation times.



P16 (1991,2005),
P18 (1994,2008),
P06 (1992,2003,2009),
A16 (1989,2005),
I08 (1994,2008)

Measurements of CFC-12 were made along sections in Southern Oceans during early 1990s (WOCE) and mid to late 2000s (CLIVAR Repeat Hydrography).

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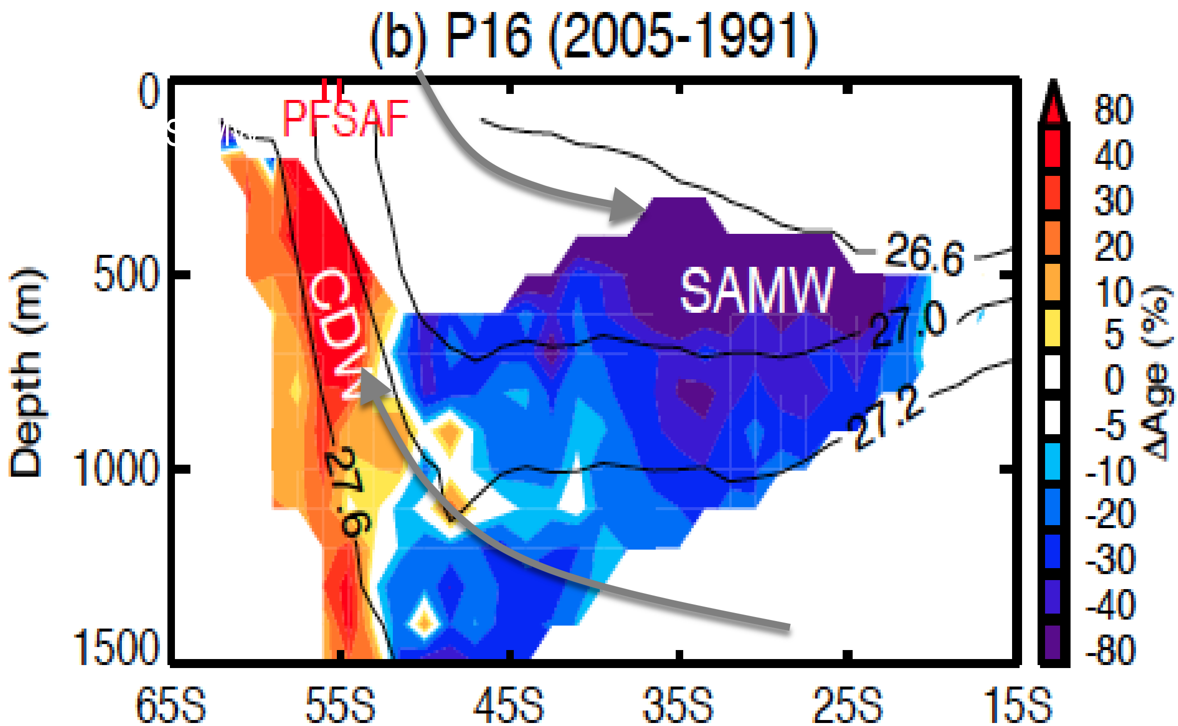
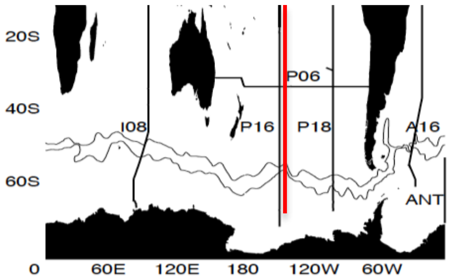
Change in Mean Water-Mass Age

Observed increases in CFC-12 within subtropical” waters smaller than expected for steady transport, and larger than expected within polar waters: => **Decrease of “age” within SAMW and increase within CDW.**

% difference in mean age between occupation.





Waugh et al. (Science, 2013).

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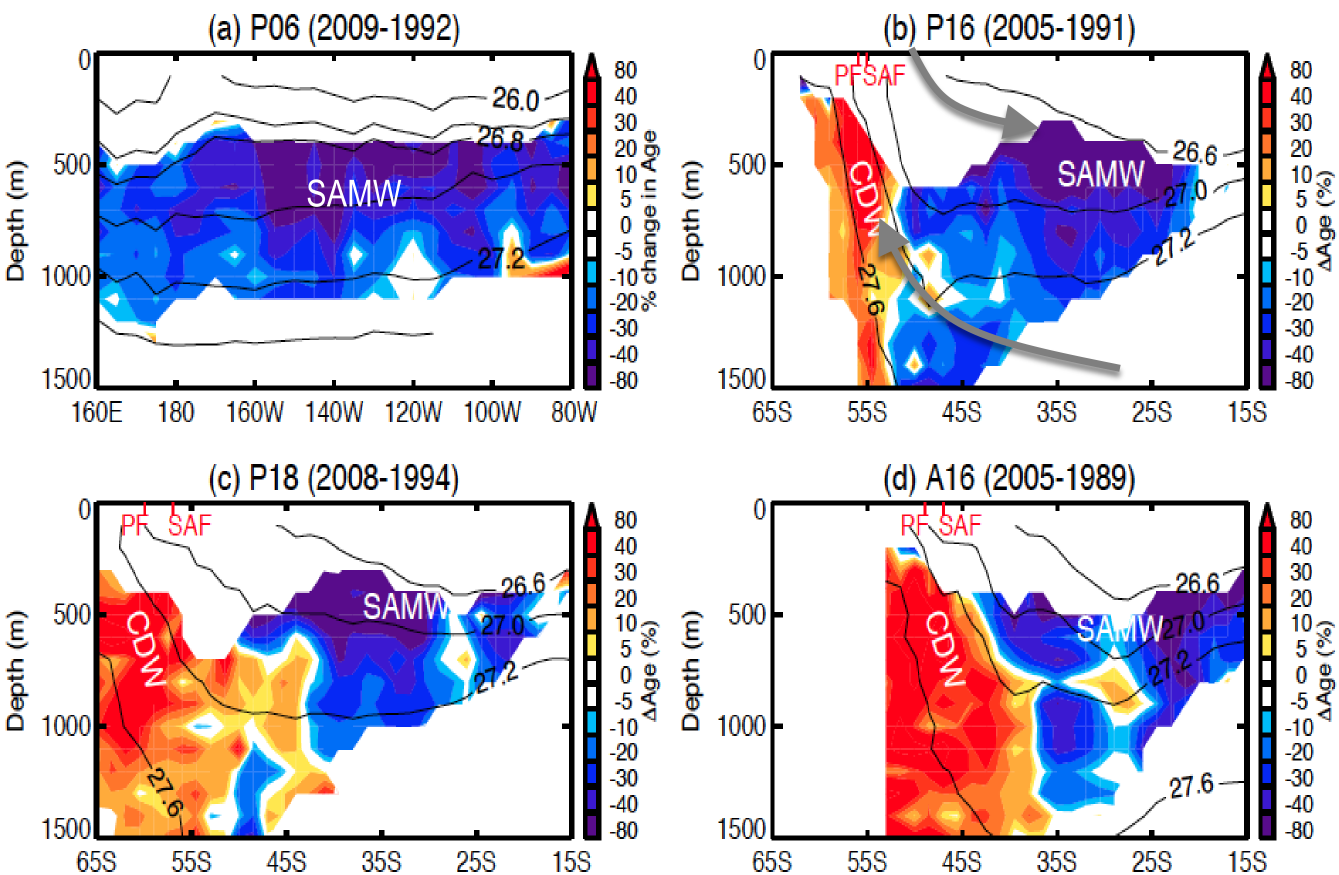
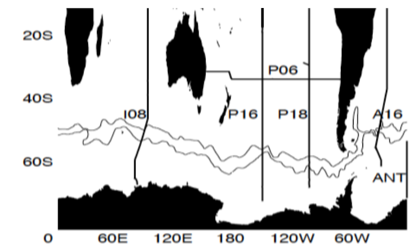
Change in Mean Water-Mass Age

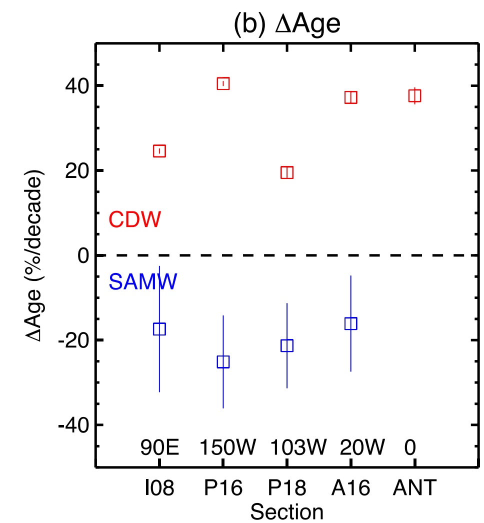
Consistent picture for all sections:

Decrease of "age" within SAMW and increase within CDW.

% difference in mean age between occupation.





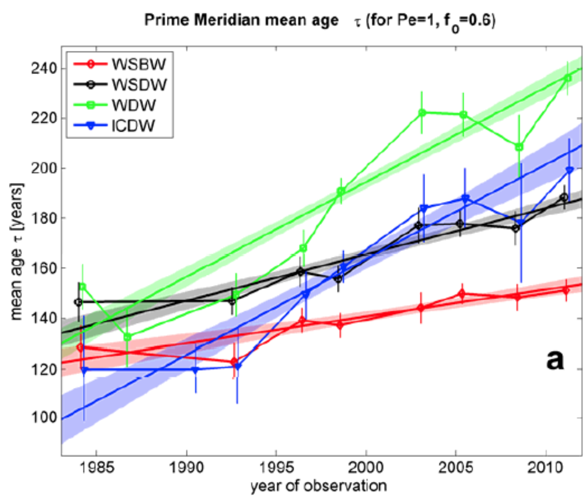


Waugh et al. (Science, 2013).

Consistency with other Studies

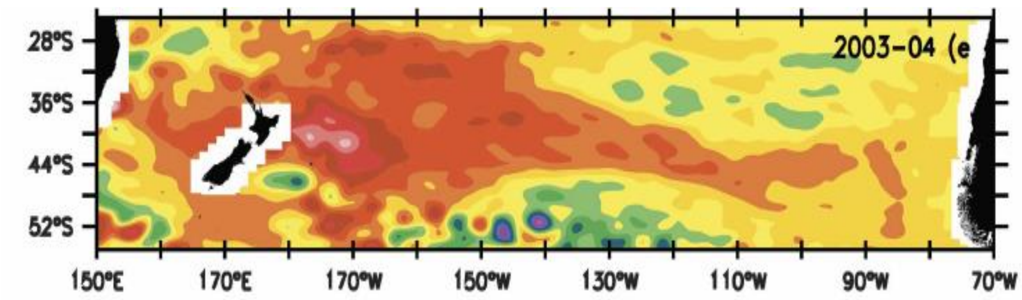
Increase in age of deep water in the Weddell Sea

[Huhn et al., DSR, 2013]



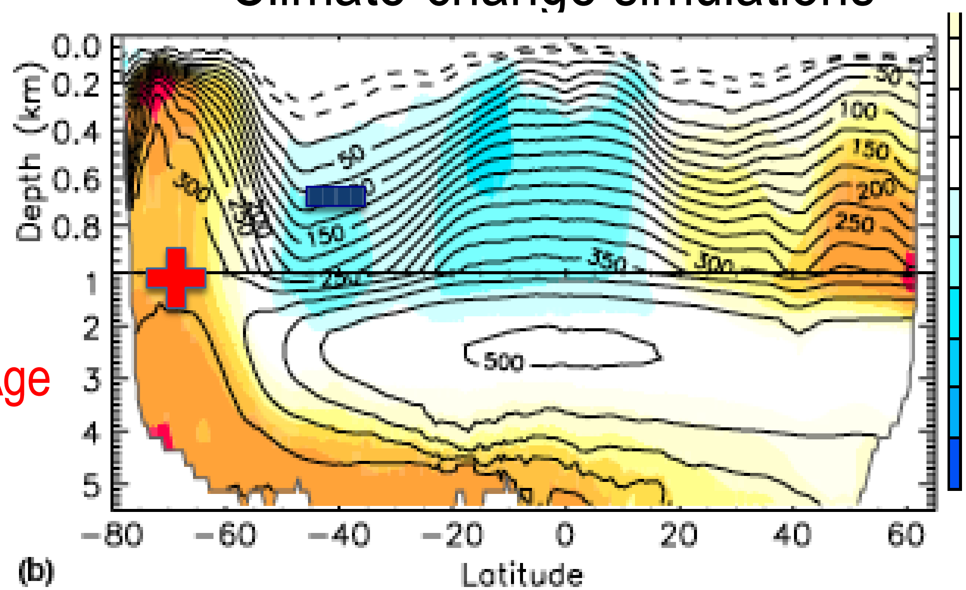
Spin-up of southern subtropical gyres [e.g., Roemmich et al. 2006].

ΔSSH 2003/04 – 1993/94



Climate-change simulations

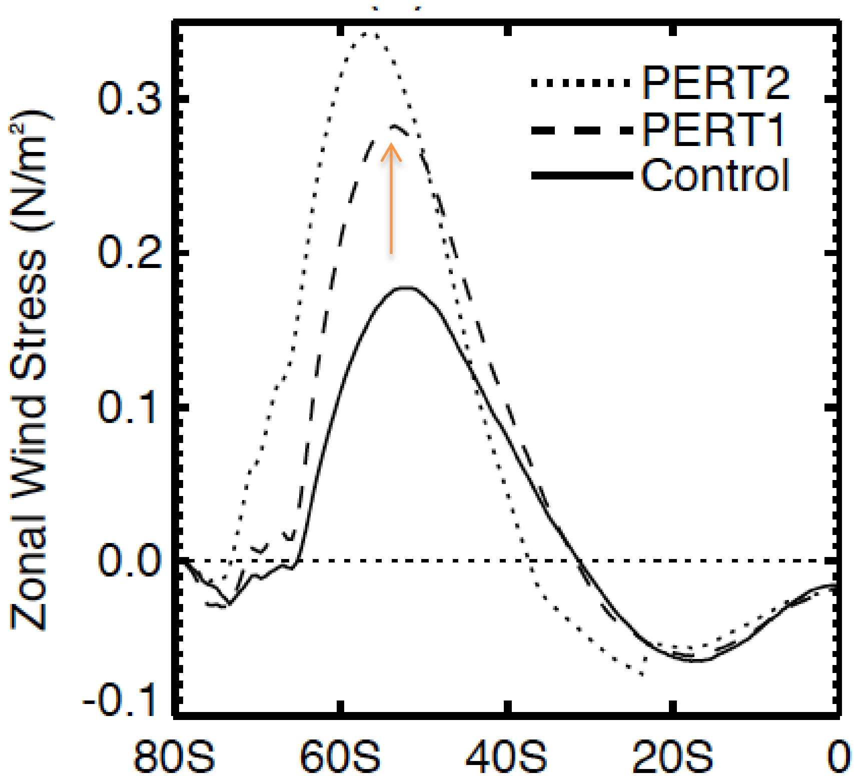
ΔAge



[CCSM; Bryan et al. 2006; GFDL; Gnanadesikan et al. 2007]

Climate Model Perturbation Experiments

Examine changes in the **ideal age** in the perturbation experiments of CCSM4 where the wind stress is instantaneously increased [Gent & Danabasoglu, 2011].



PERT1: 50% increase in wind stress.

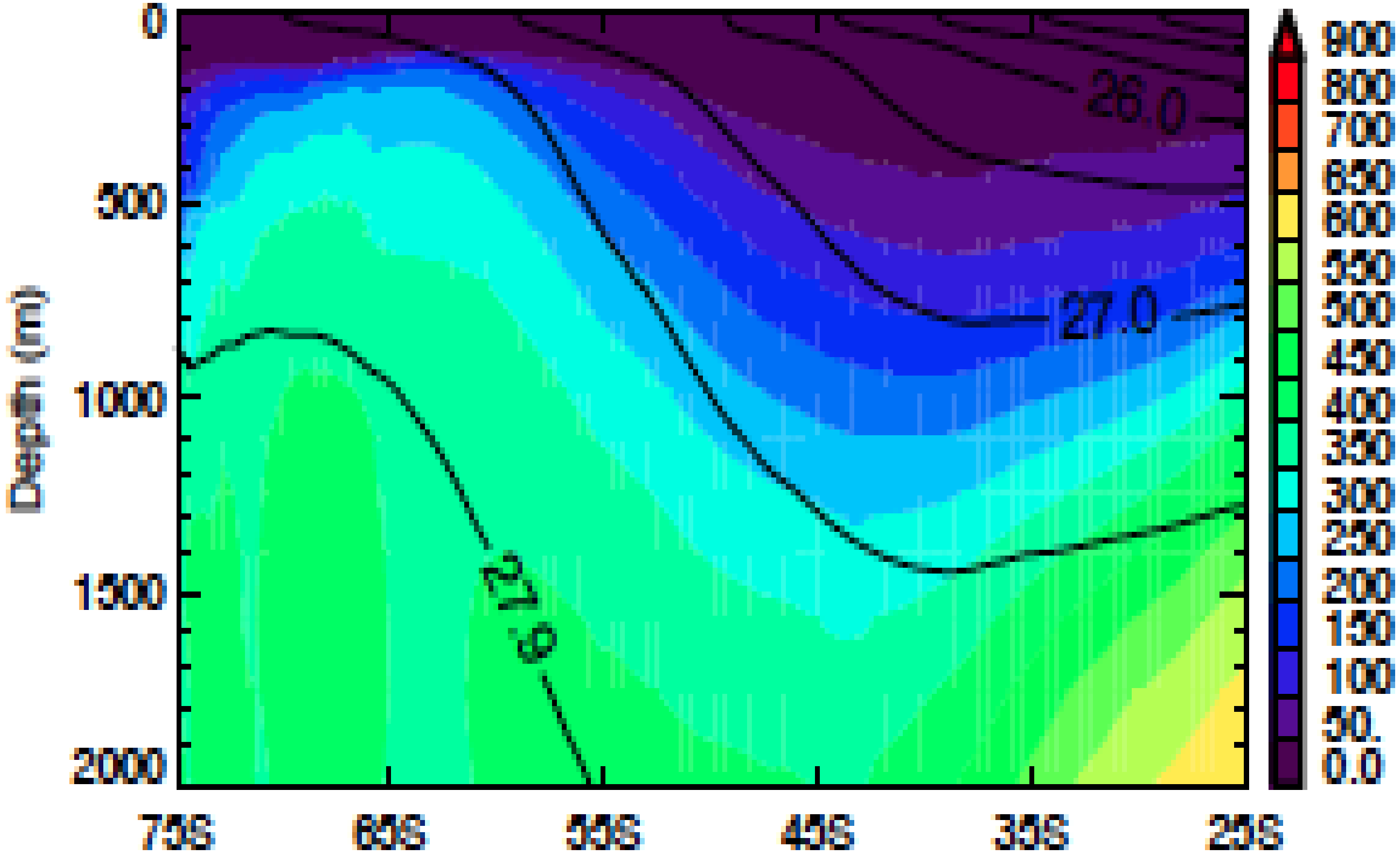
PERT2: 75% increase, plus 3° poleward movement of maximum.

[Note: Change in wind stress in model is much larger than observed increase over last 30 years.]

In steady state, the ideal age = mean water-mass age

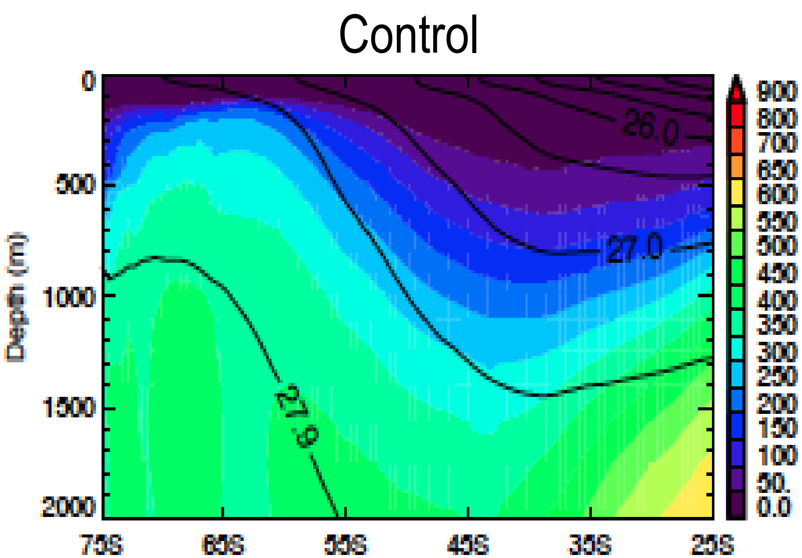
Zonal-mean Ideal Age

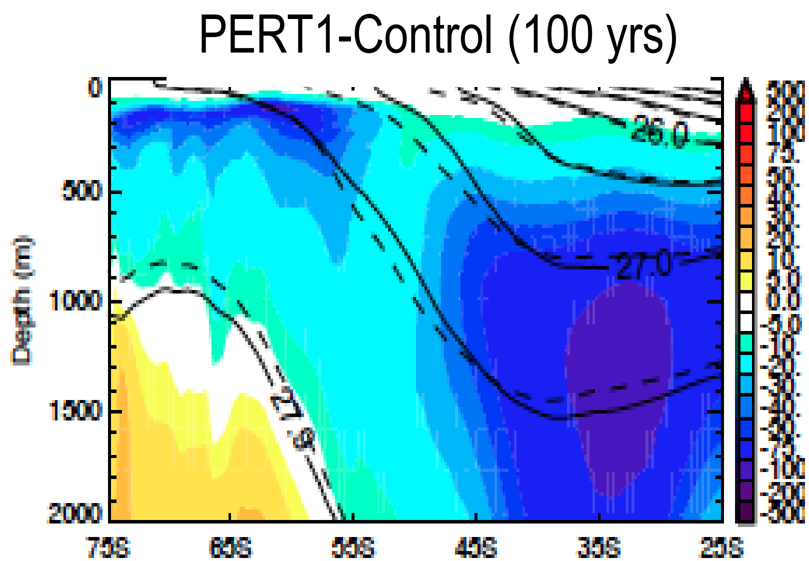
Ideal Age at t=0 in perturbation experiments



Zonal-mean Ideal Age

Increased wind stress leads to younger ages in subtropical thermocline and (slightly) older ages in circumpolar deep water.





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Zonal-mean Ideal Age

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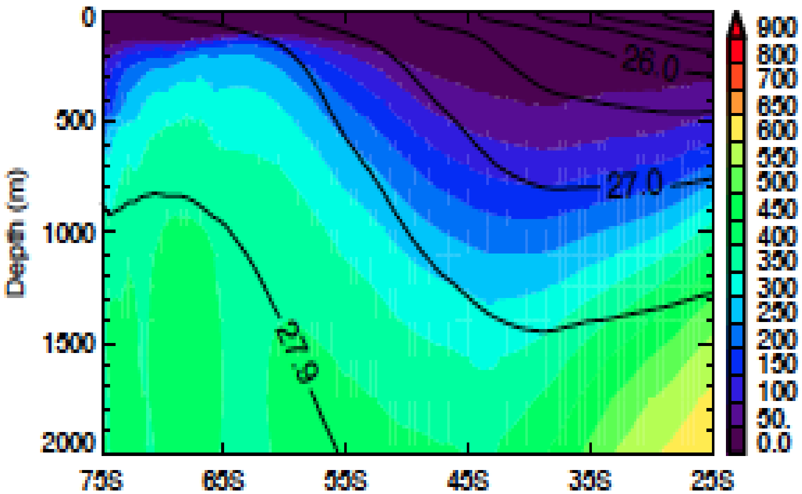
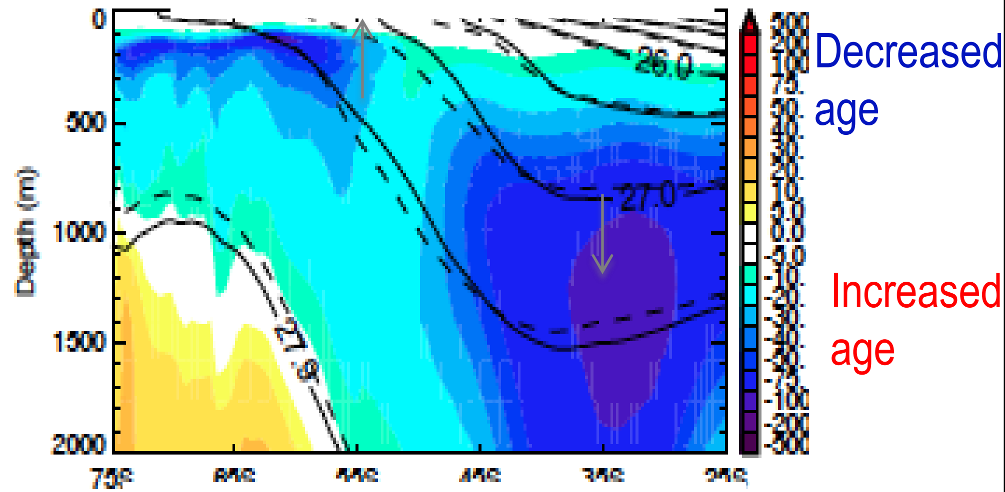
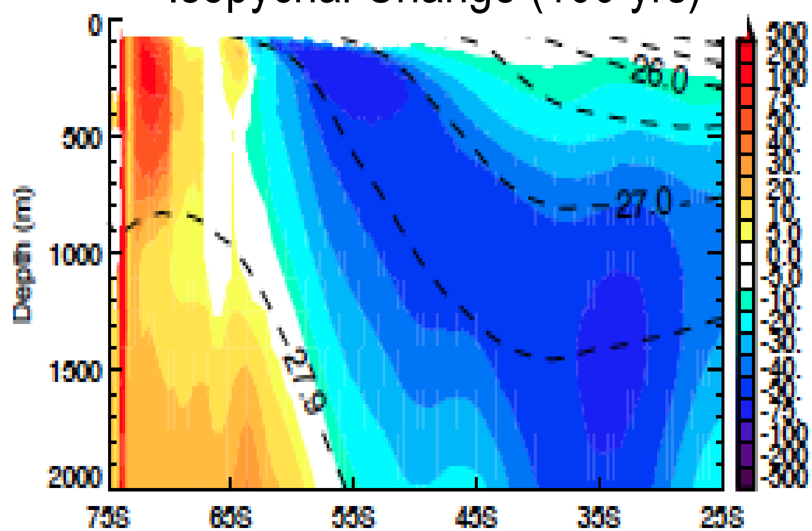
Control



PERT1-Control (100 yrs)



Isopycnal Change (100 yrs)



Decrease in ages is due to combination of movement of isopycnals and along-isopycnal transport.

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Evolution of ideal age

PERT1 – Control
after

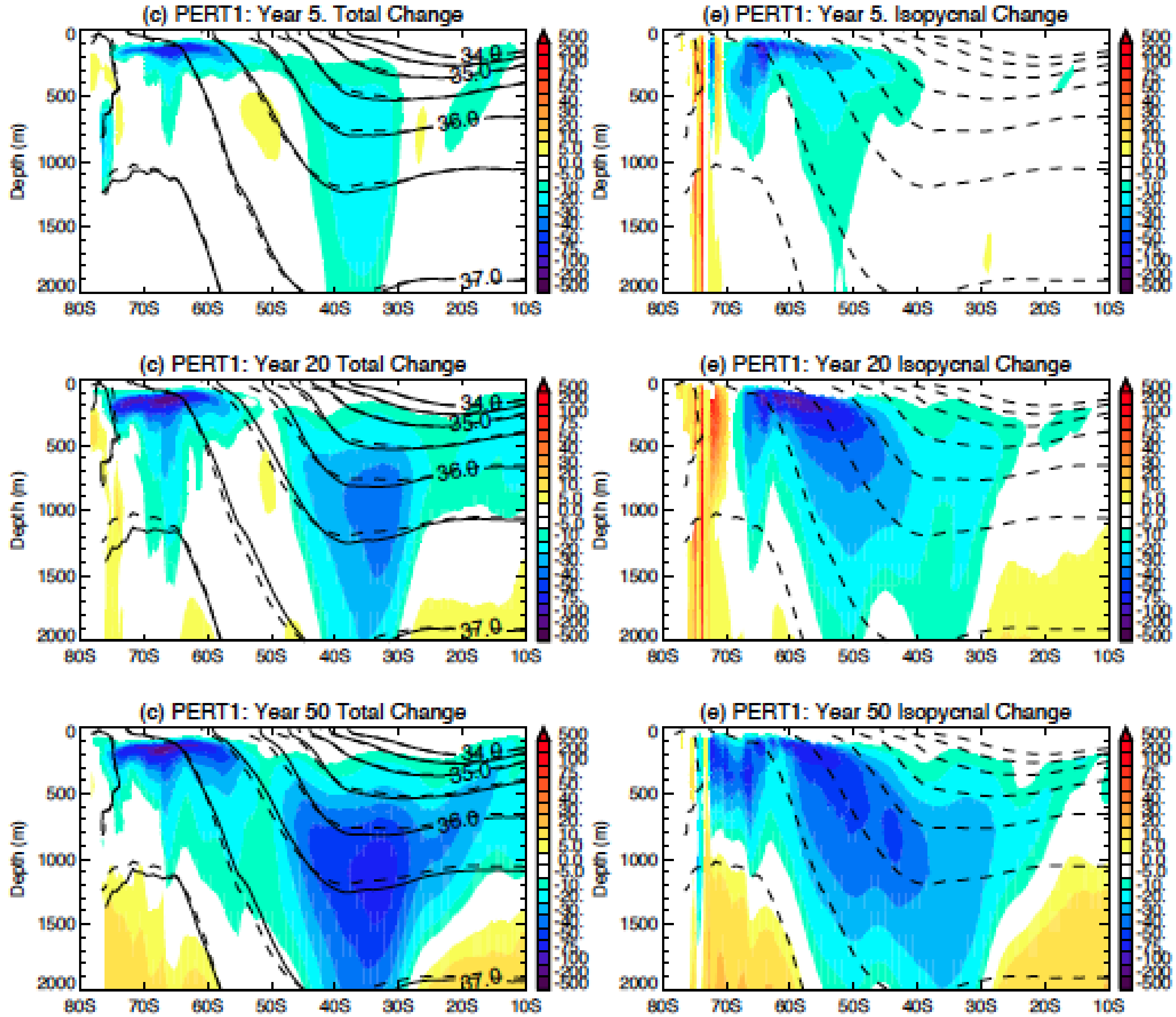
Total change

Isopycnal change

5 years

20 years

50 years



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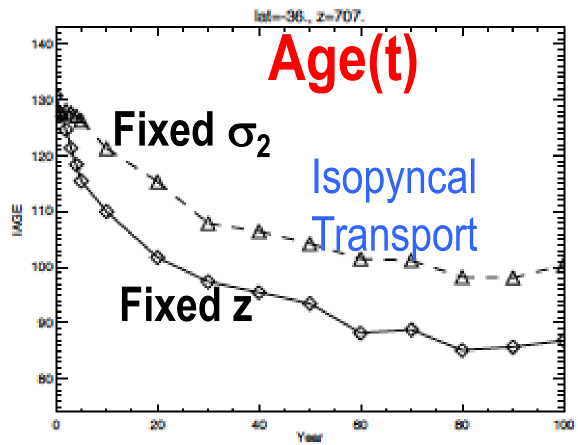
Evolution @ 36S

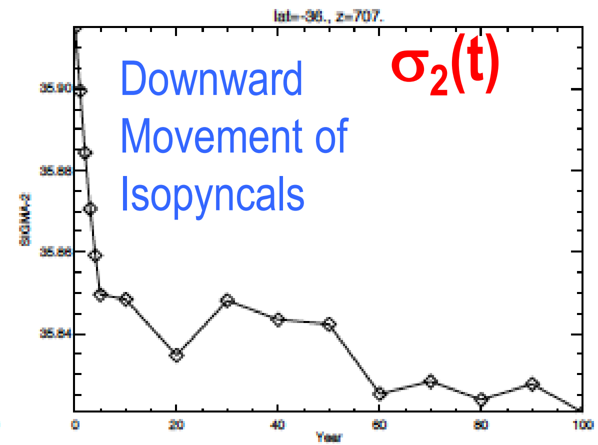
Two time-scale response:

(i) Rapid change (primarily) due to movement of isopycnals

(ii) Slower response due (primarily) to isopycnal transport.

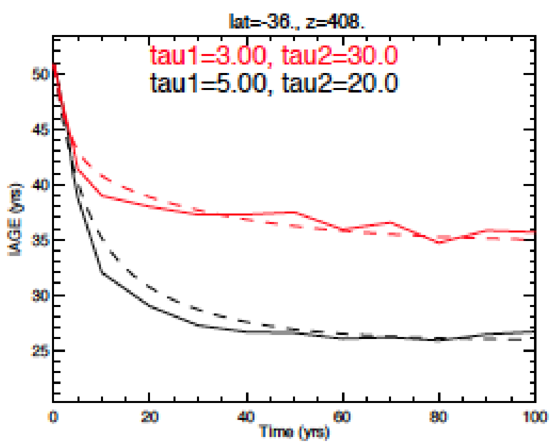
(36S, 700m)

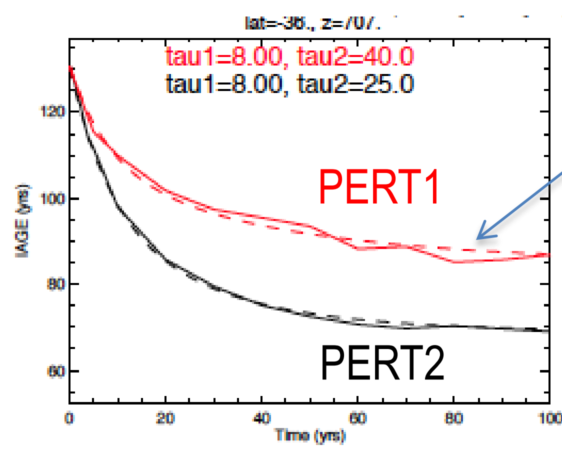




Age(t) @ 36S, 400 & 700m

$$R(t) = \alpha_1 \left(\exp\left(-\frac{t}{\tau_1}\right) - 1\right) + \alpha_2 \left(\exp\left(-\frac{t}{\tau_2}\right) - 1\right)$$





τ_1 ~ 3-8 yr, τ_2 ~ 20-40 yr

Linear Response Theory

PERT experiments have unrealistic, instantaneous increase in wind stress. Insight into response to more realistic temporal variation obtained using linear response theory:

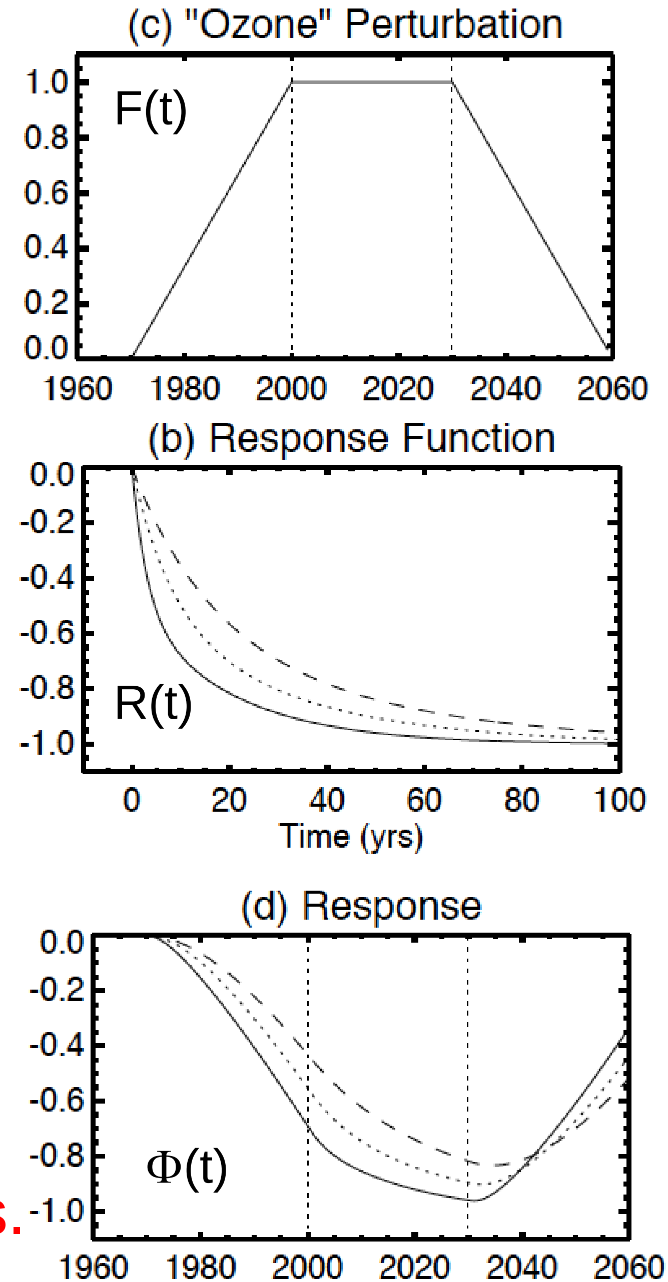
R = *Age Response of to step-function increase in wind stress.*

F = *temporal variation of wind stress*

$$\Phi(t) = \int_0^t R_\Phi(t-t')\frac{dF}{dt'}(t')dt'$$

Φ = *Age Response to* F(t)

- Delay of 10-20 yrs in age response
- Impact of 1980-2000 increase in wind stress persists for 2-3 decades.

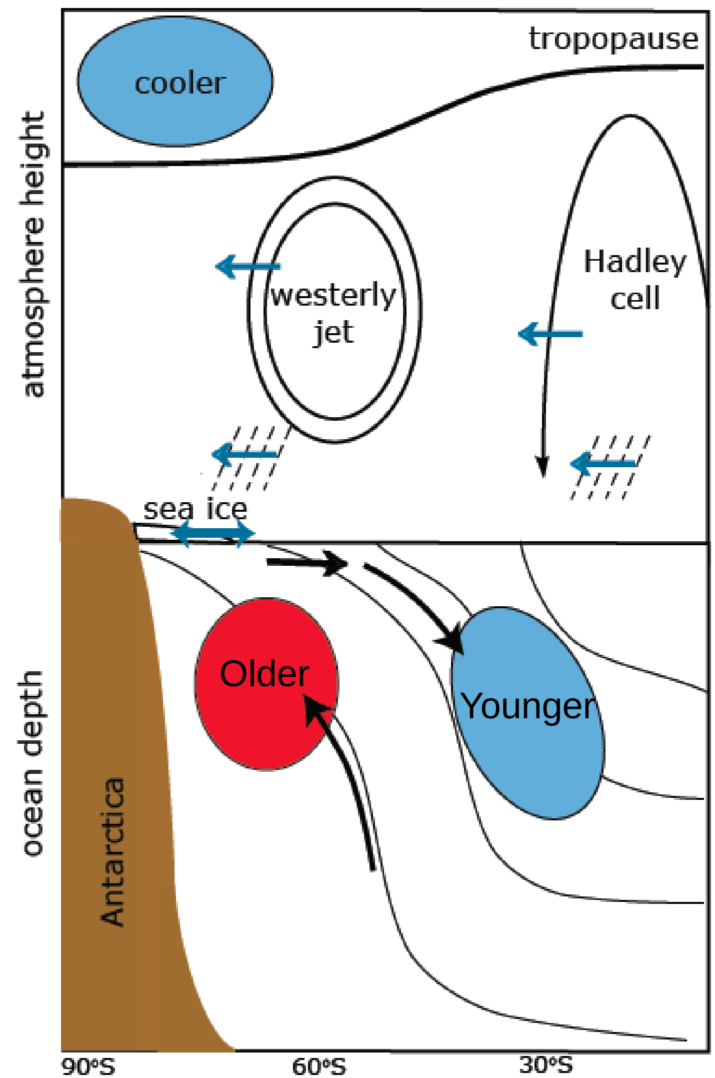


Conclusions

CFC observations indicate a decrease in age of subtropical mode waters and an increase in the age of upwelling circumpolar deep waters, over last few decades.

Consistent with expected/modeled response to an intensification of surface westerlies.

Response time to wind stress is several decades.



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Open Questions

- Role of ocean eddies
- Future changes in ventilation (as Ozone recovers, GHGs continue to increase).
- Impact on uptake of heat, freshwater, carbon, and nutrients.

THE END

Postdoctoral Research Positions in Ozone Hole – Climate Dynamics

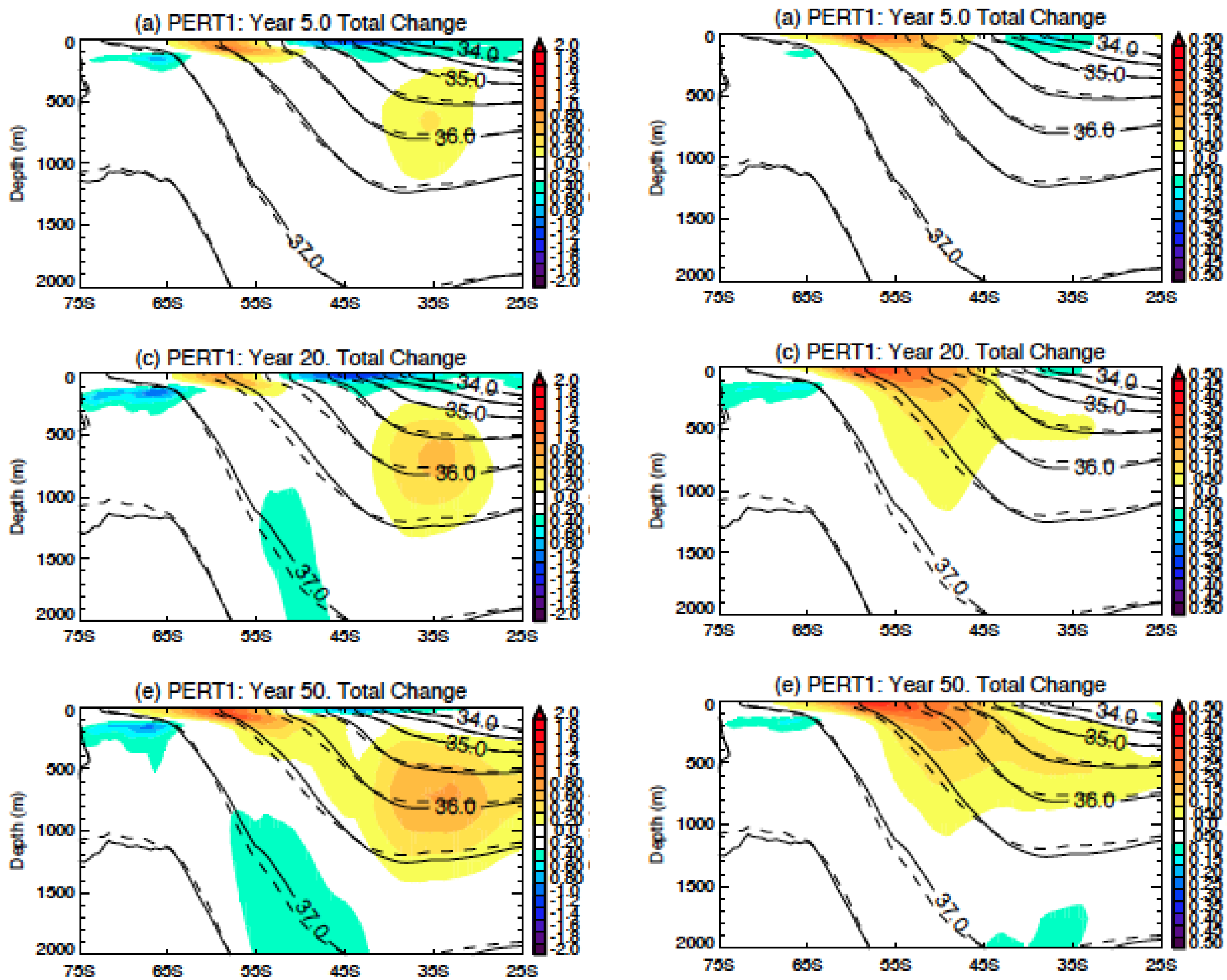
Applications are invited for multiple postdoctoral associate or research scientist positions as part of new multi-institutional, NSF-funded Frontiers of Earth System Dynamics, project to examine the impact of the ozone hole on the climate of the Southern Hemisphere. This project involves the use of a hierarchy of numerical experiments to explore the coupling between atmospheric chemistry and dynamics, ocean circulation and biogeochemistry, and the cryosphere, and brings together scientists from Massachusetts Institute of Technology (MIT), Columbia University (CU), Johns Hopkins University (JHU) and the National Center for Atmospheric Research (NCAR).

There are currently openings for postdoctoral research positions at MIT, CU, and JHU in three general areas: (1) Atmosphere-ocean-ice coupling, based at MIT; (2) Stratosphere-troposphere-chemistry coupling, based at CU; and (3) Ocean circulation and biogeochemistry, based at JHU. While based at one of three above institutions, the successful candidates will have opportunities to interact and work with scientists at all four institutions.

Further information the project and positions about can be obtained from John Marshall (jmarsh@mit.edu), Lorenzo Polvani (lmp@columbia.edu), or Darryn Waugh (waugh@jhu.edu).

Consideration of applications will begin March 1, 2014. Applications can only be submitted electronically through Interfolio https://secure.interfolio.com/apply/24114. To apply, please submit your curriculum vitae (with your email address), names and emails of three or more references, and a brief research plan.

Temperature and Salinity Perturbations



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