ODEN INSTITUTE FOR COMPUTATIONAL ENGINEERING & SCIENCES

Underwater sound propagation within ocean general circulation

ECCO Annual Meeting

Ivana Escobar[1,2], Dr. Patrick Heimbach[2,3], Dr. Feras Habbal[1,2]

21 March 2024
Austin, TX

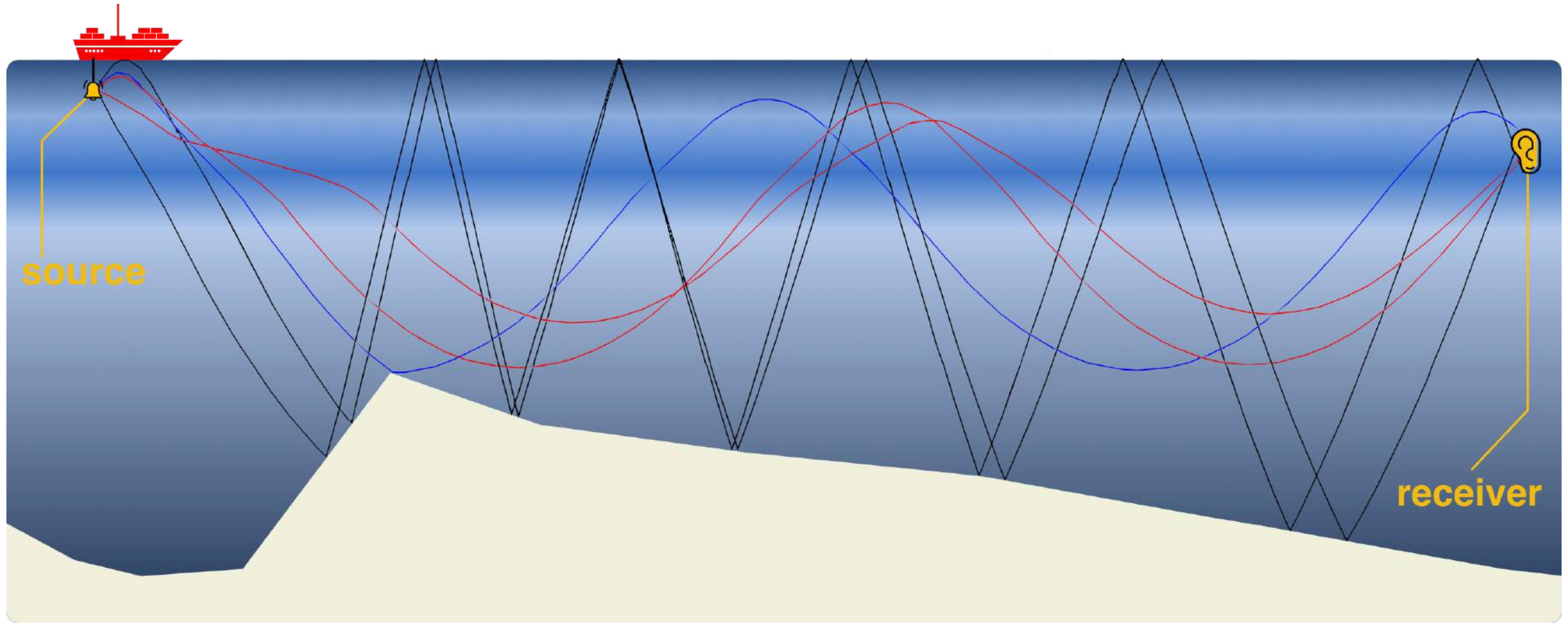
[1]Applied Research Laboratories, UT Austin; [2]Oden Institute for Computational Engineering and Sciences; [3]Jackson School of Geosciences, UT Austin

Underwater acoustic observations

Tomography offers along path information of the ocean interior

- Active sonar pulses with known source and receiver positions can provide measurements untapped by ocean state estimates.

- Measured travel times are commonly compared with ray tracing modeled travel times.[ES09]



- Acoustic remote sensing can be added to state estimates as a new constraint in model-data misfit.

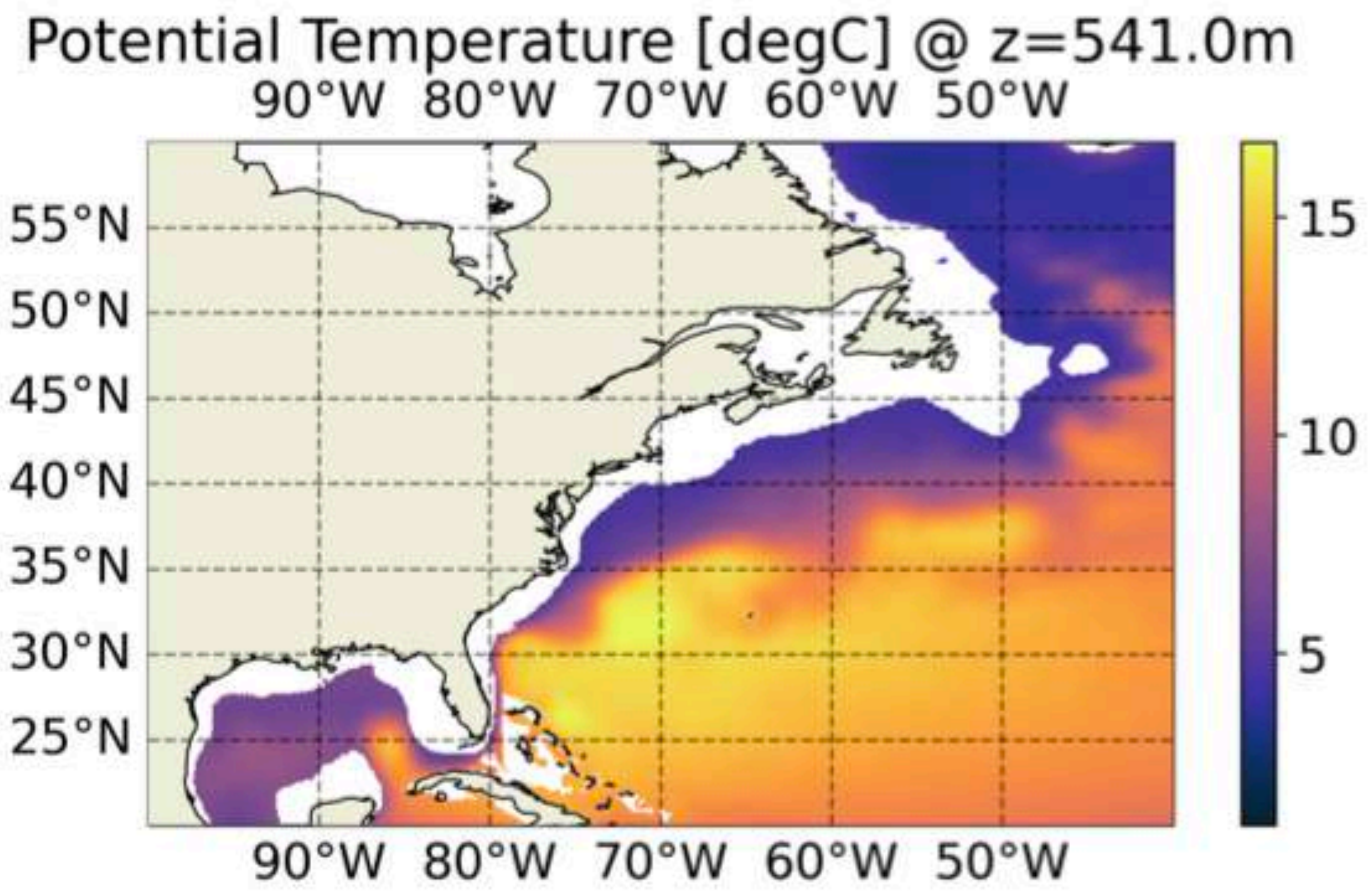
- Need a way to access acoustic diagnostics *within* a general circulation model.

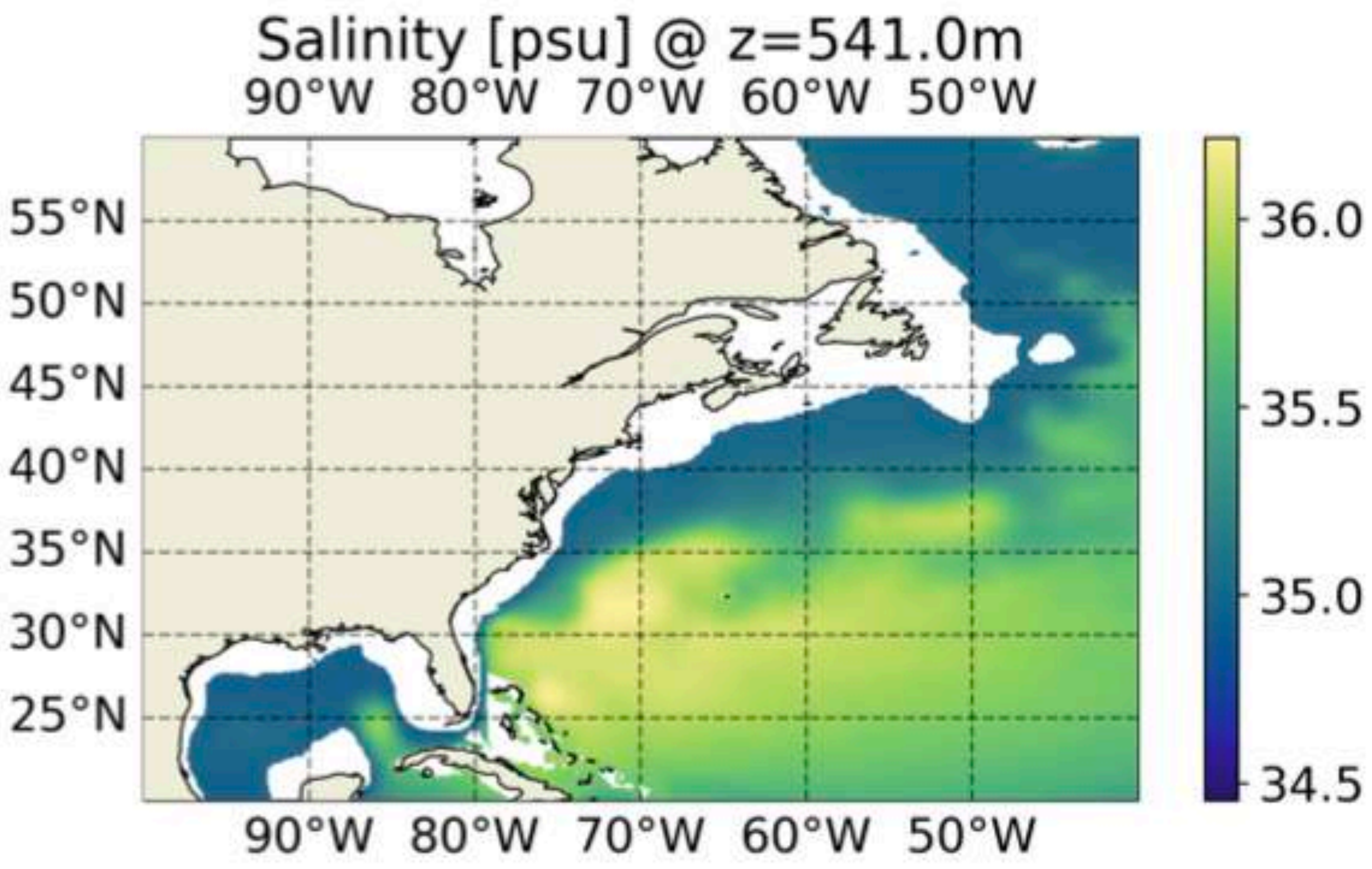
Modeled sound speed

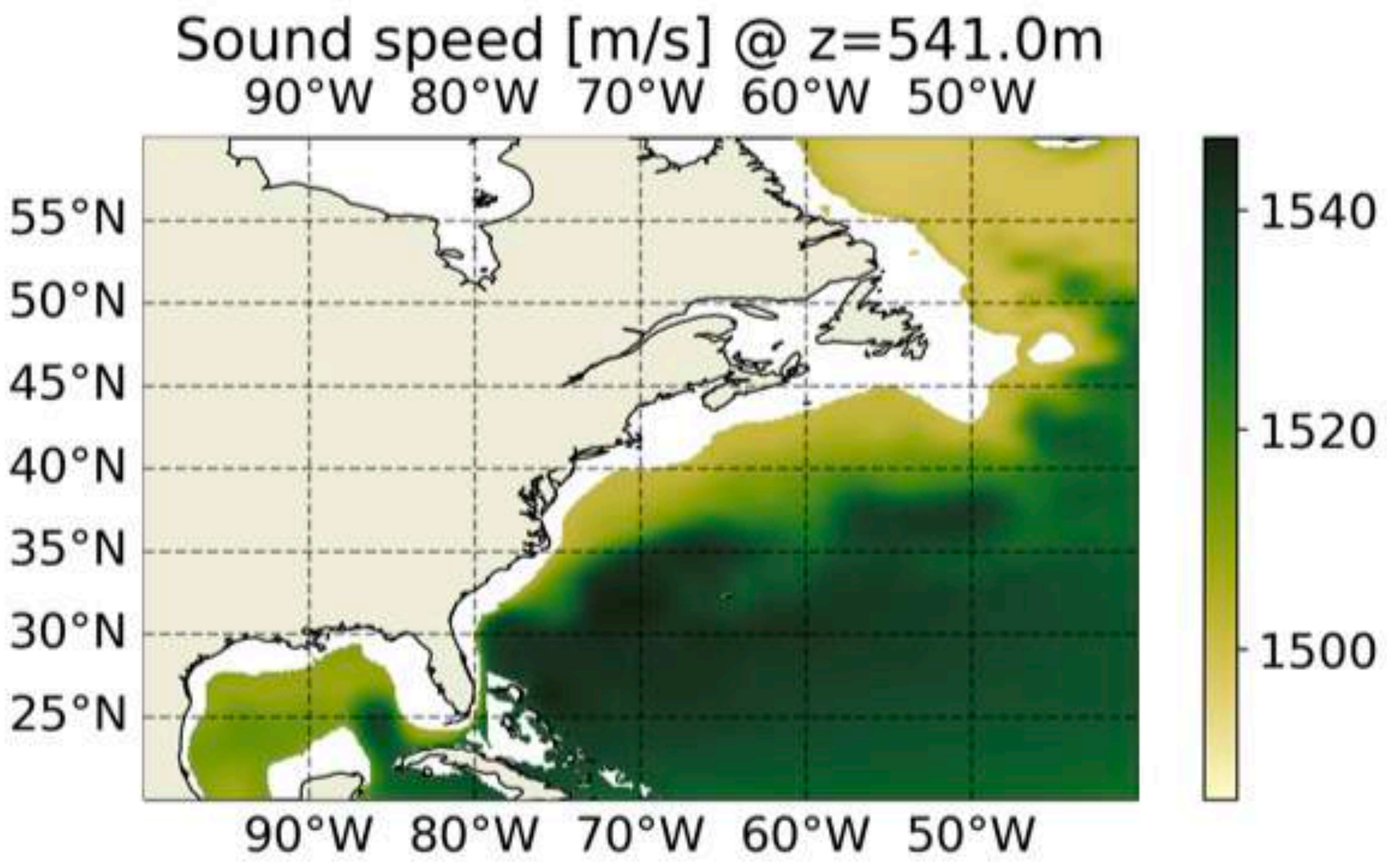
Sample diagnostic results

- From modeled hydrography, sound speed is resolved as a diagnostic at each time step. The three-dimensional field is solved from the UNESCO empirical algorithm.[CC77]

$$c(S,T,p) = C_w(T,p) + A(T,p)S + B(T,p)S^{2/3} + D(T,p)S^2\,.$$



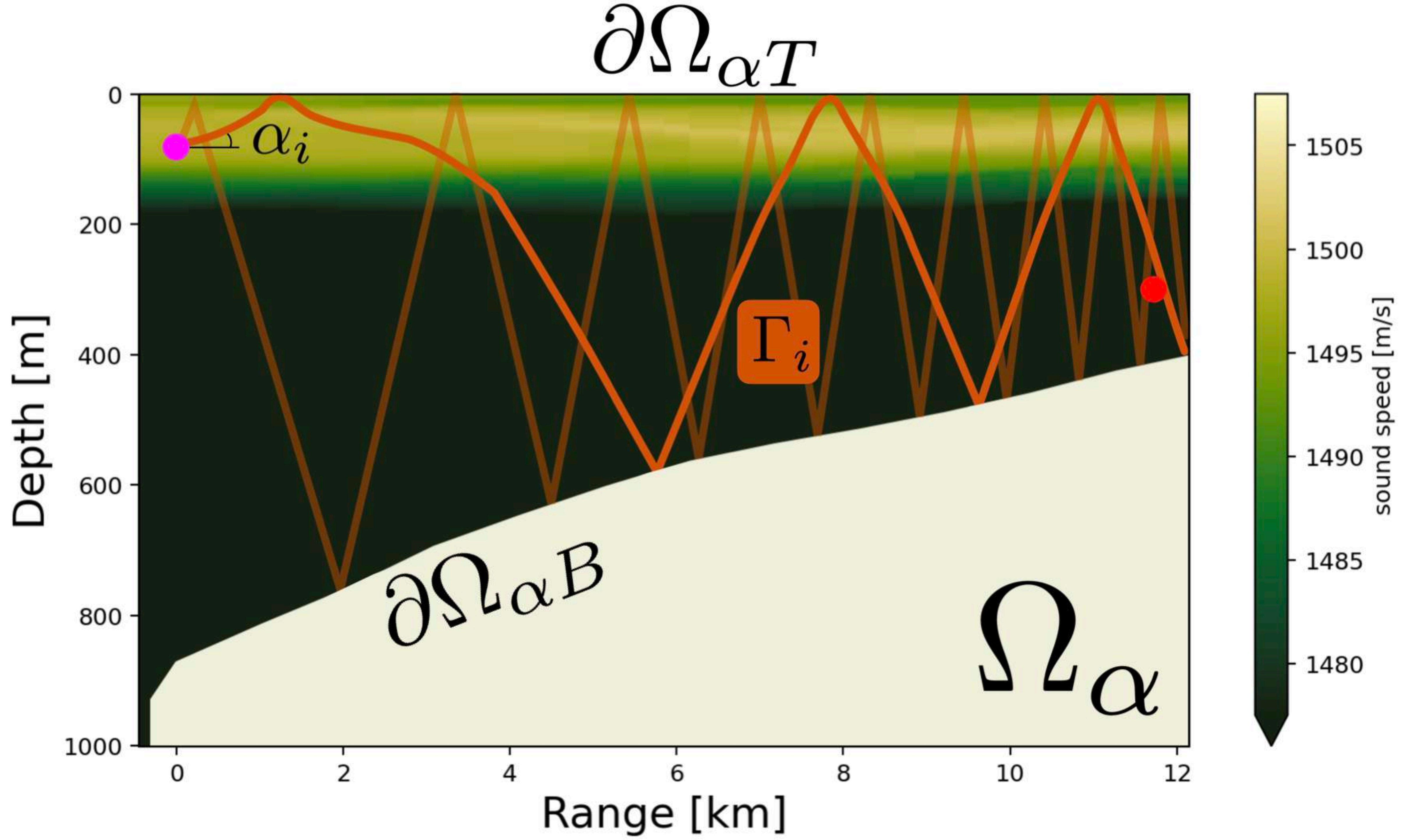




Geometric ray trace model

Two-dimensional range-dependent equations

Let $\mathbf{r} = (r, z) \in \Omega_\alpha$, $\gamma \in \Omega_\alpha$, is an arc length along a ray, $\Gamma(\gamma)$. In ray-centered coordinates, $\xi(\gamma)$ and $\zeta(\gamma)$, the tangent vector is $\mathbf{t} = c[\xi, \zeta]$.[FJ11]



$$
\begin{aligned}
\frac{d\boldsymbol{r}}{d\gamma} &= \boldsymbol{t} && \text{in } \Omega_\alpha,\\
\frac{d\boldsymbol{t}}{d\gamma} &= -\frac{1}{c}\nabla_{\boldsymbol{r}} c && \text{in } \Omega_\alpha,
\end{aligned}
$$

$$
\begin{aligned}
\boldsymbol{t} &= \boldsymbol{t}_T && \text{on } \partial\Omega_{\alpha T},\\
\boldsymbol{t} &= \boldsymbol{t}_B && \text{on } \partial\Omega_{\alpha B},\\
\nabla \boldsymbol{r} \cdot \boldsymbol{n} &= \boldsymbol{0} && \text{on } \partial\Omega_{\alpha R},\\
\boldsymbol{r} &= \boldsymbol{r}_0 && \text{on } \partial\Omega_{\alpha S},\\
\boldsymbol{t} &= \boldsymbol{t}_0 && \text{on } \partial\Omega_{\alpha S}.
\end{aligned}
$$

Dynamic acoustic modeling

Determining eigenrays seen at a receiver location

- For each $i = 1, \ldots, N_\alpha$, given a launch angle α_i, we obtain a set of paths, $\Gamma_i = \{\mathbf{r}(\gamma) \in \Omega_\alpha : i = 1, \ldots, N_\alpha\}$. Travel times, τ_i, are found along Γ_i.

$$
\begin{aligned}
\frac{d\tau_i}{d\gamma} &= \frac{1}{c} && \text{in } \Gamma_i, & A &= |\mathcal{R}|A && \text{on } \partial\Omega_{\alpha B},\\
\frac{dq_i}{d\gamma} &= cp_i && \text{in } \Gamma_i, & \tau_i &= 0 && \text{on } \Gamma_i \cap \partial\Omega_{\alpha S},\\
& && & q_i &= 0 && \text{on } \Gamma_i \cap \partial\Omega_{\alpha S},\\
\frac{dp_i}{d\gamma} &= -\frac{\nabla(\nabla c \cdot \boldsymbol{n}) \cdot \boldsymbol{n}}{c^2} q_i && \text{in } \Gamma_i, & p_i &= \frac{1}{c_0} && \text{on } \Gamma_i \cap \partial\Omega_{\alpha S},
\end{aligned}
$$

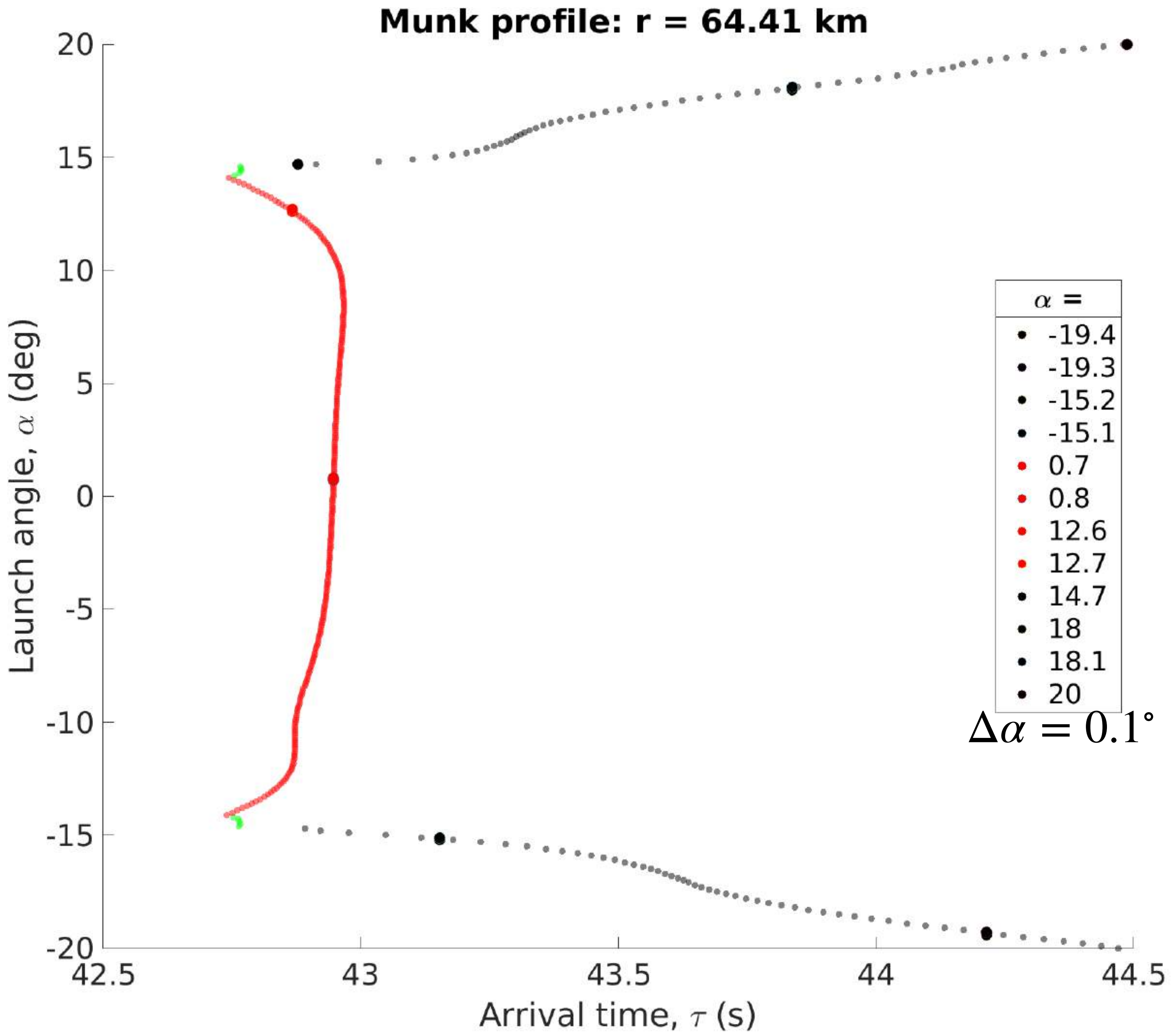
where p, q, and $|\mathcal{R}| \in [0,1]$ describe dynamic ray-centered coordinate, slowness, and Rayleigh reflection coefficient.

Geometric ray trace model

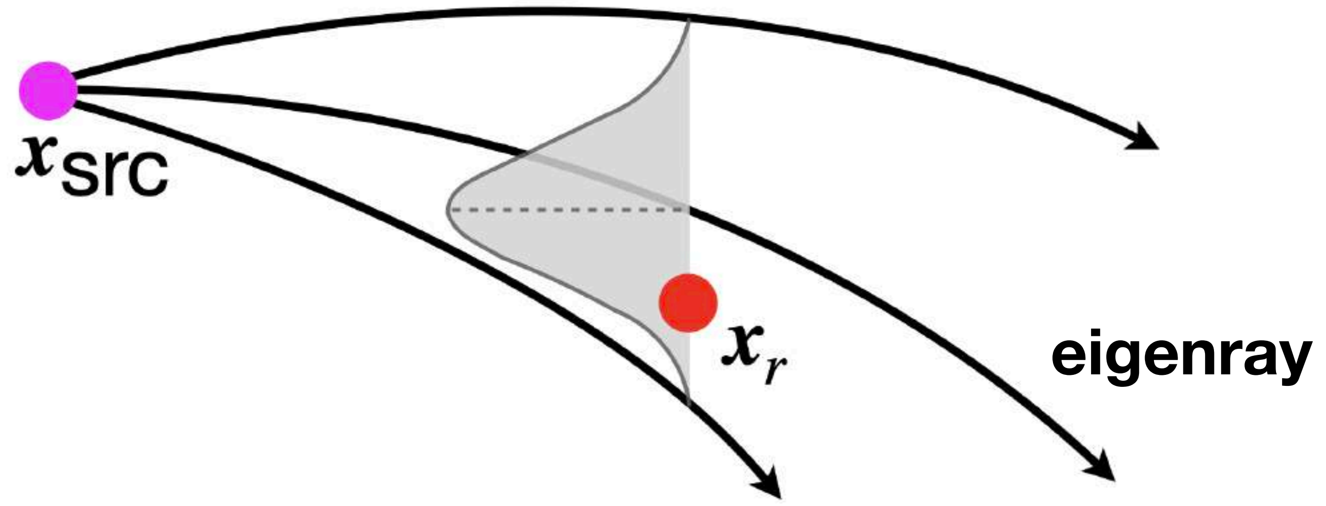
Determining eigenrays seen at a receiver location

- Geometric beams with Gaussian spreading projected onto the vertical direction from the ray path, Γ_i, as

$$W(n) = \exp\{-0.5(n(\gamma)/|q(\gamma)\delta\alpha|)^2\}$$



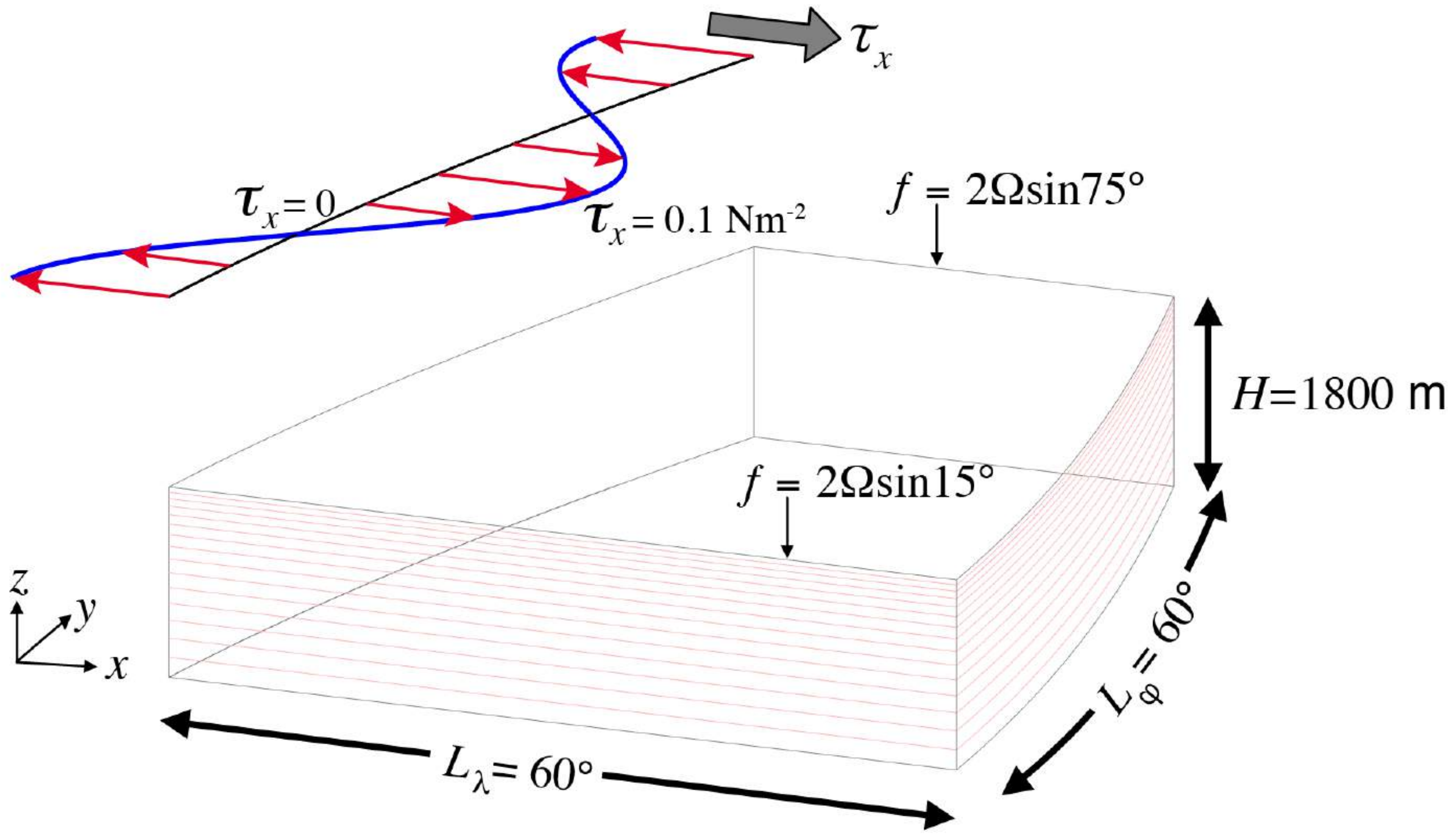
where $n(\gamma)$ is the normal distance from receiver to the ray path and $|q(\gamma)\delta\alpha|$ is a *beam halfwidth*.



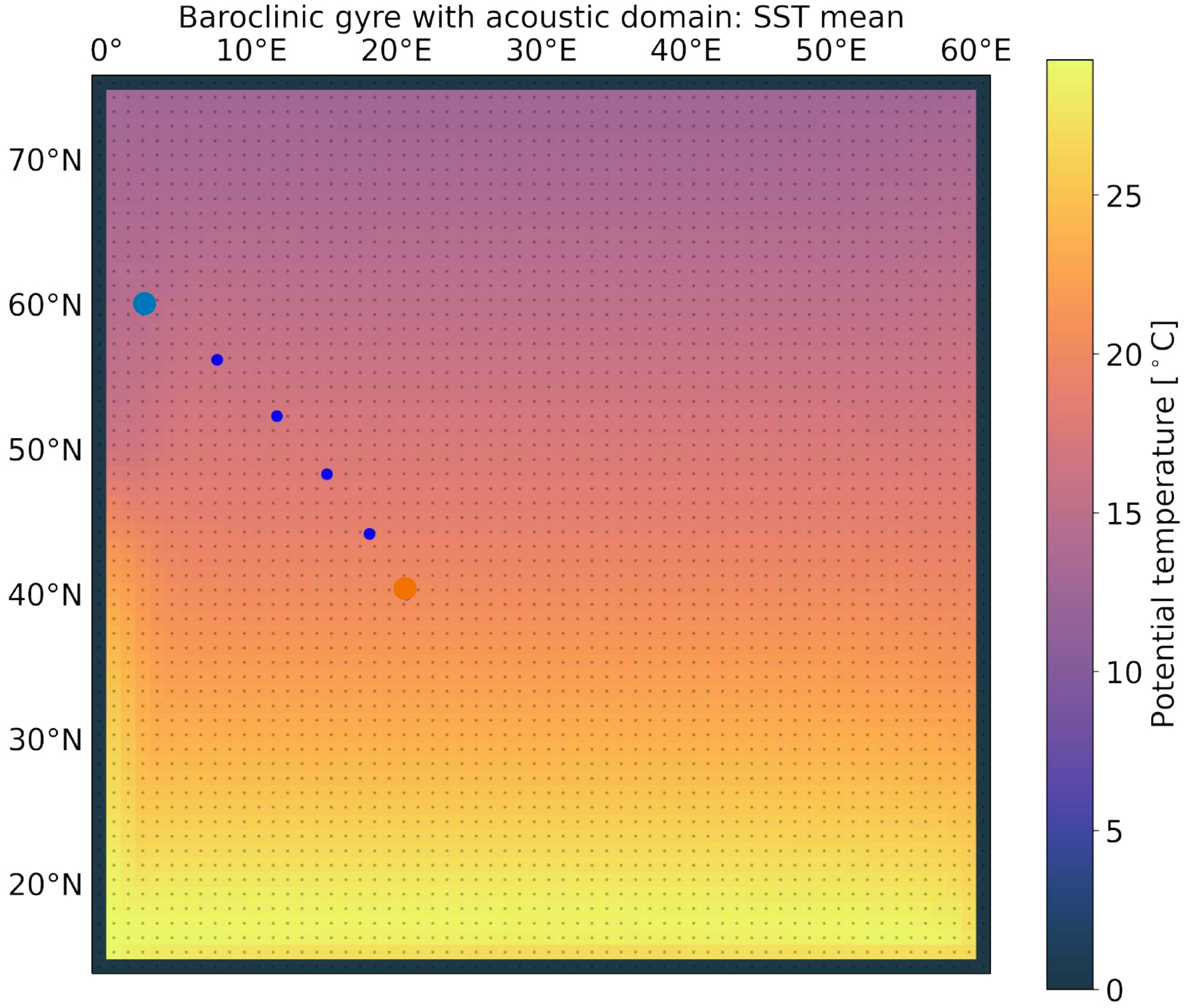
Adapted from Figure 3.9 in Jensen *et al.* (2011)

Acoustic diagnostics from evolving ocean model

Results from a modeled baroclinic gyre[MC84]

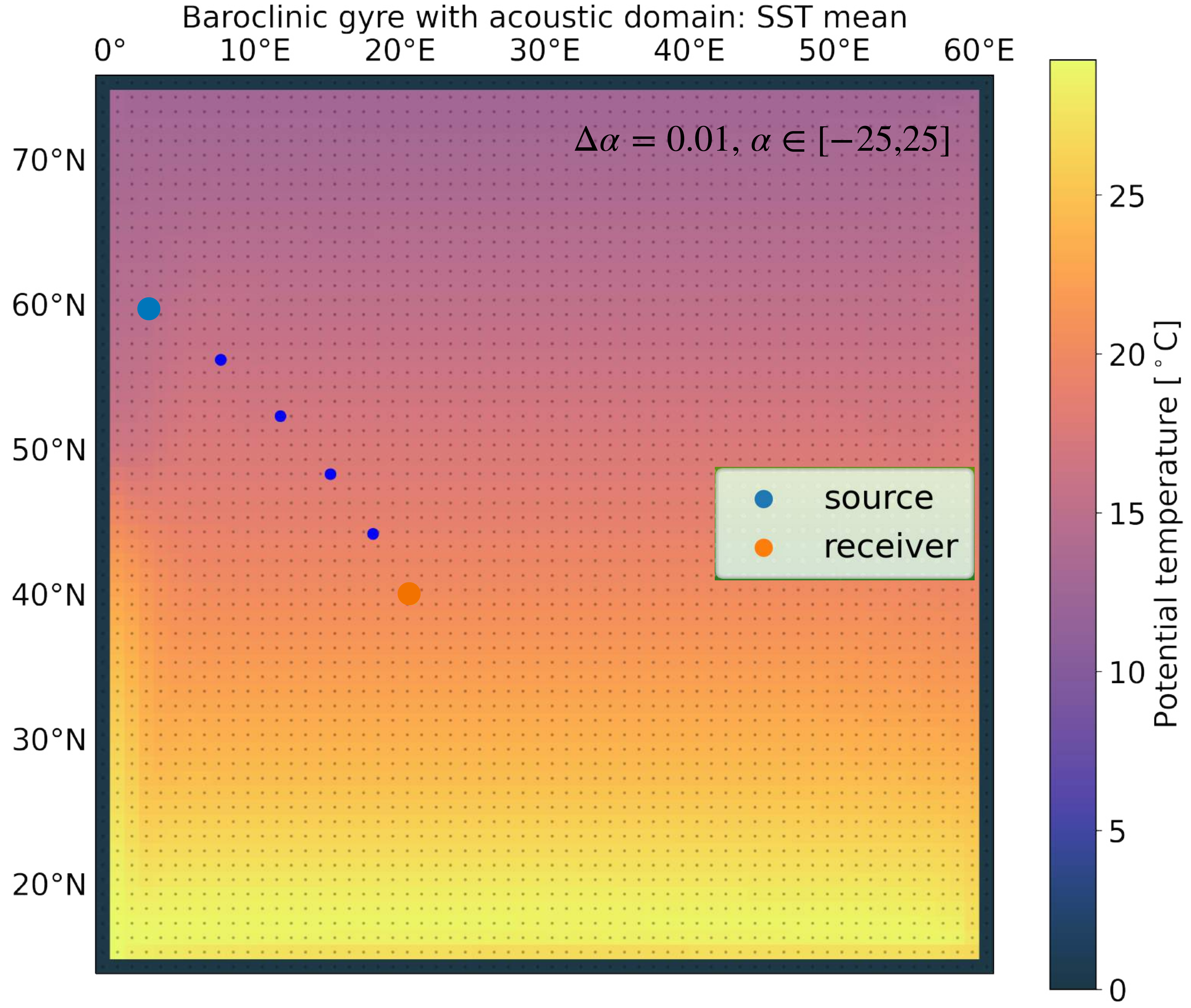


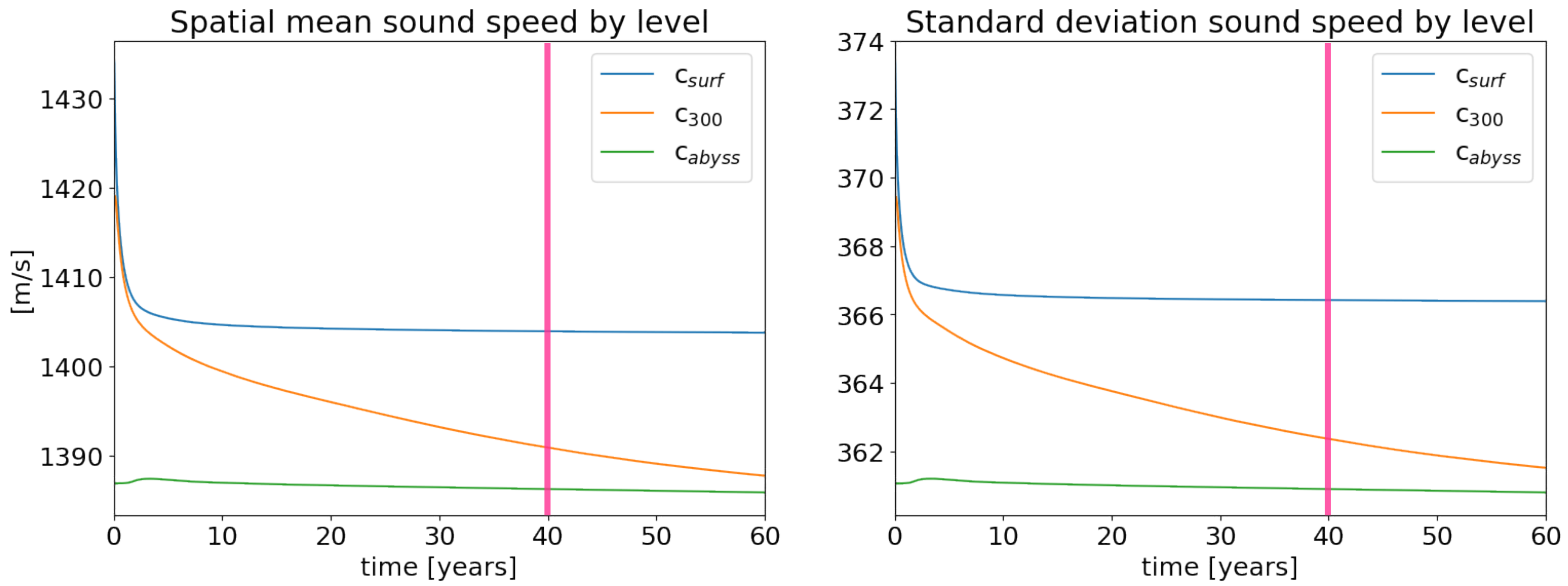
$$\tau_x(\varphi) = -\tau_0 \cos\left(2\pi \frac{\varphi - \varphi_0}{L_\varphi}\right)$$

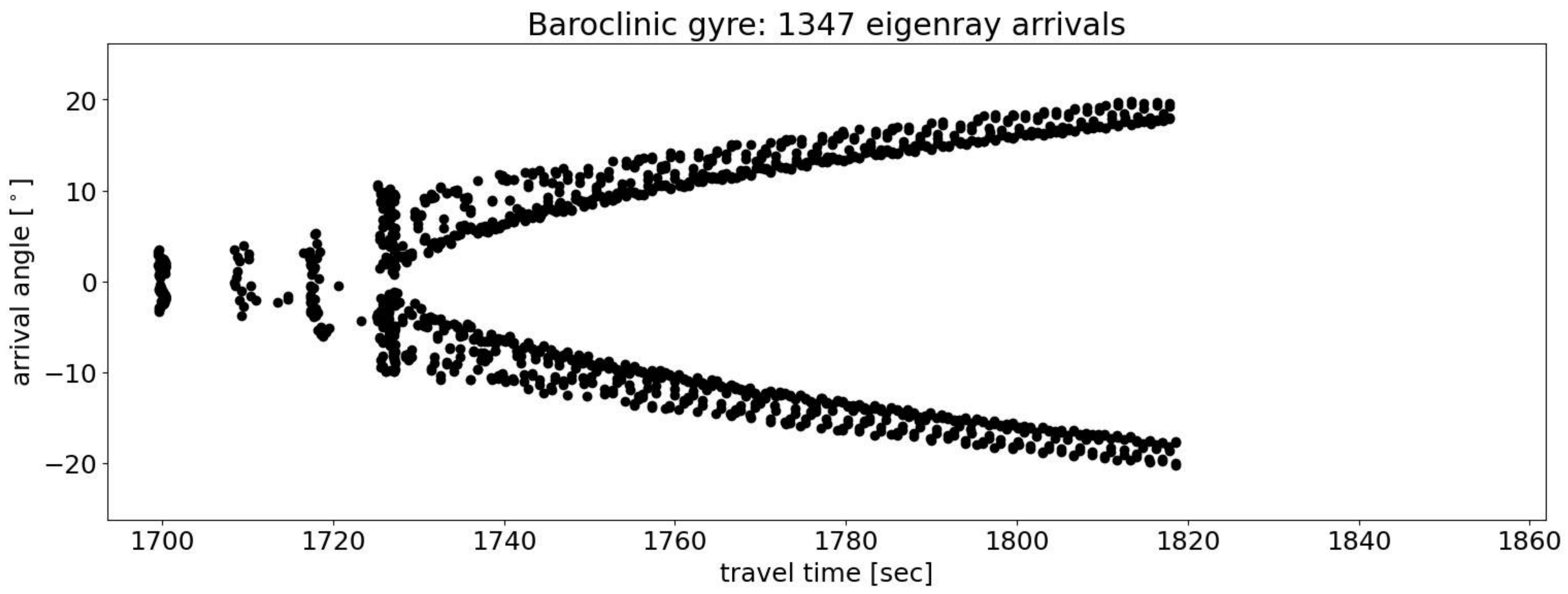


Acoustic diagnostics from evolving ocean model

Results from a modeled baroclinic gyre

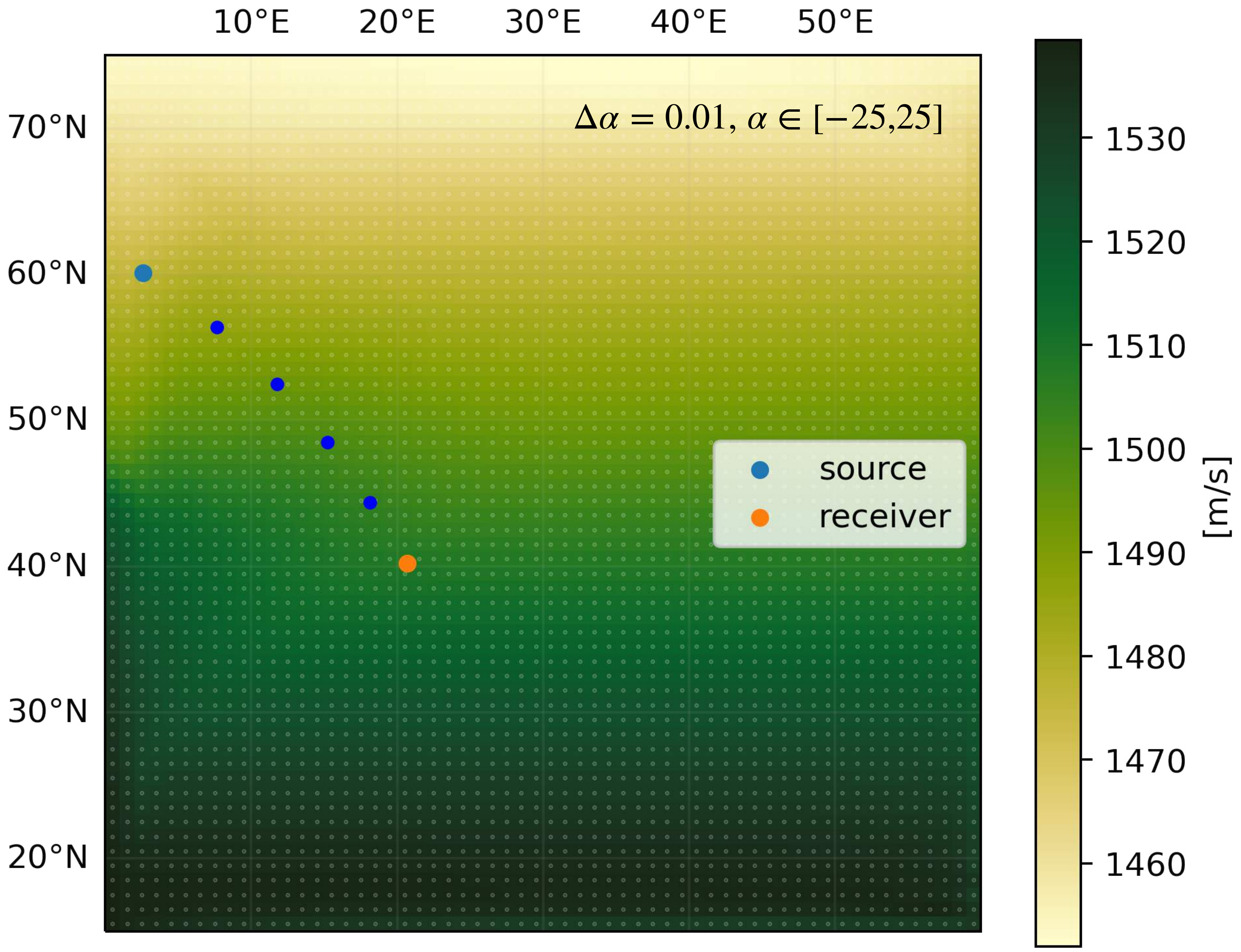




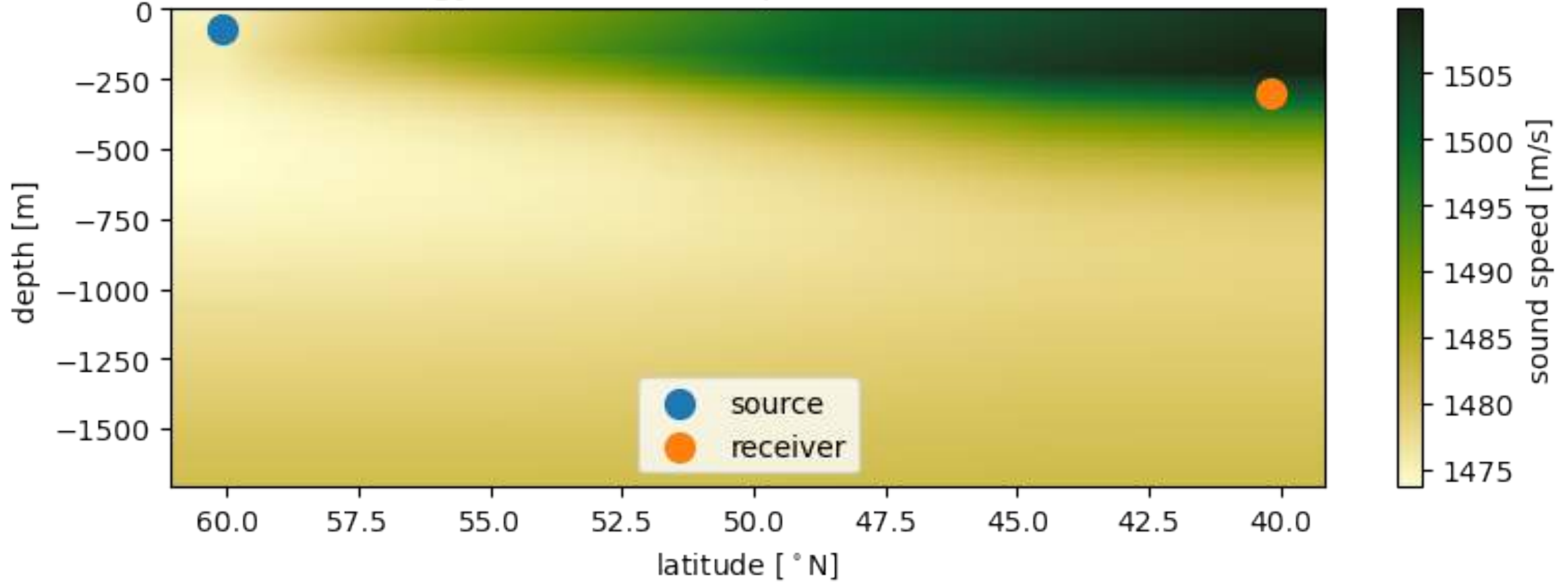


Acoustic diagnostics from evolving ocean model

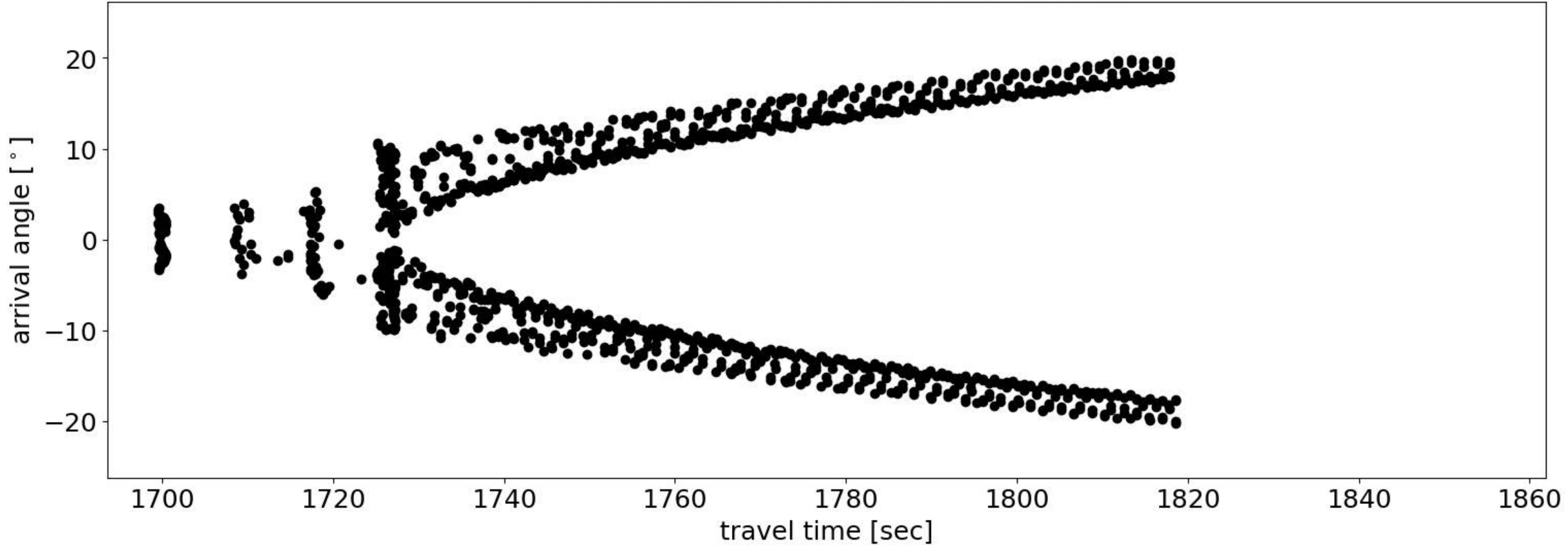
Results from a modeled baroclinic gyre



Baroclinic gyre mean sound speed at 25 m



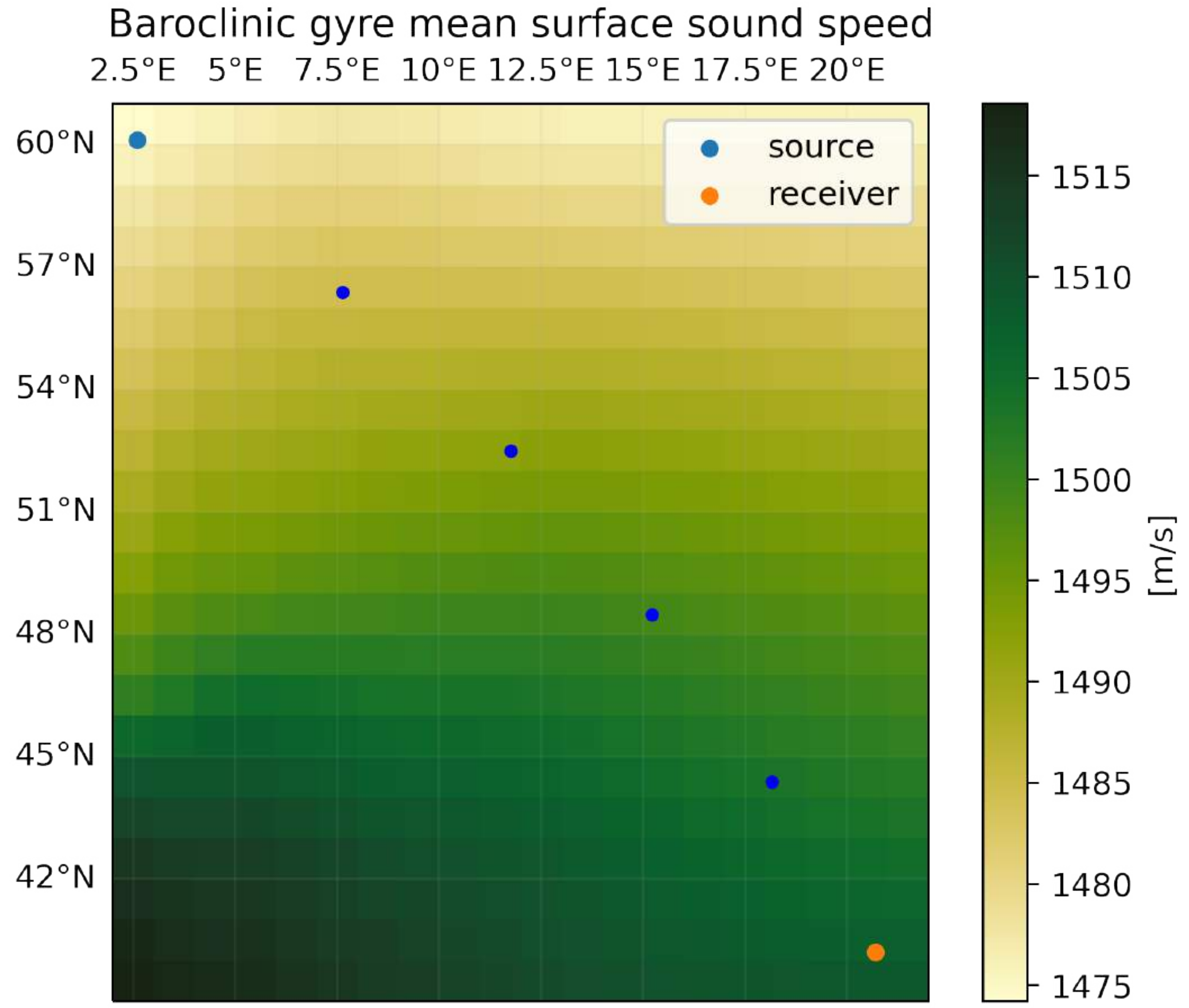
Baroclinic gyre mean sound speed in 2D acoustic domain

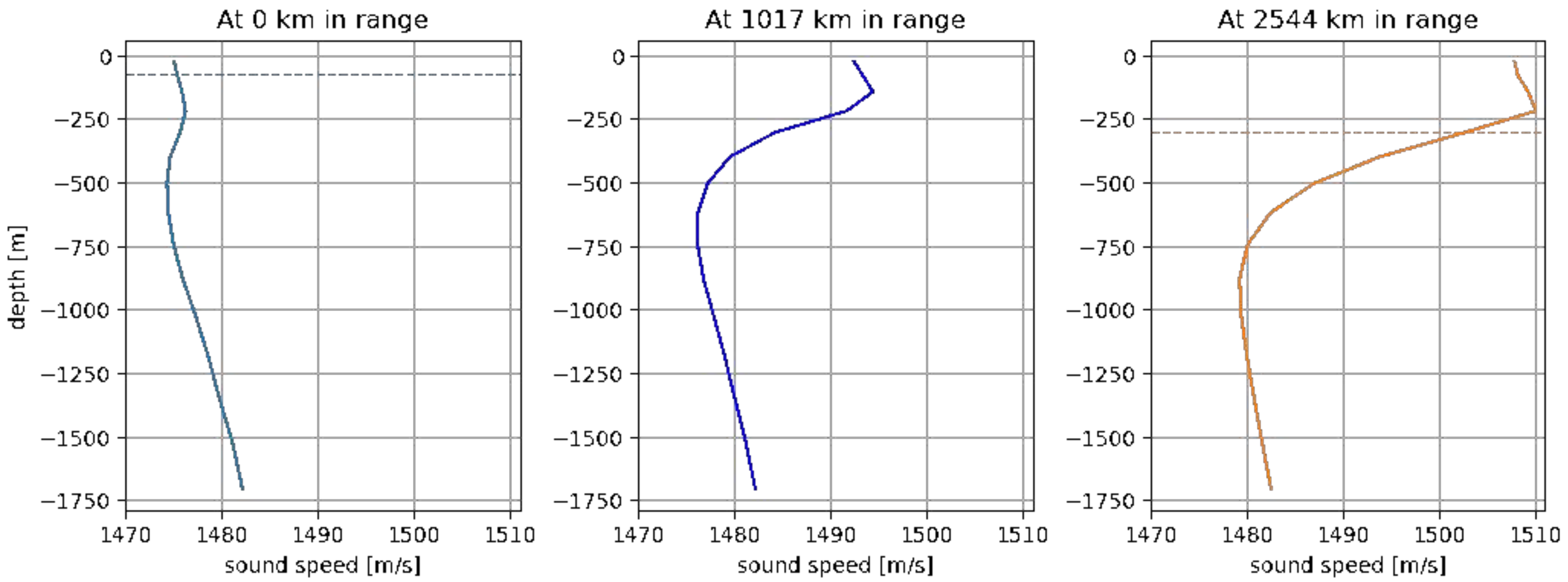


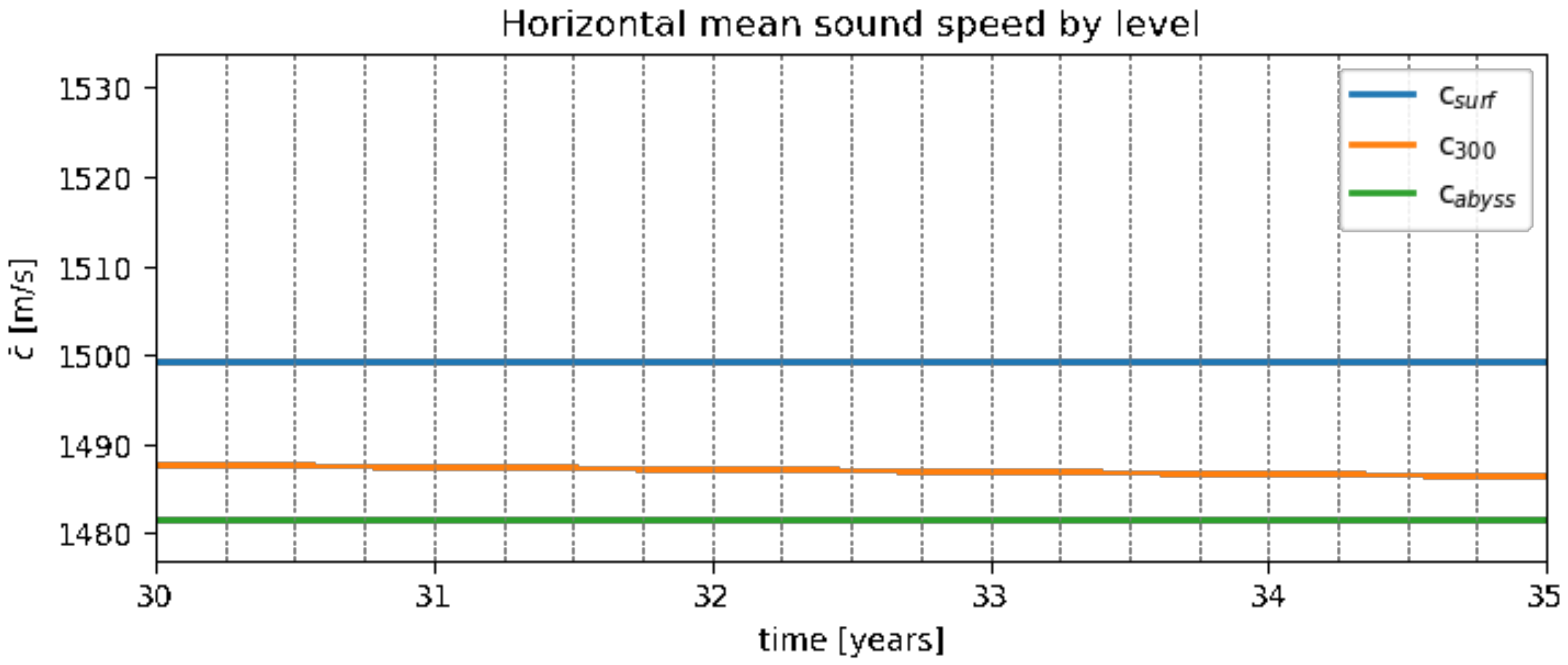
Baroclinic gyre: 1347 eigenray arrivals

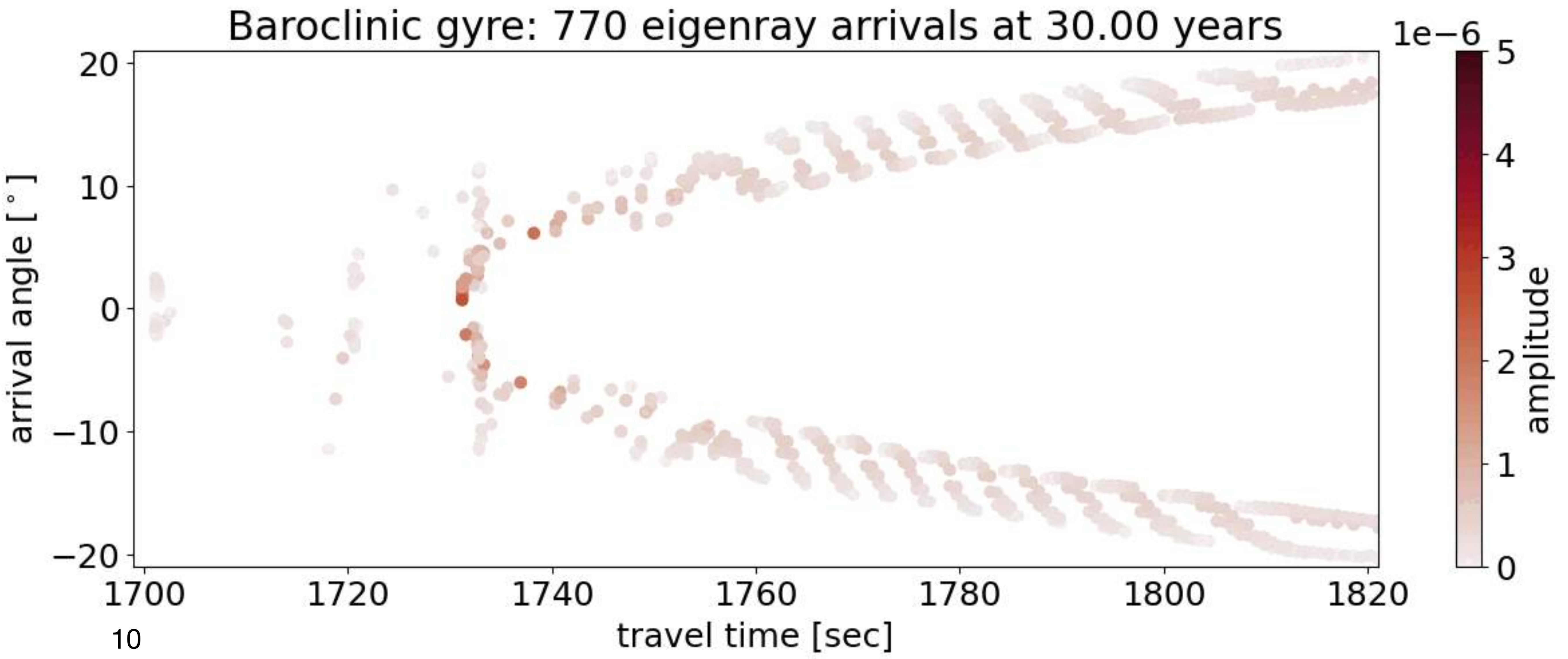
Acoustic diagnostics from evolving ocean model

Results from a modeled baroclinic gyre



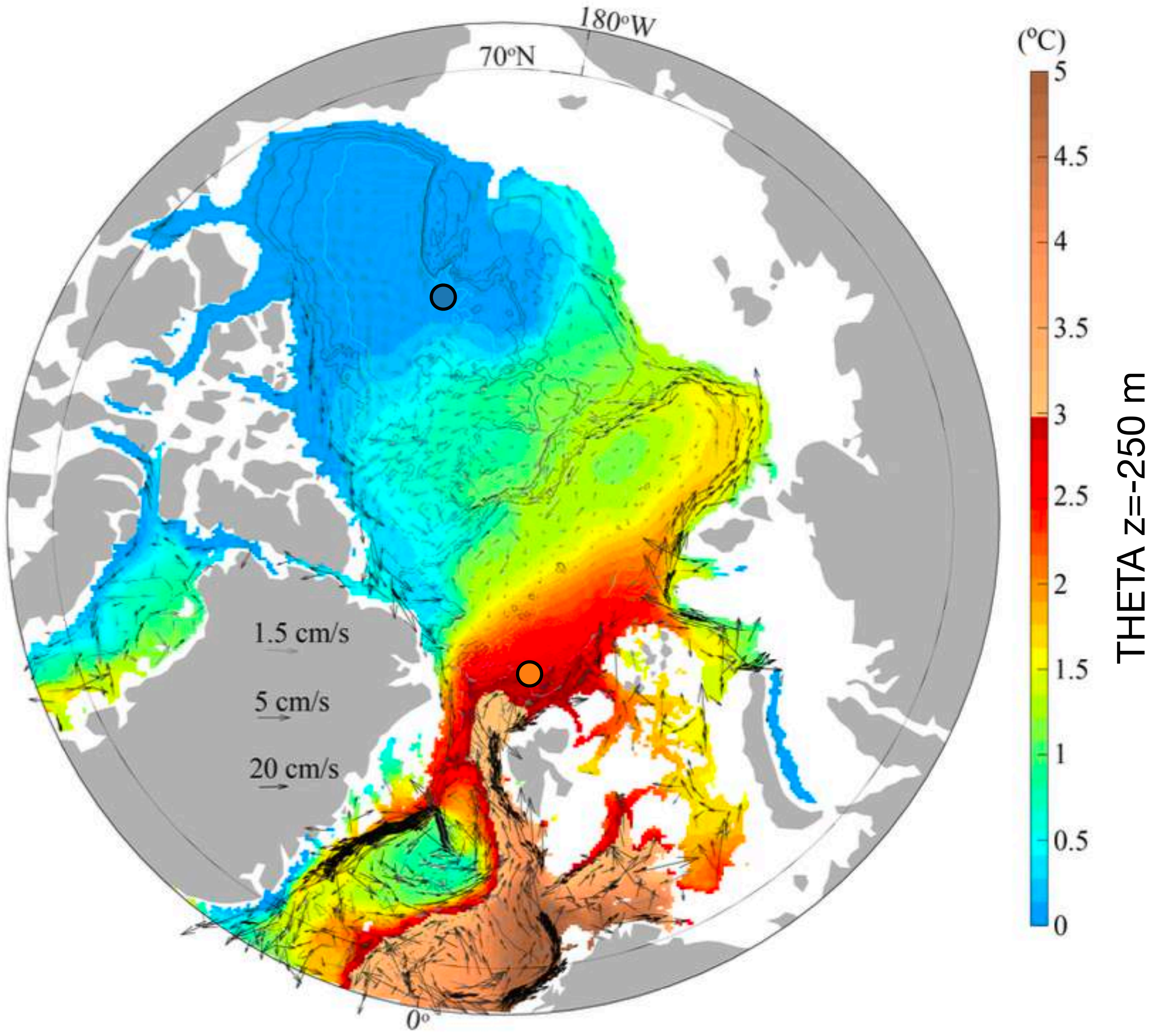






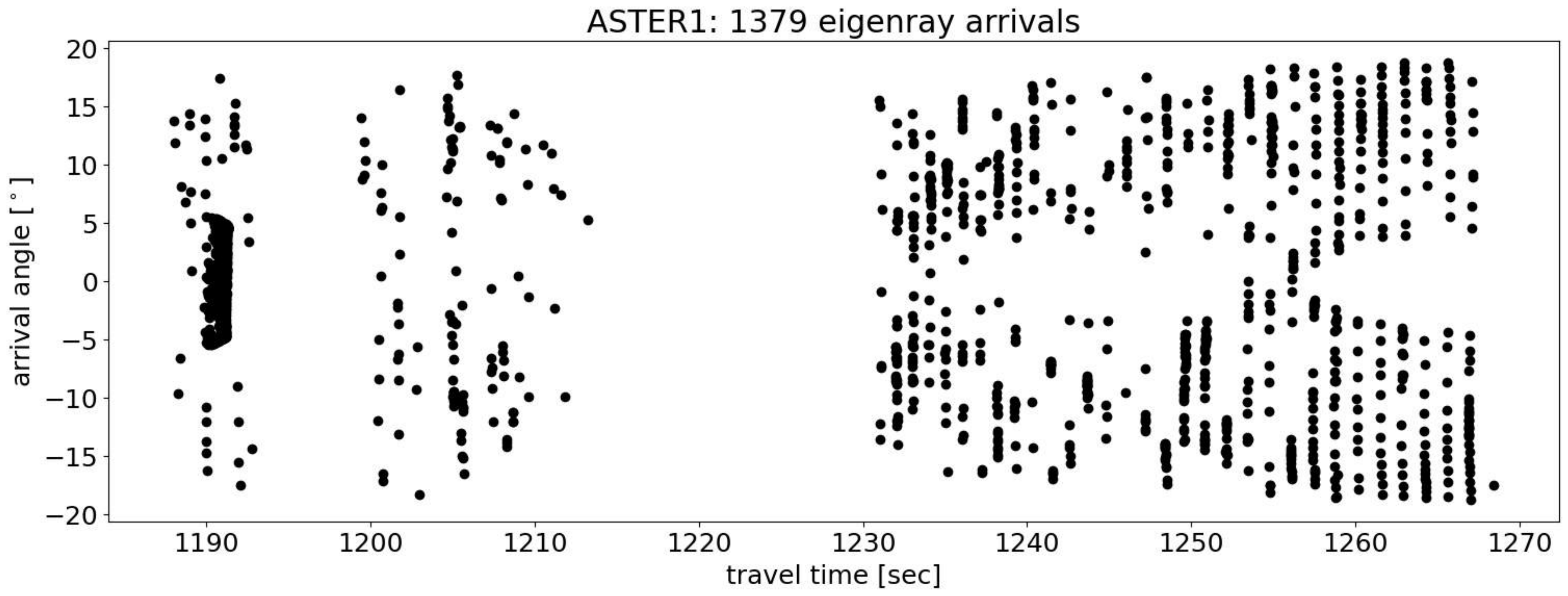
Acoustic diagnostics from evolving ocean model

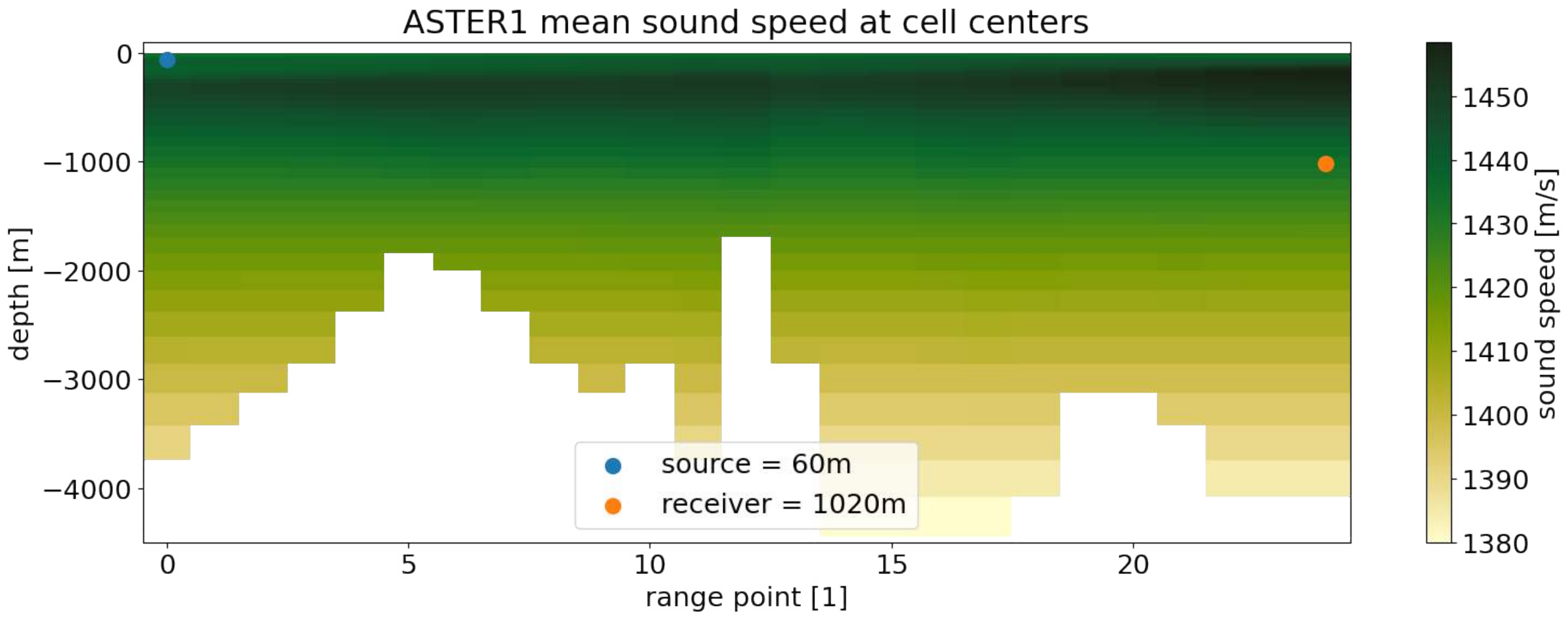
Results on a *lat lon cap* ocean grid



From Figure 2 in Nguyen *et al.* (2021)
ASTE R1: 2002-2015 mean temperature

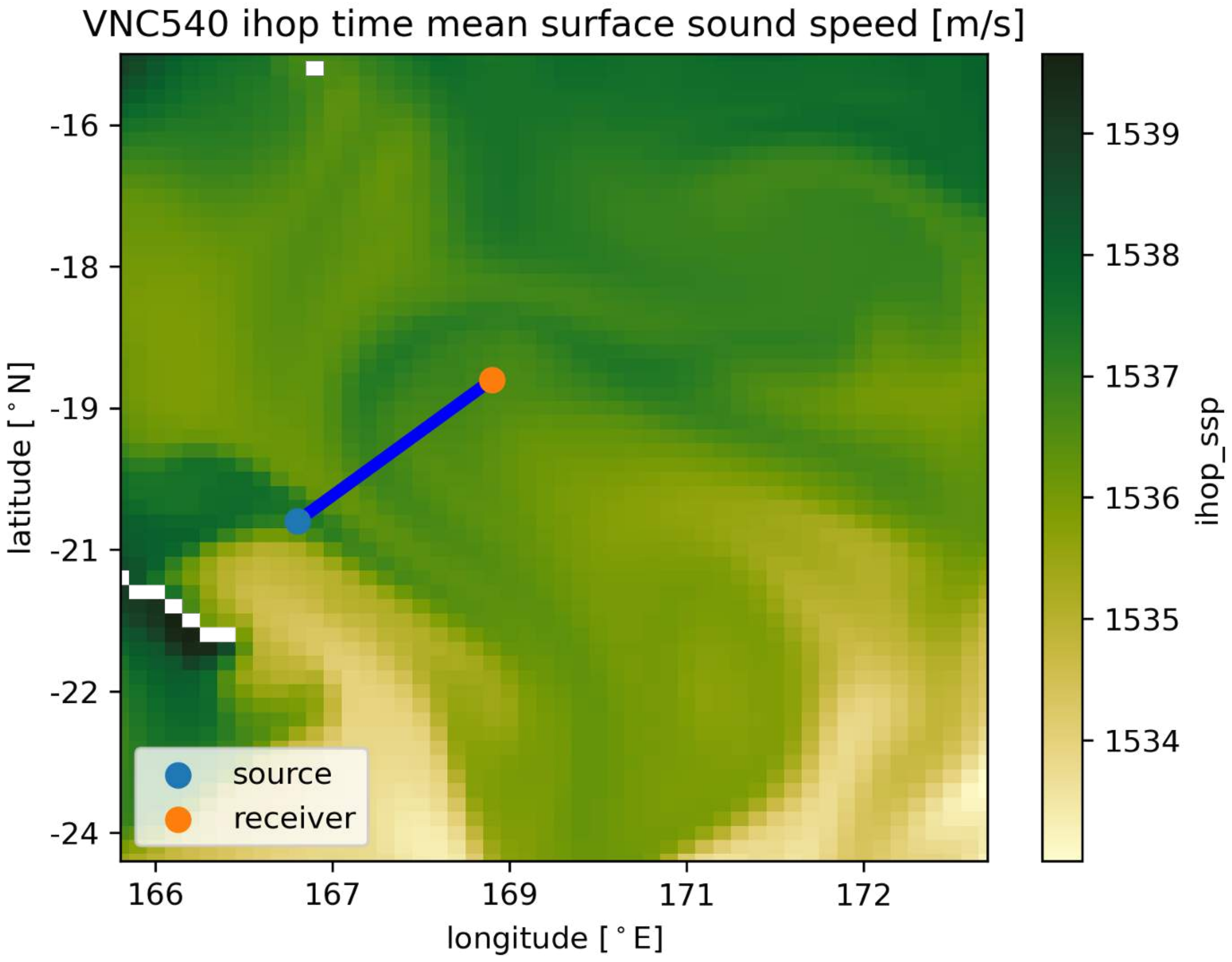
$\Delta\alpha = 0.01, \alpha \in [-13, 13]$

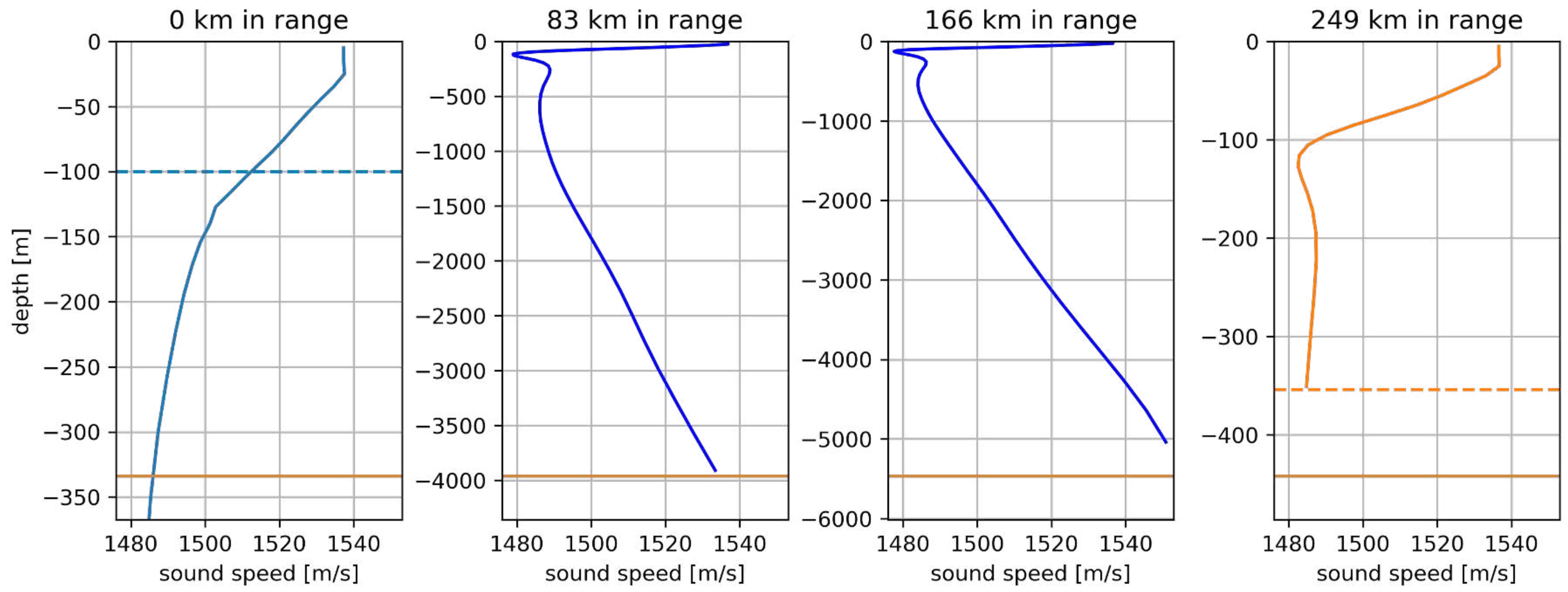


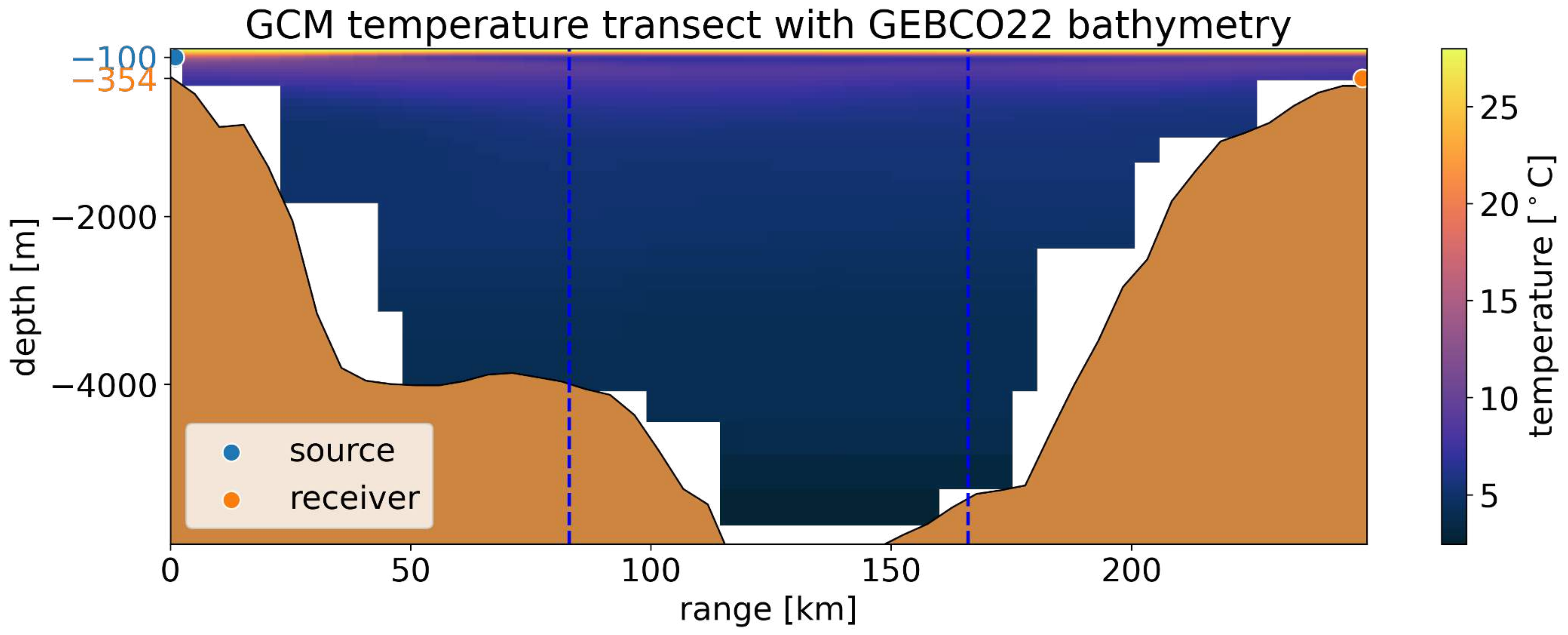


Case study: Vanuatu/New Caledonia

Region developed by Matt Goldberg (tune in to upcoming talk)







Case study: Vanuatu/New Caledonia

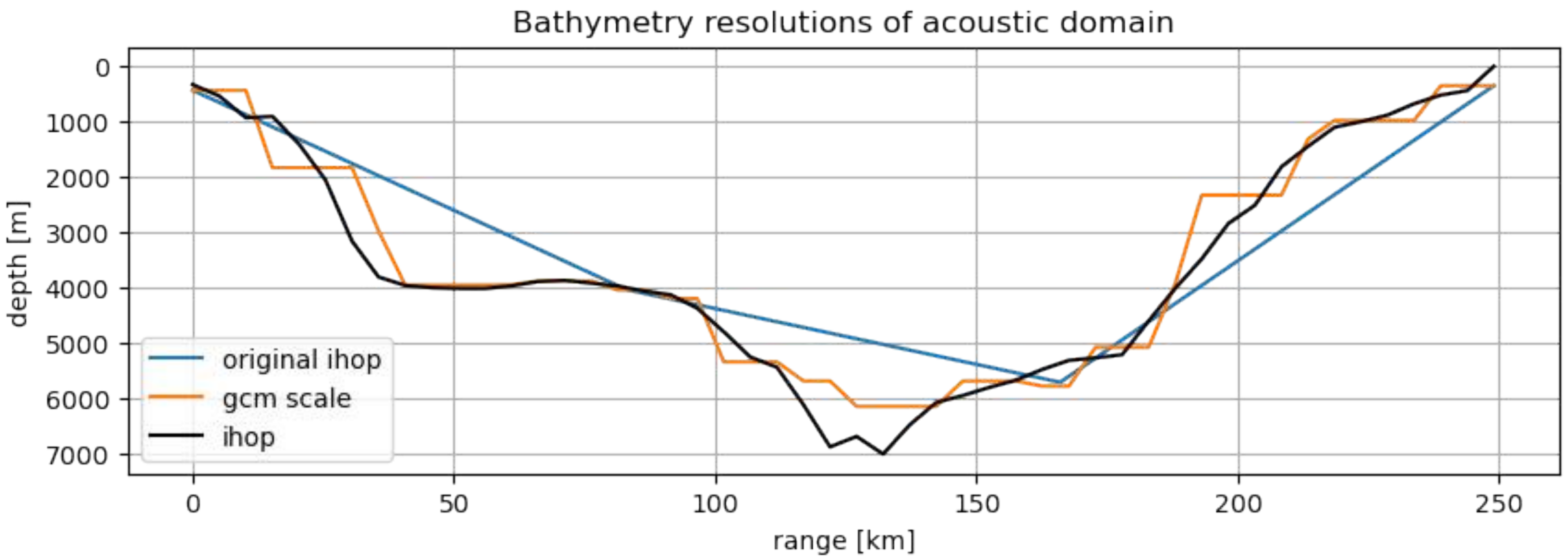
Acoustic model summary

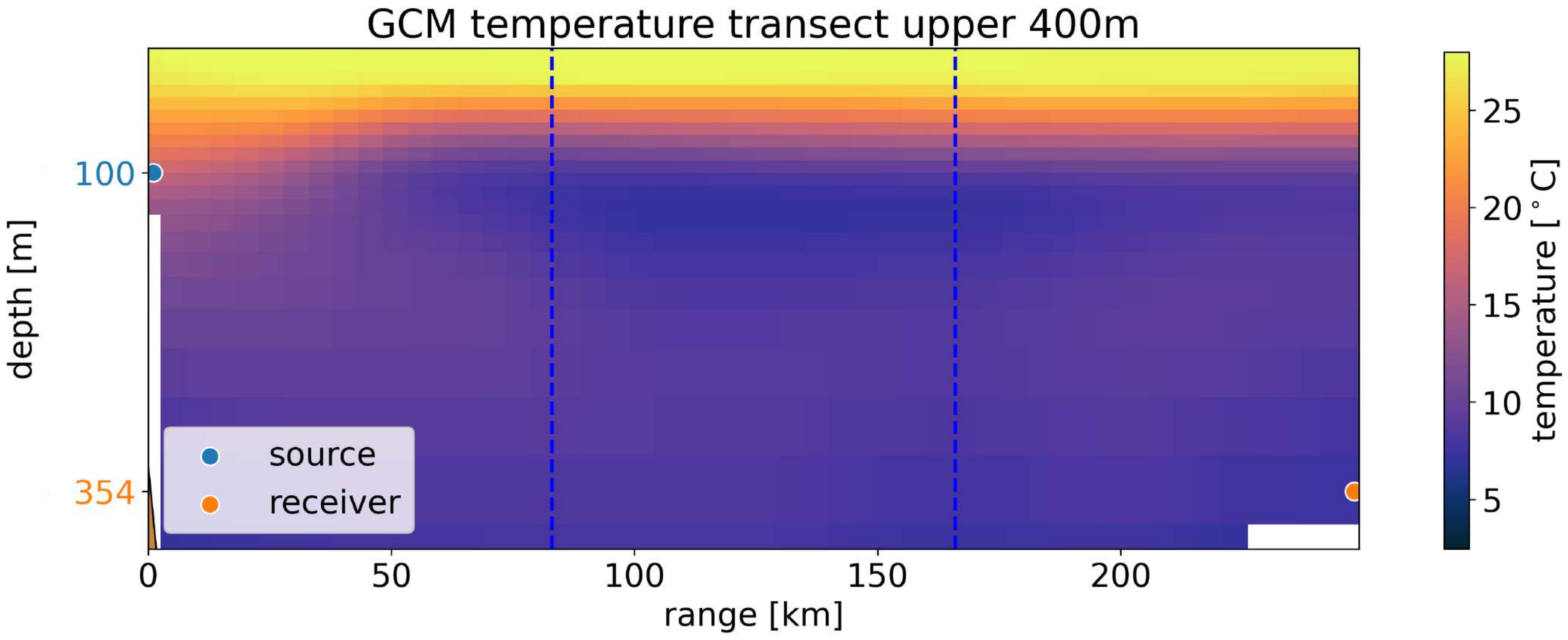
MITgcm package, ihop, set-up

- Solver: Ray tracing
- Launch angles: $\alpha \in [-70,70]^{\circ}$, $\Delta\alpha = 0.01^{\circ}$
- Eigenrays: Geometric Gaussian spreading
- Eigenray declination span: $\alpha \in [-36.4,36.4]^{\circ}$

Synthetic experiment

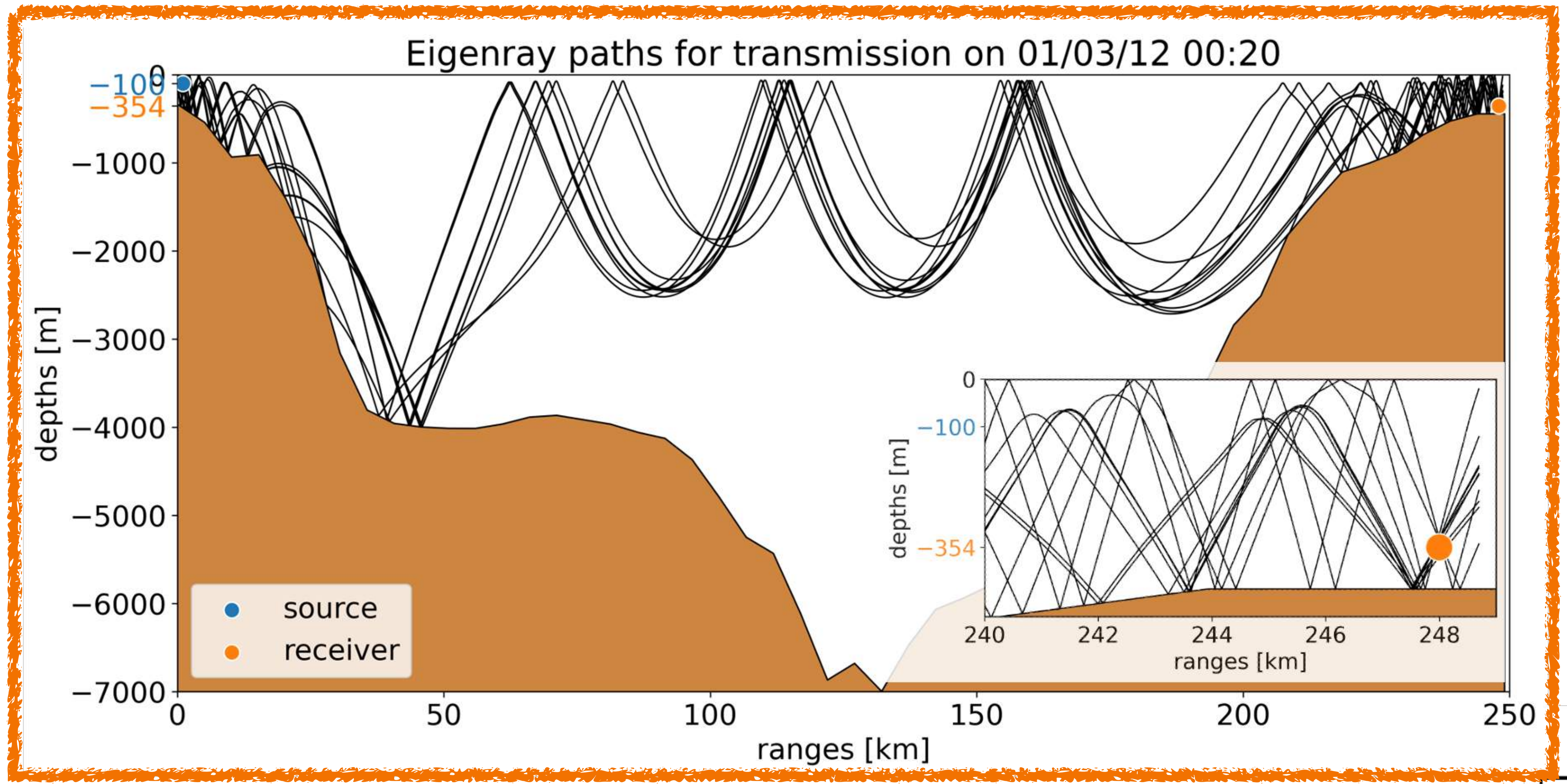
- Time span: 01 March 2012 - 08 march 2012
- Cycle: 1 signal transmission every 10 minutes
- Frequency: 550 Hz

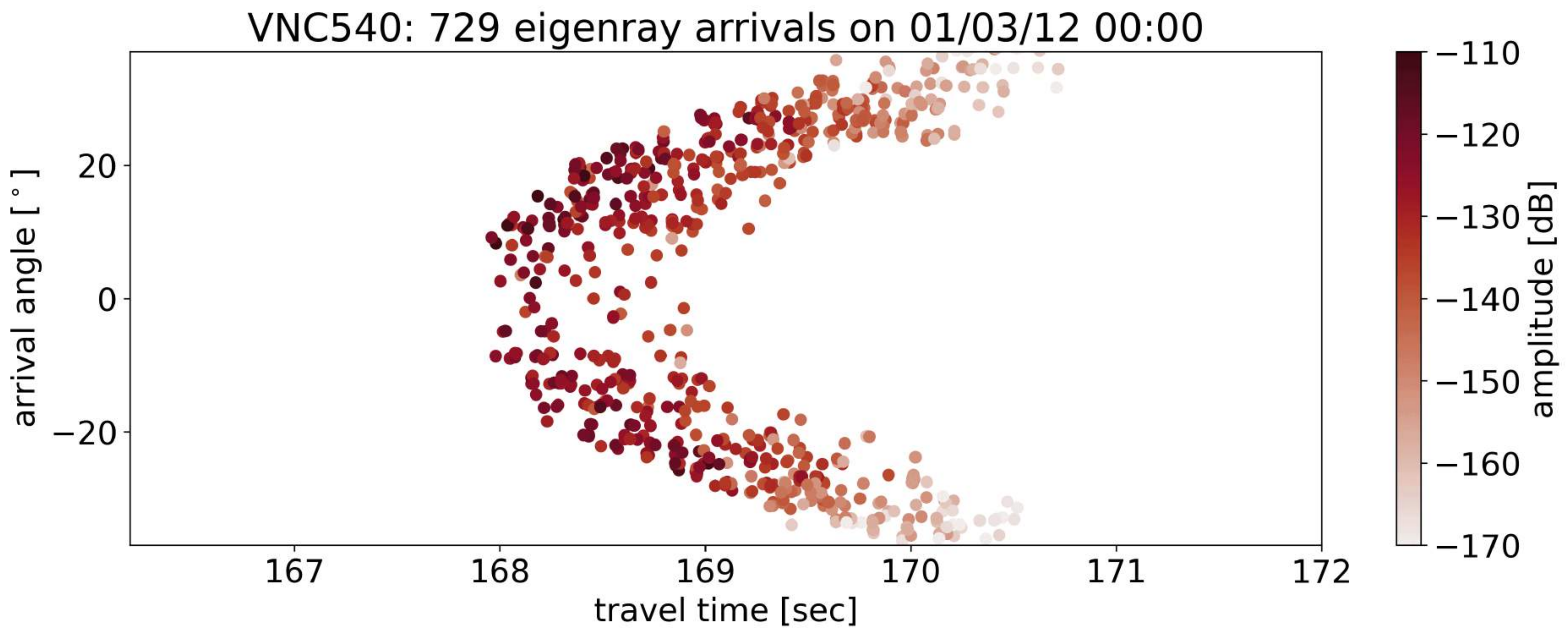


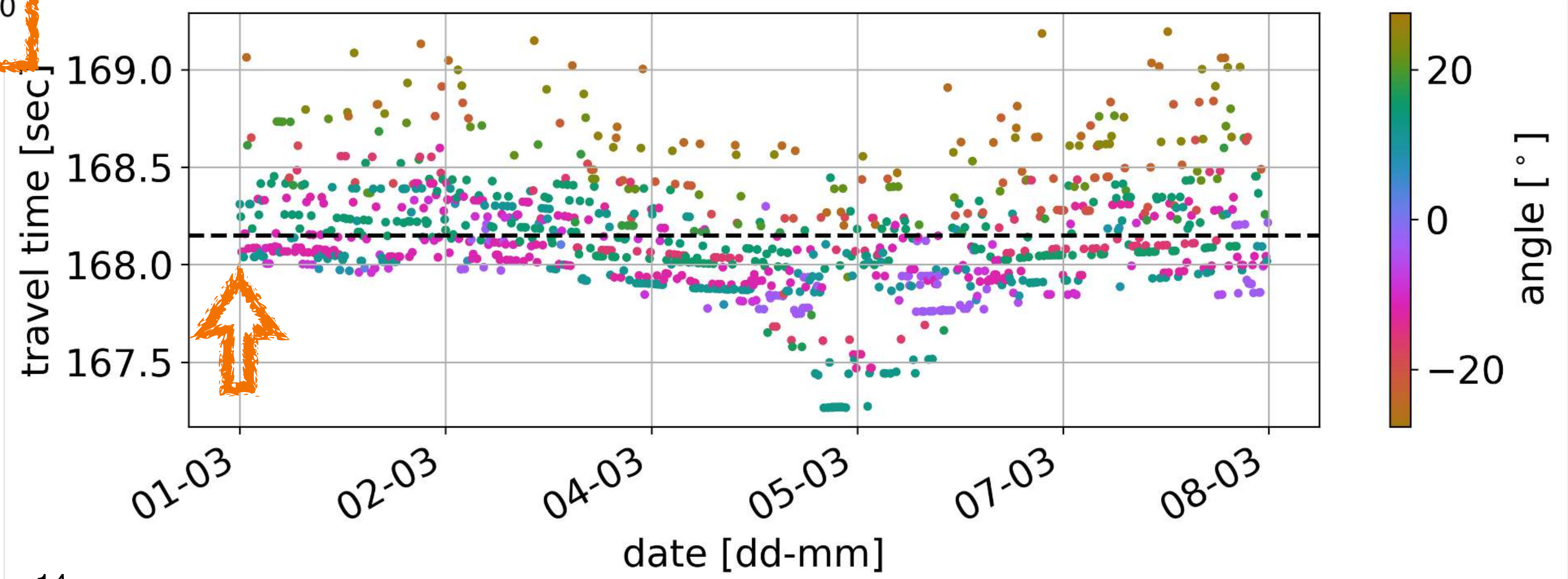


Case study: Vanuatu/New Caledonia

A time series of 1080 transmissions from MITgcm





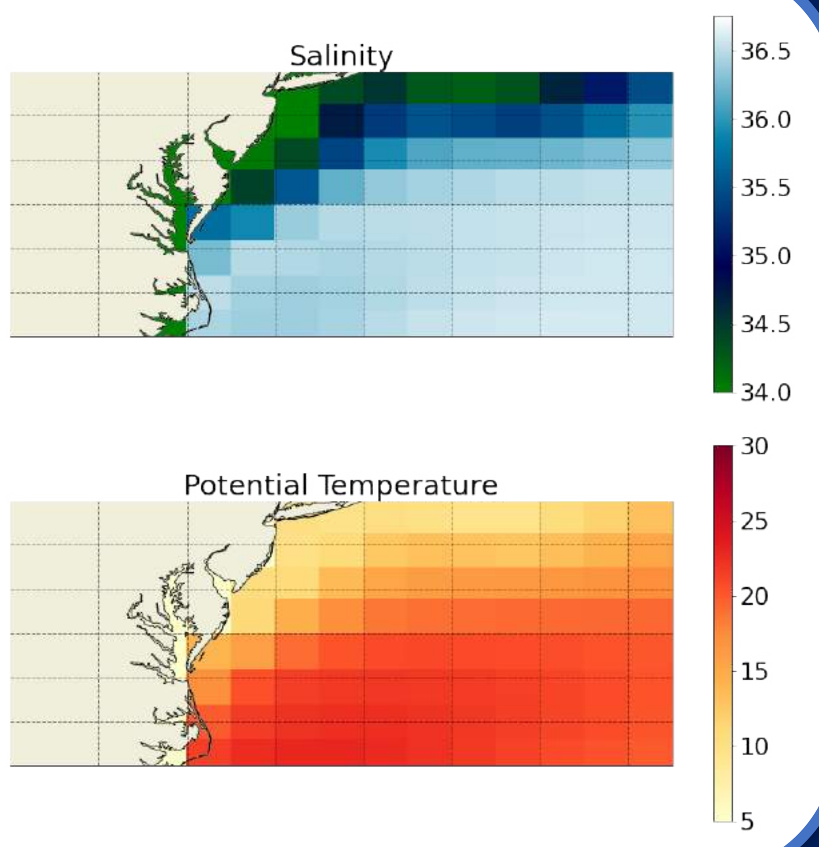


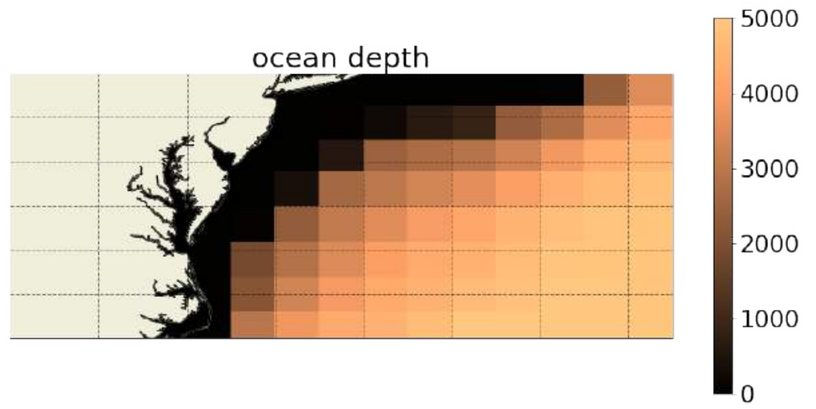
- Parameter-to-observable map can be designed around peak matching in areas with stable arrival structures

Introducing acoustics into MITgcm

Adjoint development

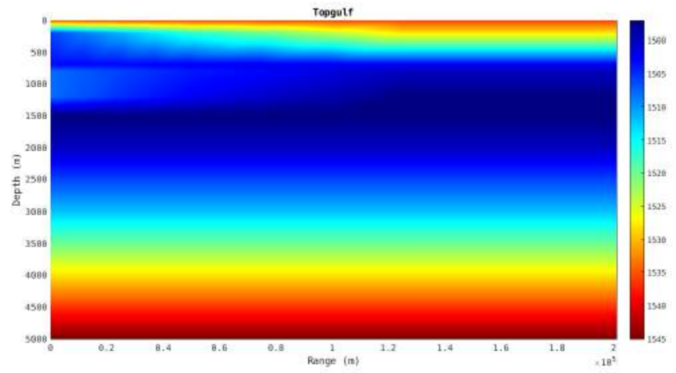
MITgcm ocean state





ihop package

Range dependent SSP



ray trace model

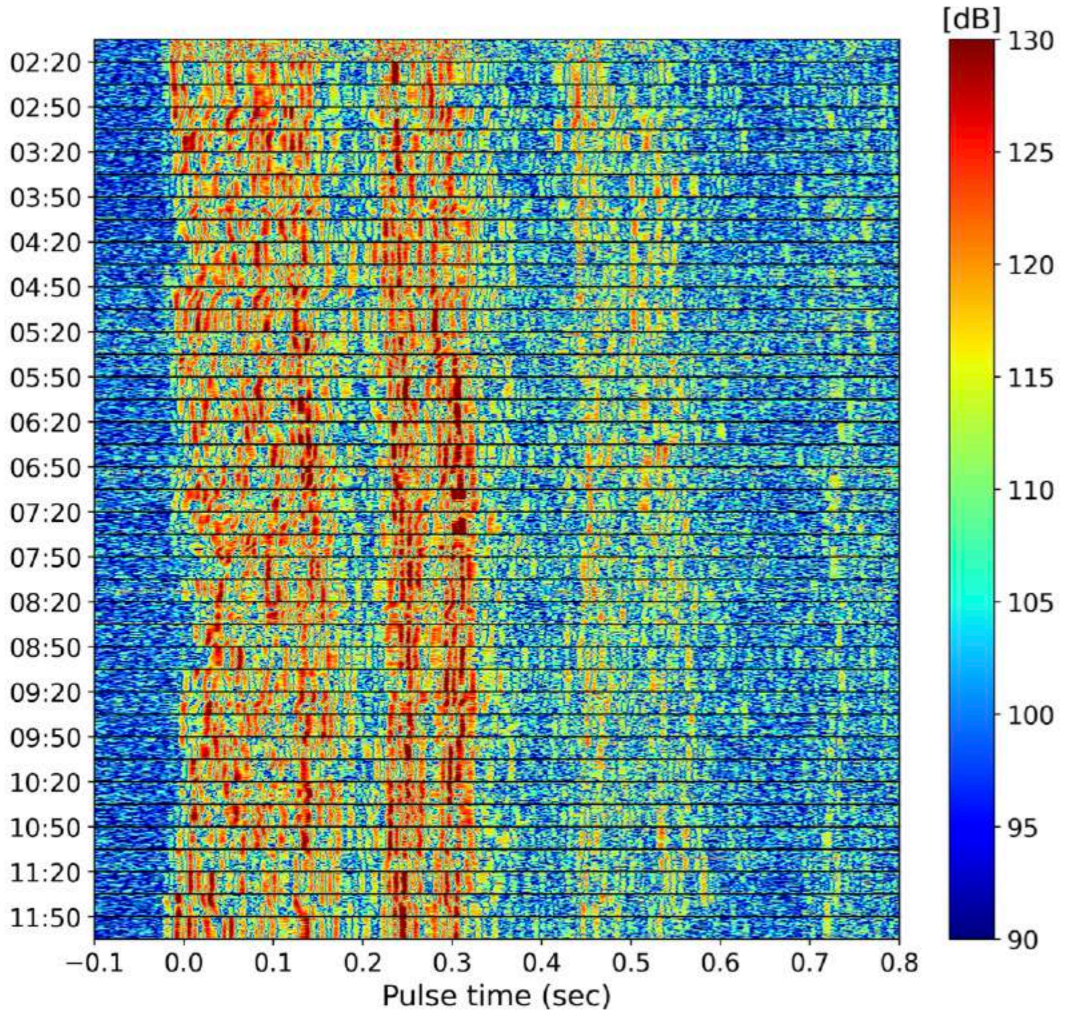
eigenray times of arrival, τ

User Input:

source(s), receiver(s), launch angles, fine-scale bathymetry, …

$$\frac{dJ}{dT}, \frac{dJ}{dS}$$

Data: Receiver time series



TFO NESBA 2021

Observed times of arrival τ_{obs}

$J :=$ cost function

Acoustic adjoint data assimilation

Summary of deterministic inversion

- Objective function $J\left(\mathbf{s}(\mathbf{m}), \mathbf{m}\right) : \mathbb{R}^{N_s} \times \mathbb{R}^{N_m} \rightarrow \mathbb{R}$ to be minimized

$$\min_{\mathbf{m}} J\left(\mathbf{s}, \mathbf{m}\right) := \min_{\mathbf{m}} \left(J_0\left(\mathbf{s}, \mathbf{m}\right) - \sum_{t=t_1}^{T} \mu^T [\mathbf{s}(t) - \mathbf{M}\mathbf{s}(t-1)] \right),$$

where J_0 is the model-data misfit and regularization, $\mathbf{M}$ is a linearized representation of the forward ocean model enforced with Lagrange multipliers, μ (bold).

- Here, measurements $\mathbf{y}_{\text{obs}} \in \mathbb{R}^{N_d}$ and control parameters $\mathbf{m} \in \mathbb{R}^{N_m}$, where $N_m \gg N_d$.

Acoustic adjoint data assimilation

Summary of deterministic inversion

- Objective function $J\big(\mathbf{s}(\mathbf{m}), \mathbf{m}\big) : \mathbb{R}^{N_s} \times \mathbb{R}^{N_m} \to \mathbb{R}$ to be minimized

$$\min_{\mathbf{m}} J\big(\mathbf{s}, \mathbf{m}\big) := \min_{\mathbf{m}} \left(J_0\big(\mathbf{s}, \mathbf{m}\big) - \sum_{t=t_1}^{T} \mu^T[\mathbf{s}(t) - \mathbf{L}\mathbf{s}(t-1)] \right).$$

- Now, $\mathbf{L}(\mathbf{s}(t)) = \mathbf{B}[\mathbf{M}(\mathbf{s}(t-1))]$ includes the acoustic model, $\mathbf{B}$, and provides calculated travel times $\tau \subset \mathbf{s} \in \mathbb{R}^{N_s+N_\tau}$.

Summary

Key points and next steps

- Modeled ray-tracing allows for generation of travel times within a forward ocean circulation run, MITgcm.
  - Method offers simulated underwater acoustics via a *package*, **ihop**.

- **Next steps:** Introduce systematic **acoustic inversion** *within* an ocean circulation state estimate, ECCO.

- Establish a methodology for understanding sensitivities of the oceanic state due to acoustic measurements.

Thank you!

Questions?

References

[GF15]: Forget, Gael, et al. "ECCO version 4: An integrated framework for non-linear inverse modeling and global ocean state estimation." *Geoscientific Model Development* 8.10 (2015): 3071-3104.

[JM97]: Marshall, John, et al. “A finite-volume, incompressible Navier Stokes model for studies of the ocean on parallel computers.” *Journal of Geophysical Research: Oceans* 102.C3 (1997): 5753-5766.

[AA18]: Adcroft, Alistair, et al. "MITgcm documentation." *Release checkpoint67a-12-gbf23121* 19 (2018).

[AN21]: Nguyen, An, et al. “The Arctic Subpolar Gyre sTate Estimate: Description and Assessment of a Data-Constrained, Dynamically Consistent Ocean-Sea Ice Estimate for 2002-2017.” *Journal of Advances in Modeling Earth Systems* 13.5 (2021): e2020MS002398.

[CC77]: Chen, Chen-Tung, et al. “Speed of sound in seawater at high pressures.” *The Journal of the Acoustical Society of America* 62.5 (1977): 1129-1135.

[ES09]: Skarsoulis, Emmanuel, et al. “Travel-time sensitivity kernels in long-range propagation.: *The journal of the Acoustical Society of America* 126.5 (2009): 2223-2233.

[FJ11]: Jensen, Finn, et al. “Computational ocean acoustics.” *Springer* (2011).

[PH05]: Heimbach, Patrick, et al. "An efficient exact adjoint of the parallel MIT general circulation model, generated via automatic differentiation." *Future Generation Computer Systems* 21.8 (2005): 1356-1371.

[CW06]: Wunsch, Carl. “Discrete inverse and state estimation problems: with geophysical fluid applications.” *Cambridge University Press* (2006).