Flow at the top of the free stream in geodynamo calculations

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Prior information on the flow derived from dynamo simulations

- Prior information: necessary ingredient in core surface flow estimation
- Statistics of the core surface flow and its evolution derived from time series of a geodynamo simulation (see for example Istas et al. (2023) who used a dynamo simulation from Aubert and Gillet (2021))

Issues:
- Definition of the core surface flow for no-slip simulations where the velocity vanishes at the core-mantle boundary: 'at the top of the free-stream'
- 'Top of the free stream': 'where viscous force becomes negligible' or 'where magnetic diffusion becomes unimportant'
- Arbitrariness of the location 'below the viscous boundary layer'
- Variation of the Ekman depth $\frac{\delta_E}{\sqrt{\cos\theta}}$ with colatitude θ, with $\delta_E = \sqrt{\frac{\nu}{\Omega}}$, ν kinematic viscosity and Ω Earth's rotation rate

Asymptotic limit for the flow inside the Ekman boundary layer

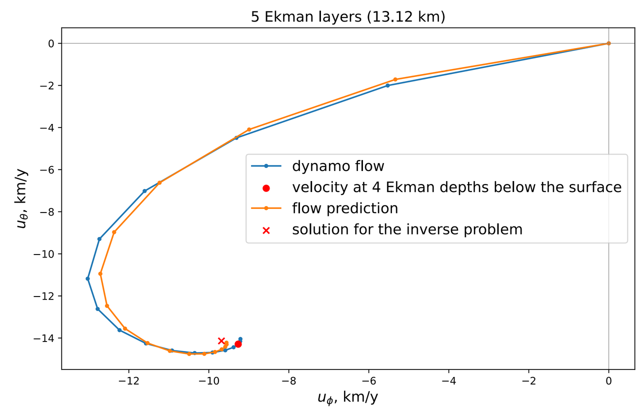
Ekman spiral:

$$Z = u_\theta + \mathrm{i}u_\phi = Z_\infty\left(1 - \exp(-(1+\mathrm{i})\frac{\sqrt{\cos\theta}(r_c - r)}{\delta_E})\right) = Z_\infty f(r)$$

r_c core radius

Methodology:

- Select a set of radii (r_i), typically $r_i \in [r_c - 6\delta_E, r_c]$
- Extract $Z(r_i)$ from the simulation
- Estimate Z_∞ minimizing the norm $\|Z(r_i) - Z_\infty f(r_i)\|$

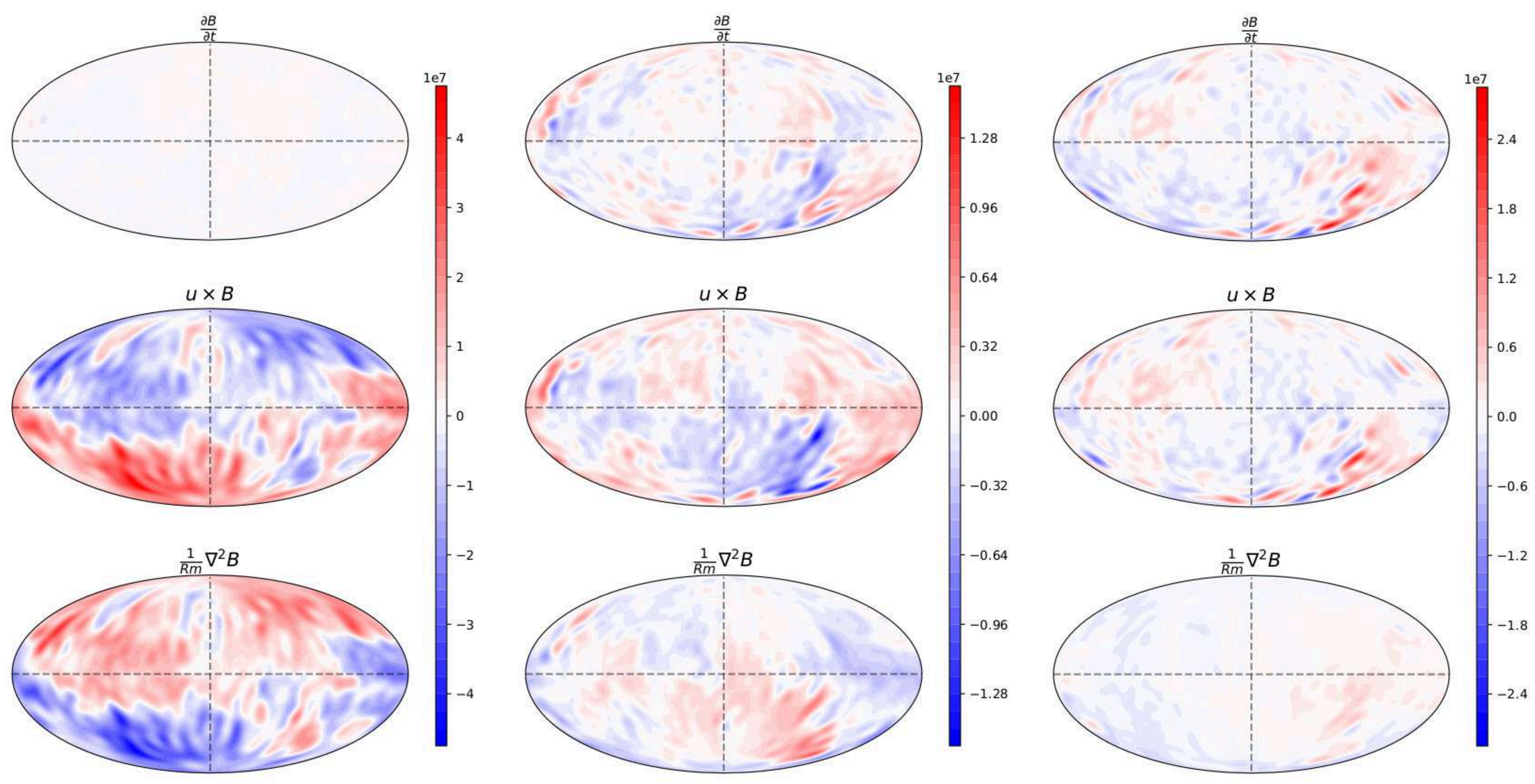


Boundary layer in no-slip geodynamo simulations

Horizontal (here: toroidal) components, S1 simulation (Schaeffer et al., 2017), $R_m = 546$, $E = 10^{-6}$

$R_m = \frac{UD}{\eta}$ magnetic Reynolds number, $E = \frac{\nu}{\Omega D^2}$ Ekman number,

$D = r_c - r_i$ thickness of the fluid outer core



Balance between induction and diffusion inside the Ekman layer ($r = r_c - 2.5\delta_E$)

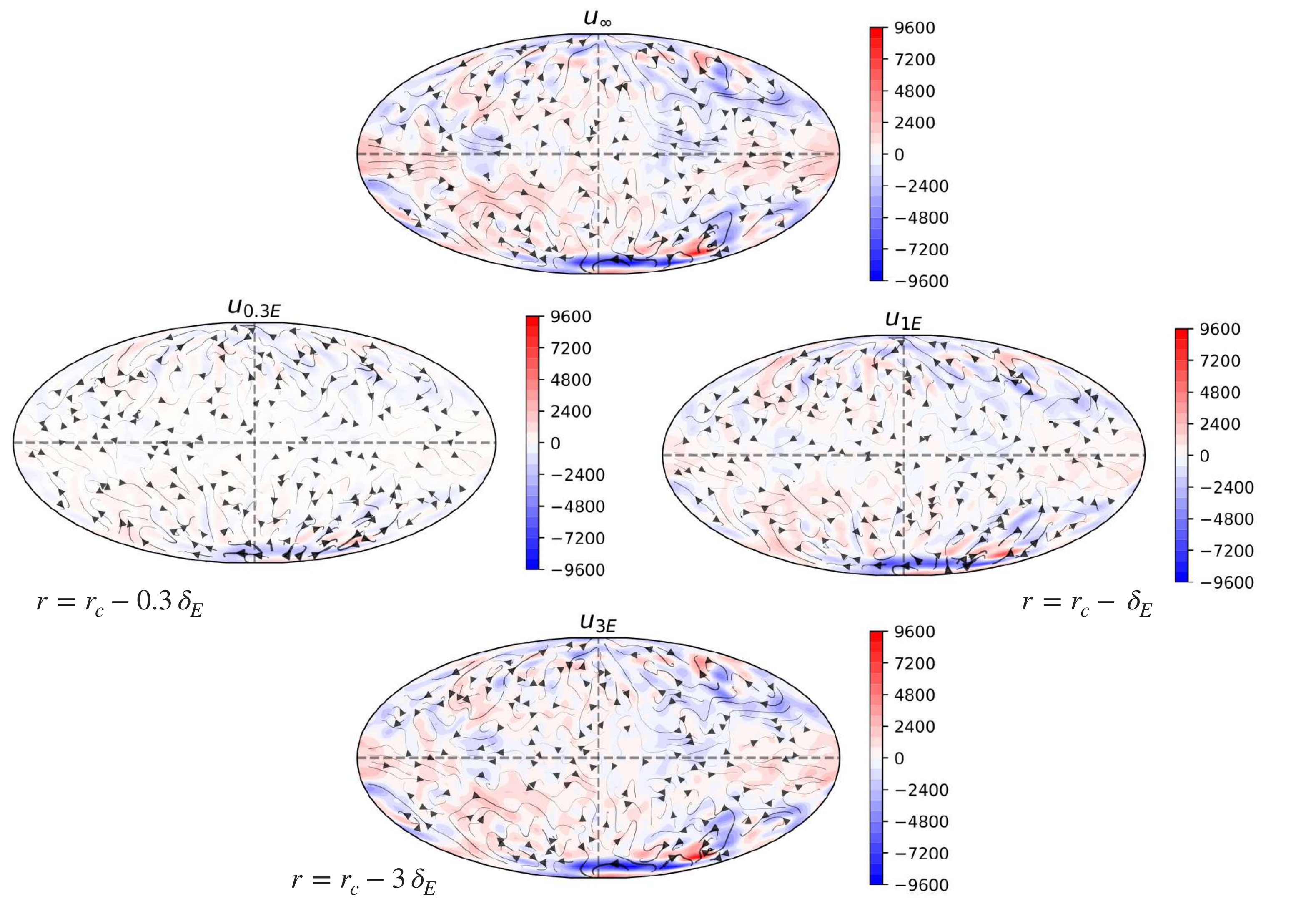
Transitional depth ($r = r_c - 18.5\delta_E$)

Diffusion negligible in the core interior ($r = r_c - 58.5\delta_E$)

$R_m^{-1/2} D \simeq 43\,\delta_E$

- Transitional region between the viscous boundary layer where diffusion balances induction and the interior of the core where diffusion is negligible (see also Tsang & Jones, arXiv)
- Thickness of the region where diffusion is important, about $40\,\delta_E$ in simulation S1 (i.e. ~ 80 km)

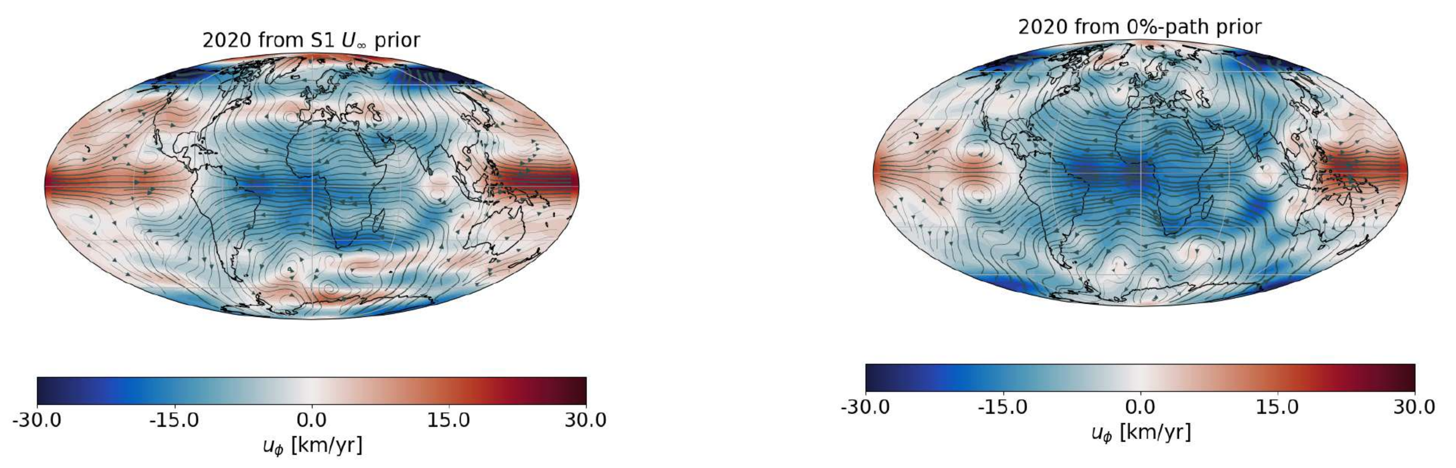
Flow at the top of the free stream



Influence of the variation of the Ekman depth with latitude
Velocity close to its asymptotic value at a depth where there is balance between induction and diffusion

Core surface flow from Swarm data, no-slip prior vs stress-free prior

CHAOS-7 model (Finlay et al., 2020)
stress-free prior: 0% path, $E = 3\,10^{-5}$, $R_m \simeq 1000$ (Aubert et al., 2013)



Main features reproduced: e.g. eastward flow under the Equatorial Pacific
Significant impact of the prior (see also the poster by H.F. Rogers, 'Core flow ingredient: sensitivity to the geodynamo priors')

Perspectives

- Prior information from no-slip simulations, limitation: spin-up timescale $E^{-1/2}\Omega^{-1}$ too short in comparison with the geophysical value, core and mantle firmly attached and resulting core surface flow estimation not suitable for investigations of the changes in the length of the day → better to use prior from stress-free simulations instead
- How do the boundary conditions for the velocity and the magnetic field combine? Investigation of the radial shear in the flow (see the presentation 'Radial shear in the core surface flow from Swarm data' and Firsov et al., 2023). Study of the horizontal components of the induction equation
- Investigation of the boundary layer to be refined by varying E and R_m; comparison with the scalings $\delta_D = R_m^{-1/2}D = (\eta D/U)^{1/2}$ and $\delta_D = (\eta/\omega)^{1/2}$ of the magnetic boundary layer width δ_D in studies with imposed flow (see Weiss, 1966 and Braginsky, 1984 respectively; ω frequency)?

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