Implementation of Artificial Radionuclides (ARs) in CESM2: Model Evaluation Using Historical ^{137}Cs and $^{239+240}$Pu Distributions

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Artificial radionuclides in the ocean

◆ Artificial Radionuclides (ARs) serve as valuable tracers for evaluating ocean model performance.

◆ Their source terms are relatively well constrained, making them efficient validation tools.

◆ Unlike natural radionuclides, they provide a clear temporal evolution from zero initial state, enabling assessment of model's transient response.

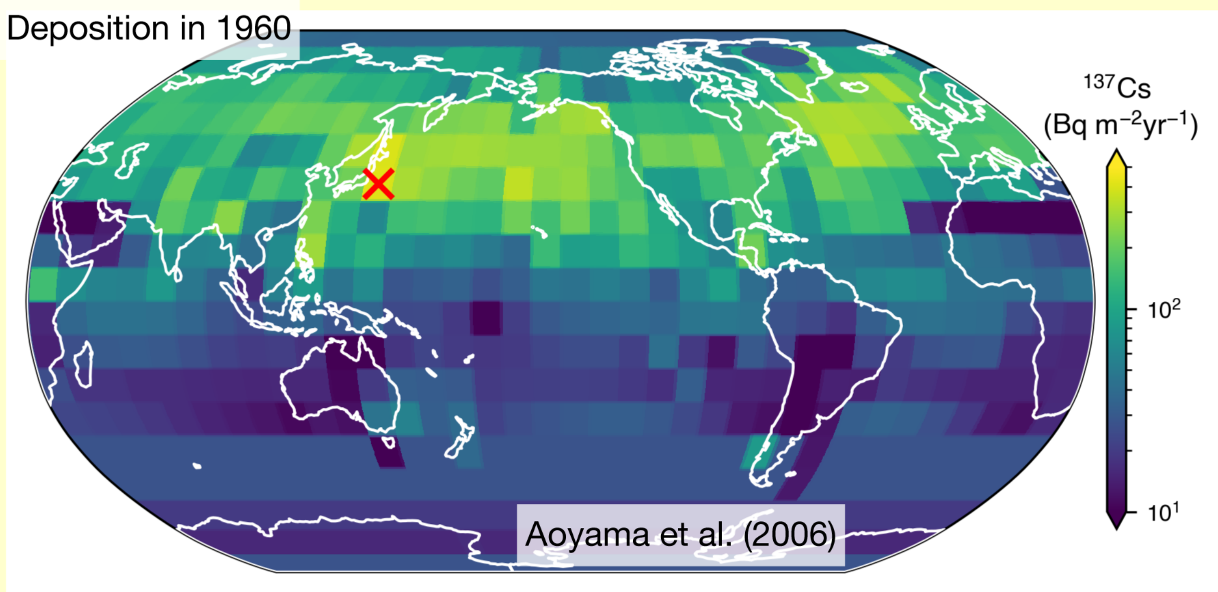
Target ARs: ^{137}Cs & $^{239+240}$Pu

- ^{137}Cs $t_{1/2}$=30.2 yrs
  - Low affinity to particles K_p=2×10^3
  - Good proxy for water mass movement
- $^{239+240}$Pu $t_{1/2}$=24110; 6654 yrs
  - Modest affinity to particles K_p=1×10^5
  - Good proxy for particle scavenging
- Sources
  - Both ARs were supplied to the ocean mainly by the global fallout due to nuclear weapon tests.

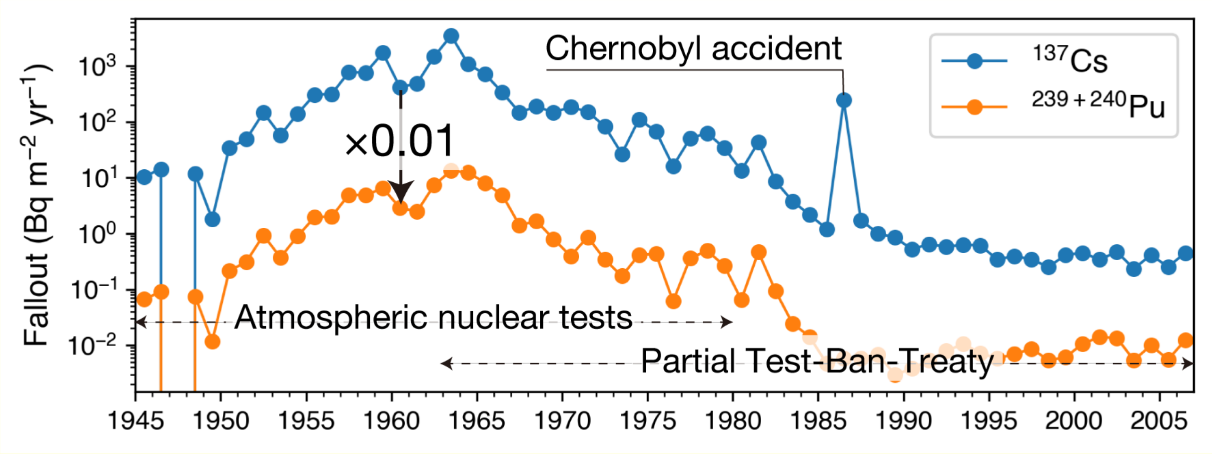
Target ARs: ^{137}Cs & $^{239+240}$Pu

Global fallout

Atmos. nuclear tests were mainly conducted in the NH.



Aoyama et al. (2006)

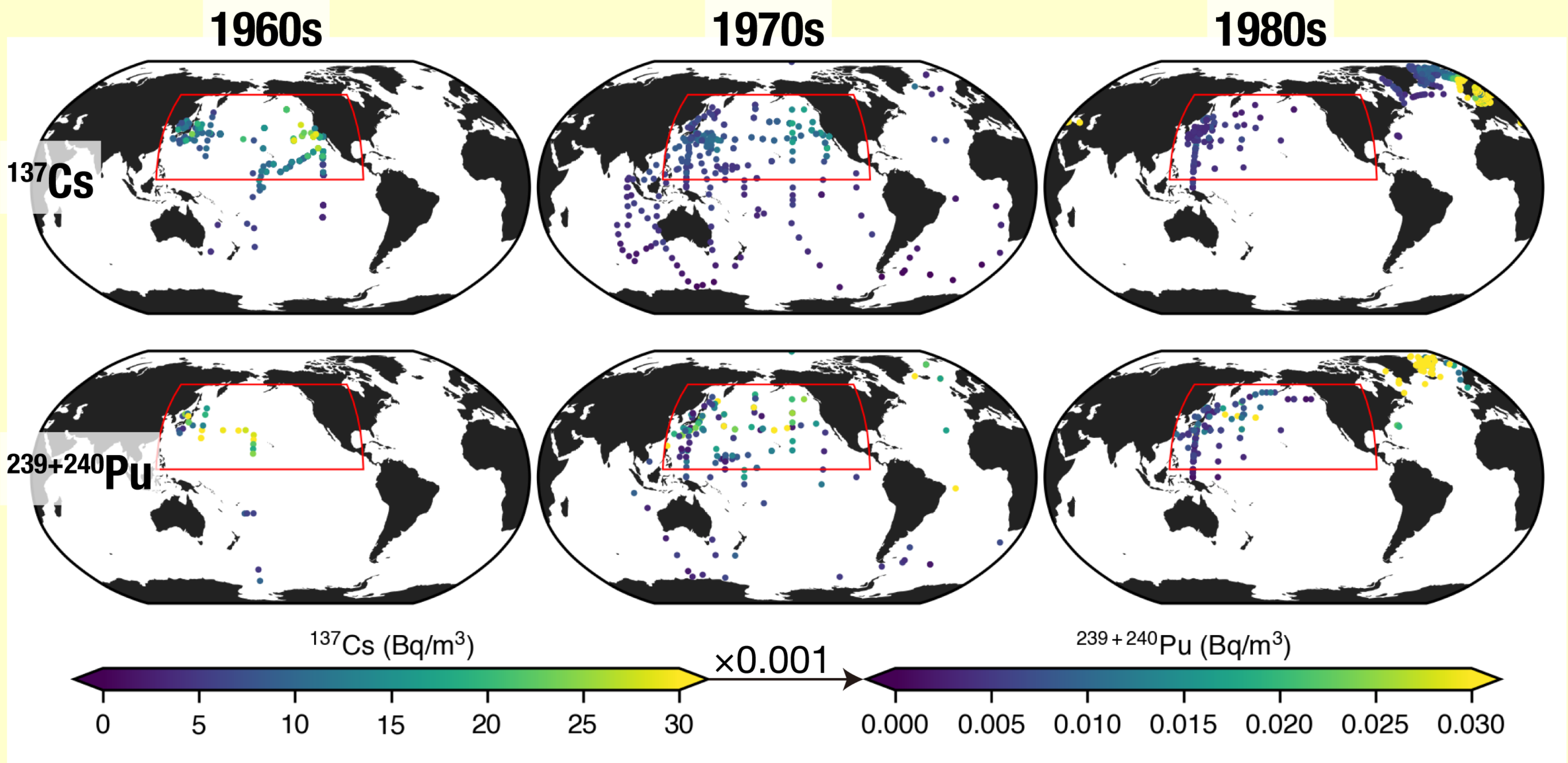


Other sources

Discharge from nuclear reprocessing facilities (Sellafield, UK; La Hague, France) and close-in fallout from Pacific nuclear test sites are also important soruce for Cs and Pu, but they are not considered in the current simulations.

Observed features of ^{137}Cs & $^{239+240}$Pu

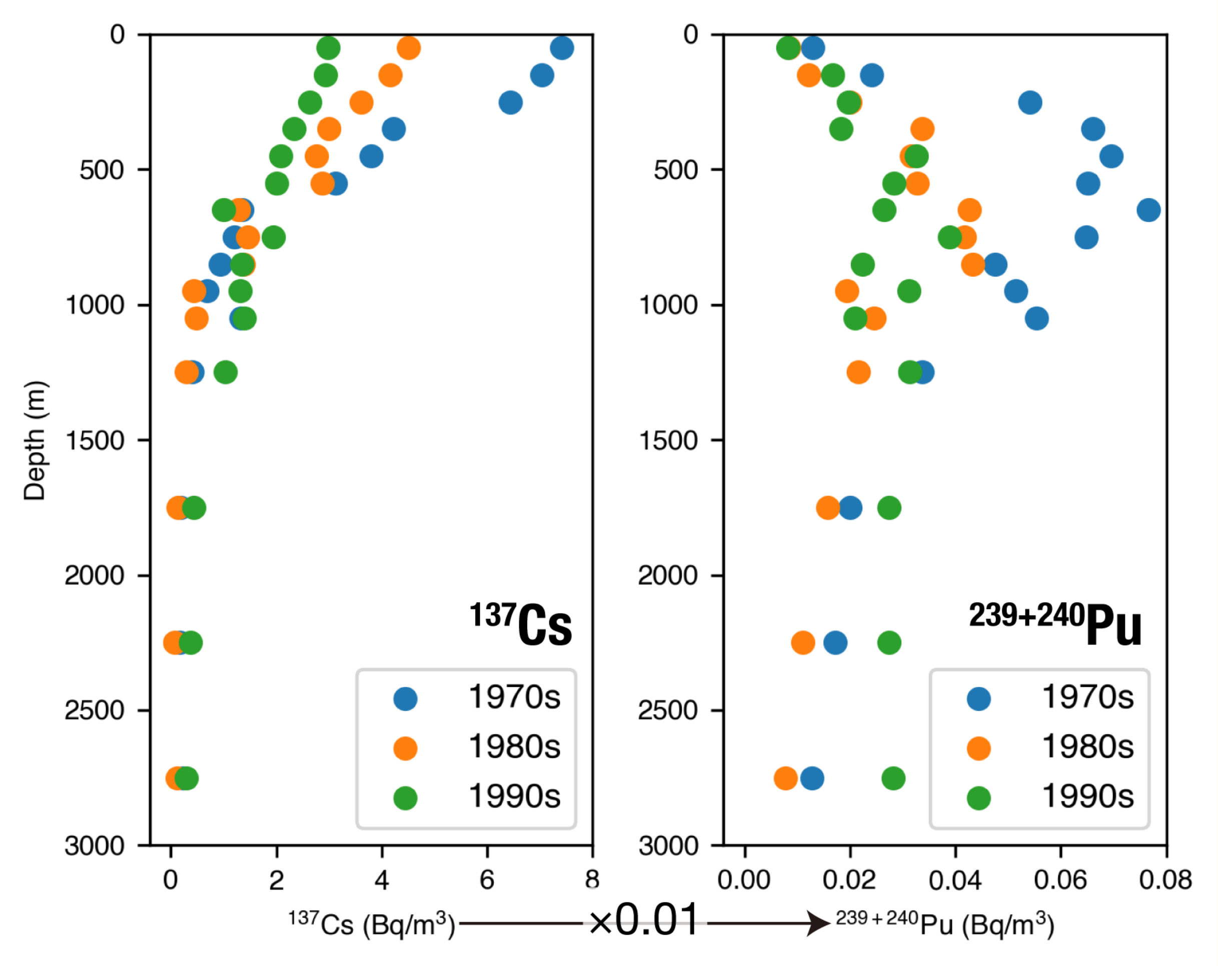
Observed distribution in the surface water



Data are obtained from HAM global 2021 (Aoyama, 2021).

Observed features of ^{137}Cs & $^{239+240}$Pu

Spatial averages over the N Pacific

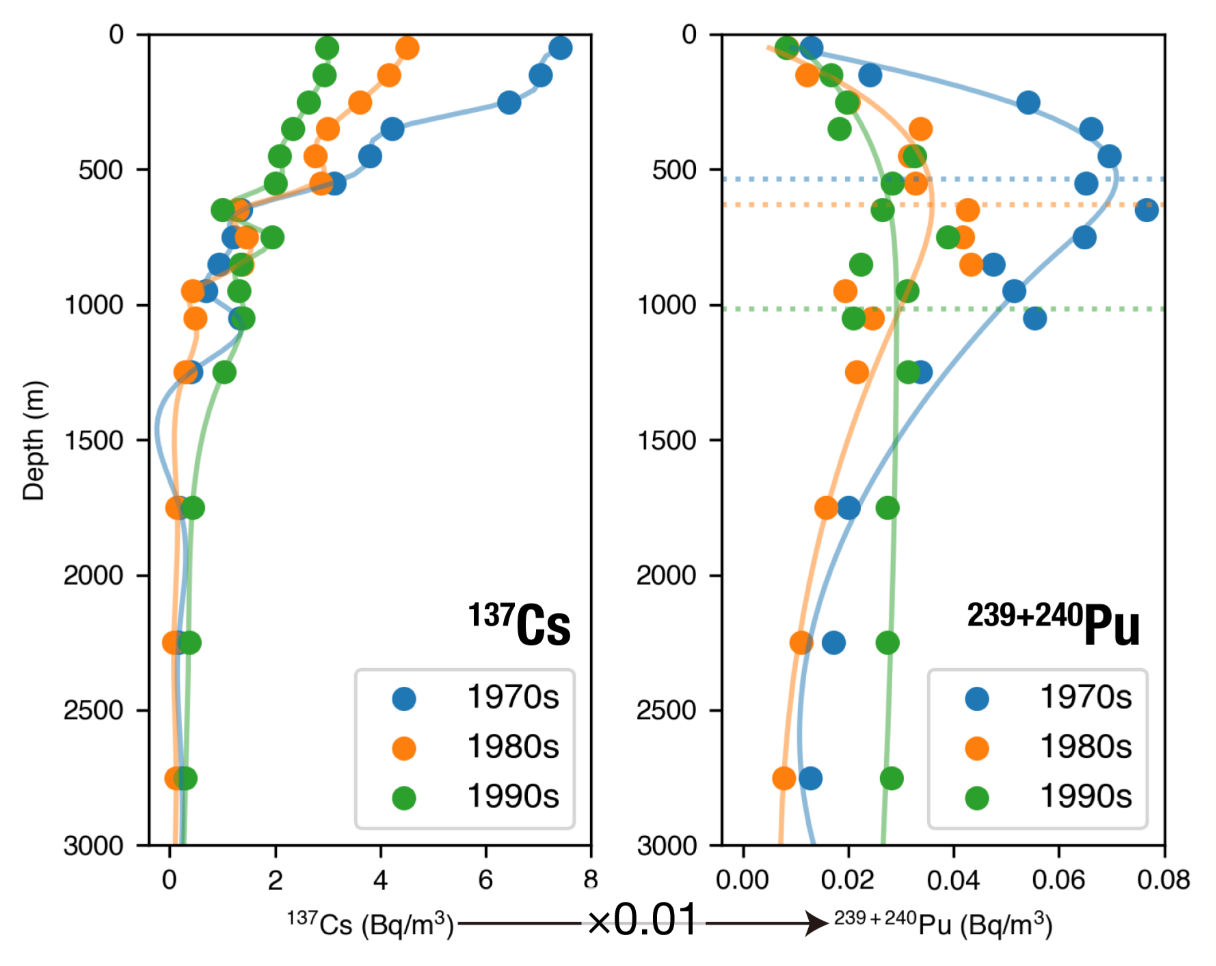


Despite the similar forcing, the vertical distributions are very different, suggesting particle mediated vertical transport for $^{239+240}$Pu.

Data are obtained from HAM global 2021 (Aoyama, 2021).

Observed features of ^{137}Cs & $^{239+240}$Pu

Spatial averages over the N Pacific



The lines are arbitrary.

Worthwhile investigating the different behavior using numerical model.

Data are obtained from HAM global 2021 (Aoyama, 2021).

Purpose of this study

◆Try incorporating the ARs module into CESM2 to reproduce the different behaviors of ^{137}Cs and $^{239+240}$Pu.

CESM2 configurations

- CESM2.1.5
  - G1850ECO (gx1v7)
  - POP2-CICE5-MARBL

- Caveats
  - Start from the default initial condition; No spin-up.
  - Simulated from 1945 to 2006 with changing the AR deposition but forced with NYF.
  - Planning to redo the calculations with appropriate initial and boundary conditions.

Radionuclide model of Siddall et al. (2005)

- Originally developed to investigate ^{231}Pa/^{230}Th.
  - ^{231}Pa/^{230}Th is used as a proxy for AMOC.

- Features of the model
  - Prognostic variable is total amount (dissolved + particulate) of radionuclides.
  - Diagnose dissolved and particulate fractions assuming instantaneous equilibrium in model grid cells using the distribution coefficient K_p.

Siddall et al. (2005) and coupling with MARBL

Nuclide i dissolved particulate

$$A^{\mathrm{i}}_{\mathrm{total}} = A^{\mathrm{i}}_{\mathrm{d}} + A^{\mathrm{i}}_{\mathrm{p}}$$

(Bq/m^3) (Bq/m^3) (Bq/m^3)

$$\underset{\text{tendency}}{\frac{\partial A^{\mathrm{i}}_{\mathrm{total}}}{\partial t}} = \underset{\text{transport}}{\mathcal{L}\left(A^{\mathrm{i}}_{\mathrm{total}}\right)} + \underset{\text{source}}{\beta^{\mathrm{i}}} - \underset{\text{decay}}{\lambda^{\mathrm{i}} A^{\mathrm{i}}_{\mathrm{total}}} - \underset{\text{sinking}}{w_{\mathrm{p}} \frac{\partial A^{\mathrm{i}}_{\mathrm{p}}}{\partial z}}$$

(Bq/m^3) / (kg/m^3) (Bq/m^3) particle density

$$K^{\mathrm{i}}_{\mathrm{p}} = \frac{\left(A^{\mathrm{i}}_{\mathrm{p}}/\rho_{\mathrm{p}}\right)}{\left(A^{\mathrm{i}}_{\mathrm{d}}/\rho_{\mathrm{w}}\right)} = \frac{A^{\mathrm{i}}_{\mathrm{p}}}{A^{\mathrm{i}}_{\mathrm{d}} C_{\mathrm{p}}}, \quad C_{\mathrm{p}} = \frac{\rho_{\mathrm{p}}}{\rho_{\mathrm{w}}}; \quad \therefore A^{\mathrm{i}}_{\mathrm{p}} = K^{\mathrm{i}}_{\mathrm{p}} C_{\mathrm{p}} A^{\mathrm{i}}_{\mathrm{d}}$$

(-) (Bq/m^3) / (kg/m^3) (Bq/m^3) (-) water density

Siddall et al. (2005) and coupling with MARBL

$$A^{\rm i}_{\rm d} = \frac{A^{\rm i}_{\rm total}}{1+\underbrace{K^{\rm i}_{\rm p}}_{\text{parameter}}\underbrace{C_{\rm p}}_{\text{diagnosed in model}}}$$

The IAEA provides recommended $K_{\rm p}^{\rm i}$ values for various radionuclides.

$$= \frac{A^{\rm i}_{\rm total}}{1+\underbrace{\underset{\text{aeolian dust}}{K^{\rm i}_{\rm dust}C_{\rm dust}} + \underset{\text{organic carbon}}{K^{\rm i}_{\rm POC}C_{\rm POC}} + \underset{\text{calcium carbonate}}{K^{\rm i}_{\rm ca}C_{\rm ca}} + \underset{\text{opal}}{K^{\rm i}_{\rm op}C_{\rm op}}}_{\substack{\text{If different types of particles do not interact with each other,}\\ \text{then the effects can be expressed as a linear combination.}}}}$$

$$\text{e.g., } \underset{\text{(-)}}{C_{\rm dust}} = \frac{\overset{\text{(kg/m}^3\text{)}}{\rho_{\rm dust}}}{\underset{\text{(kg/m}^3\text{)}}{\rho_{\rm w}}};\ \underset{\text{(kg/m}^3\text{)}}{\rho_{\rm dust}} = \frac{\overset{\text{(kg/m}^2\text{/sec)}}{F_{\rm dust}}}{\underset{\text{(m/sec)}}{w_{\rm dust}}}$$

← Sinking fluxes are calculated in MARBL for all the types.

Experiments

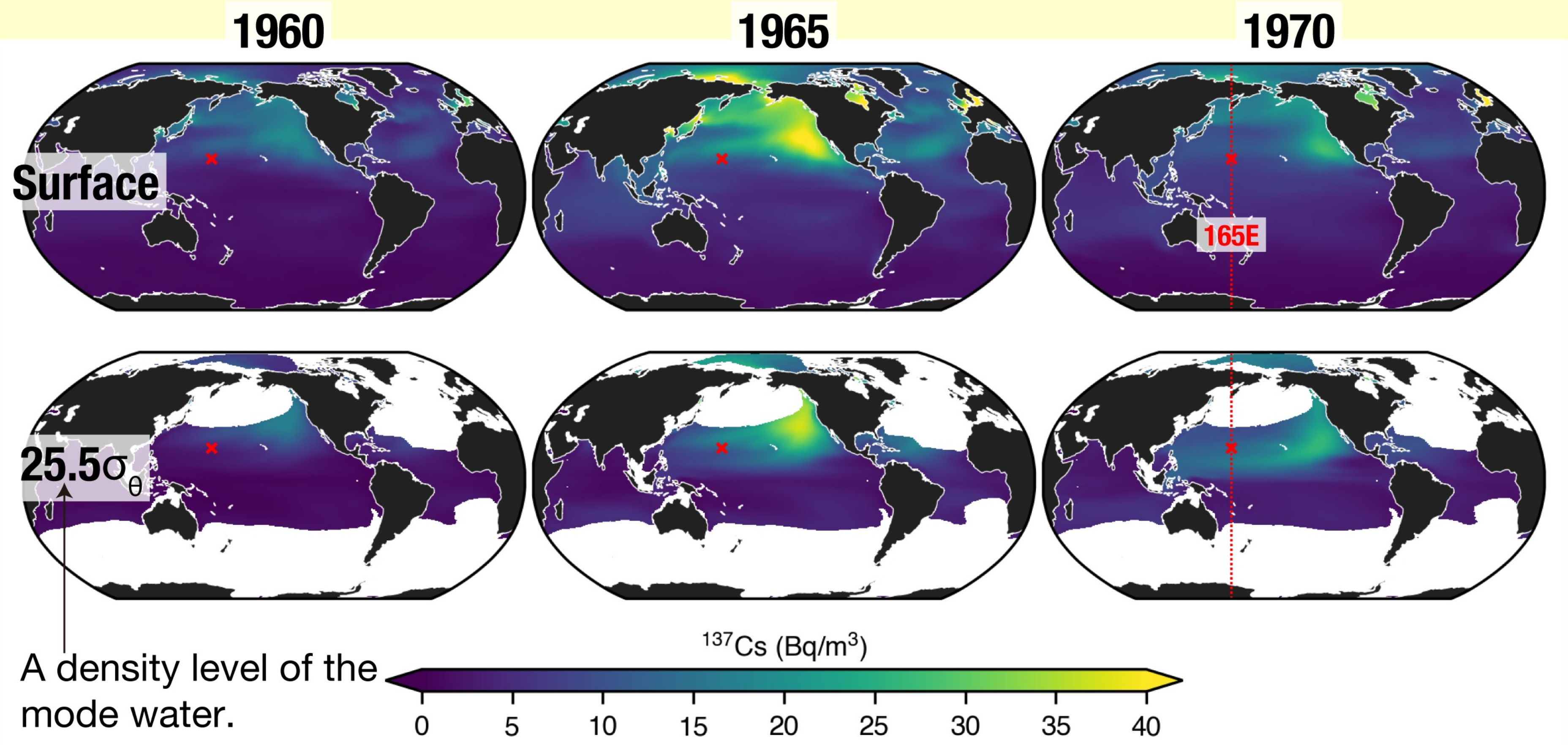
$$w_{\mathrm{dust}},\ w_{\mathrm{POC}},\ w_{\mathrm{ca}},\ w_{\mathrm{op}} \sim w_{\mathrm{s}} = 1000\,\mathrm{m/yr}$$

$$K_{\mathrm{dust}},\ K_{\mathrm{POC}},\ K_{\mathrm{ca}},\ K_{\mathrm{op}} \sim K_{\mathrm{p}}$$ Just for simplicity.

Case	Nuclides	K_p	Notes
Cs low	^{137}Cs	0	Simplified approach*
Cs mid	^{137}Cs	2×10^3	IAEA ref.
Cs high	^{137}Cs	2×10^4	Max. from literatures
Pu low	$^{239+240}$Pu	1×10^4	Min. from literatures
Pu mid	$^{239+240}$Pu	1×10^5	IAEA ref.
Pu high	$^{239+240}$Pu	1×10^6	Max. from literatures

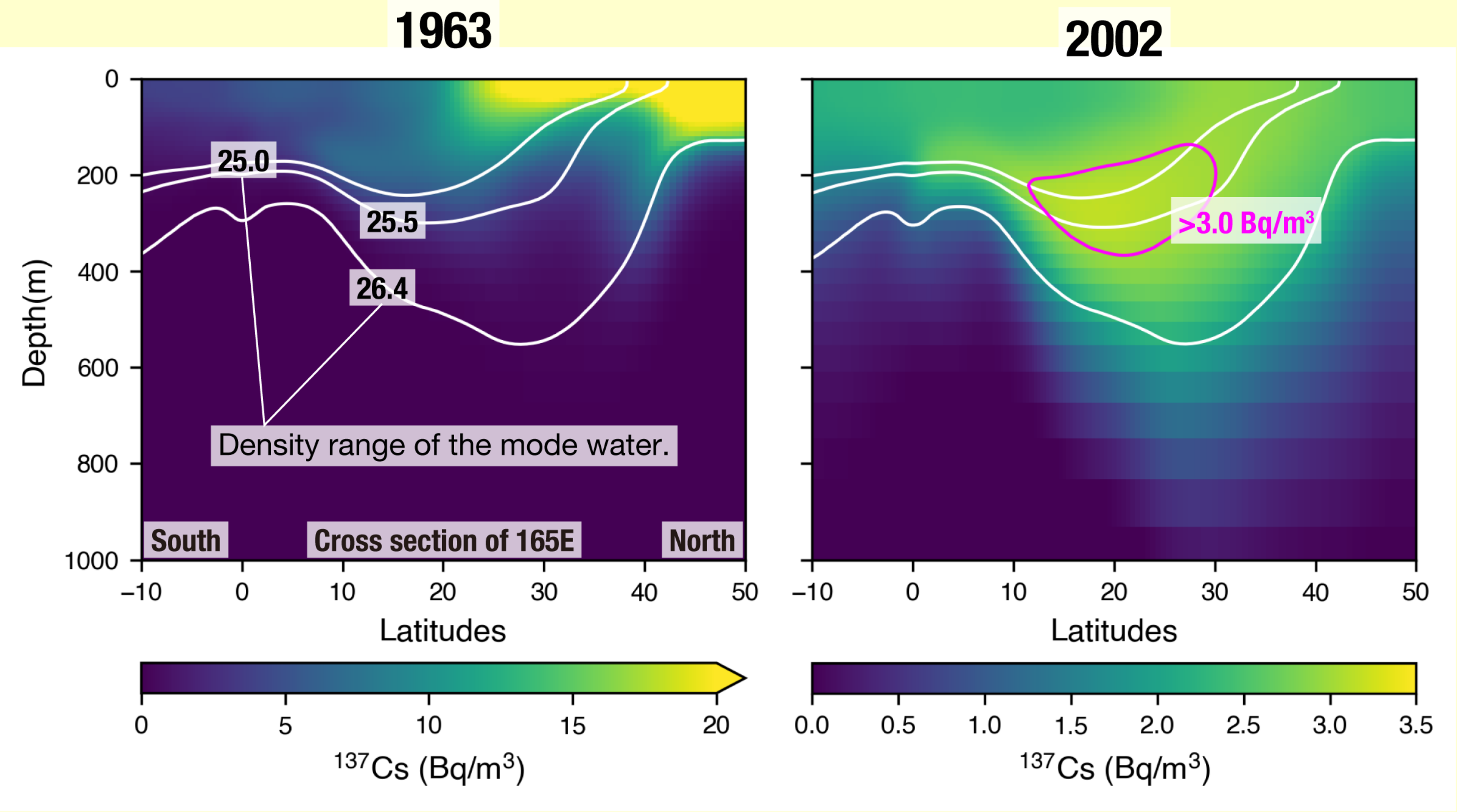
* When the distribution coefficient is 0, it becomes a tracer that moves with the water mass, eliminating the need for particle calculations. This is widely used as an approximation in Cs calculations.

Cs mid horizontal distribution



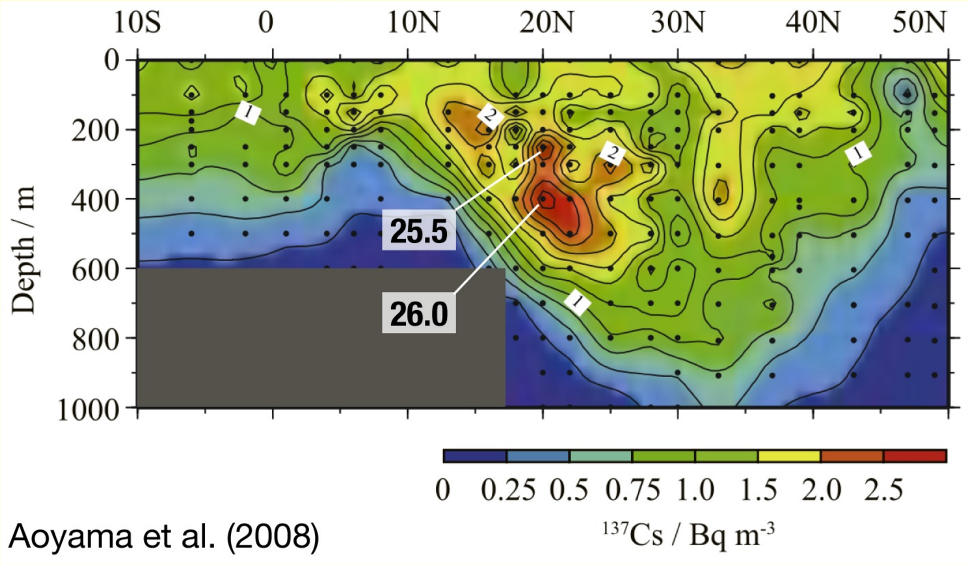
A density level of the mode water.

Cs mid cross section at 165E



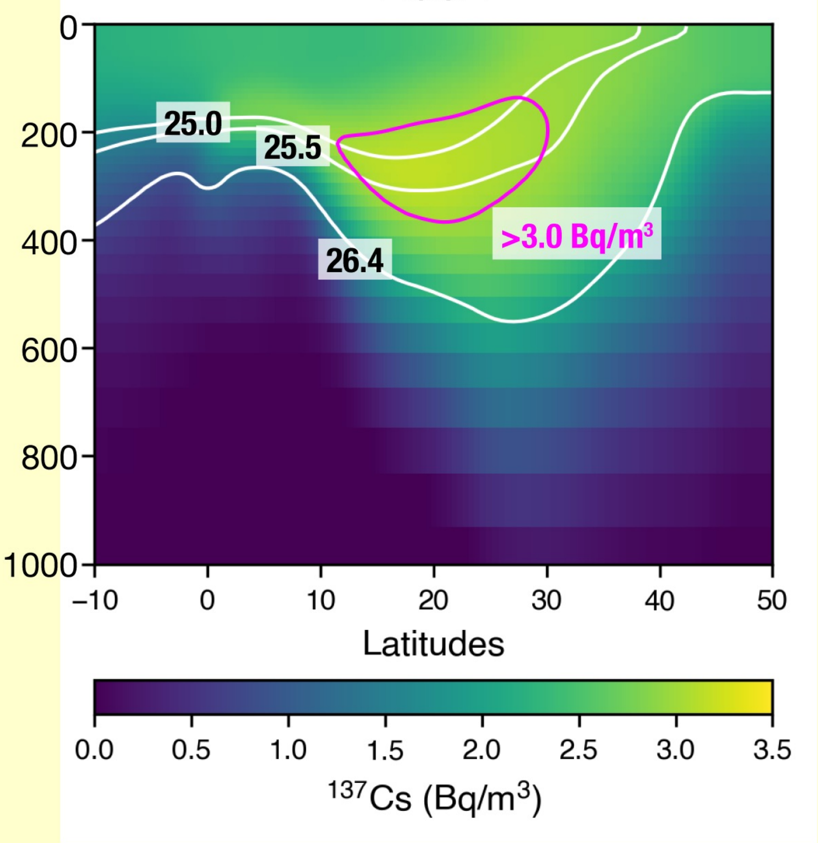
Cs mid cross section at 165E

Obs. in 2002

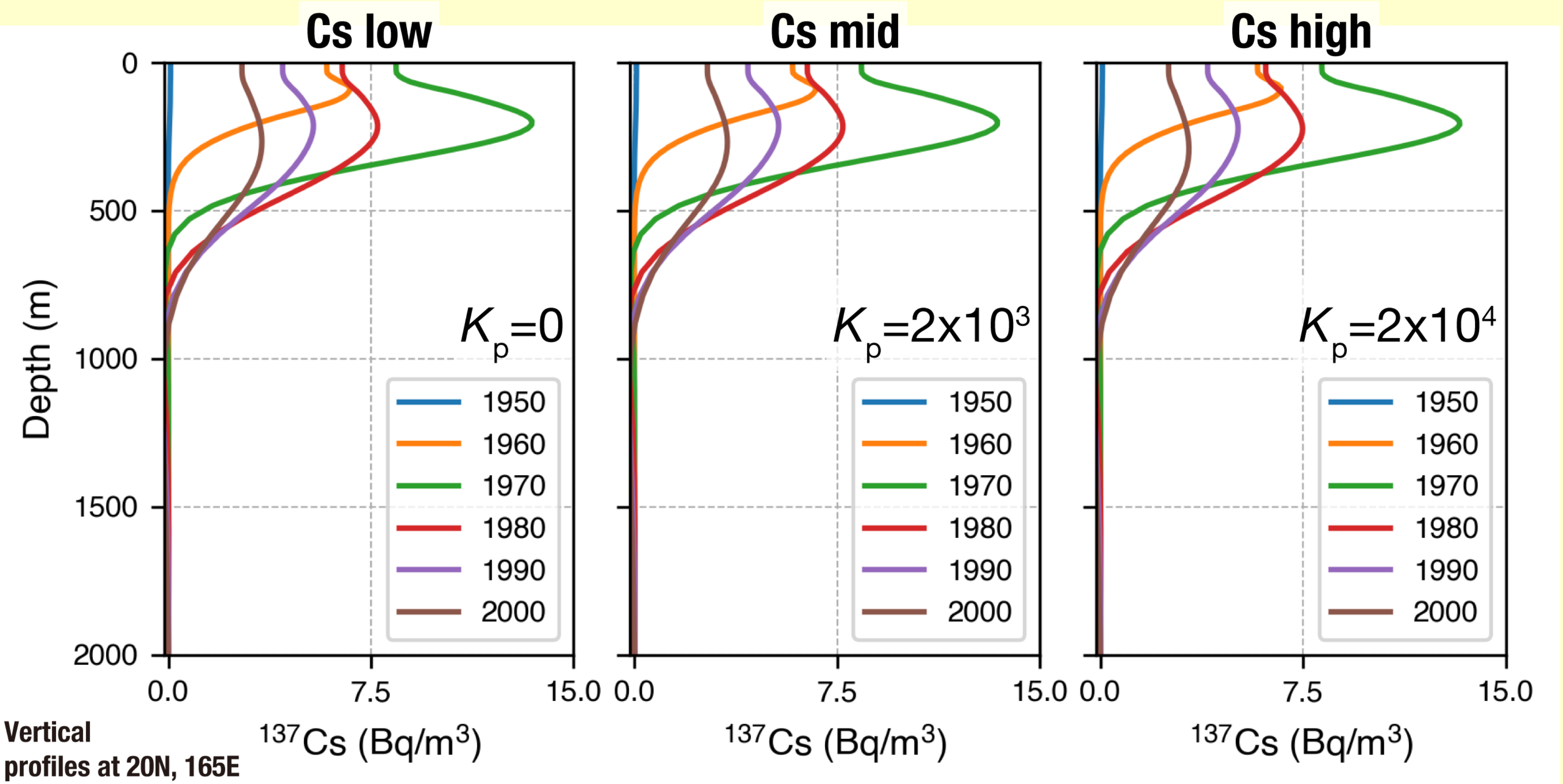


Aoyama et al. (2008)

2002

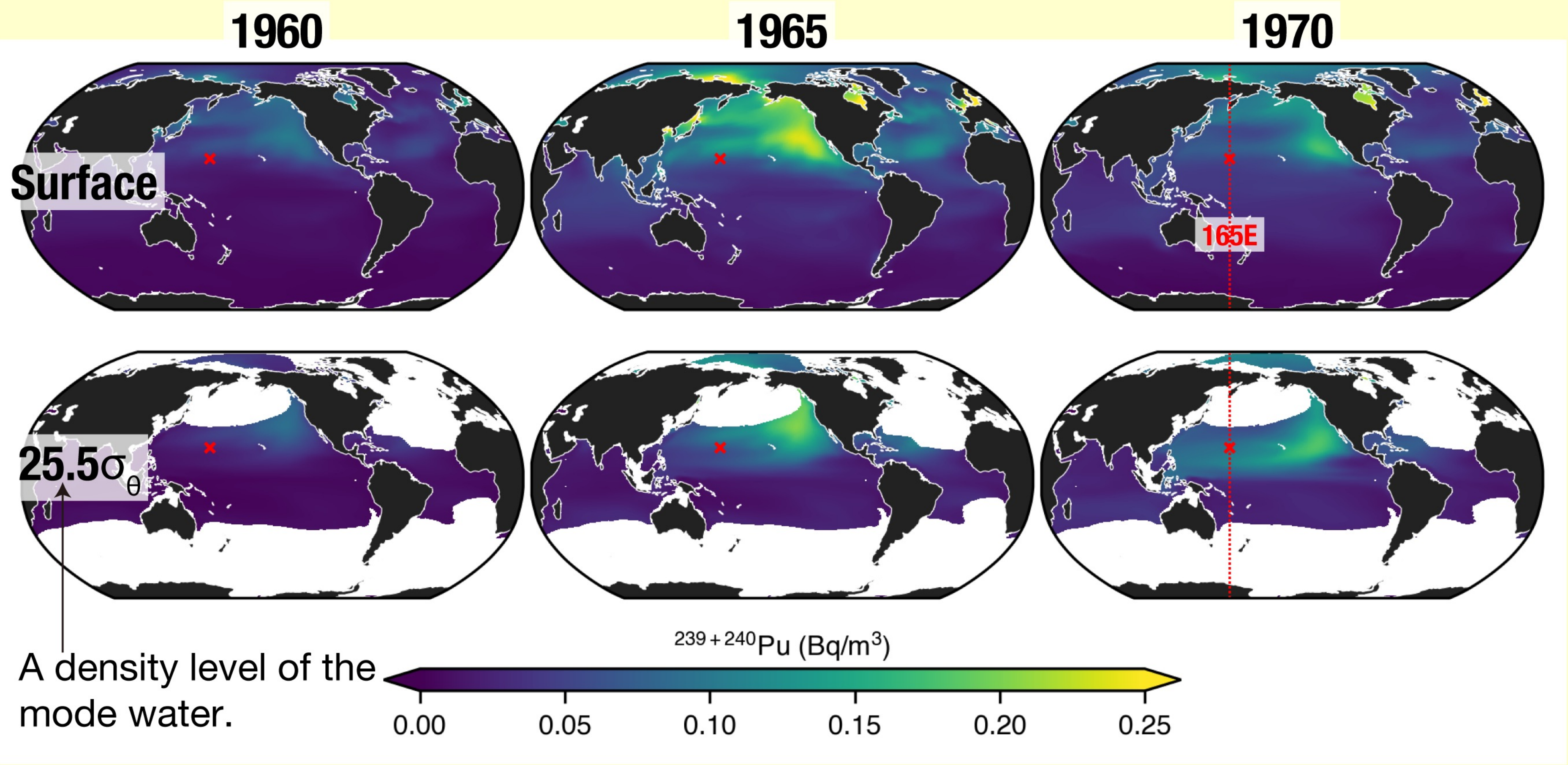


Comparison among the cases in 20N 165E



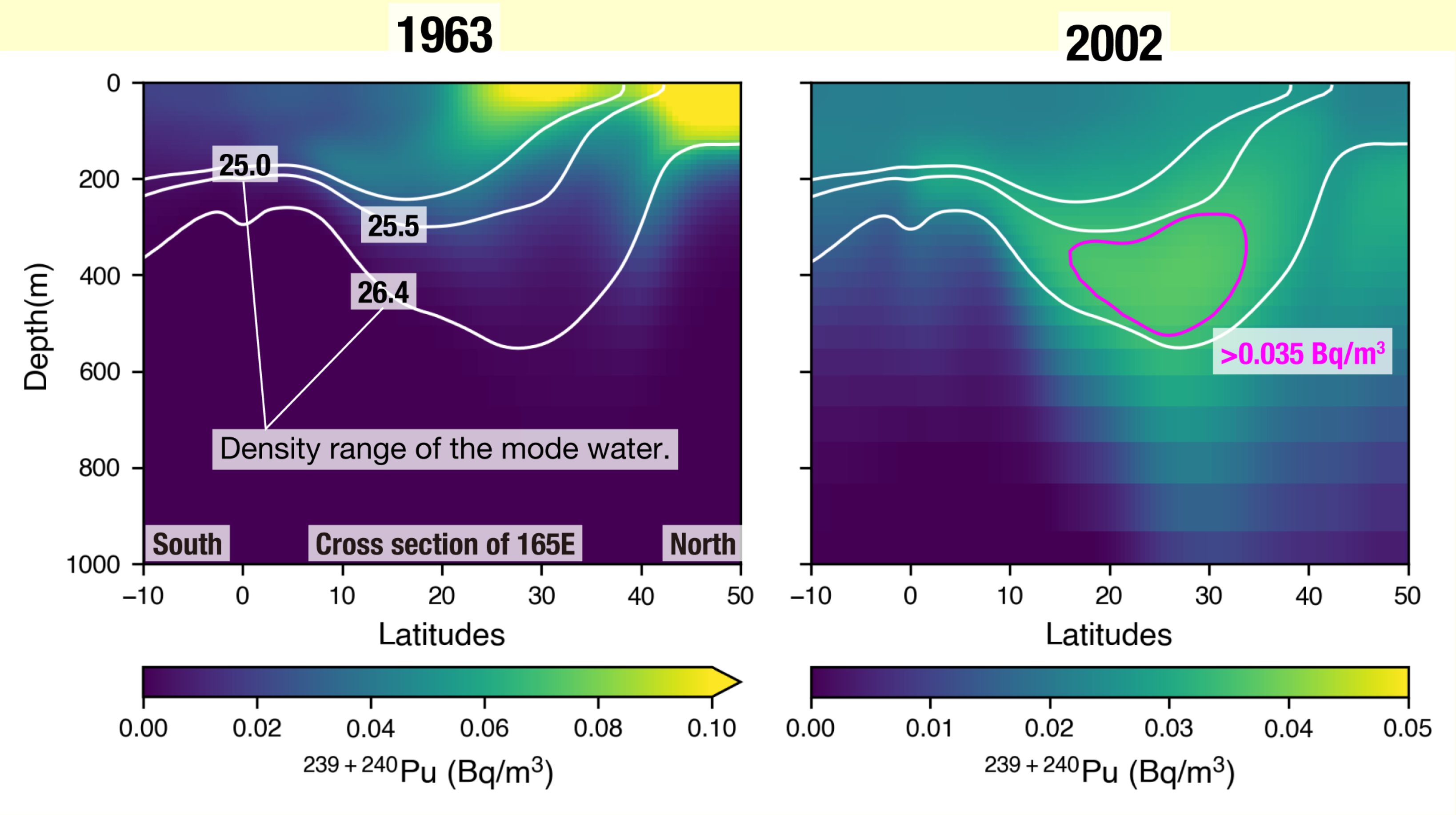
Vertical profiles at 20N, 165E

Pu mid horizontal distribution

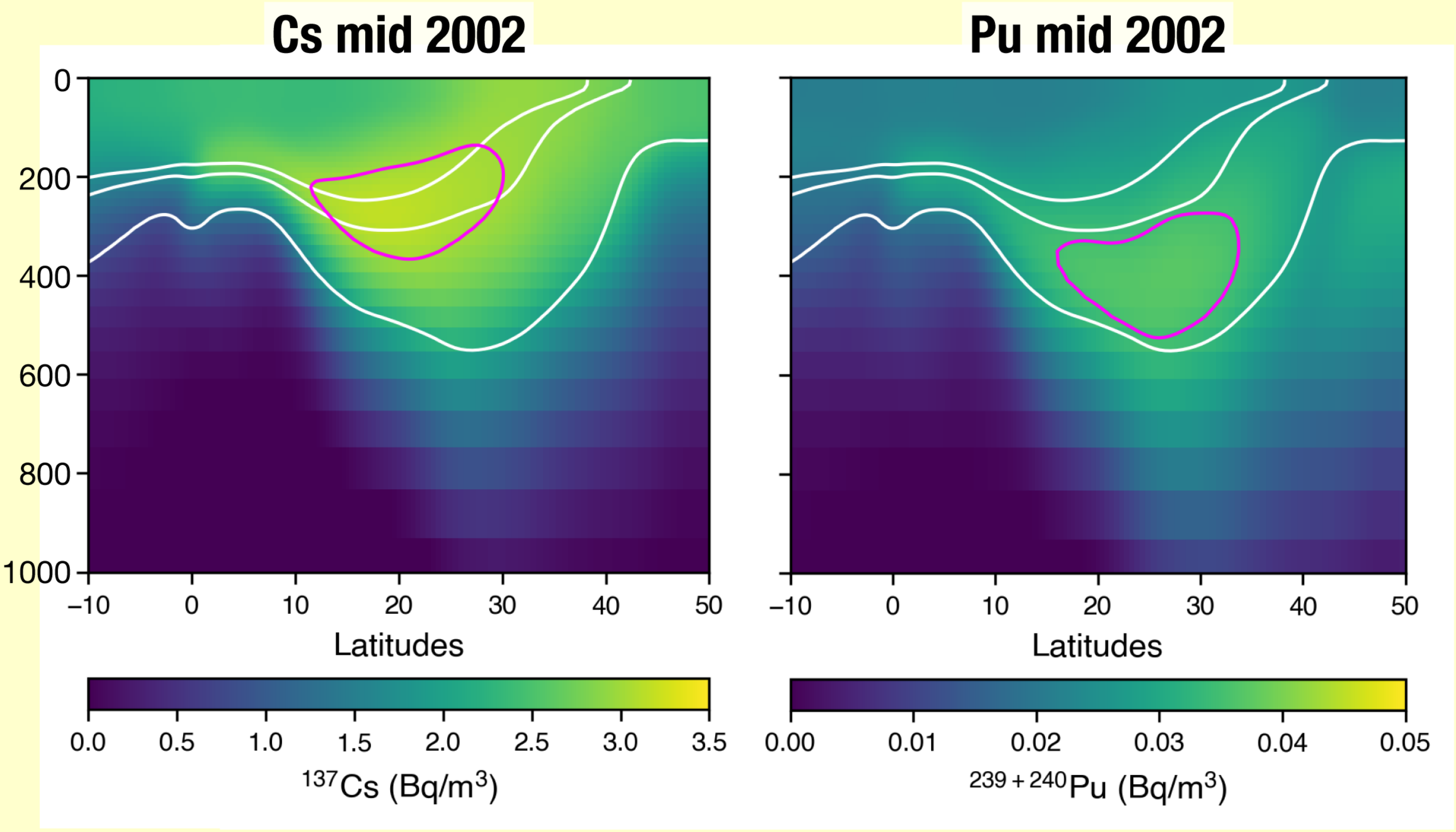


A density level of the mode water.

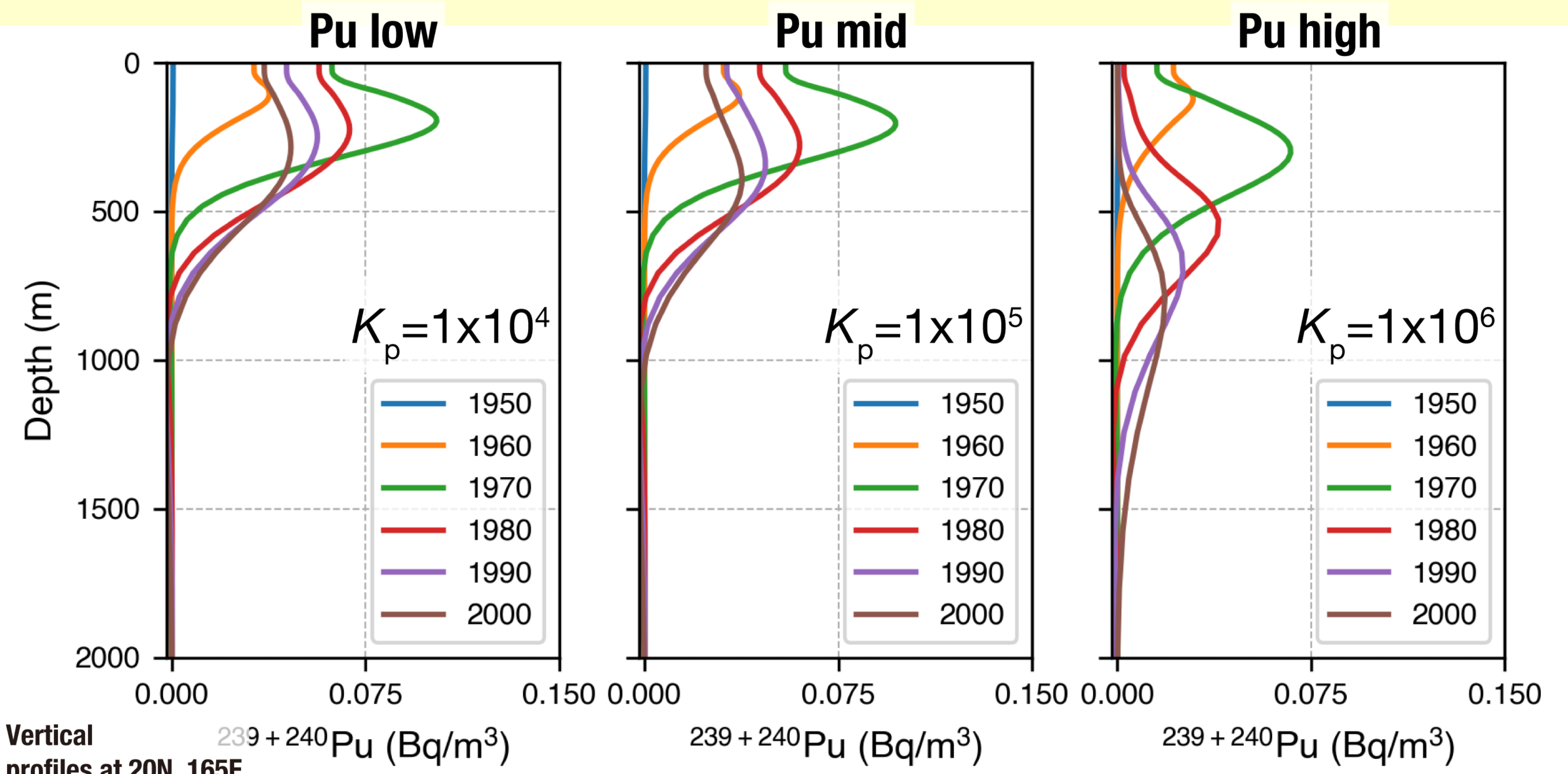
Pu mid cross section at 165E



Pu mid cross section at 165E

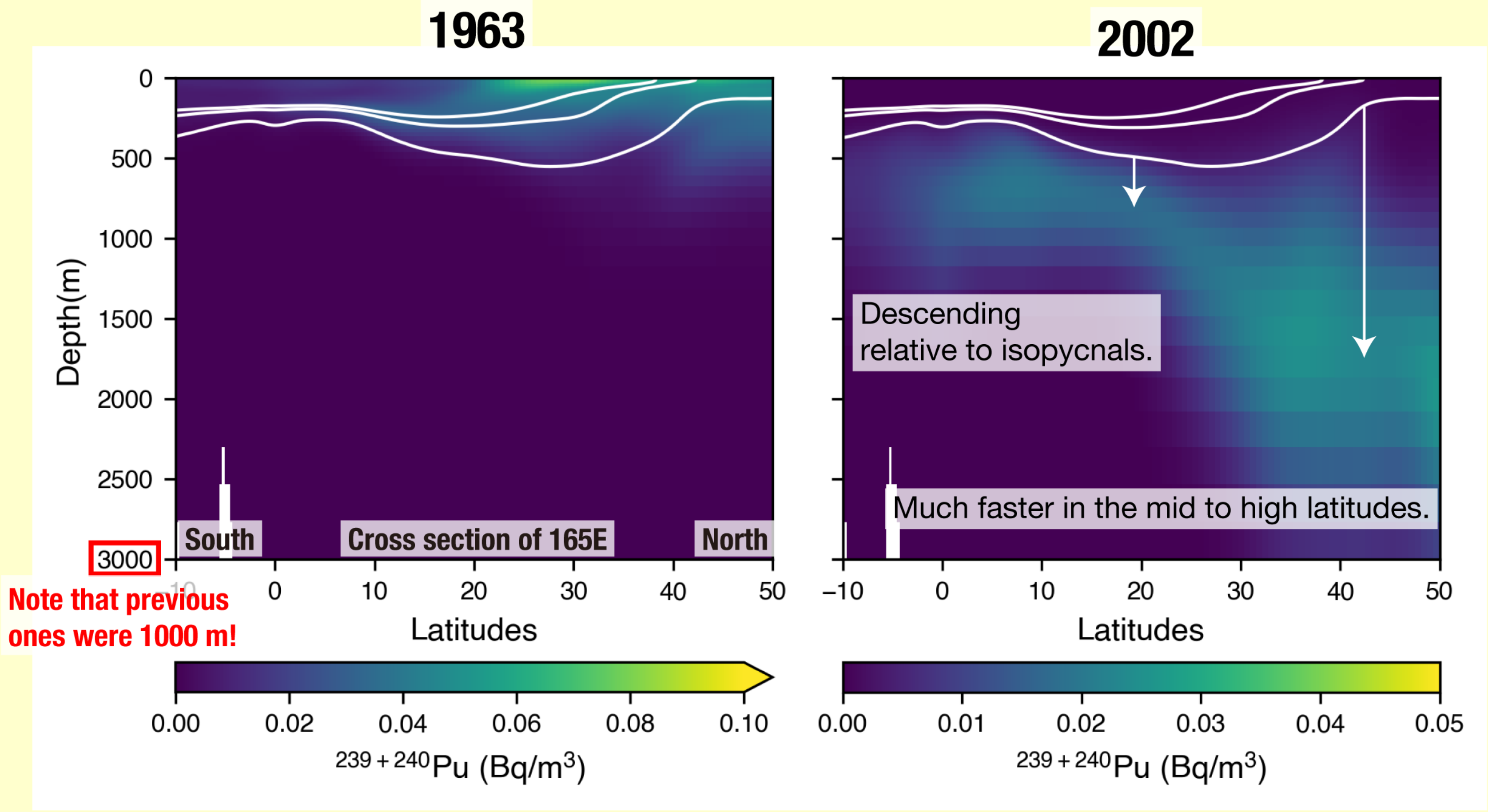


Comparison among the cases in 20N 165E



Vertical profiles at 20N, 165E

Pu high cross section at 165E



Note that previous ones were 1000 m!

Descending relative to isopycnals.

Much faster in the mid to high latitudes.

Summary

- Particle-mediated transport shows varying significance with K_p: negligible at K_p=10^4, becoming apparent at K_p≈10^5, and prominent at K_p=10^6.
- For ^{137}Cs, where K_p is expected to be around 10^4 or less, setting K_p=0 serves as a good approximation, allowing simplified calculations.
- For $^{239+240}$Pu, observed data showed qualitatively similar behavior to higher K_p range ($K_p > 10^5$).
- The differences in vertical transport seen in the observed data could be explained by differences in K_p based on the literature values.

Future directions

- Develop theoretical understanding of why particle-mediated transport becomes apparent at $K_p \approx 10^5$, focusing on the balance between physical and particle-mediated processes.

- Conduct more quantitative comparisons with the observational data.
  - The simulated results suggested that horizontal distribution of particles can affect horizontal distribution of $^{239+240}$Pu, if $K_p > 10^5$ is adequate.
  - Can we find such feature in the observed data?

- Perform experiments with varying settling velocities and K_p values for different particle types.

- Redo simulations with adequate forcings and IC.