Tracer Based Ages, Transit Time Distributions, and Water Mass Composition: Observational and Computational Examples

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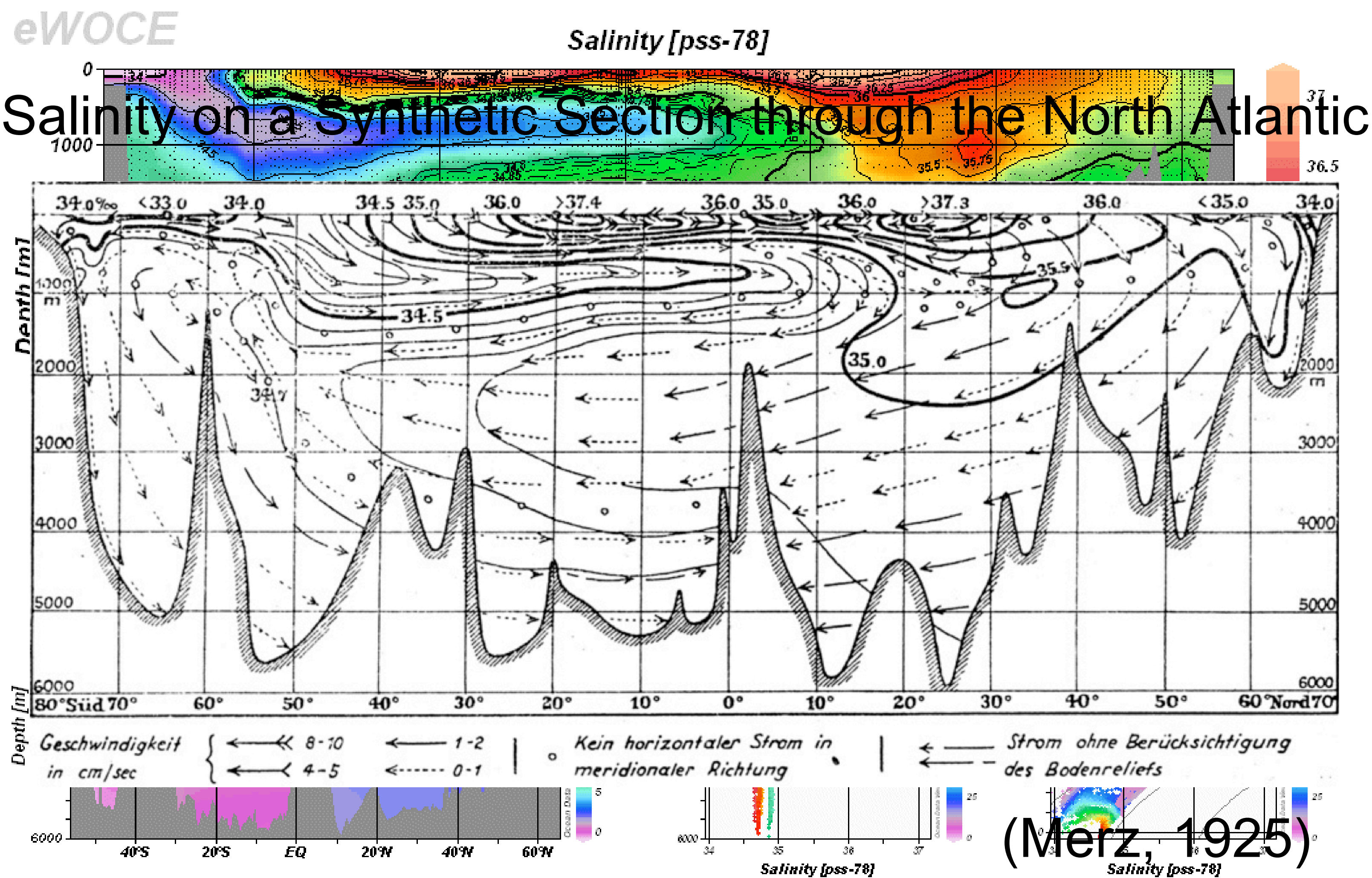
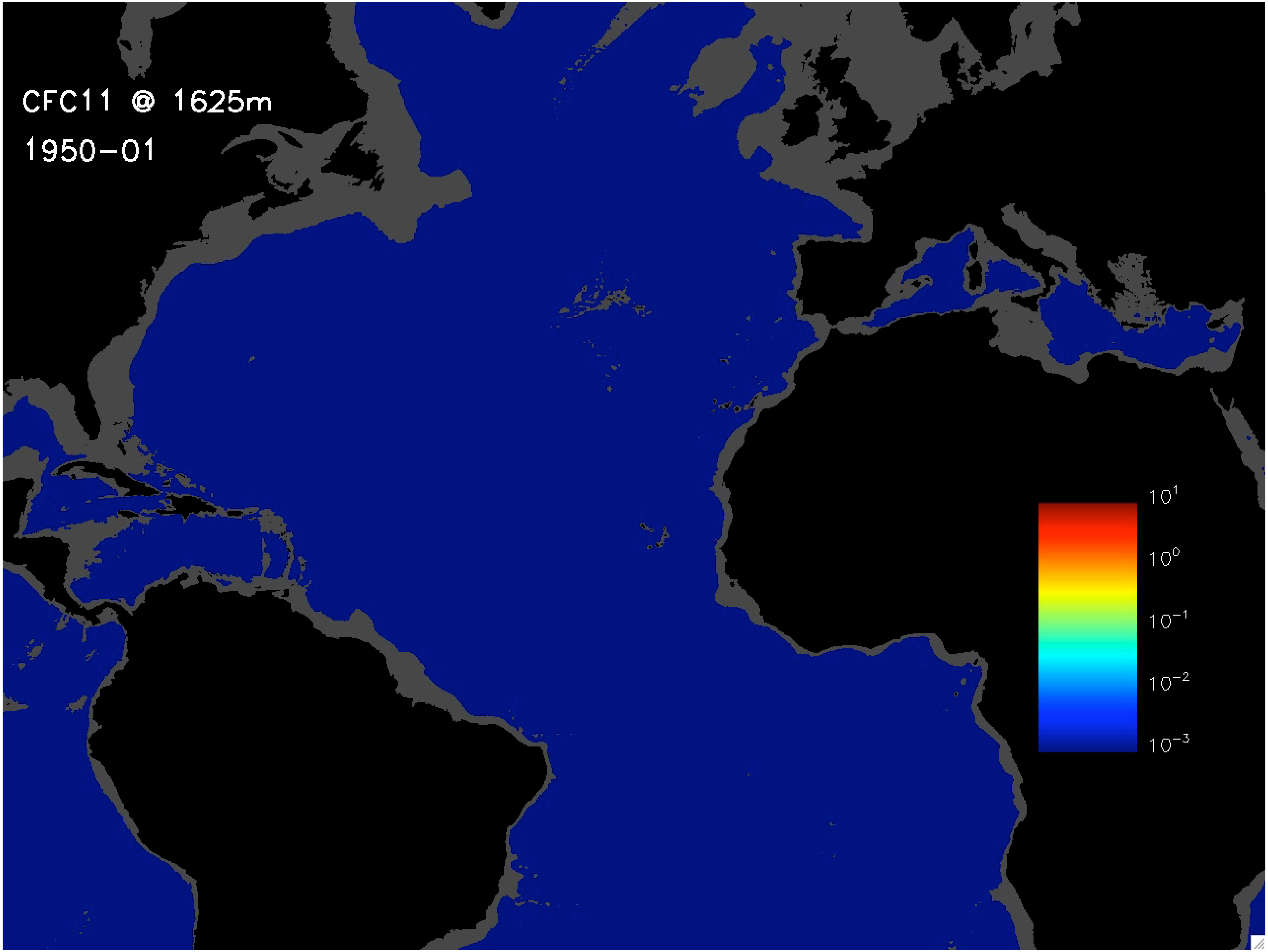
Interpretation of Tracer Distributions is the Foundation Conceptual Framework of Physical Oceanography



Salinity on a Synthetic Section through the North Atlantic

(Merz, 1925)

From Richardson (2007)


CFC11 @ 1625m
1950-01
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}

Scientific Objectives

- Using ocean models to help us interpret tracer observations
  - At what rate and and by which pathways will material entering the ocean at its surface be distributed through its interior?
  - Are current estimates of the ocean uptake of radiatively important anthropogenic trace-gases biased by an incomplete representation of ocean turbulent transport?
- Using tracers to help diagnose and assess ocean model solutions
  - What are the relative roles of the broad-scale time-mean flow, small-scale structures in the mean flow, and turbulent eddies (explicit or parameterized) in transporting material through the ocean interior?

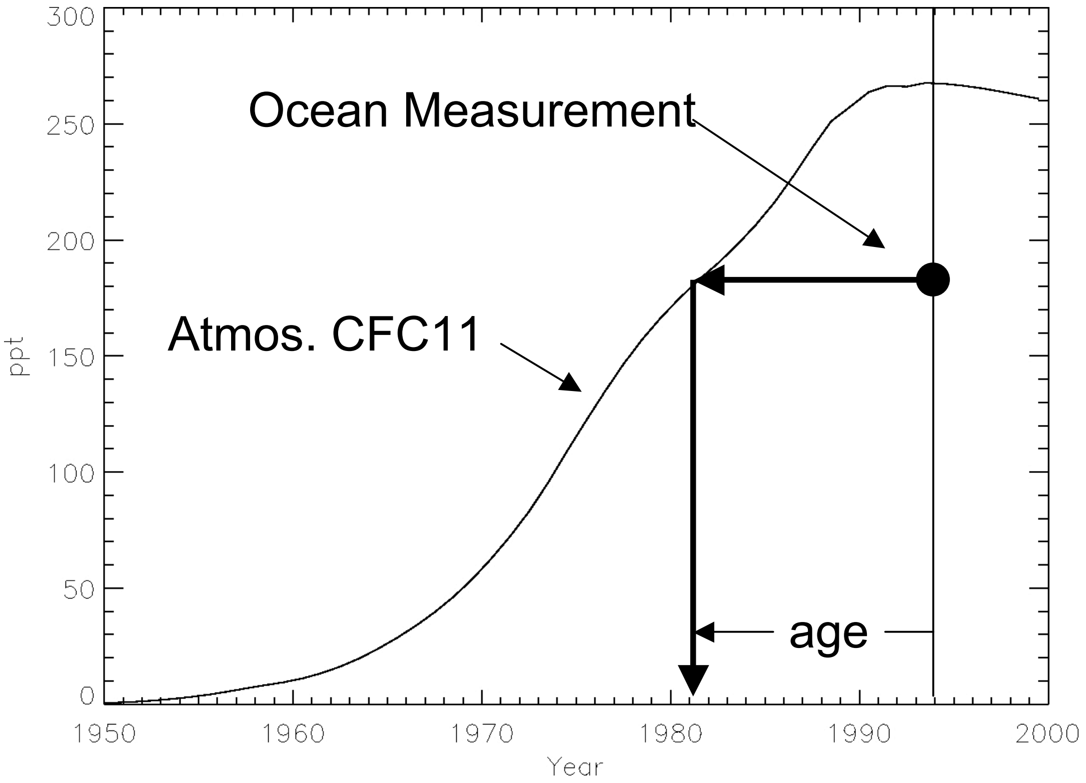
Outline

- Scientific objectives
- Concepts
  - Tracer ages
  - Biases in tracer based age estimates
  - The age spectrum or TTD
- Tracer Observations of Decadal Variability
  - Secular age trends vs. circulation changes
- Using Tracers to Assess Ocean Models
  - TTDs as a model diagnostic

Water Mass “Age”

- The timescale for transport from a boundary (usually the sea surface), to an interior point of the ocean.
- Using T (and L) to characterize of the flow instead of V.
- Closely related to residence time: used in estimates rate of oceanic uptake of material, e.g., $CO_{2,}$ estimating biological productivity (AOU), etc$_.$

pCFC Ages



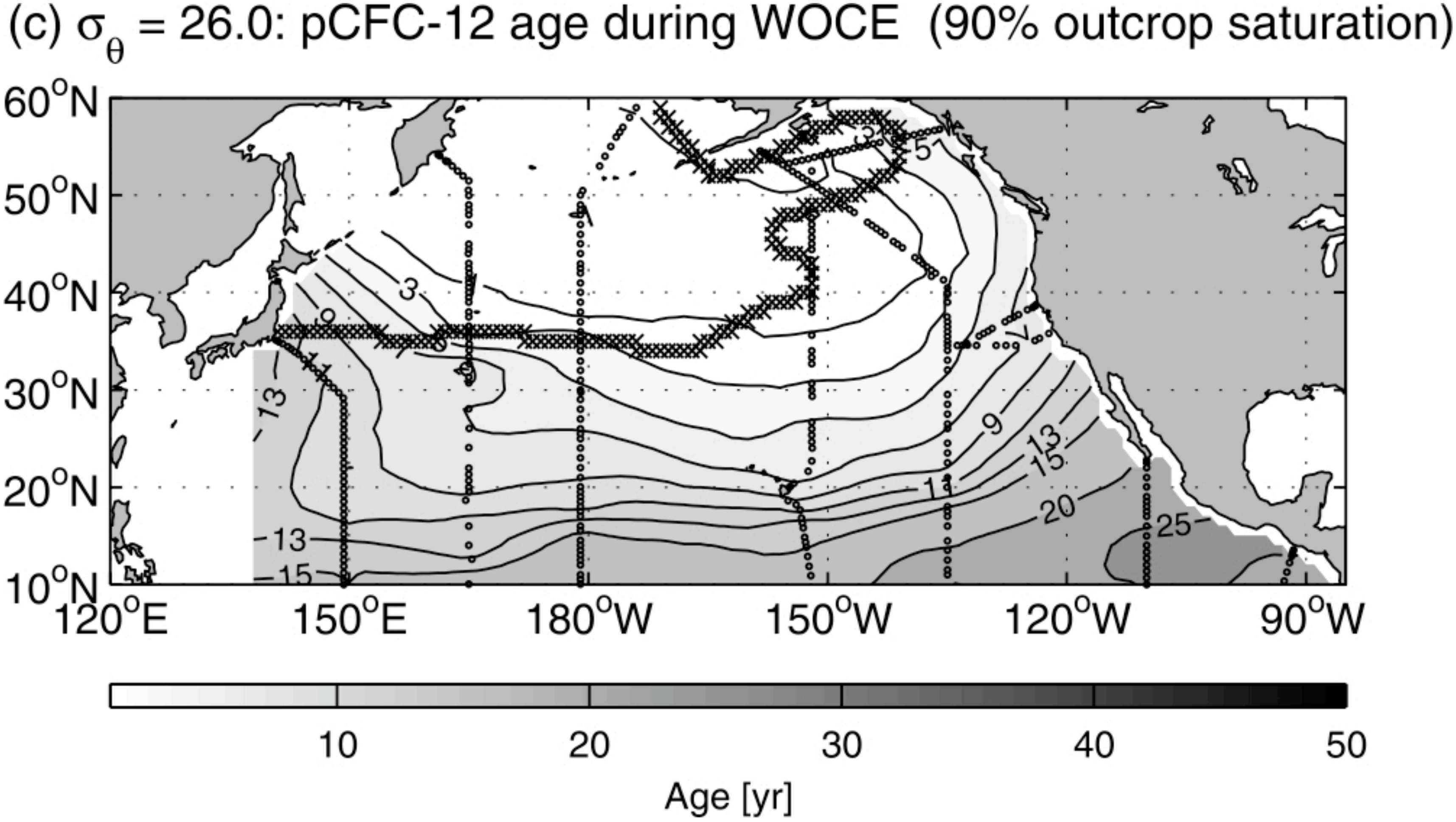
$$pCFC11 = \frac{C}{f_{sat} F_{sol}(\Theta, S)}$$

% Saturation
In Mixed Layer

Solubility

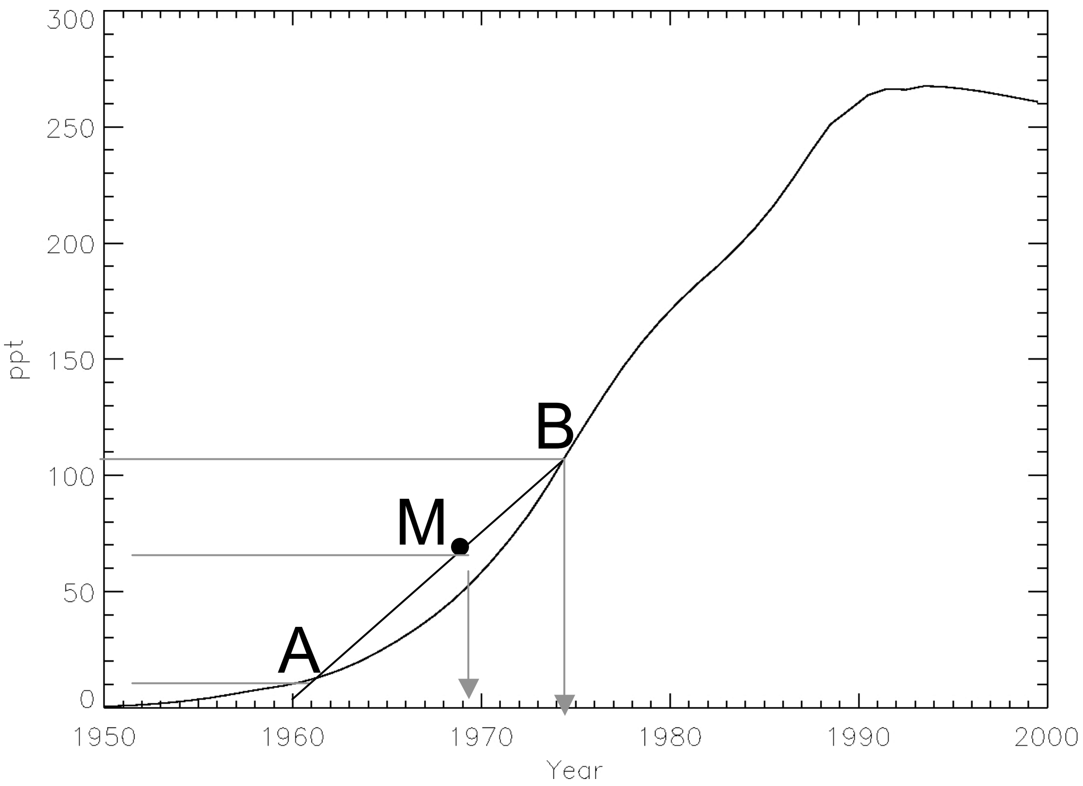
- In 1994 measure:
  - Θ=16.0˚C, S=35.75psu, CFC11=1.95 pmol/kg
- pCFC11 =180.3 ppt
- Water parcel subducted in 1981
- Age = 13 years

Ages in N. Pacific Thermocline



Mecking et al (2004)

So Simple. What Could Go Wrong?



	A	B	Mix
pCFC11	10	110	60
Age (1994)	34	19.5	24
26.75≠24			

- For nonlinear atmos. history mixing biases pCFC age:
  - +ve curvarture ~ young
  - -ve curvature ~ old
- Different tracers will yield different ages: Tracers ages are not a fundamental property of the flow

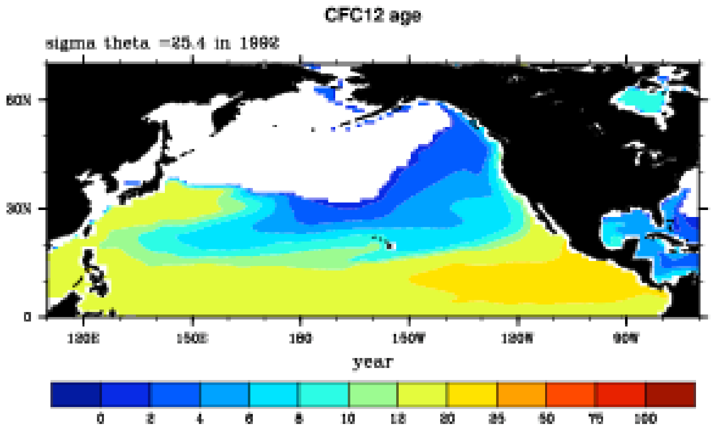
A Modelers Solution: Ideal Age

$$\frac{\partial A}{\partial t} = -u \bullet \nabla A + \nabla \kappa \nabla A + 1$$

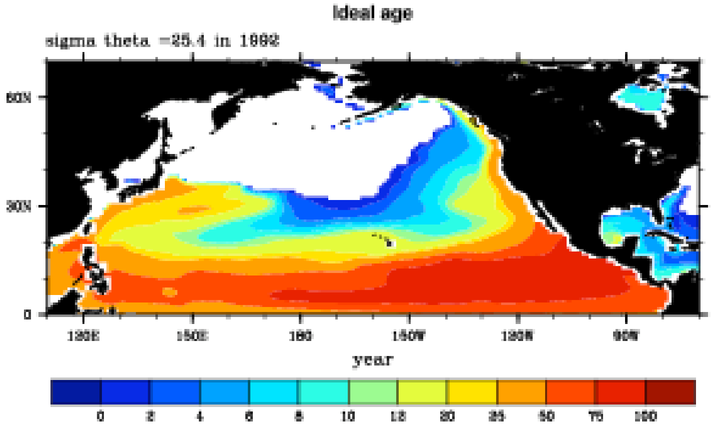
$$A(z=0) = 0$$

- Linear source ~ age mixes linearly
- Not directly observable, but easily modeled

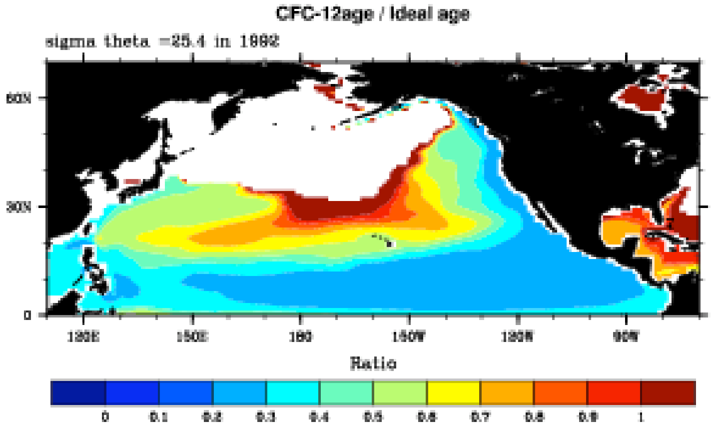
From a 500 yr.
simulation
w/ CCSM Ocean
Component Model



pCFC12
Age



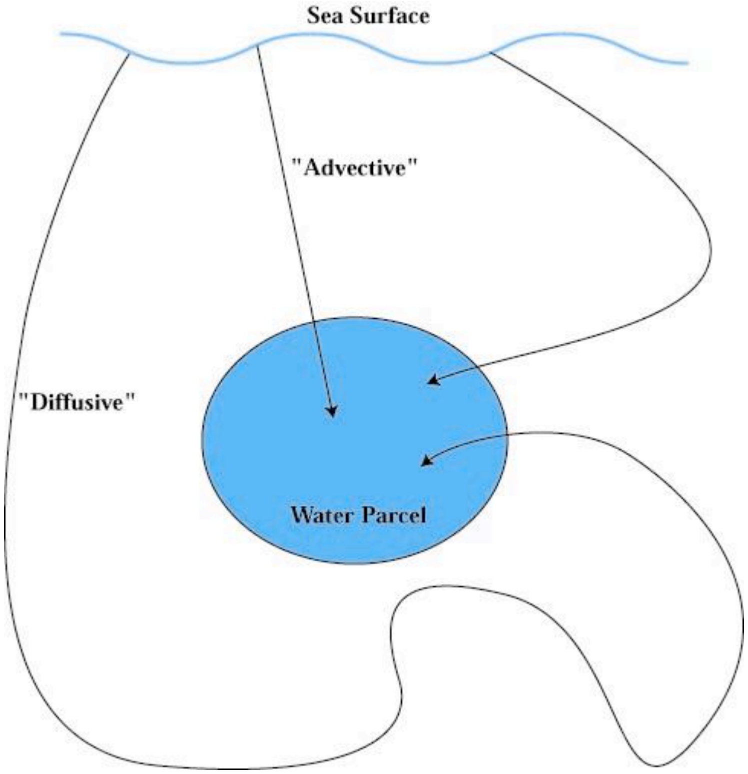
Ideal
Age



Ratio

A Better Solution: Transit Time Distributions

- Recognize that mixing is a fundamental property of the oceanic circulation.
- A water mass is composed of a mixture of parcels with different ages.
- Seek the PDF of age, not just the mean age.



Khatiwala et al., (2000)

TTD Formalism:
Connection to Green’s Functions

The solution of the advection-diffusion equation:

$$\frac{\partial \chi}{\partial t} + L(\chi) = 0 \qquad \chi(\Omega, t) = \chi_\Omega(t)$$

Can be written:

$$\chi(r,t) = \int_{-\infty}^{t} \chi_\Omega(\xi) G(r,t;\Omega,\xi)\, d\xi$$

“Boundary Propagator”

where

$$\frac{\partial G}{\partial t} + L(G) = 0 \qquad G(\Omega, t, \xi) = \delta(t-\xi)$$

For steady flow, G is independent of t:

$$\chi(r,t) = \int_{0}^{\infty} \chi_\Omega(t-\tau) G_\Omega(r,\tau)\, d\tau$$

“TTD”

1D Example

For constant velocity U, diffusivity K:

$$\frac{\partial \chi}{\partial t} + U\frac{\partial \chi}{\partial z} - K\frac{\partial^2 \chi}{\partial z^2} = 0$$

The analytical solution is given by an "*Inverse Gaussian*":

$$G(z,t) = \frac{z}{2\sqrt{\pi K t^3}}\exp\left[\frac{-(ut-z)^2}{4Kt}\right] = \frac{\Gamma}{2\Delta\sqrt{\pi t^{*3}}}\exp\left[\frac{-\Gamma^2\left(t^*-1\right)^2}{4\Delta^2 t^*}\right]$$

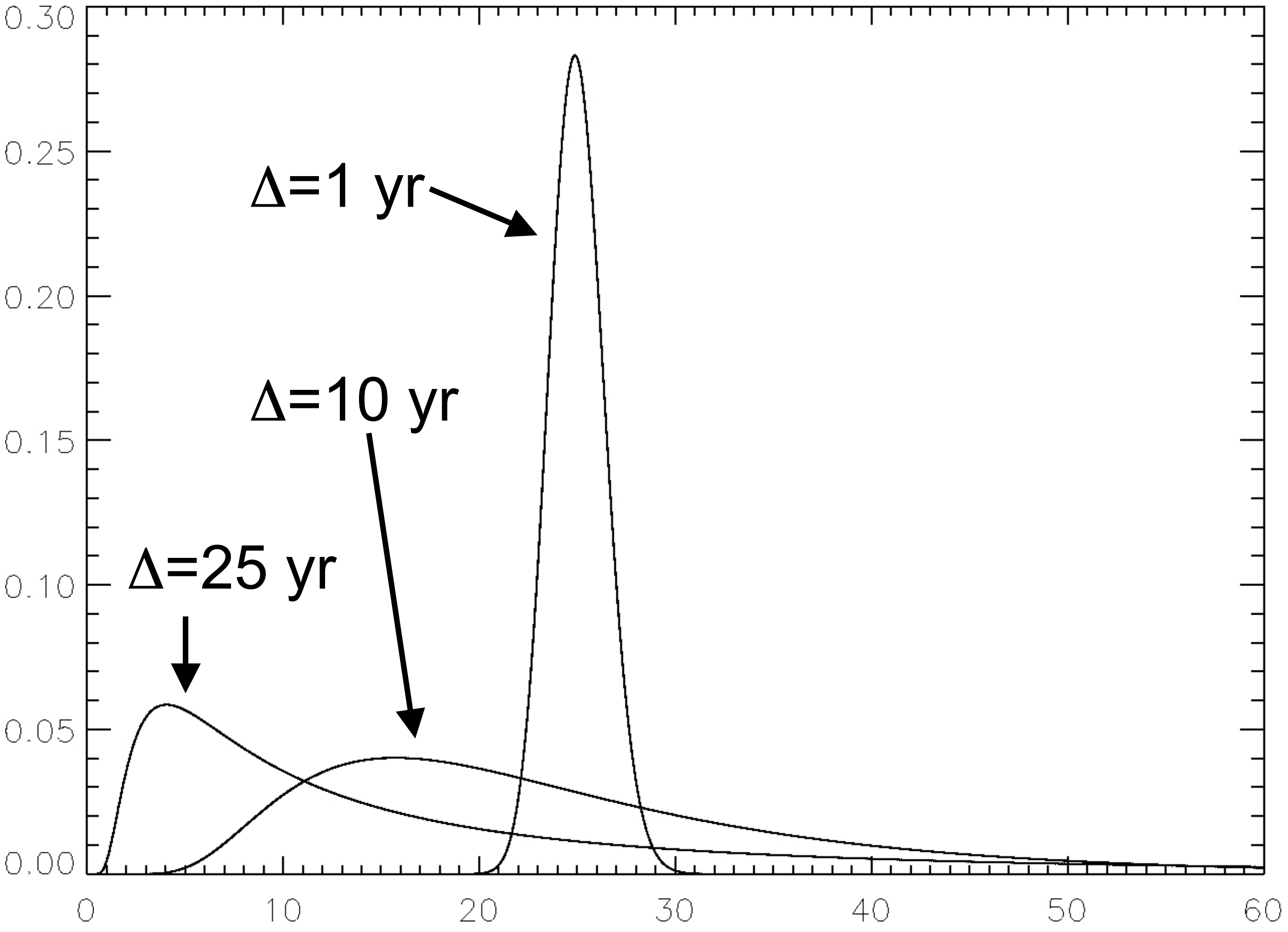
$\Gamma = \frac{z}{U}$ Mean age

$\Delta = \sqrt{\frac{Kz}{U^3}}$ Width

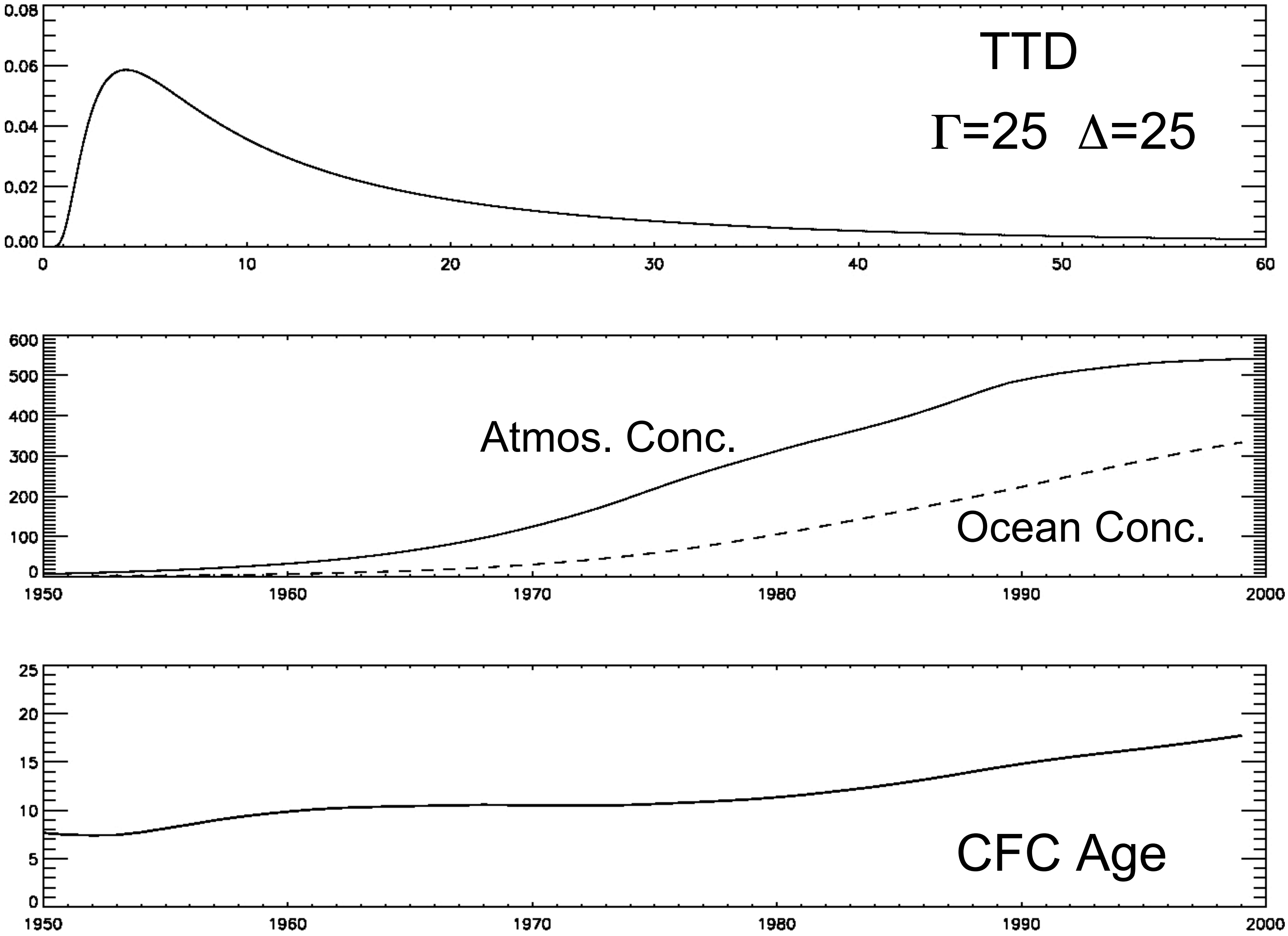
$Pe = \frac{Uz}{K} = \frac{\Gamma^2}{\Delta^2}$ Peclet Number

Example Inverse Gaussians

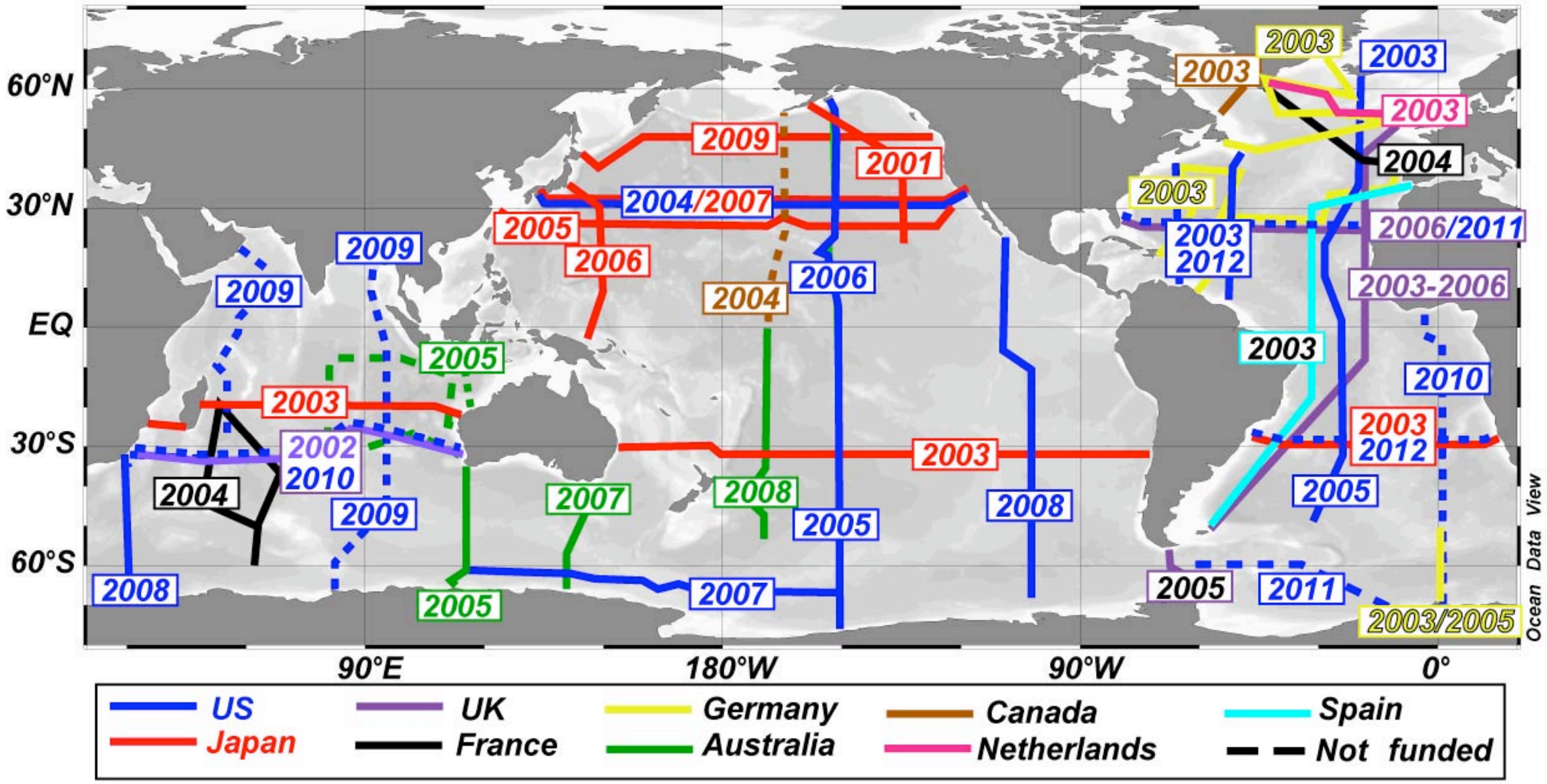
Γ=25 years



Age Changes For Steady Flow

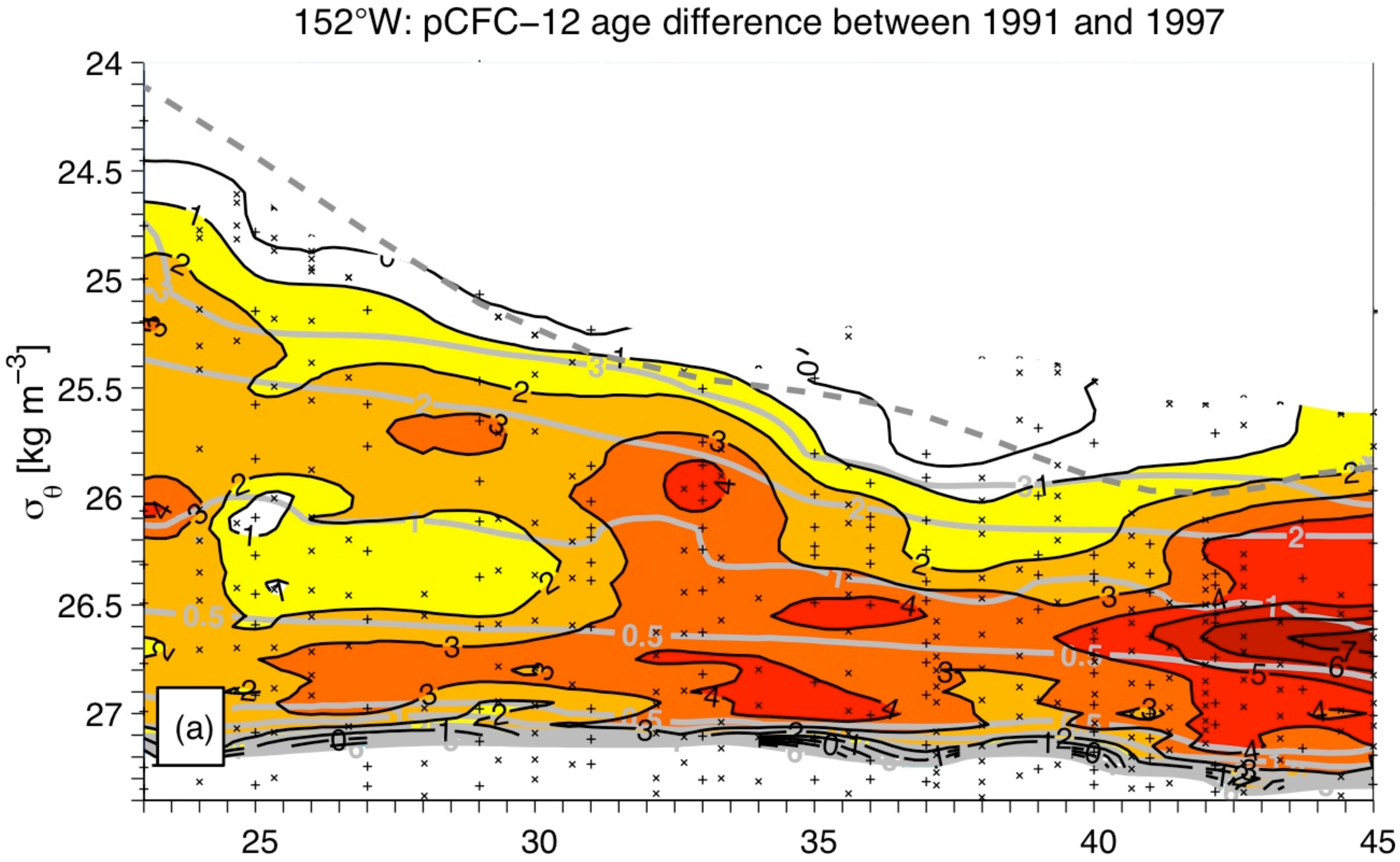


Case Study: Variability in N. Pacific Ventilation Rates



- How do true age changes resulting from changes in circulation compare with tracer age drifts related to nonlinearities in atmos. history?

Observed Change in CFC Age

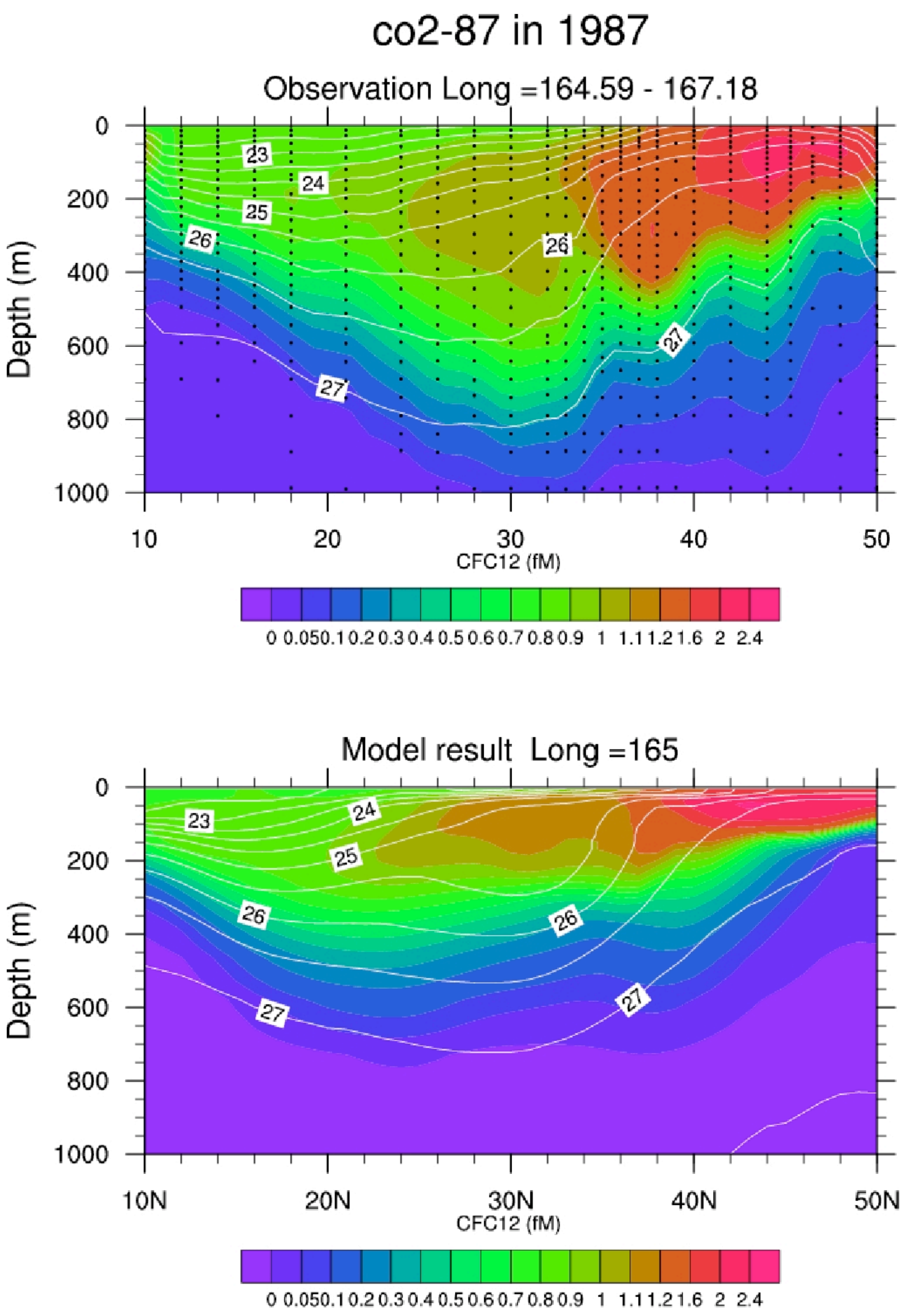


Mecking et al (2006)

CCSM Ocean Component

- Derivative of LANL POP model
- Curvilinear orthogonal grid: Greenland dipole
- 1˚ (0.3˚ at equator), L40
- KPP boundary layer
- Anisotropic viscosity
- Isotropic GM eddy-mixing
- NCEP reanalysis based daily avg. surface forcing 1958-2000
- Integrated ~500 years from obs. Climatology
- CFCs included for final 70 years

CFC-12 165˚E

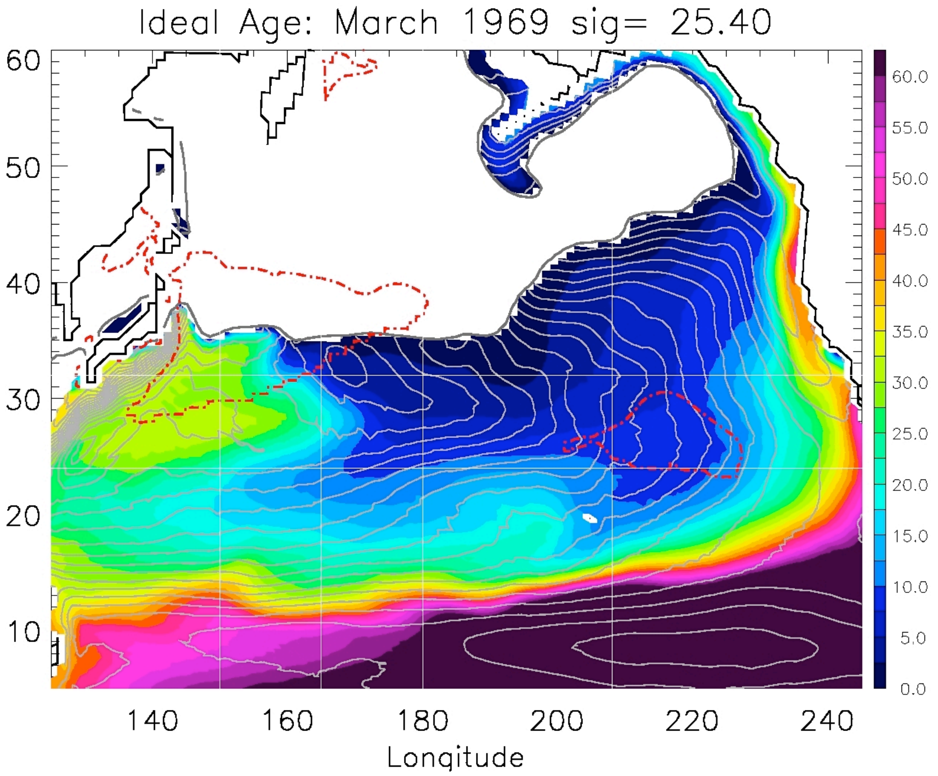


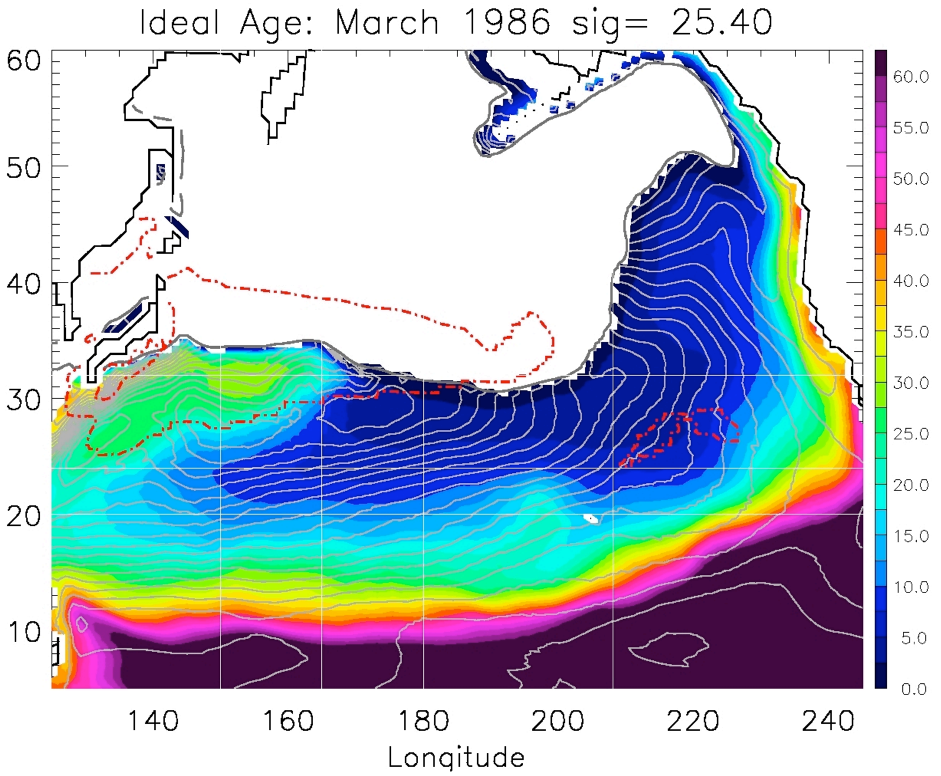
co2-87 in 1987

Observation Long =164.59 - 167.18

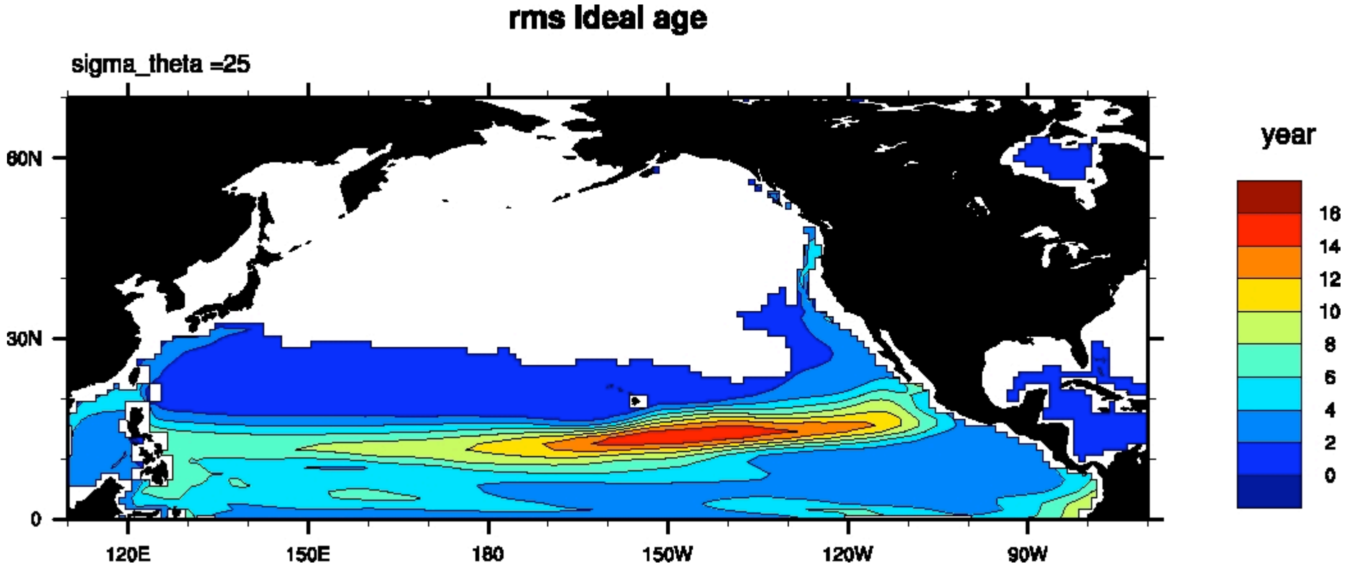
Model result Long =165

Increased Ventilation Following Late 1970’s PDO Shift

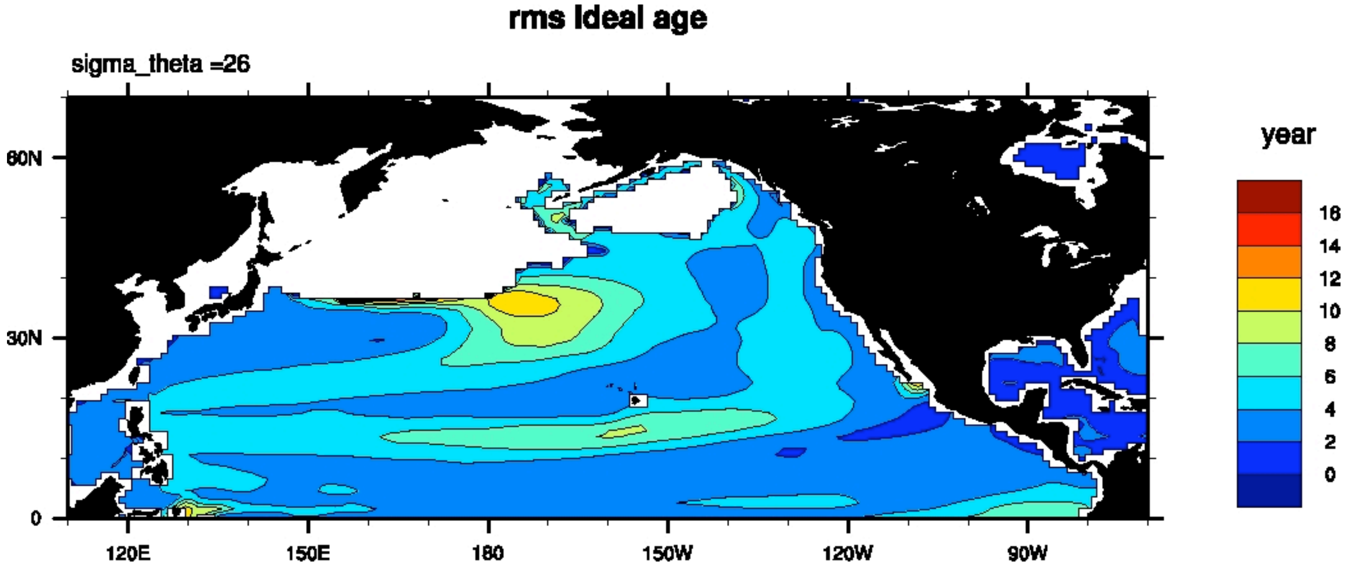




RMS Variability of Ideal Age

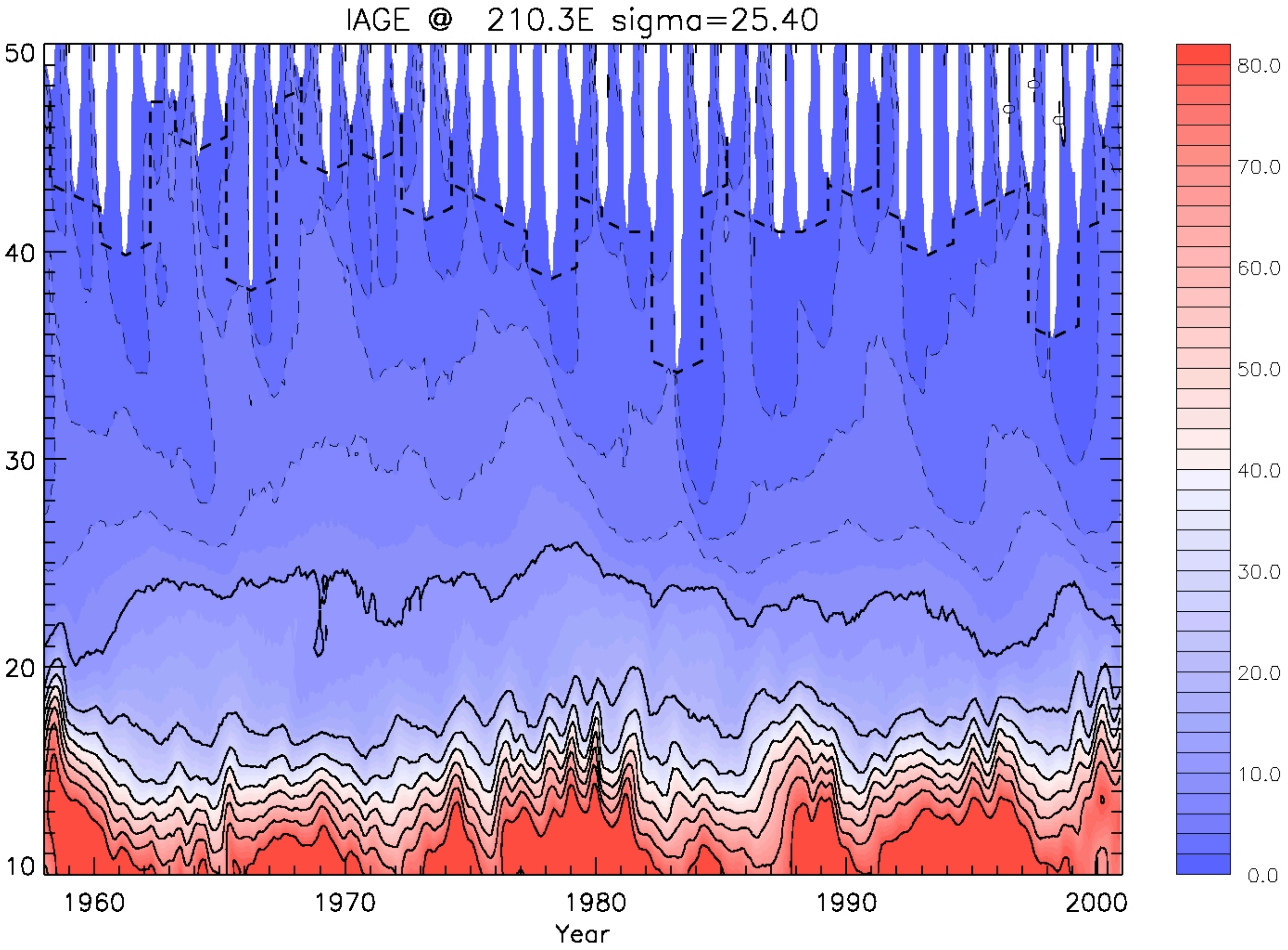

rms Ideal age

sigma_theta =25

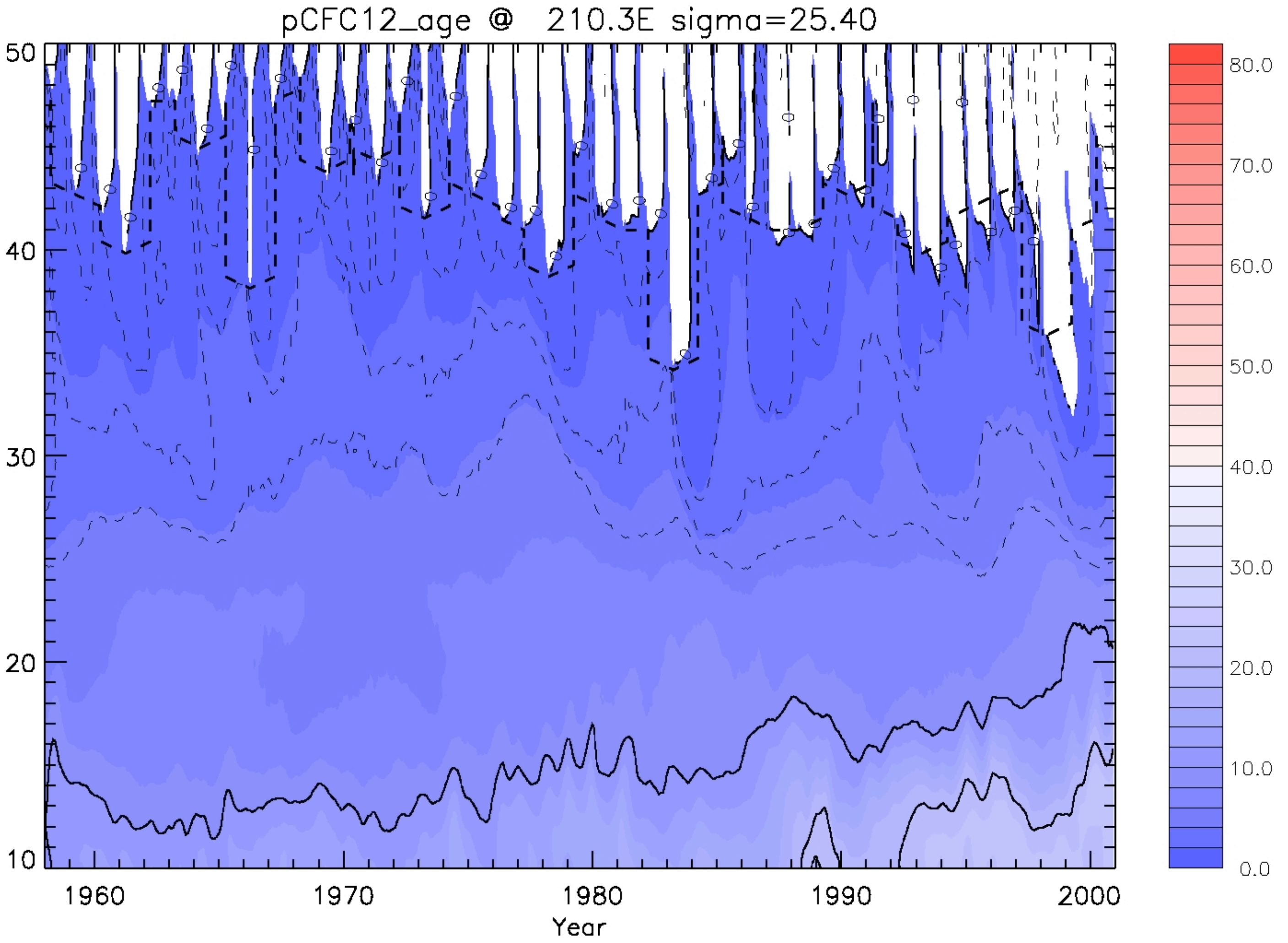

rms Ideal age

sigma_theta =26

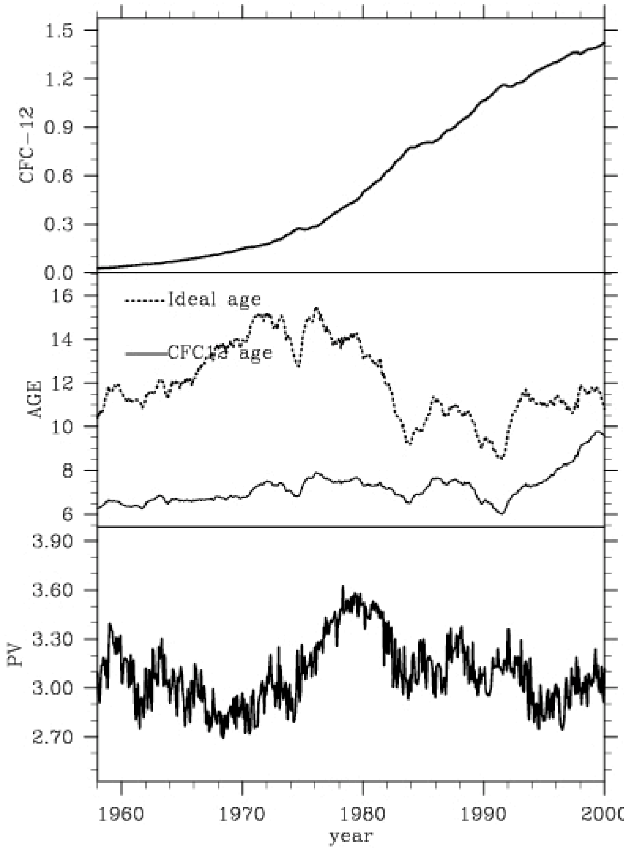
Ideal Age 152˚W σ_θ=25.4



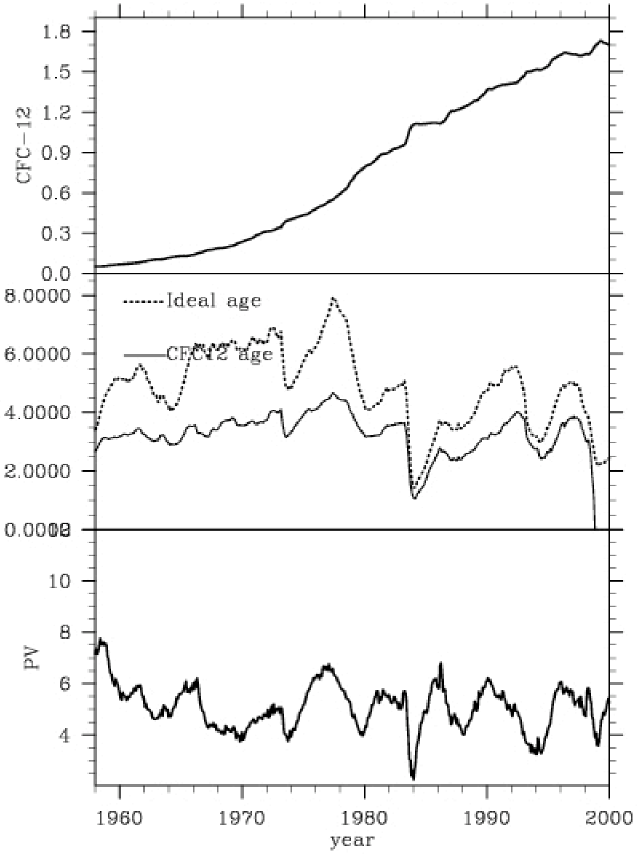
pCFC-12 Age 152˚W σ_θ=25.4



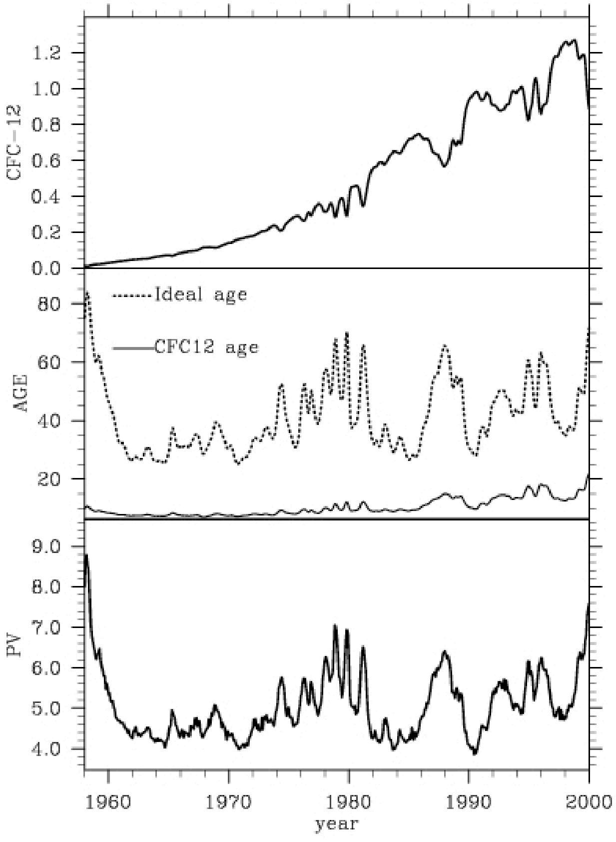
pCFC Age Variability Compared to Ideal Age Variability



(20N,165E)



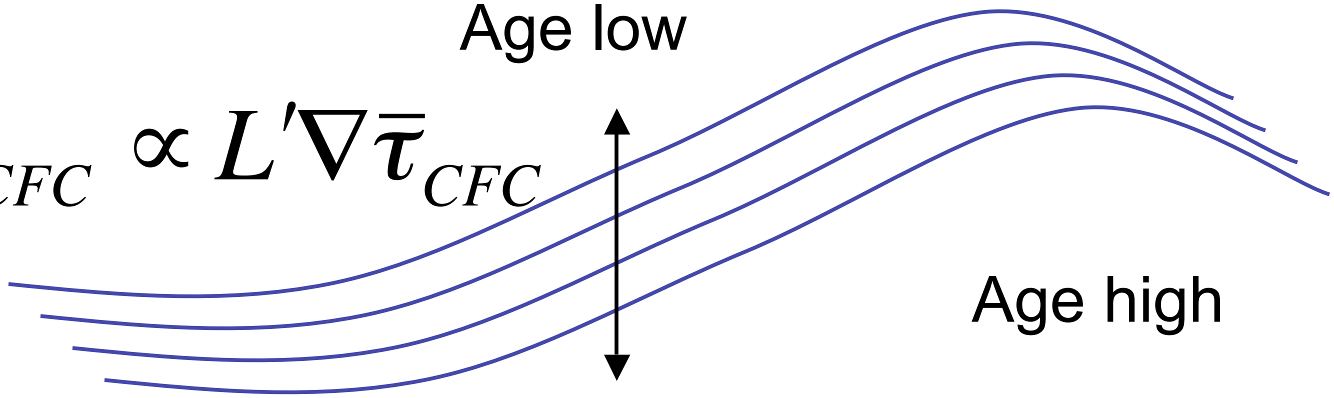
(30N,150W)



(15N,150W)

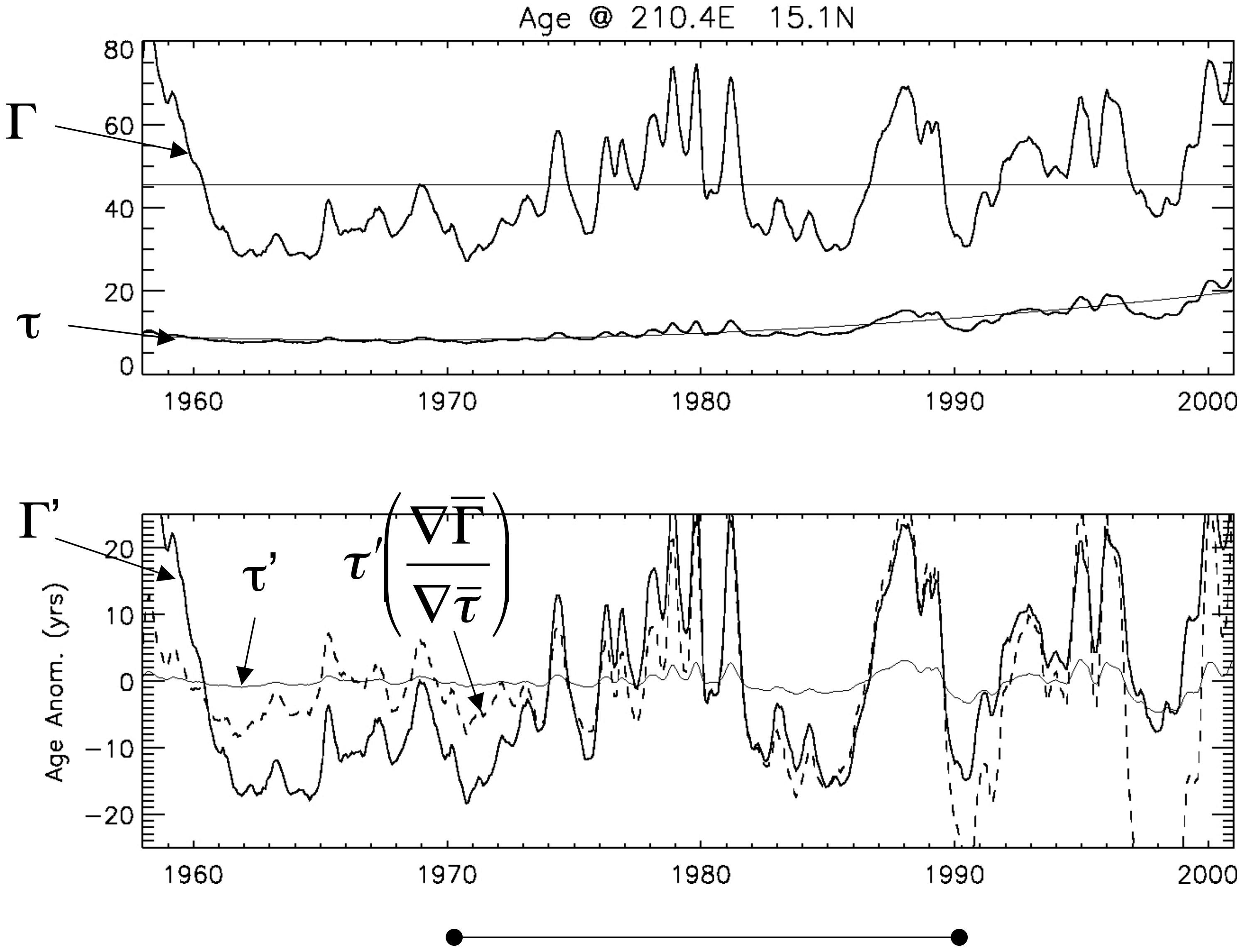
Why Does RMS pCFC Age Underestimate RMS Ideal Age?

- Spatial gradients in age bias



$$\tau'_{CFC} \propto L' \nabla \overline{\tau}_{CFC}$$

$$\tau'_{CFC} \propto \Gamma' \left(\frac{\nabla \overline{\tau}_{CFC}}{\nabla \overline{\Gamma}} \right)$$

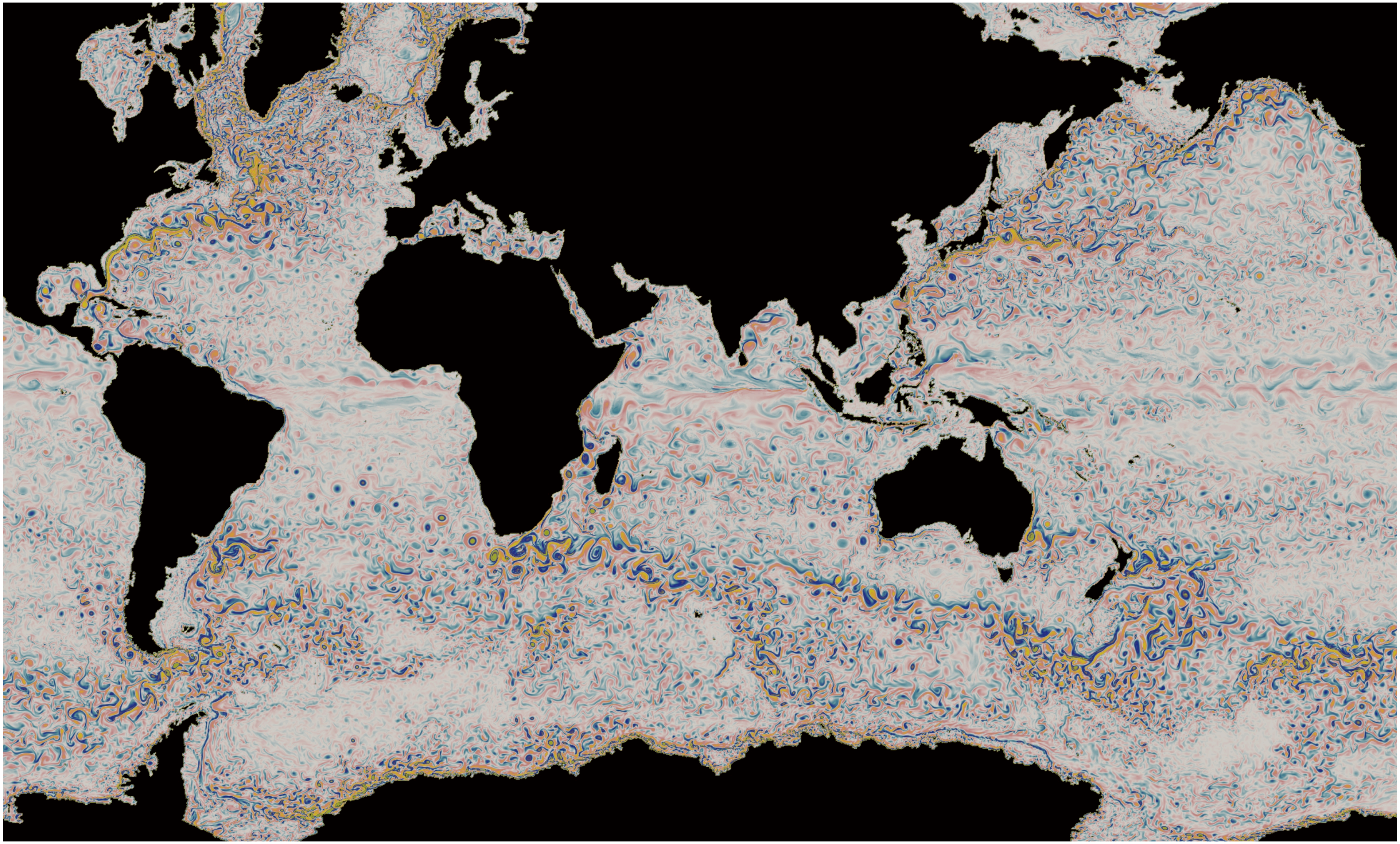


Age @ 210.4E 15.1N
Γ
τ
0
20
40
60
80
1960
1970
1980
1990
2000
Γ'
τ'
$\tau'\left(\frac{\nabla\bar{\Gamma}}{\nabla\bar{\tau}}\right)$
Age Anom. (yrs)
−20
−10
0
10
20
1960
1970
1980
1990
2000

Summary of Case Study

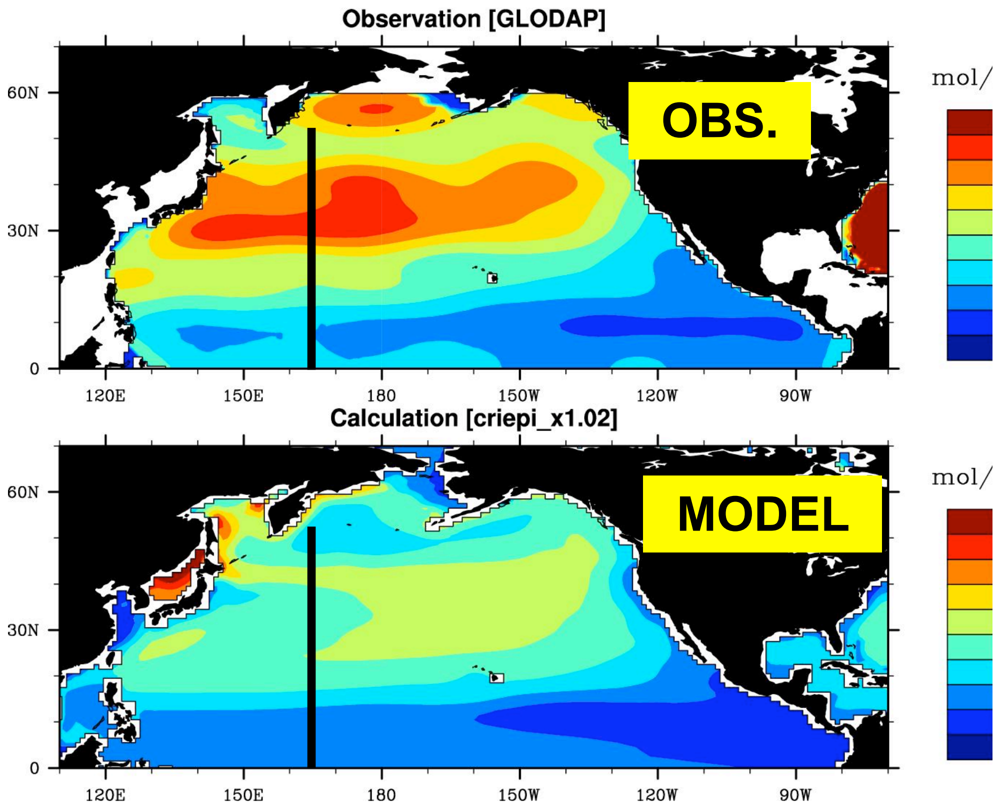
- pCFC ages are biased low nearly everywhere in the N. Pacific
- The pCFC age bias changes with time - The trend in the thermocline is such as to lead to the appearance of enhanced ventilation.
- Spatial gradients in the bias lead to an underestimate of changes in age resulting from water mass displacements.

Computing the Global Surface TTD With An Eddy Rich OGCM

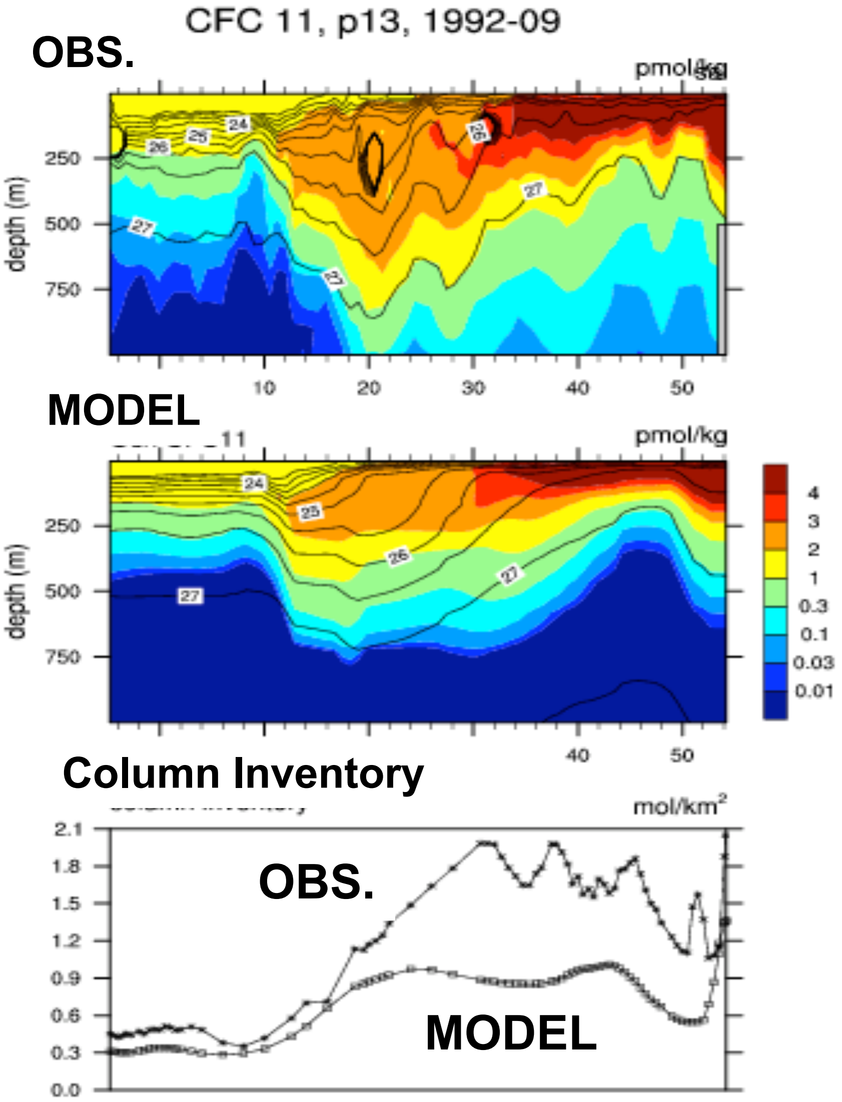


How Do We Attribute Biases in Tracer Simulations to Deficits in Specific Processes?

CFC-11 Inventory in 1994



Tsumune et al., submitted



Eddy-Resolving (0.1˚) Model Configuration

- Similar to the POP configuration of Maltrud and McClean (2005)
- Modified by:
  - Partial bottom cells
  - Tripole grid
  - Lower explicit horizontal diffusivity of T&S
  - Large-Yeager normal year “CORE” forcing
  - Flux-limited advection and zero explicit diffusion for passive tracers

Low (~1˚) Resolution Models for Comparison

CCSM 3.0

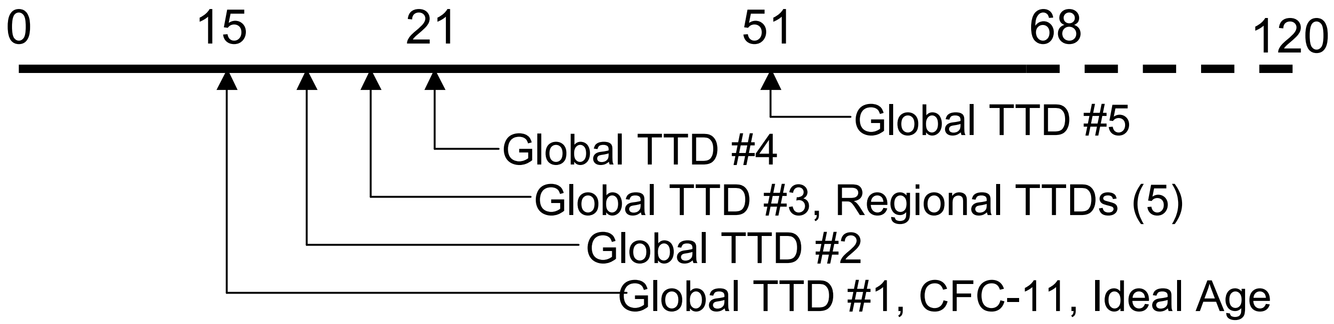
- 40 levels
- KPP with Bryan-Lewis IW mixing profile
- Constant κ GM
- Anisotropic viscosity with Smagorinsky dependence

CCSM 3.5

- 60 levels
- Abyssal tidal mixing
- Near surface eddy flux and N^2 dependent κ
- Anisotropic viscosity without Smagorinsky

Tracer Experiment Design

- 0.1˚ Experiment



Global TTD #5

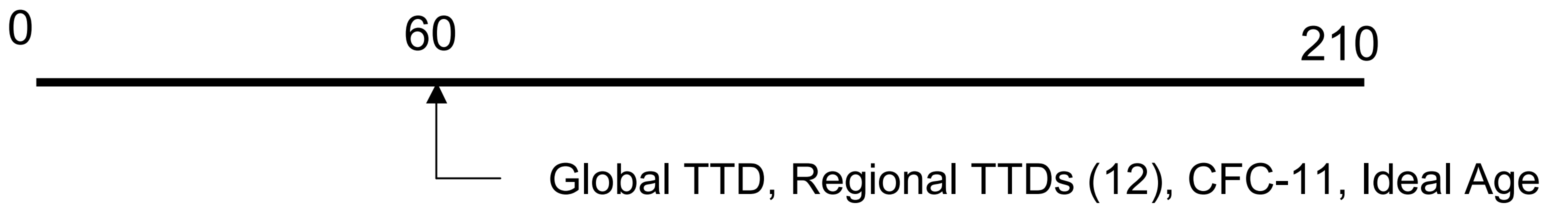
Global TTD #4

Global TTD #3, Regional TTDs (5)

Global TTD #2

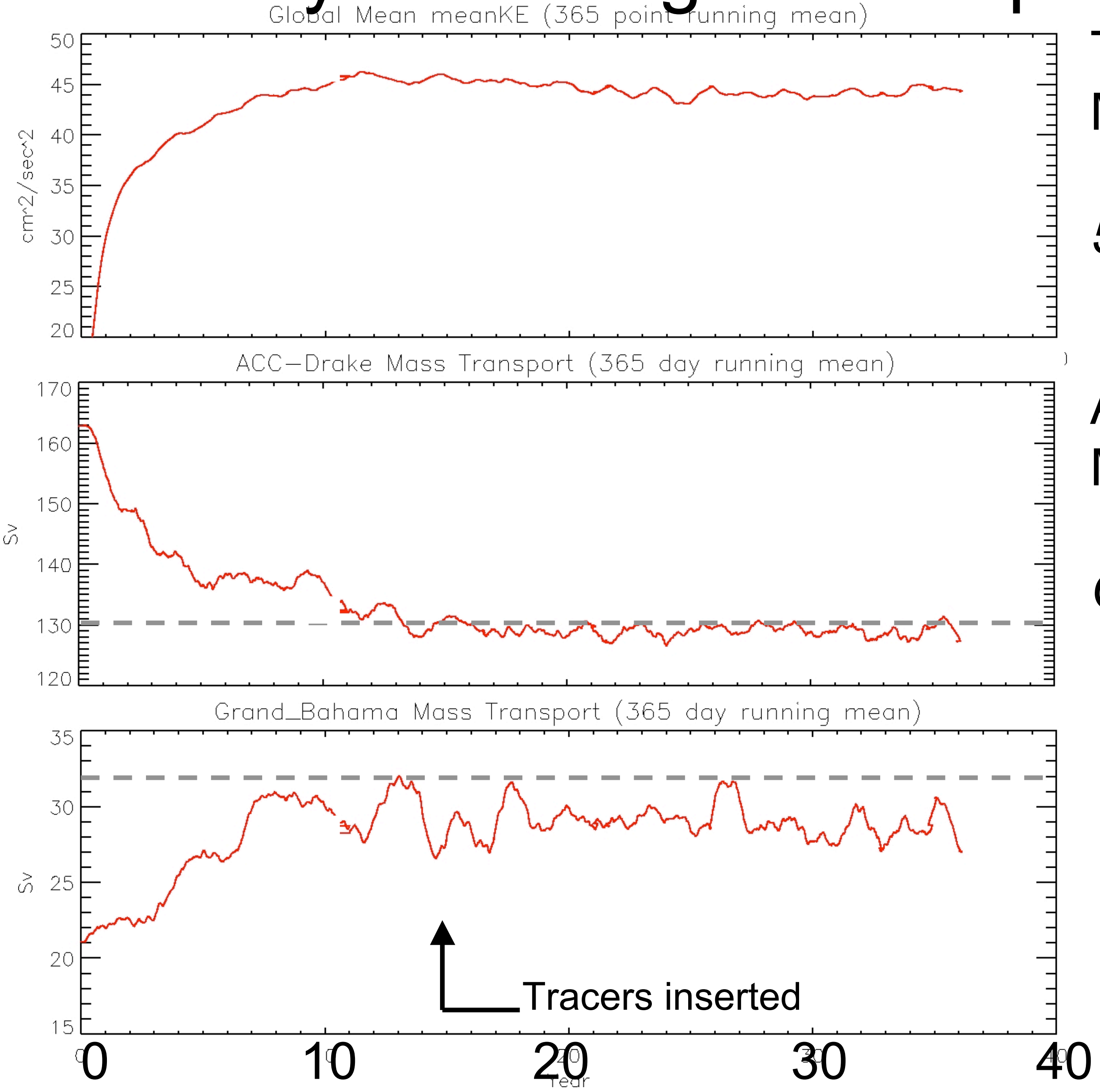
Global TTD #1, CFC-11, Ideal Age

- 1.0˚ Experiments



Global TTD, Regional TTDs (12), CFC-11, Ideal Age

Eddy Resolving Model Spin-Up



Total KE
Mean=44cm^2/s^2

50% > MM

ACC
Mean=129.1 Sv

Obs ~ 130 Sv

Florida Sts
Mean=29.0 Sv

Obs ~ 32 Sv

Moments of the TTD

By definition:

$$1 \equiv \int_0^\infty G(\tau)d\tau$$

Hall and Haine (2002) show that
1st momentconverges to ideal age

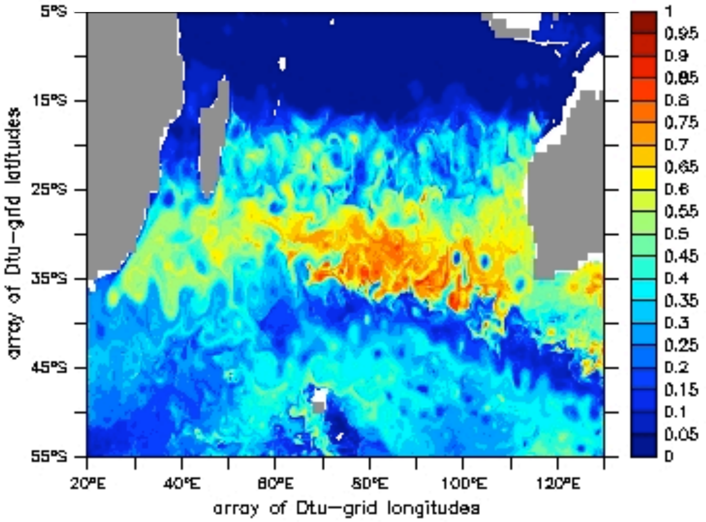
$$\Gamma \equiv \int_0^\infty \tau G(\tau)d\tau$$

Width is given by the
second centered moment

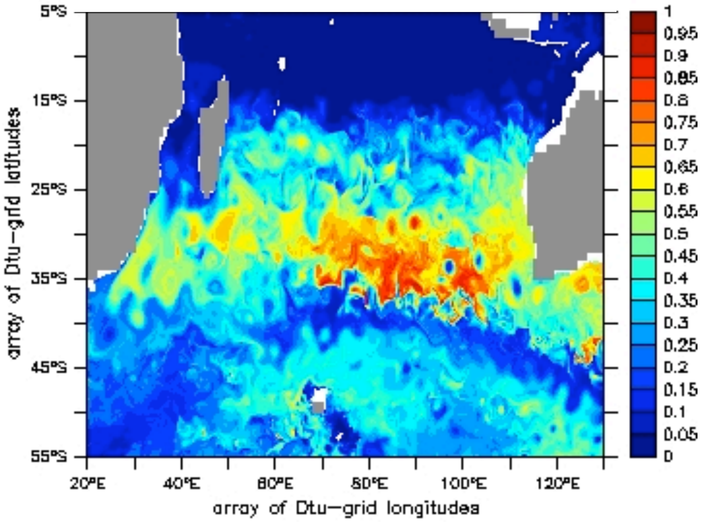
$$\Delta^2 \equiv \frac{1}{2}\int_0^\infty (\tau - \Gamma)^2 G(\tau)d\tau$$

Global TTD 250m (End of Year 2)

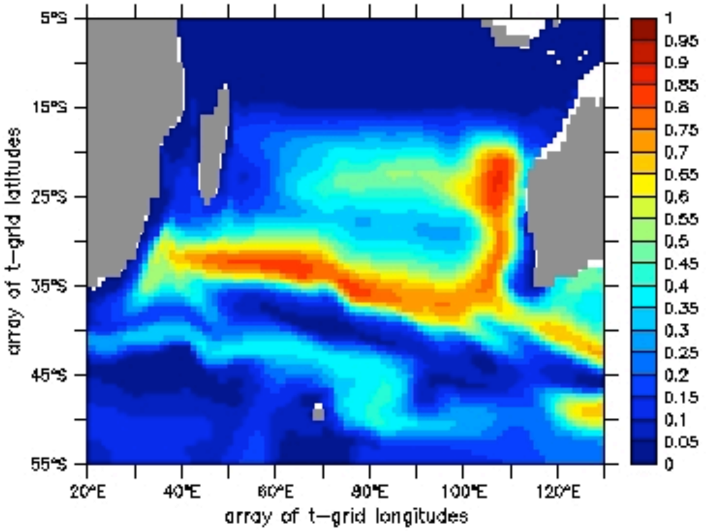
Hi-Res Member A



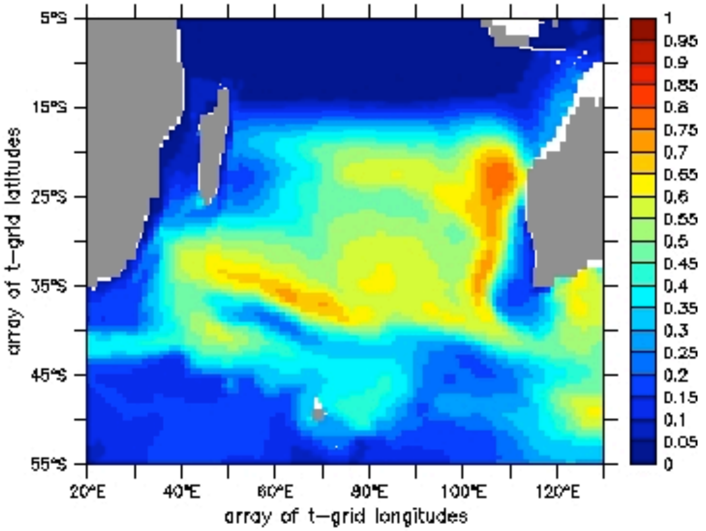
Hi-Res Member B



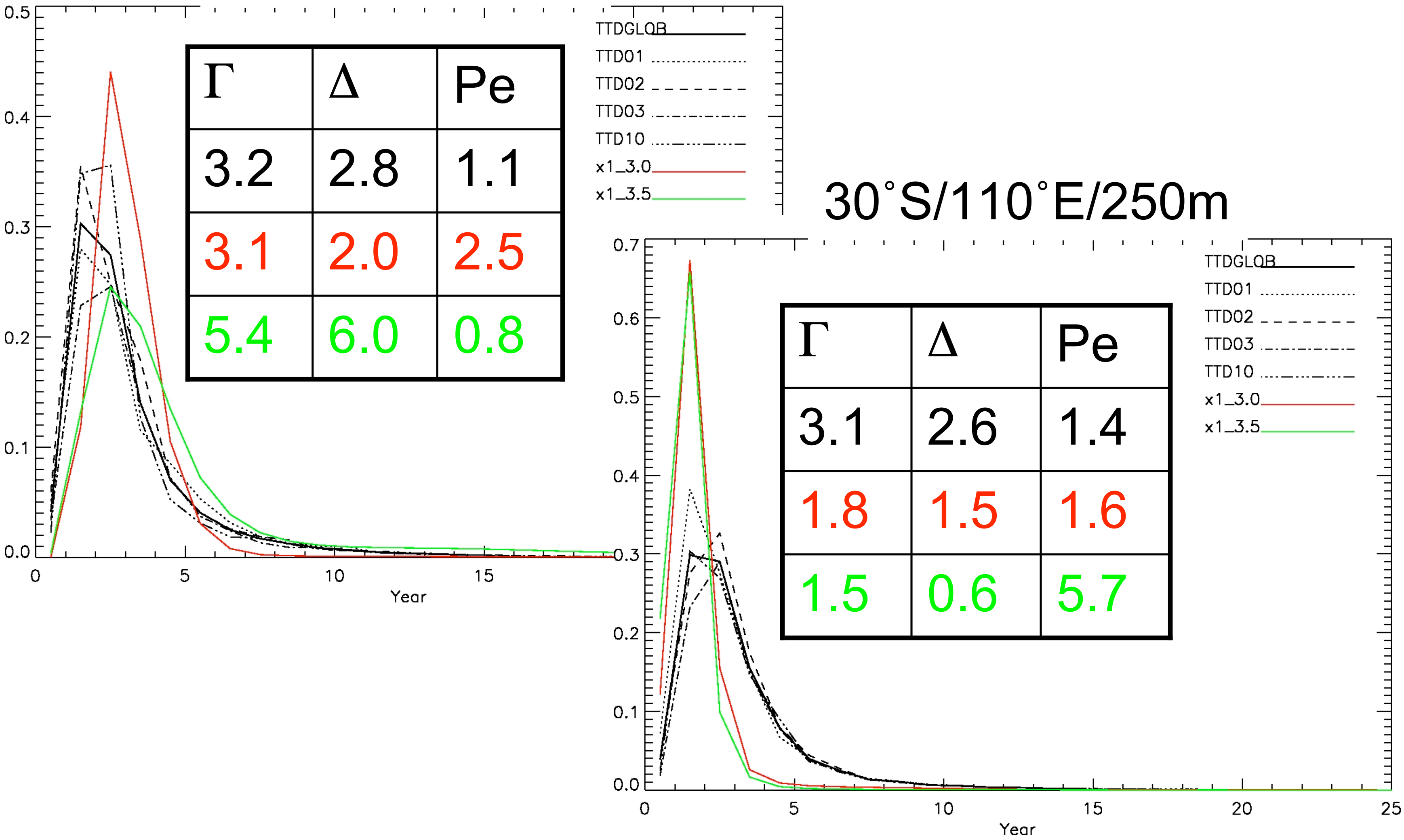
CCSM 3.0



CCSM 3.5



TTD History Indian Ocean Thermocline



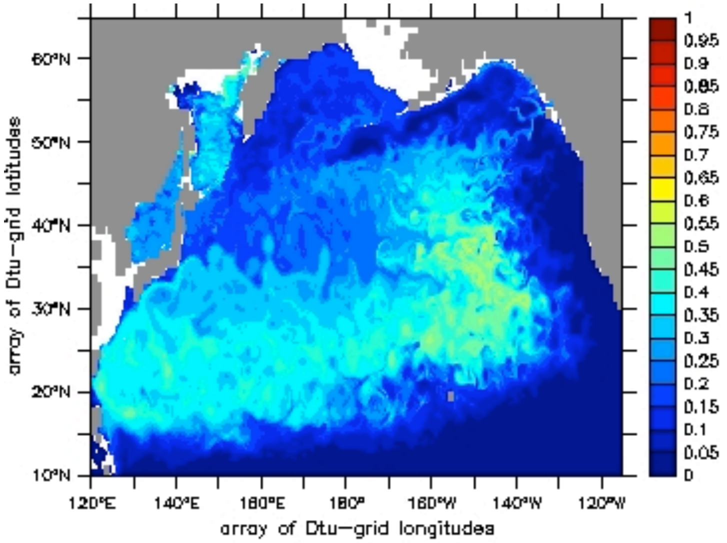
30˚S/60˚E/250m

Γ	Δ	Pe
3.2	2.8	1.1
3.1	2.0	2.5
5.4	6.0	0.8

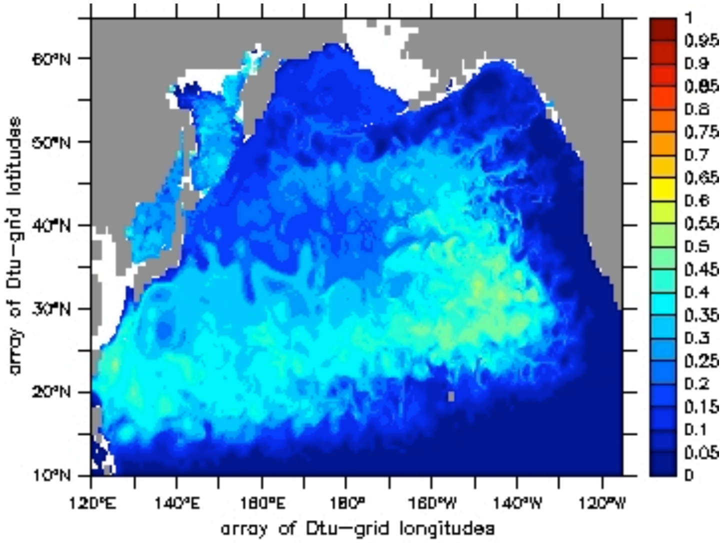
30˚S/110˚E/250m

Γ	Δ	Pe
3.1	2.6	1.4
1.8	1.5	1.6
1.5	0.6	5.7

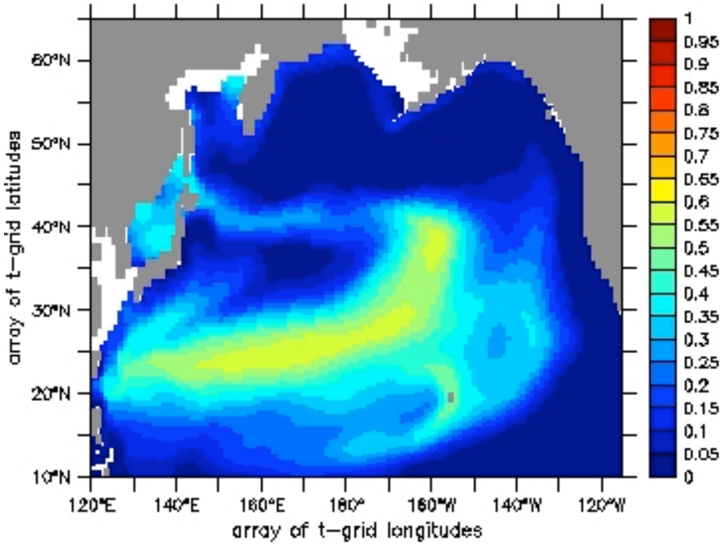
Year 3 Global TTD @ 250m



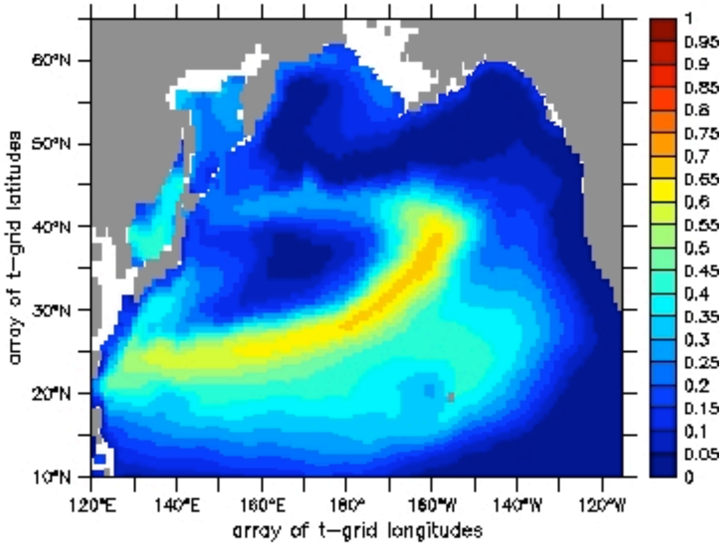
TTD~0.5, Hires A



TTD~0.5, Hires B

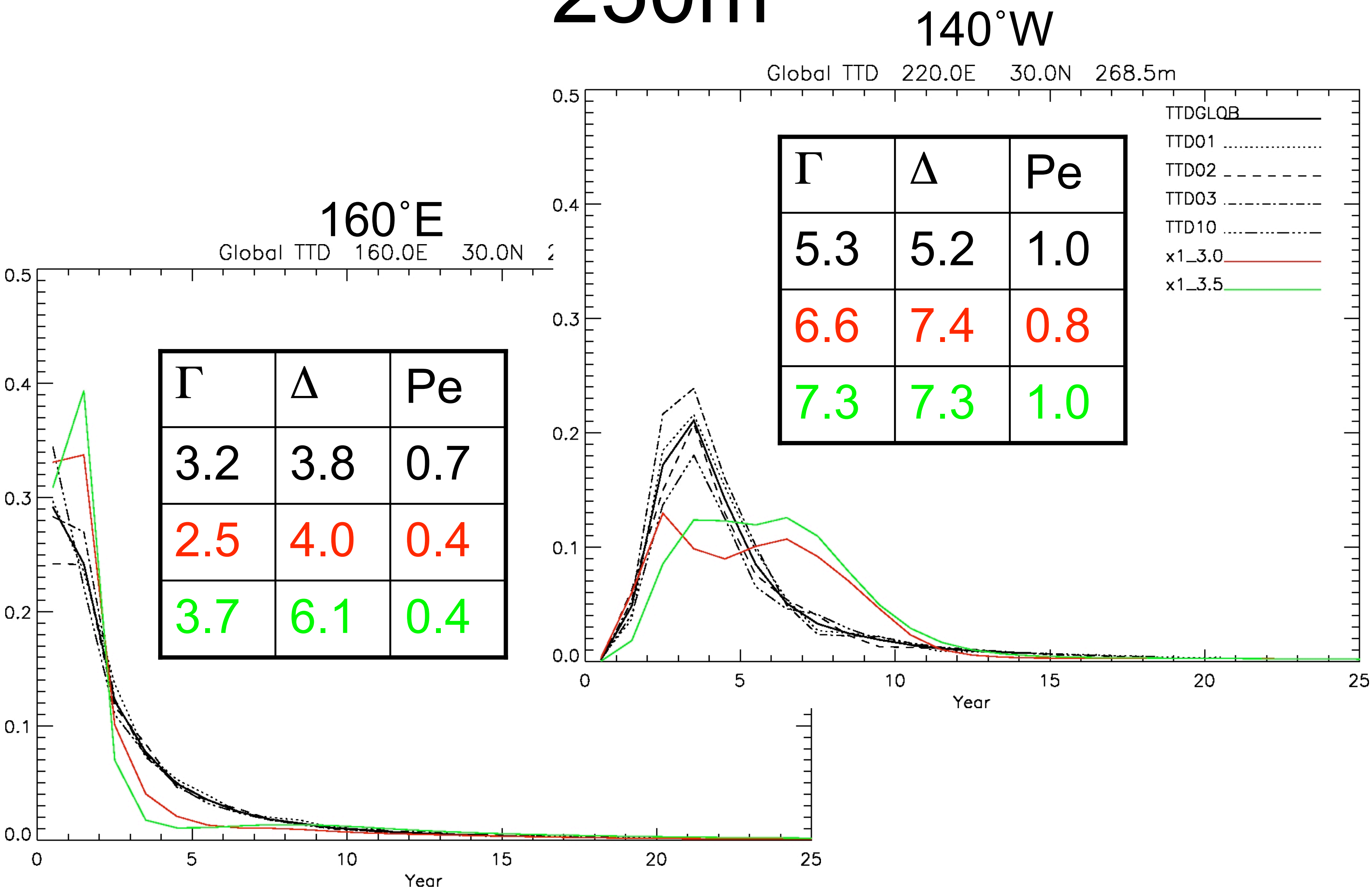


TTD~0.5, CCSM3.0



TTD~0.5, CCSM3.5

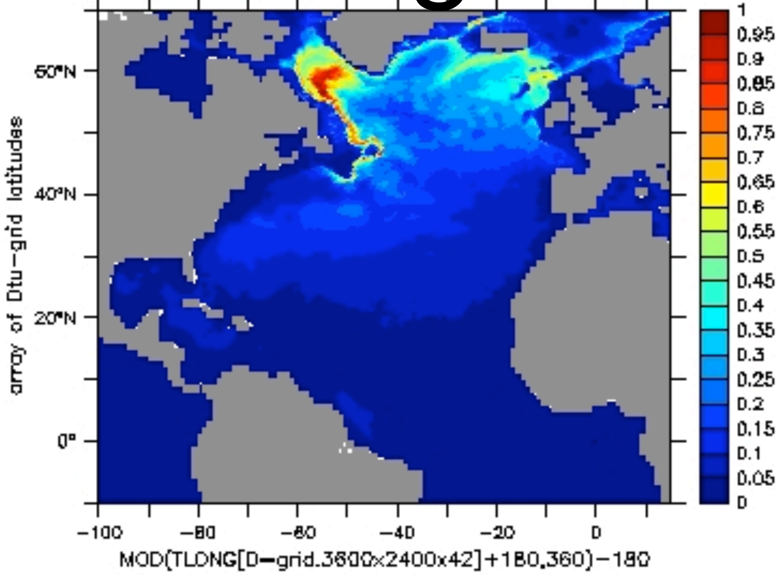
Global TTD History at 30N 250m



Γ	Δ	Pe
3.2	3.8	0.7
2.5	4.0	0.4
3.7	6.1	0.4

Γ	Δ	Pe
5.3	5.2	1.0
6.6	7.4	0.8
7.3	7.3	1.0

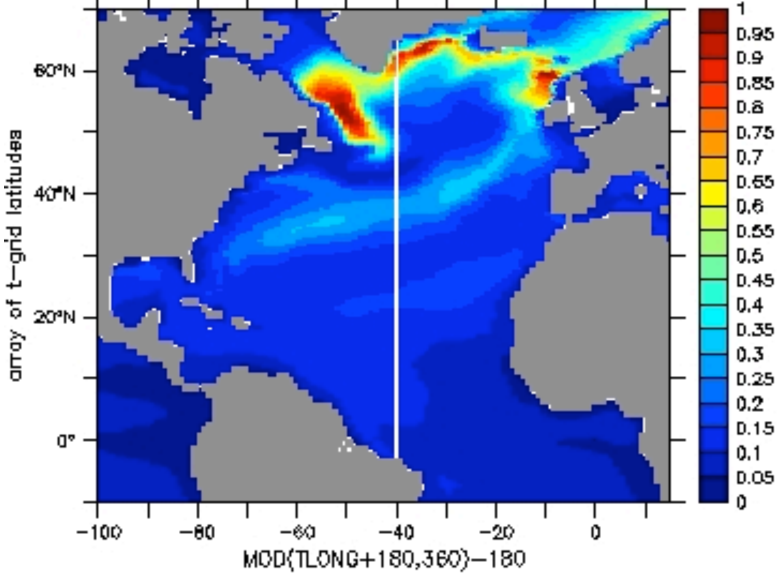
Column Integrated TTD



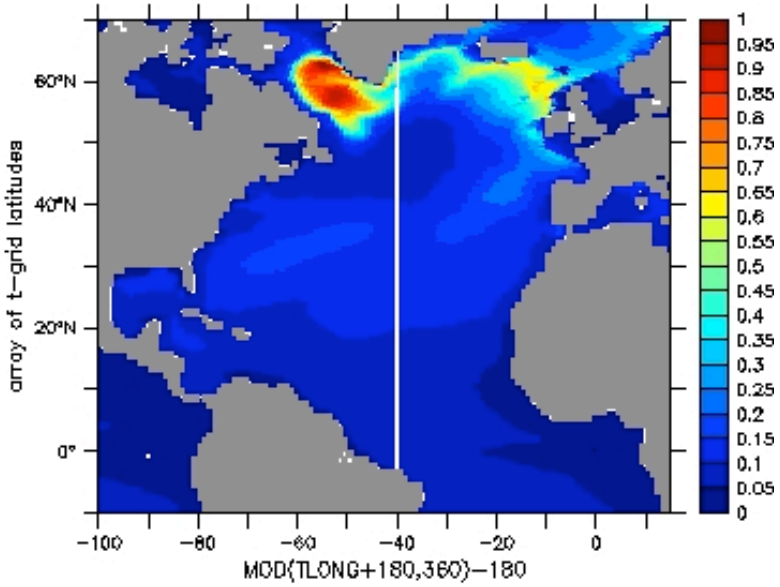
TTD vert int, Hires A

0.1° Model

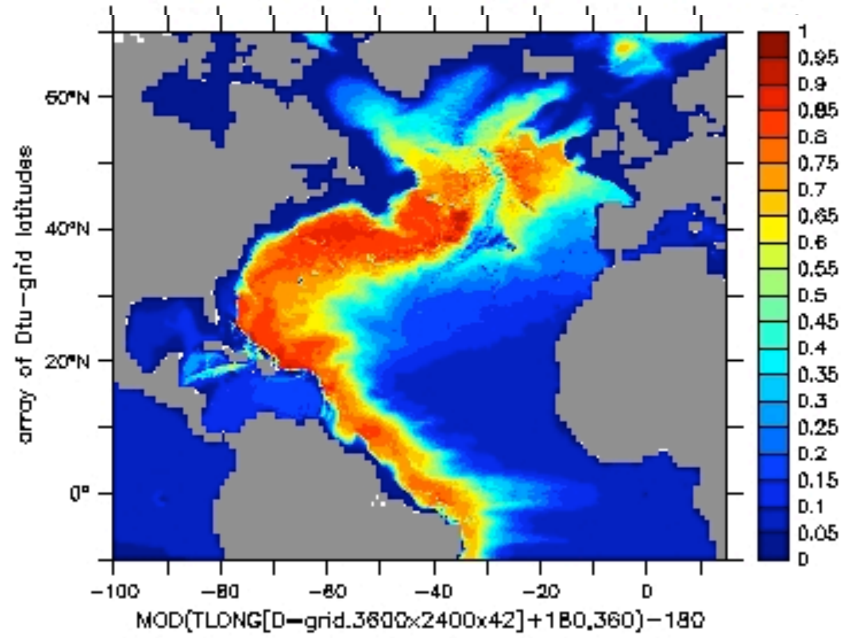
1° v3.0 Model



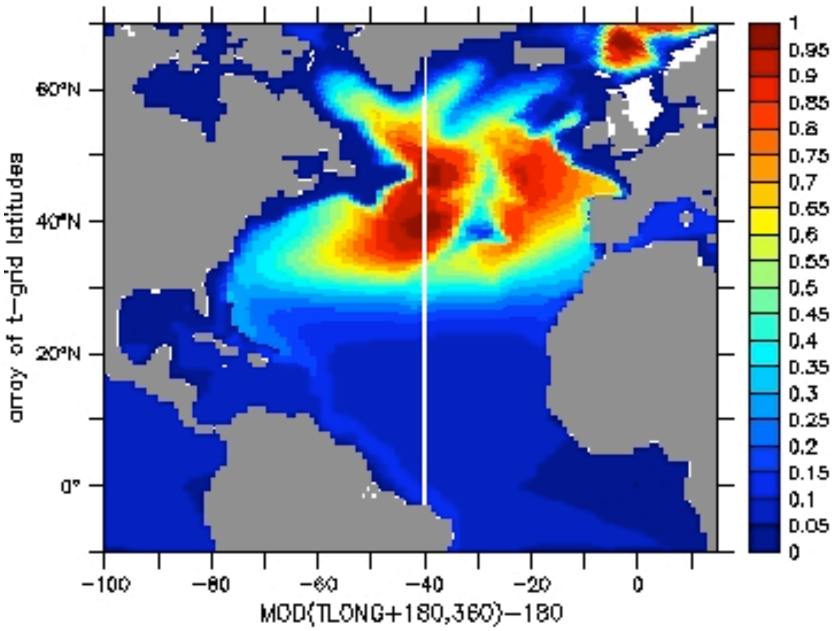
1° v3.5 Model



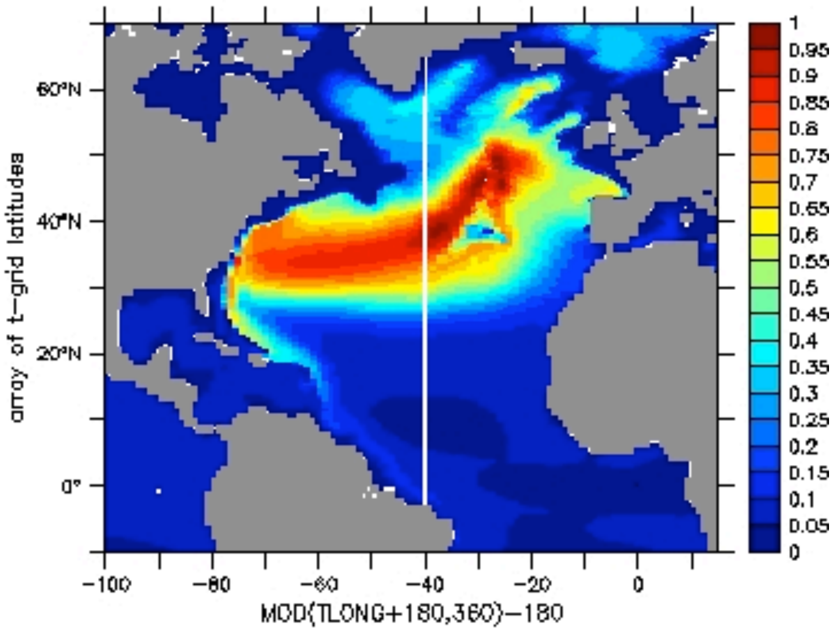
Year 21



TTD vert int, Hires A

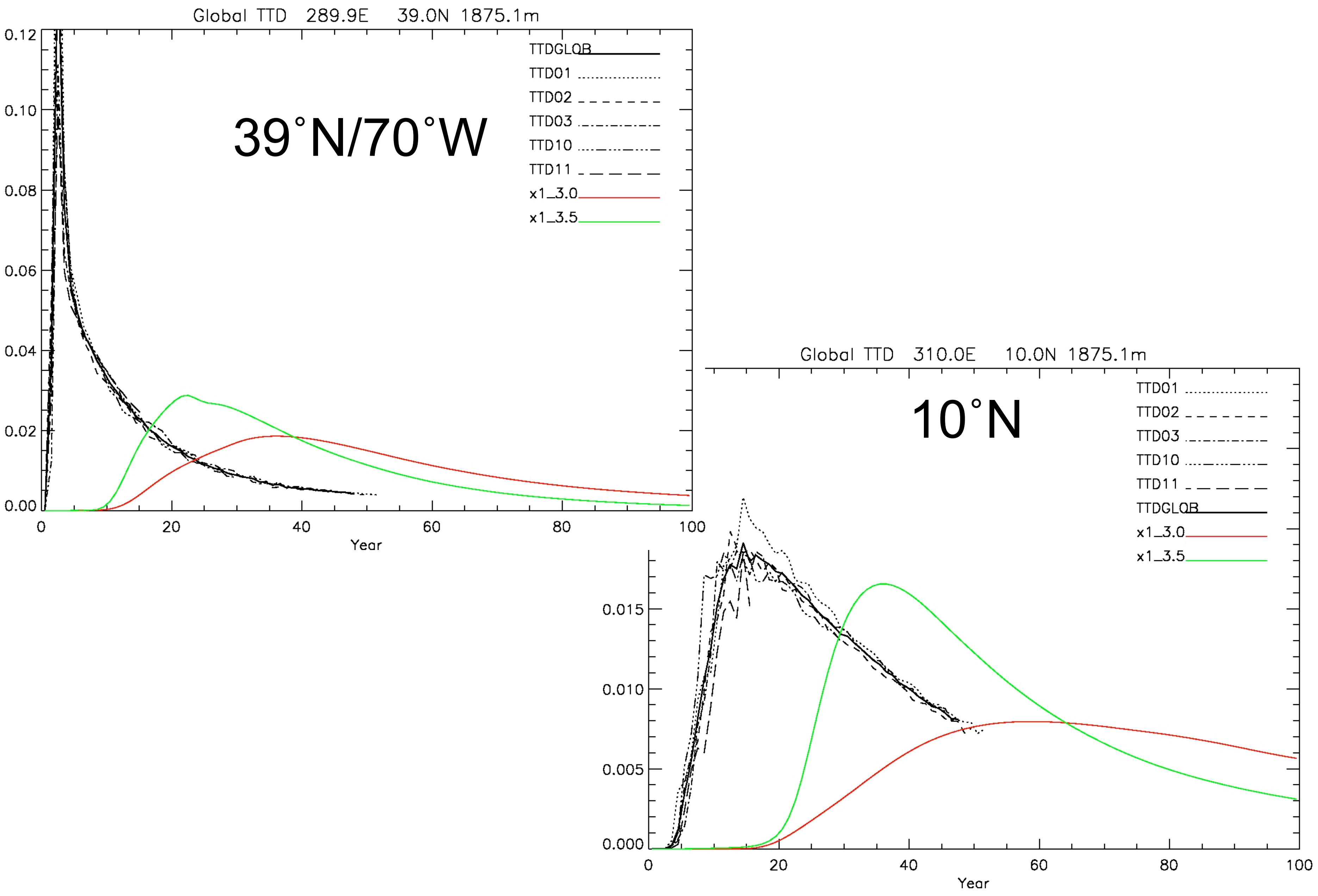


TTD vert int, CCSM3.0



TTD vert int, CCSM3.5

TTD History in DWBC (1875m)



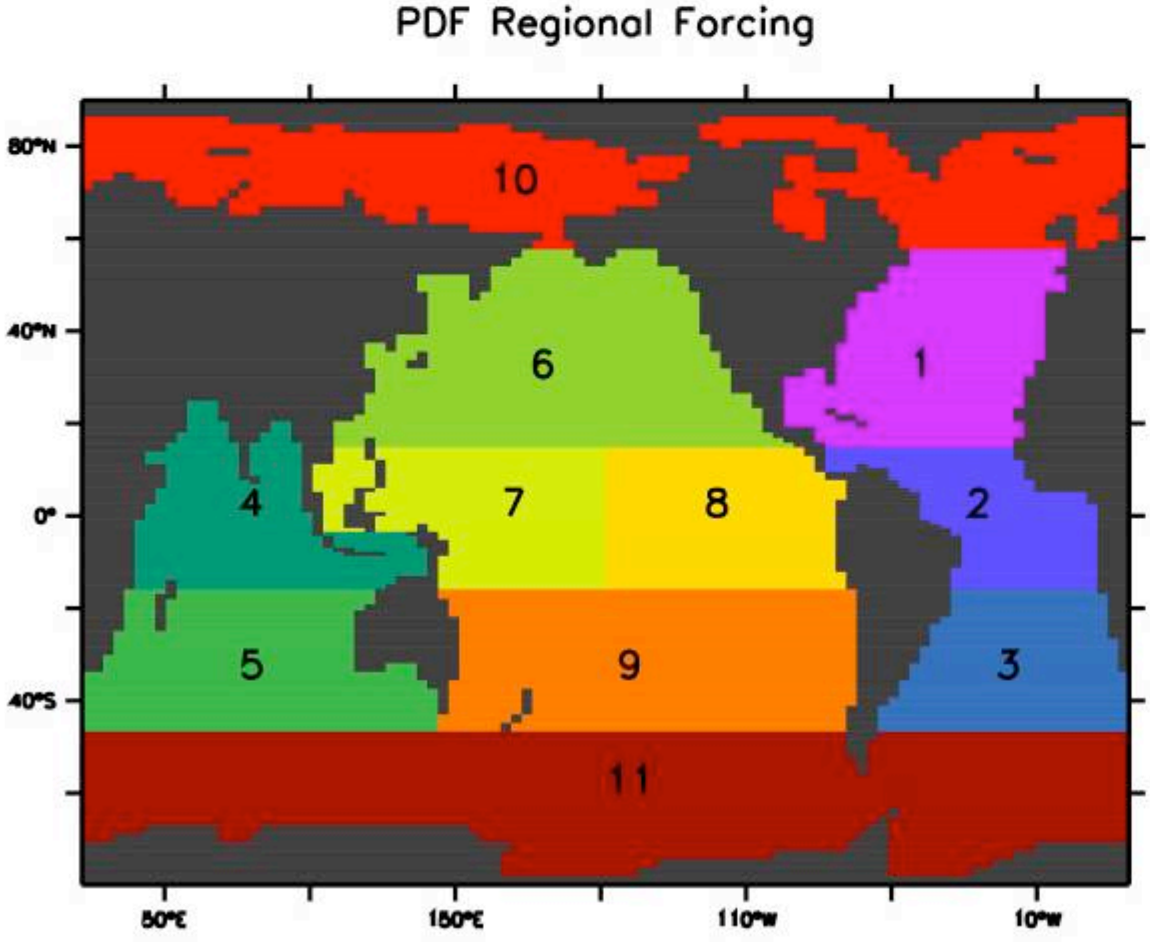
Conclusions

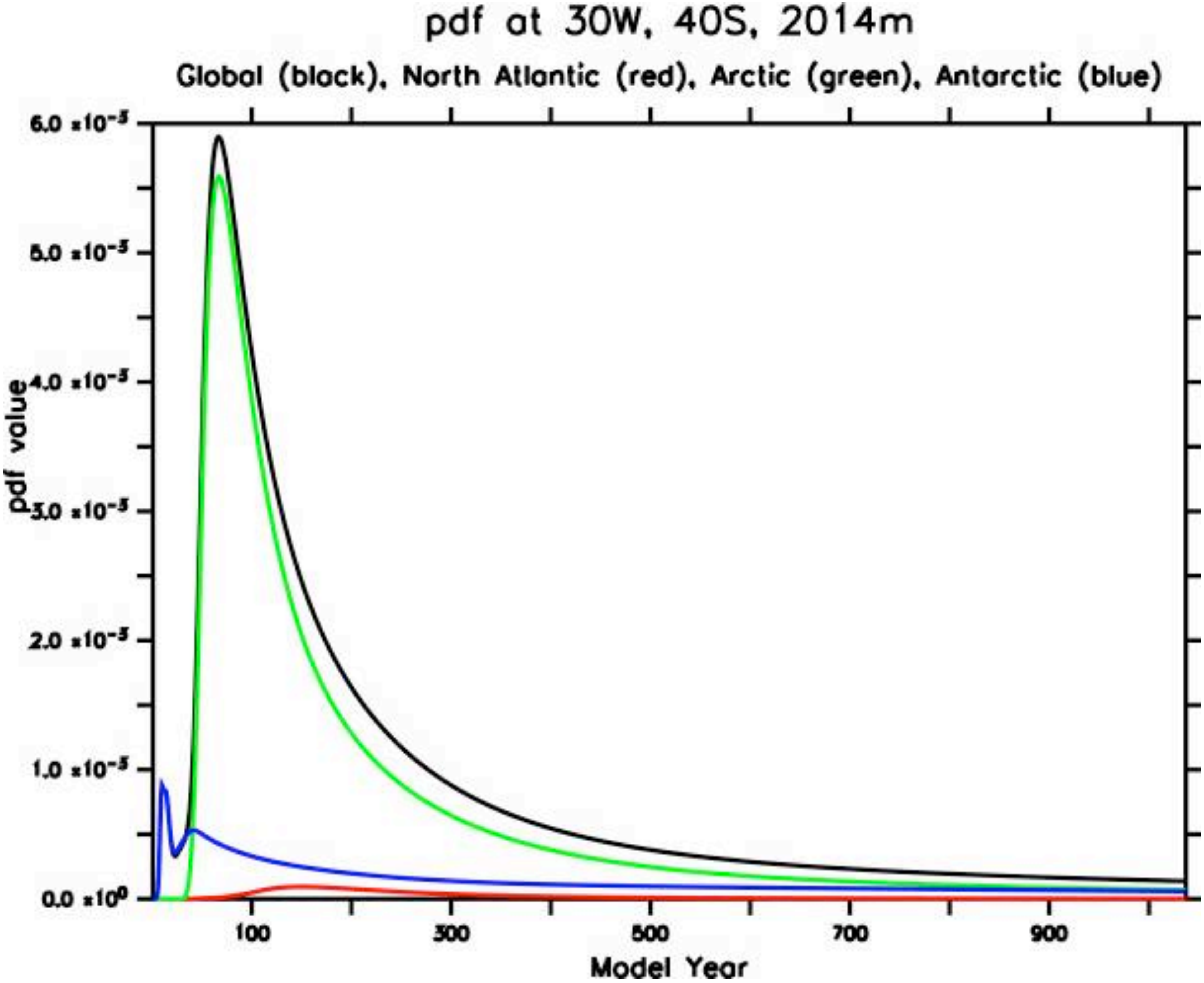
- TTDs show promise as a useful generalization beyond ideal age as a diagnostic of model transport processes at the same computational cost
- TTDs can distinguish between relatively modest changes in parameterization choices in cases where ideal age may not
- Parameterizations currently used in coarse resolution ocean models can be both overly diffuse and insufficiently diffusive
- The TTD for non-steady flow converges rapidly for small ensemble size when smoothed over annual time scales

Future Work

- Complete the experiment!
- Regional TTDs and water mass provenance
- Connection of TTDs to observable tracers
- Additional investigations of local eddy-mixing processes
- Make output publicly available

Water Mass Provenance




pdf at 30W, 40S, 2014m
Global (black), North Atlantic (red), Arctic (green), Antarctic (blue)
pdf value
6.0 ×10⁻⁵
5.0 ×10⁻⁵
4.0 ×10⁻⁵
3.0 ×10⁻⁵
2.0 ×10⁻⁵
1.0 ×10⁻⁵
0.0 ×10⁰
100
300
500
700
900
Model Year