Can geomagnetic measurements by used to monitor ocean flows?

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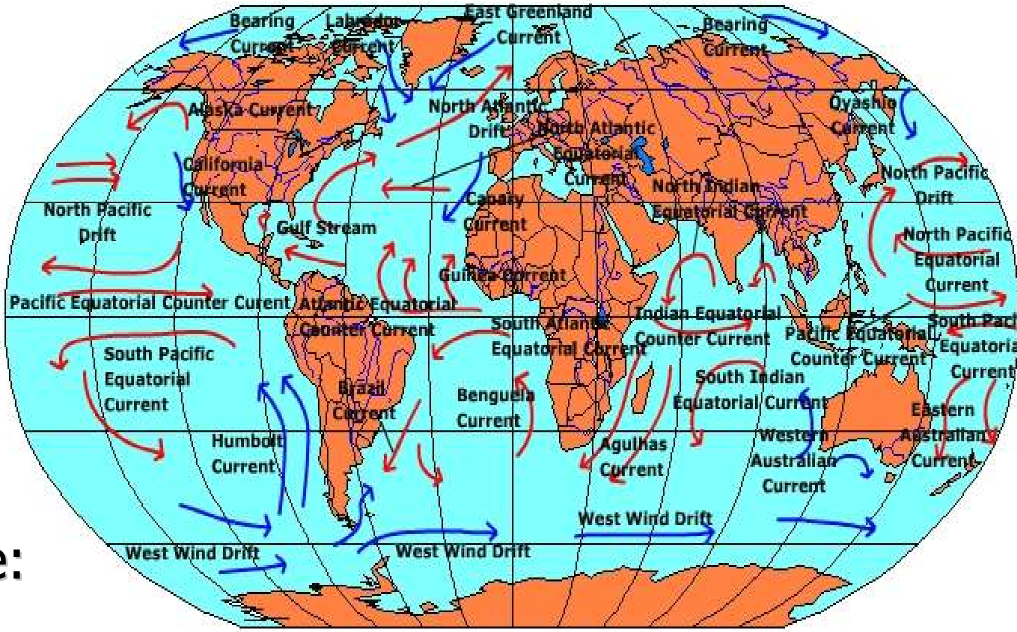
Motivation



- The geomagnetician perspective:
  - Ocean signal as a "correction"
  - Tidal signal identified (Tyler et al 2003)
  - Ocean circulation signal (time scales beyond a few days).
    - How big of a magnetic signal? Measurable?
    - Spatial structure and time variability

- The oceanographers' perspective:

  - Suppose all other magnetic contributions have been sorted out.
  - Can you make inferences about the ocean flow (U) variability from B?
  - Are there simple, practical, relationships between B and U?
  - Interest compared to more orthodox measurements?
  - Can such relationship be used to help separate magnetic signals?

- Forward modeling approach (Stephenson and Bryan (1992), ……)

Outline

- Description of ocean models
- Description of the 2D induction model
- Mean and variability of simulated magnetic fields
  - At the Earth’s surface
  - At satellite altitude (400km)
- Large scale patterns of variability of B
- Covariability of B and ocean flows in three examples:
  - Tropical Indian ocean
  - Equatorial Pacific
  - Southern Ocean

Ocean General Circulation Models

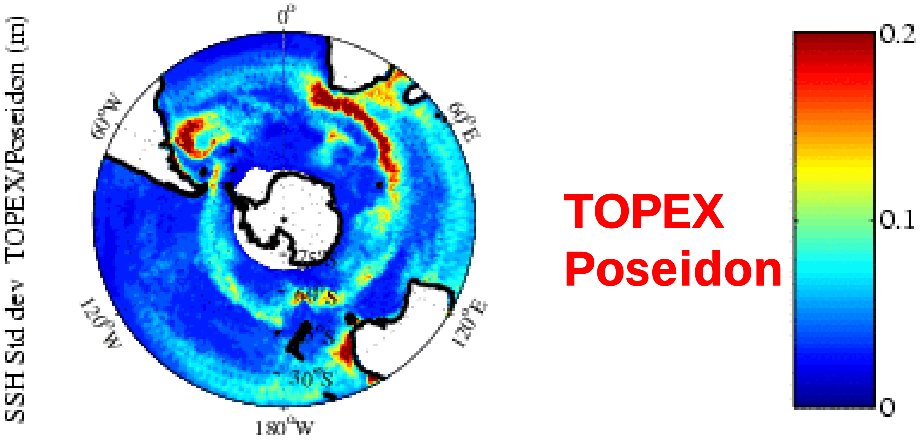
- OPA 8.1: LODYC model (Madec et al.)
  - Primitive Equation model
    Prognostic variables: U, V, T, S
  - 31 vertical levels, curvilinear grid (2 deg).
  - Forced with NCEP winds and heat fluxes.
  - 5d averaged outputs

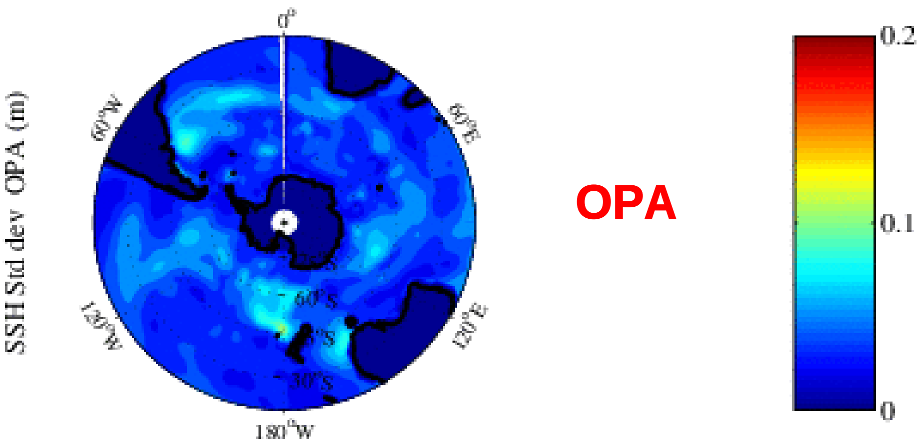
- HOPE: Hamburg Ocean Primitive Equation. (Maier-Reimer et al.)
  - 13 vertical levels. 2° resolution
  - Forced with NCEP surface fluxes.
  - 10d averaged outputs

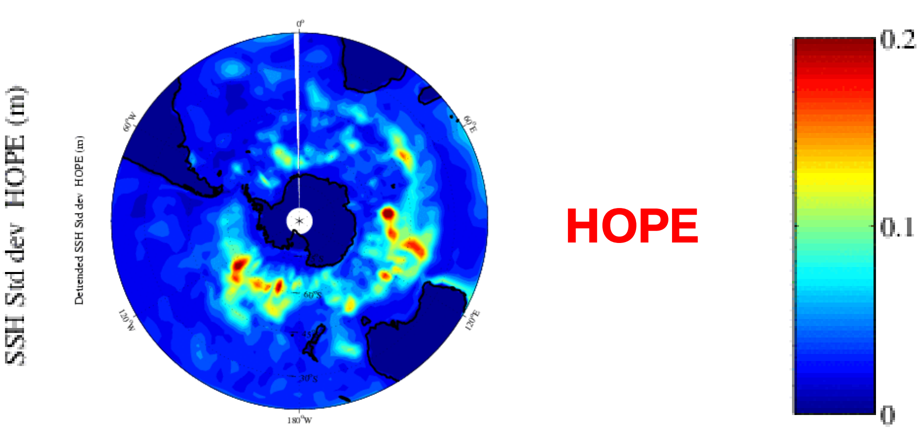
- ECCO: based on the MIT model
  - 46 vertical levels, 1° resolution, assimilates altimeter data
  - Monthly outputs

Sea Surface Height (SSH) variability

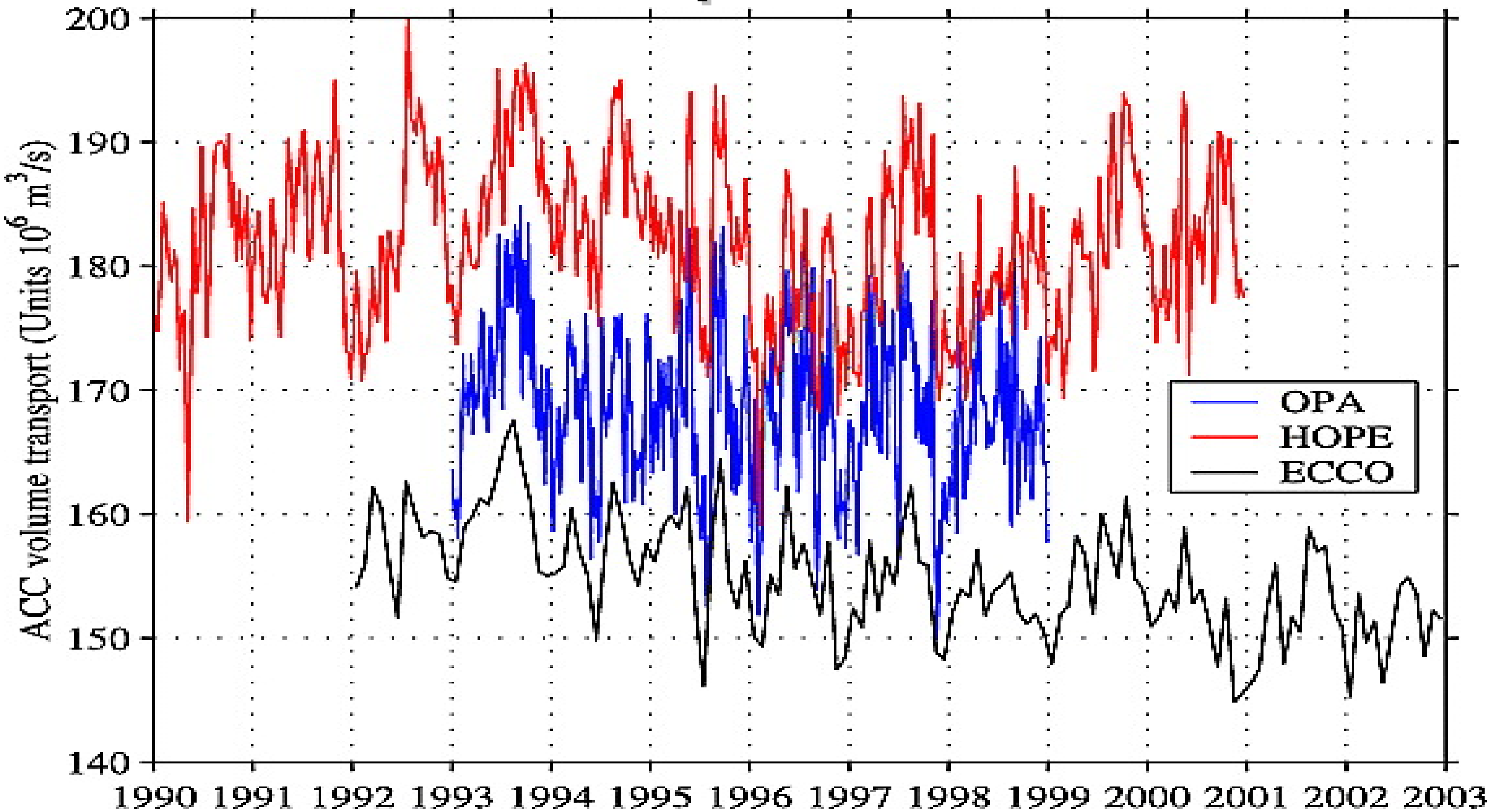
- Smaller SSH variance compared to TOPEX/ Poseidon: models are not eddy resolving.
- Spatial structure of the variability not perfectly reproduced







ACC volume transport at Drake Passage

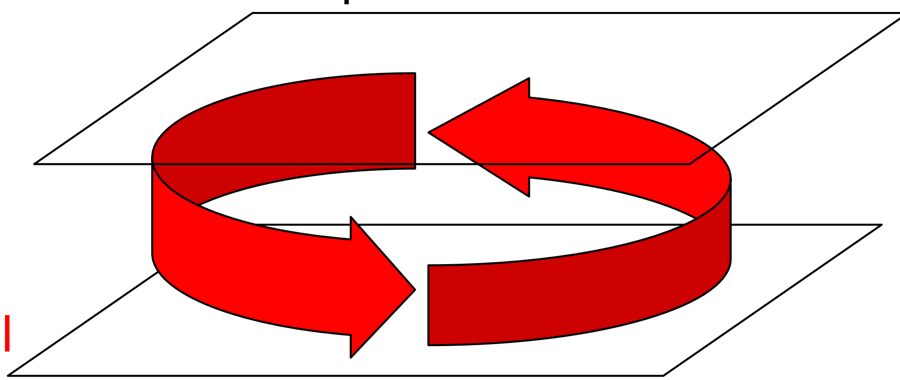


- Observations:
  - 134 +/- 20Sv; variability over a year 10Sv (Whitworth, 85)
  - Recent snapshots in the 90s: 90 to 180 Sv (Cunningham et al,2002)
- Models:
  - Mean seems overestimated for all models (up to 30%)
  - Variability 4 to 6.5 Sv. Underestimates somehow the real ocean ~10 Sv

Thin shell approximation

(Price (49), Tyler et al 97)

- Induction equation, diffusive regime (T>2 days) : $\nabla \times (K\, \nabla \times B - (u \times B)) = 0$

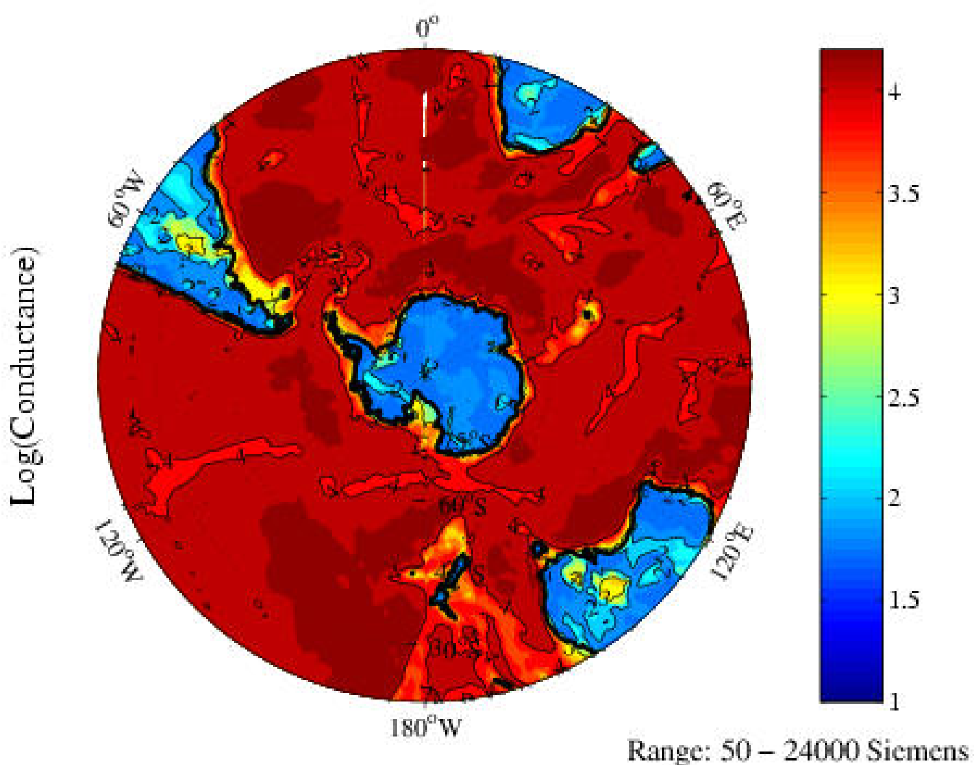


- Formulation in terms of electric streamfunction Ψ
  Charge conservation: J non divergent, hence $J = \nabla \Psi \times k$
- B=F+b : F main field and b ocean component. $|b| << |F|$
- Much simpler 2D induction equation:

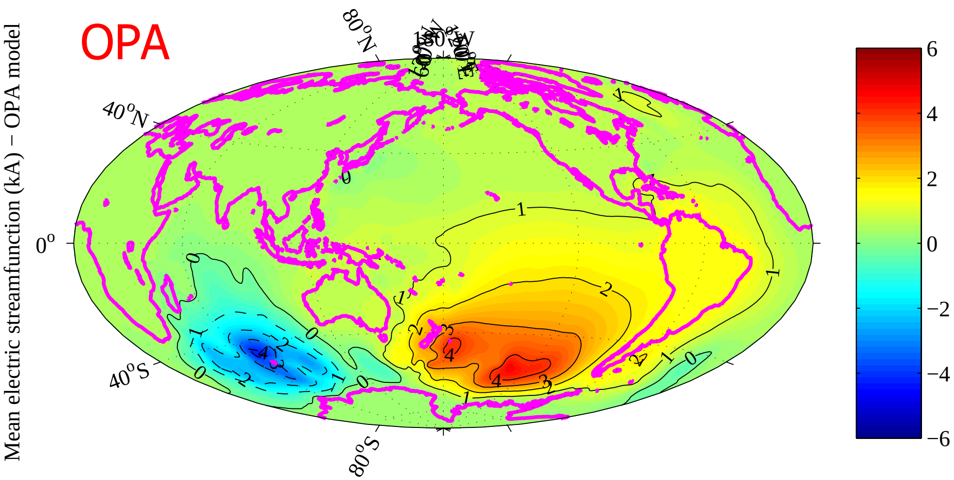
$\nabla \cdot (\nabla \Psi / \Sigma) = \nabla \cdot (F_z \, \bar{u}^*)$ with $\bar{u}^* = 1/\Sigma \int \sigma \, u \, dz$

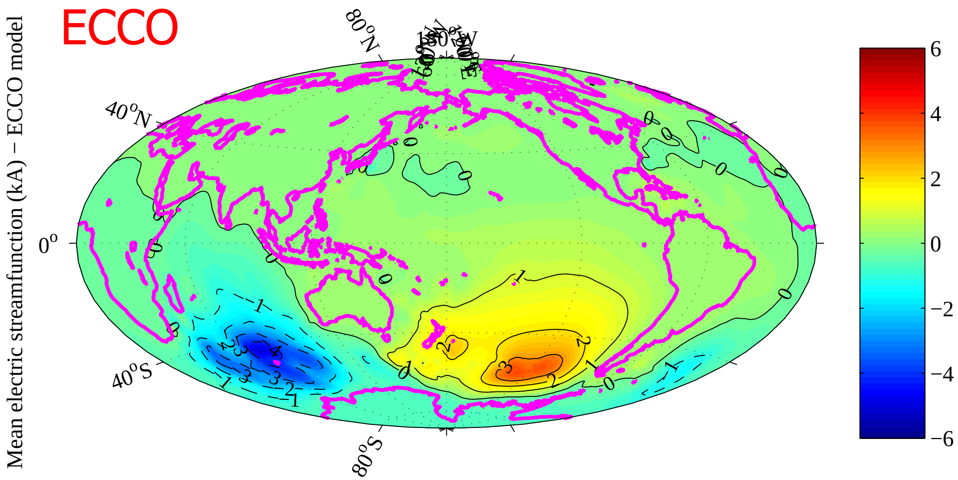
Electric streamfunction 2D model

- $\nabla_H \cdot (\nabla_H \Psi / \Sigma) = \nabla_H \cdot (F_z \bar{u}_H^*)$
- Finite difference model
- Main field Fz: CO2 model (Holme et al.)
- Sediment conductance: Everett et al., 1999; Laske and Masters, 1997
- Conductivity in the ocean computed from T and S

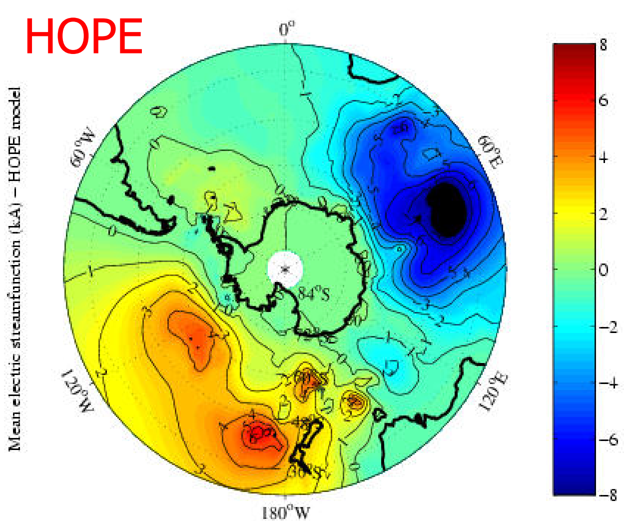


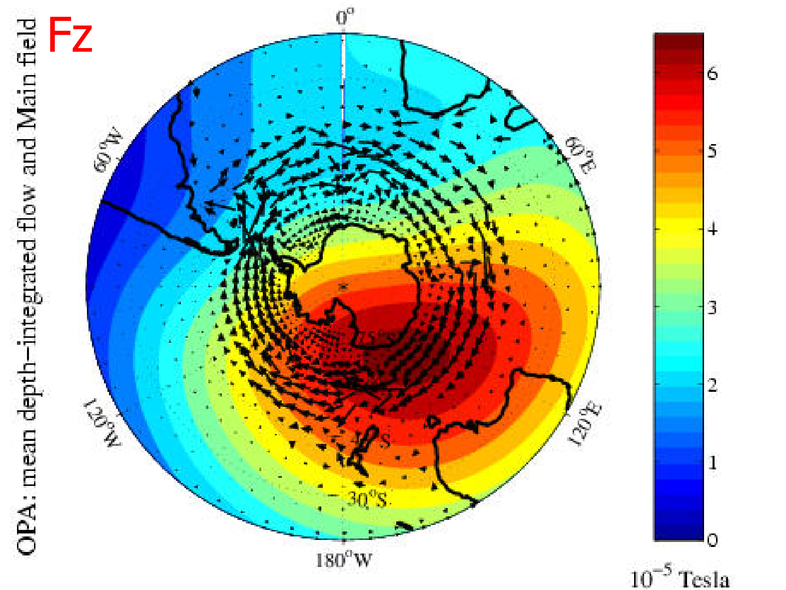
Mean electric streamfunction





Large scale current loops (-5 to 5 KA) in the Indian and West Pacific sectors. Generated where the ACC pathway intercepts isolines of the radial component of the main magnetic field $\nabla \cdot (Fz \; \bar{u}^*)$





Derivation of Magnetic fields

- In insulating regions, b is irrotational and can be written in terms of a magnetic potential:

  $b = -\nabla M$

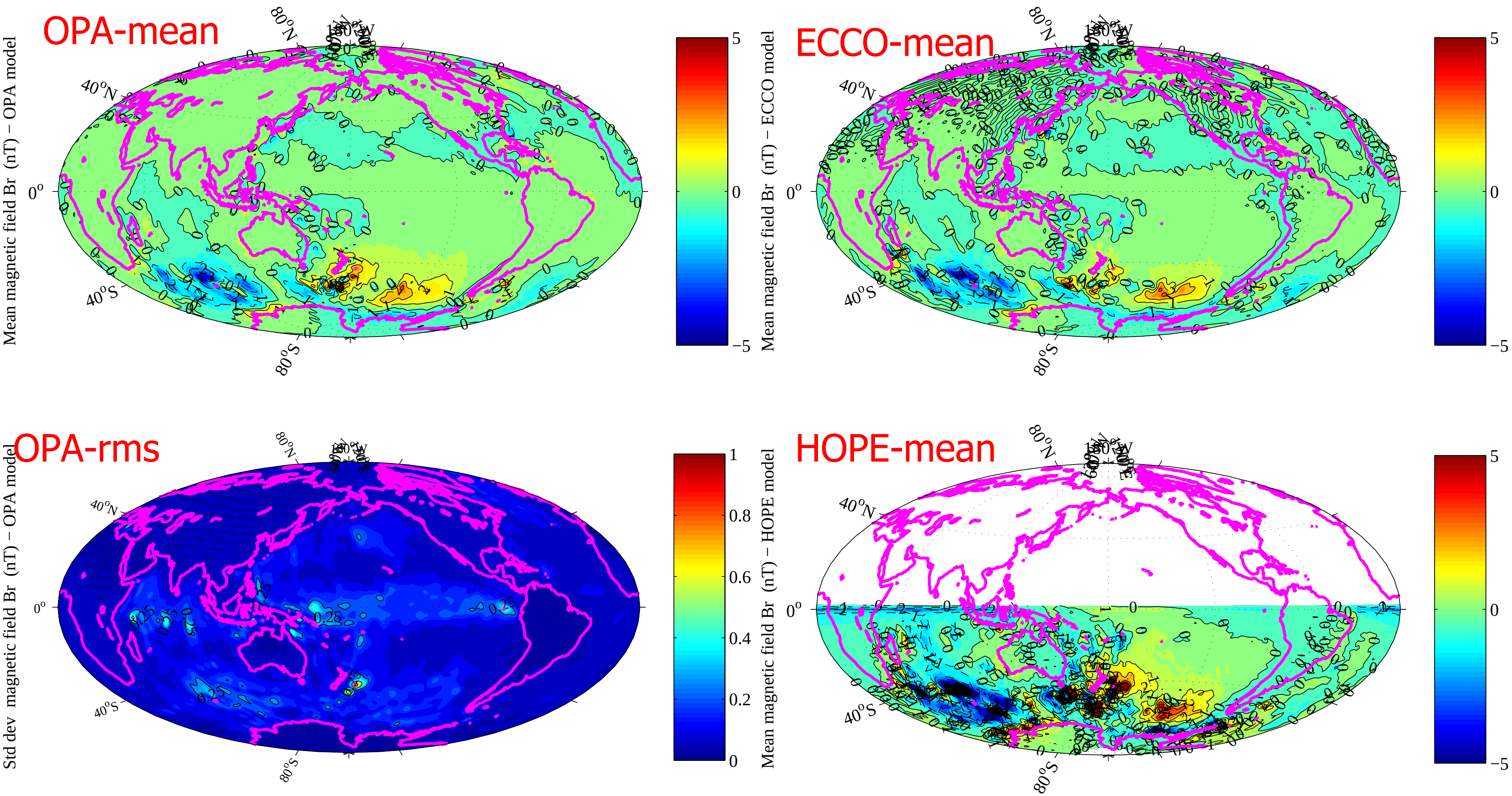
- Since b non divergent: $\nabla^2 M = 0$

- Boundary conditions:
  - Ocean surface: M obtained from the electric streamfunction: $M = \mu_0 \Psi/2$
  (assuming $\mathbf{b}_H$ opposite on each side of the thin shell by symmetry)

  - $M \rightarrow 0$ for large distances above the ocean

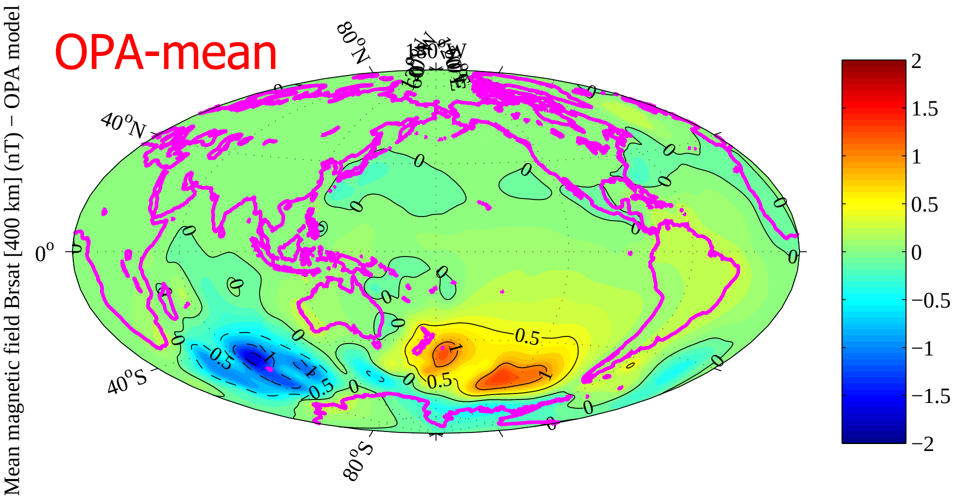
- Solved using Spherical Harmonics (order 80)

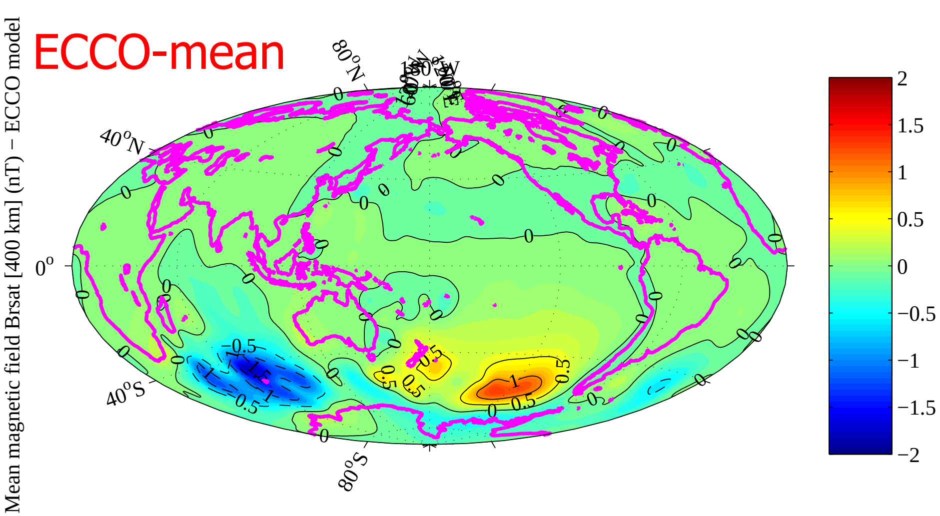
Radial Magnetic field at sea surface

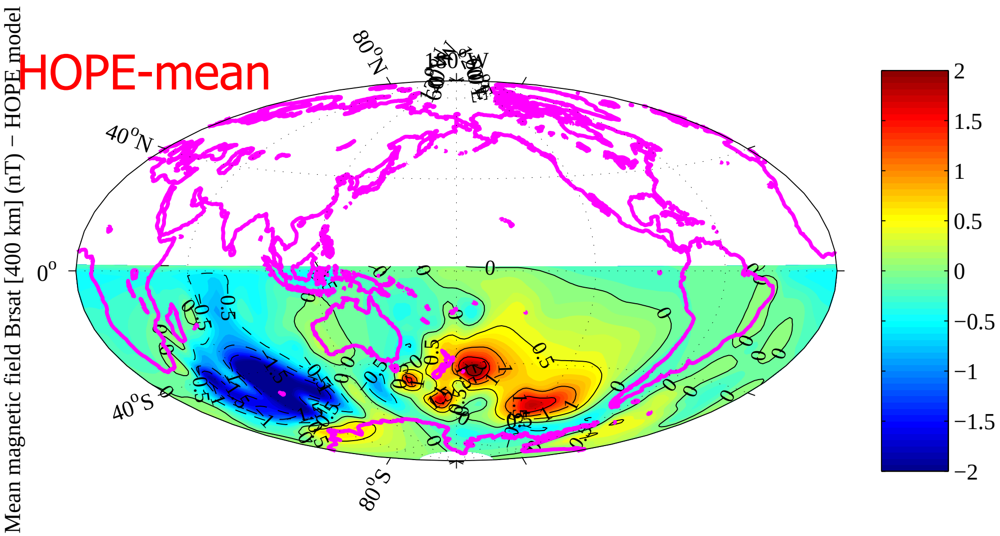


OPA, ECCO: Mean range: -5 to 5nT, RMSmax:0.9nT, Total range -6 to 6nT
Consistent with estimates by Kuvshinov et al, 2005 based on IE.
Larger values with HOPE (-12 to 12 nT), RMSmax:2.3nT

Radial Magnetic field at 400km



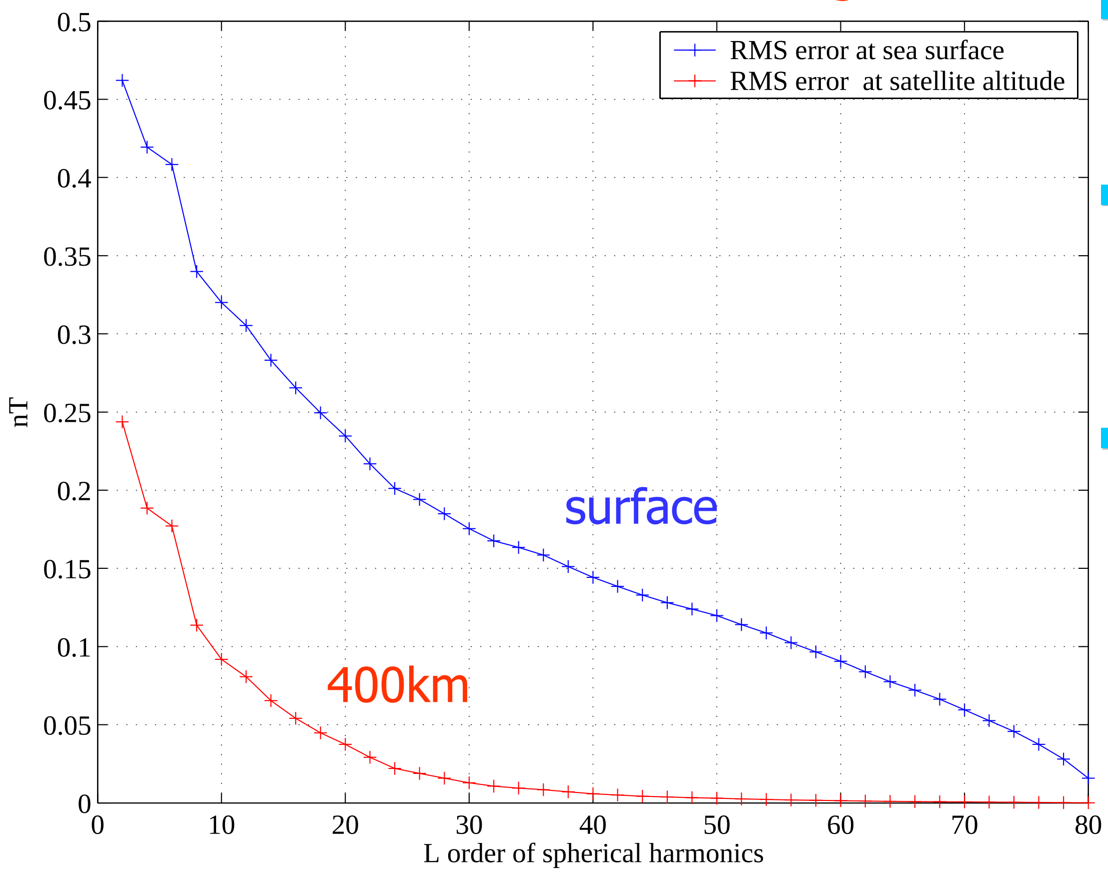




- OPA: -1.7 to 1.4 nT
- ECCO: -1.8 to 1.4 nT
- HOPE: -2.3 to 3.8 nT (large!)

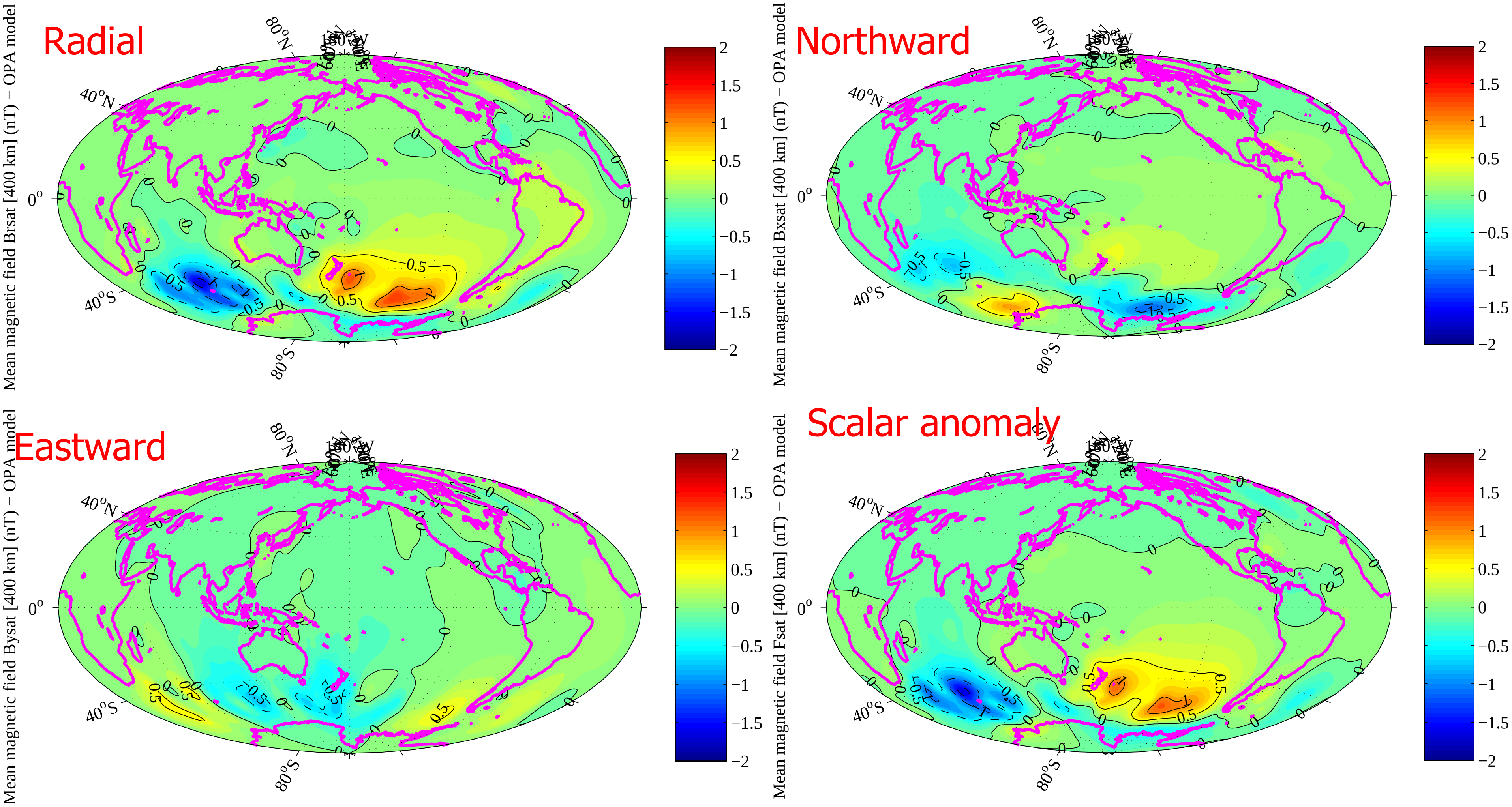
Sensitivity of the results to ocean model resolution?

RMS residual from the order 80 magnetic field



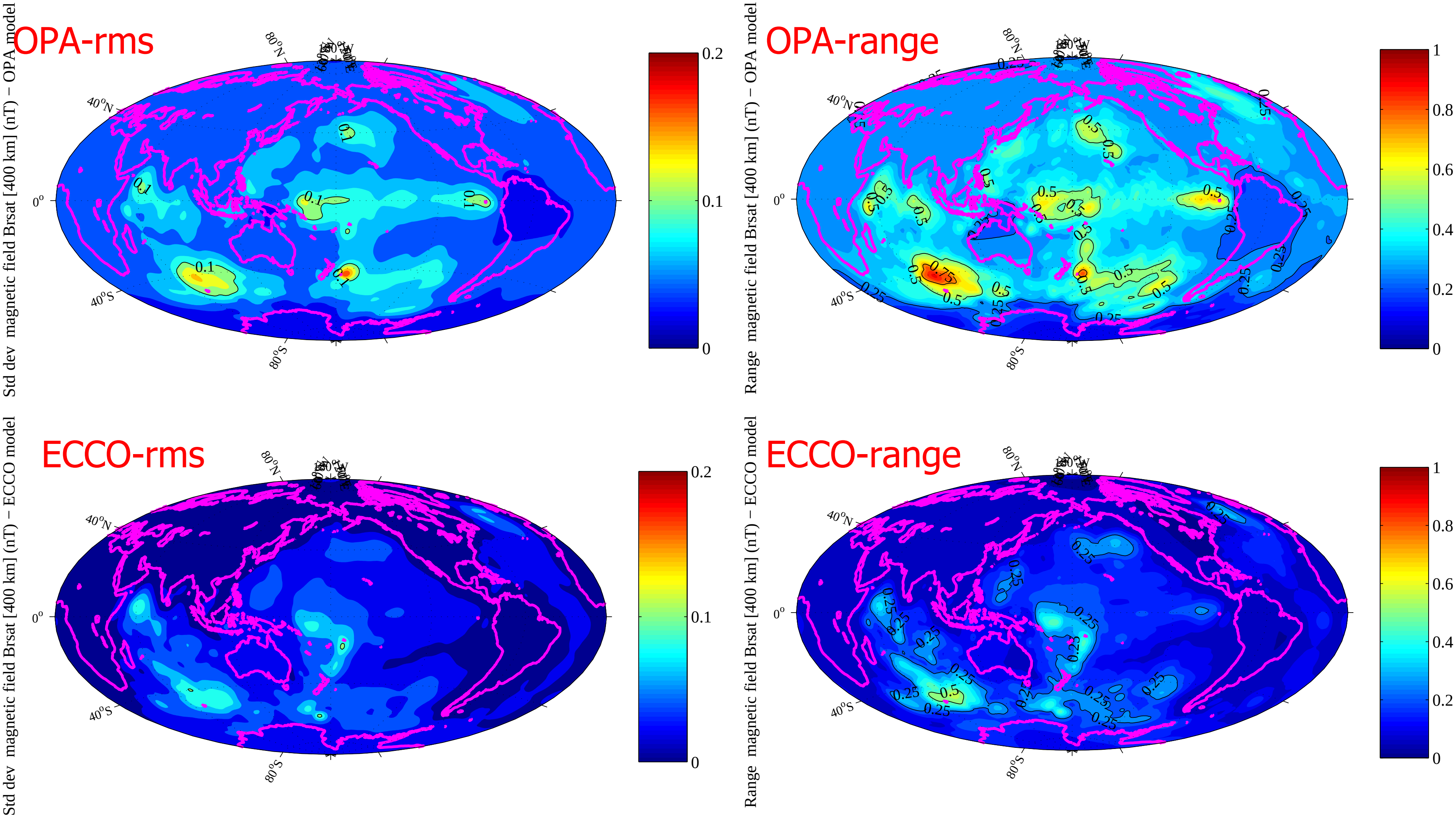
- Geometric attenuation damps short spatial scales ~(0.94)^(L+1)
- Spherical harmonics to order ~60 sufficient to represent the ocean signal at satellite altitude.
- Increasing OGCM resolution increases the magnetic field at short spatial scales, hence with little influence at satellite altitude (see experiments by Kuvshinov et al, with OCCAM ¼° model)

Components of the Magnetic field at 400km



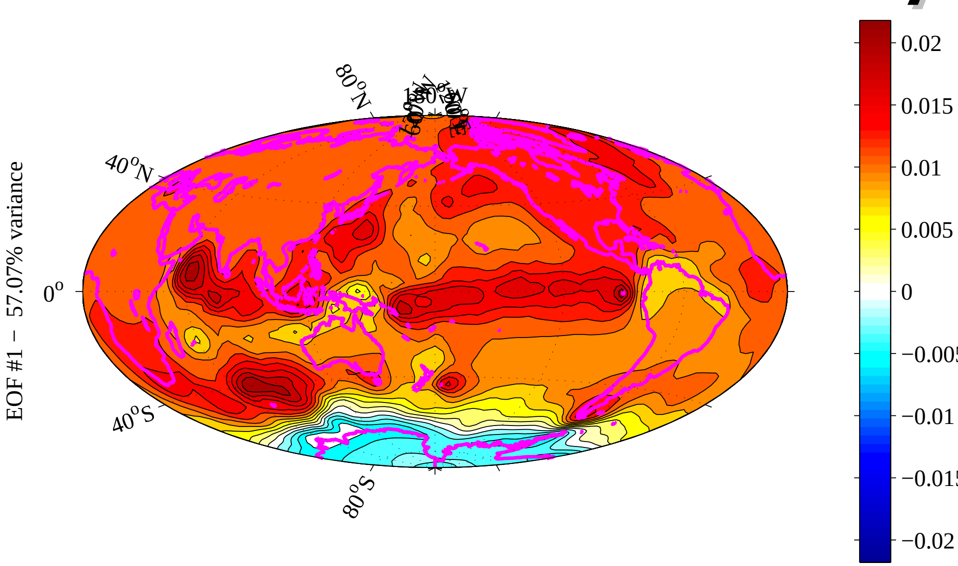
- Radial component strongest
- Scalar anomaly reflects mostly the radial component.

Variability of Br at 400km

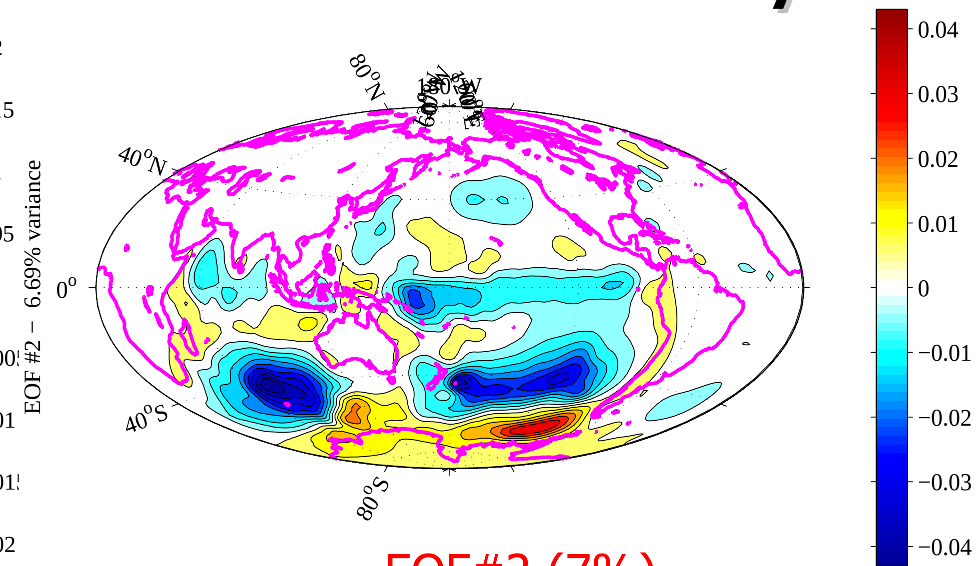


- RMS up to 0.18nT (OPA), 0.1 nT (ECCO), and 0.24nT (HOPE).
- Only part of the discrepancy is due to high frequencies (ECCO: monthly sampling)
- Range (at a fixed location) up to 1nT: variability measurable.
- Signal in Pacific and Indian oceans (Equatorial and Southern Ocean), little in Atlantic

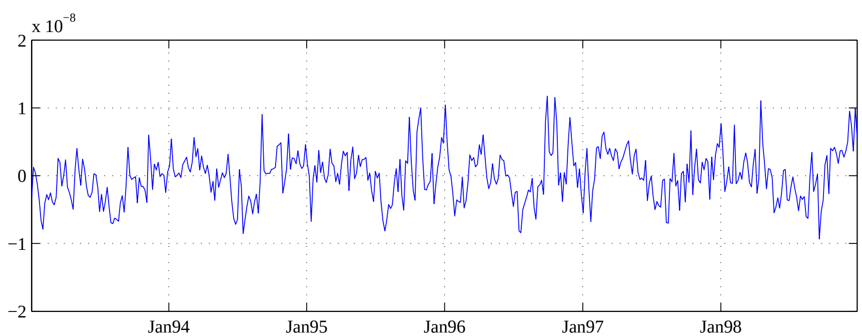
Modes of variability of Br: EOF analysis

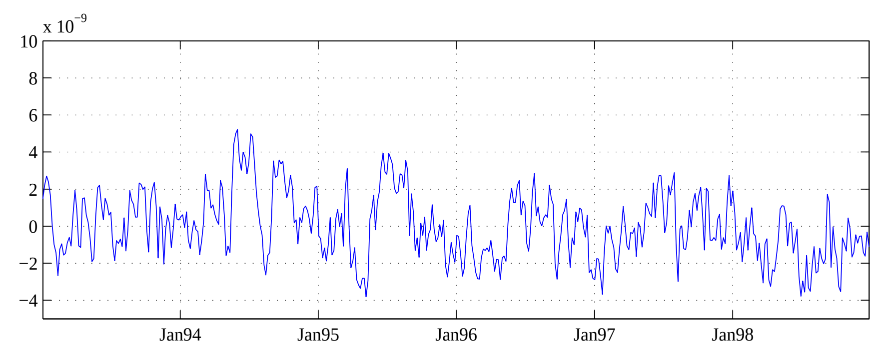


EOF#1 (57%)



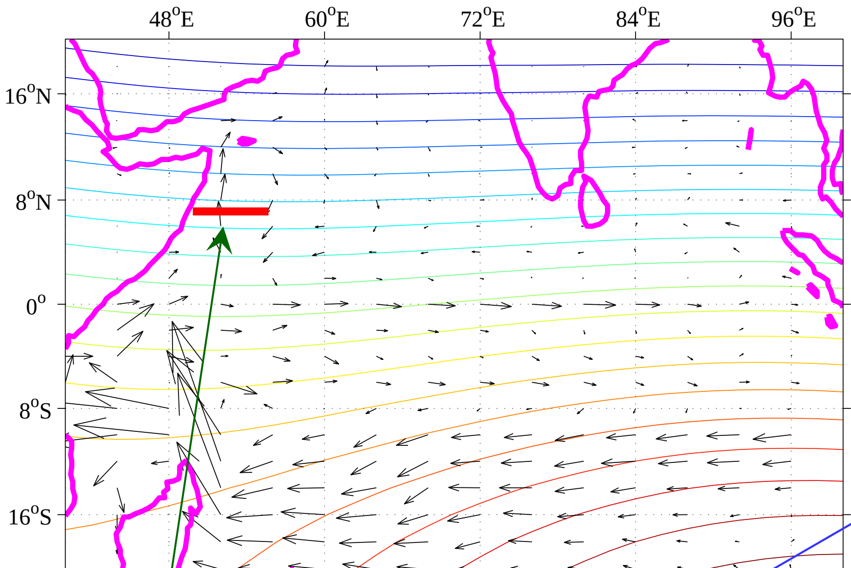
EOF#2 (7%)

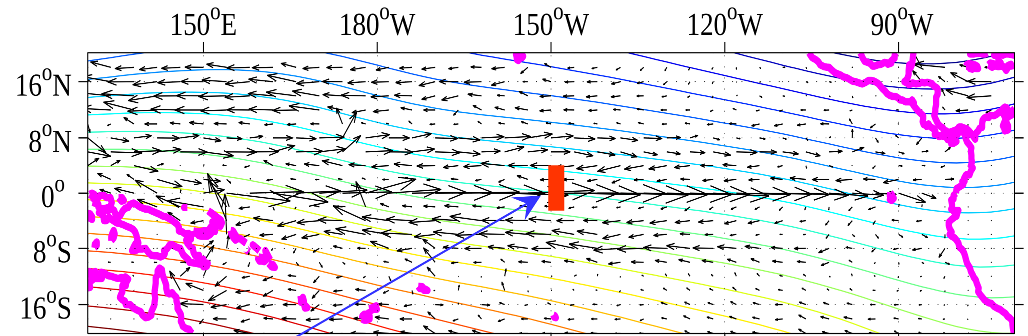




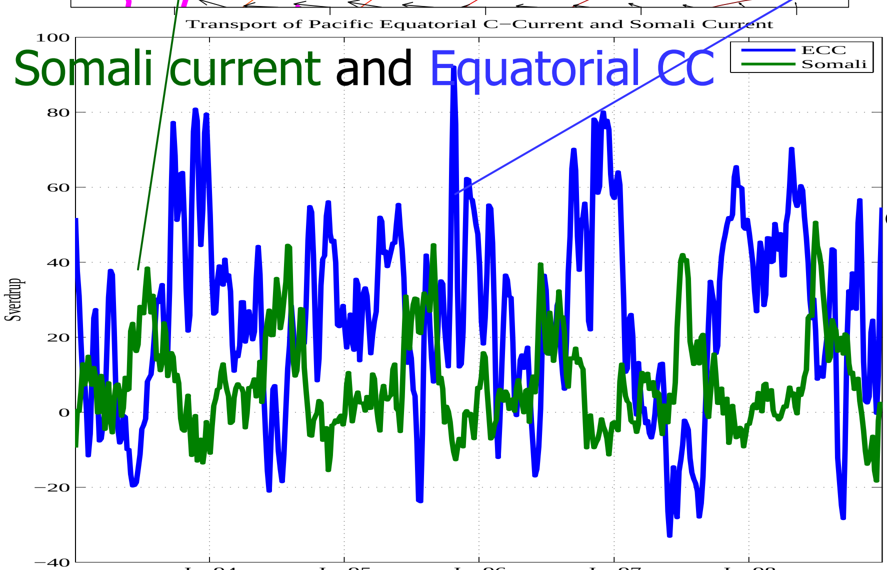
- EOF1: Tropics, South Indian ocean: significant annual modulation
- EOF2: Southern Ocean seasonal variability.

Equatorial regions





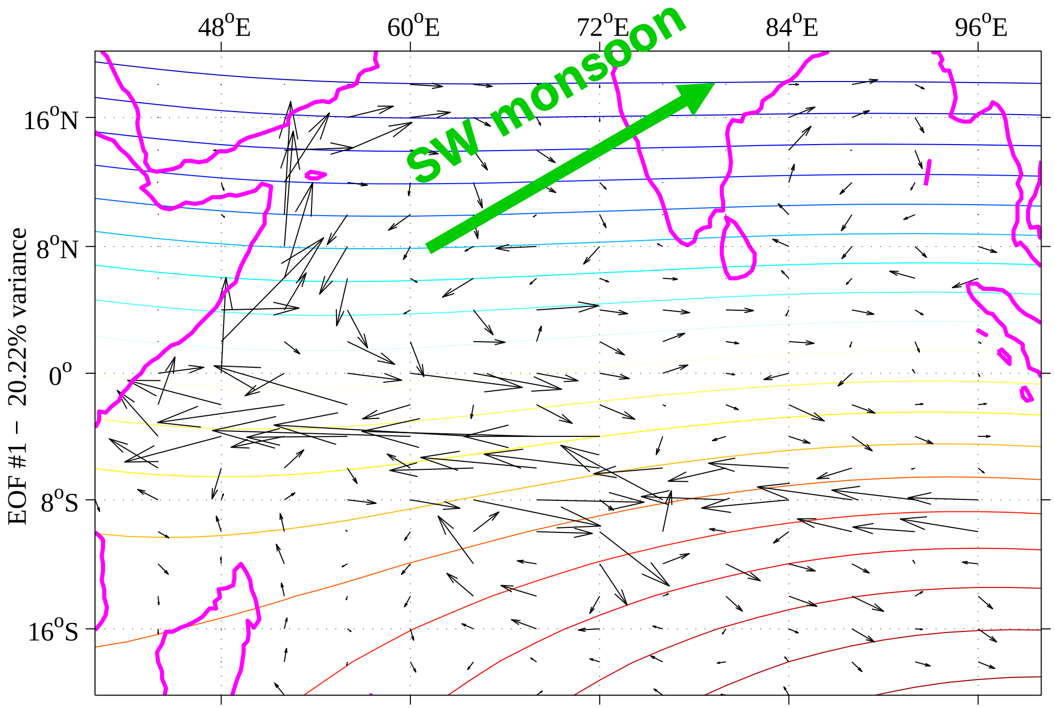
Somali current and Equatorial CC



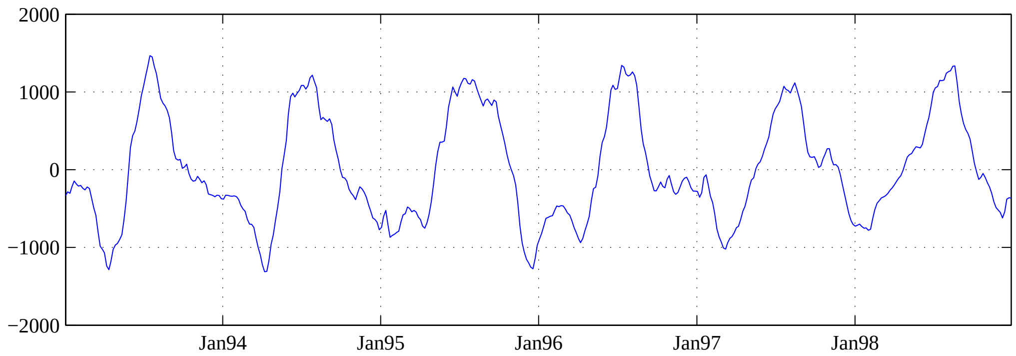
Fz has large gradient in equatorial regions

- Somali Current:
  - large seasonal cycle (amplitude ~25Sv)
  - Parallel to ∇Fz: strong magnetic signal
- Pacific Equatorial Current system:
  - Very large seasonal cycles (amplitude ~45Sv for EUC)
  - But zonal currents, nearly orthogonal to ∇Fz,
  - not as efficient in producing magnetic signals

Tropical Indian ocean

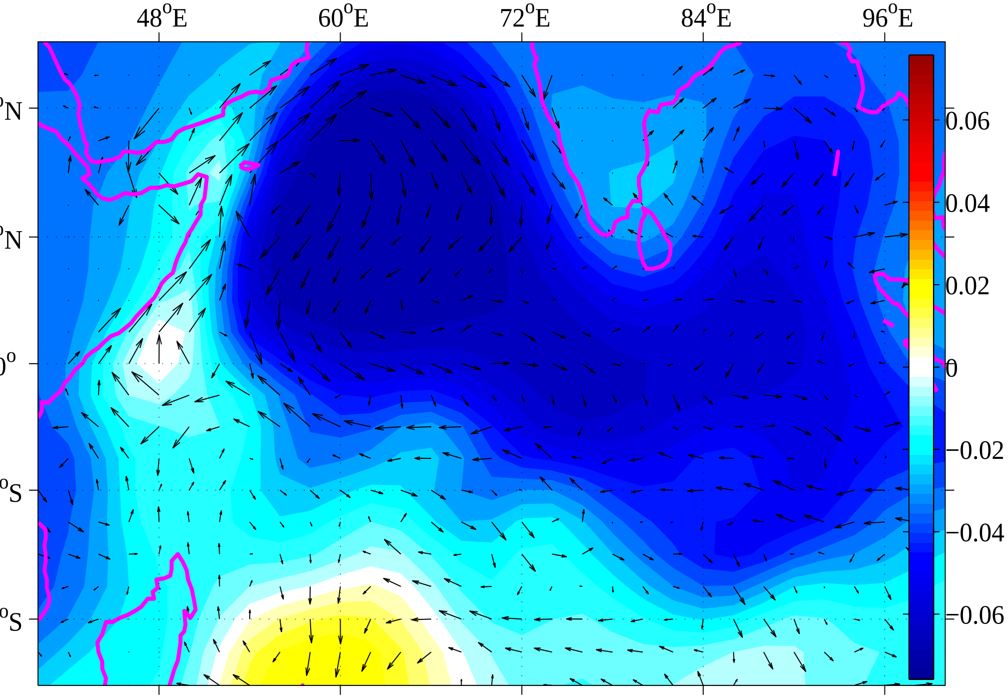


EOF1 20%

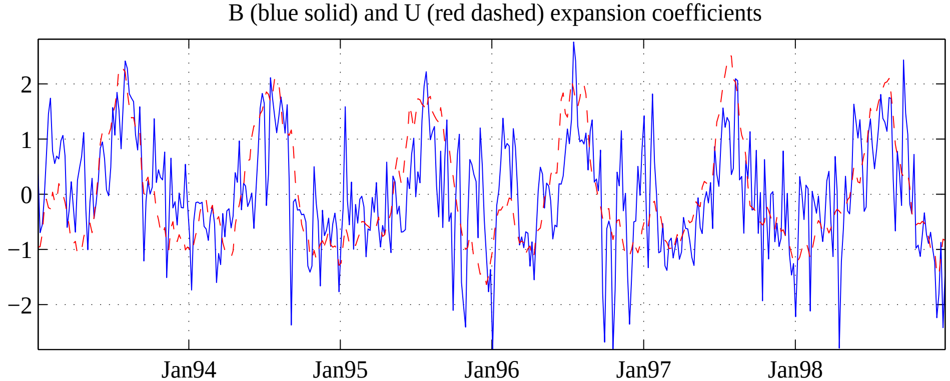


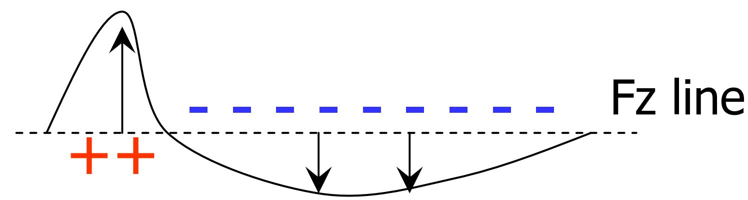
- Small mean circulation but Large seasonal cycle associated with monsoons
- SW monsoon May to Sept
  - Spins up of the Arabian sea
  - Somali current picks up to the north
- NE monsoon(winter): reverse situation
- large magnetic signature expected from advection of Fz contours .

Covarying Flow/Br modes



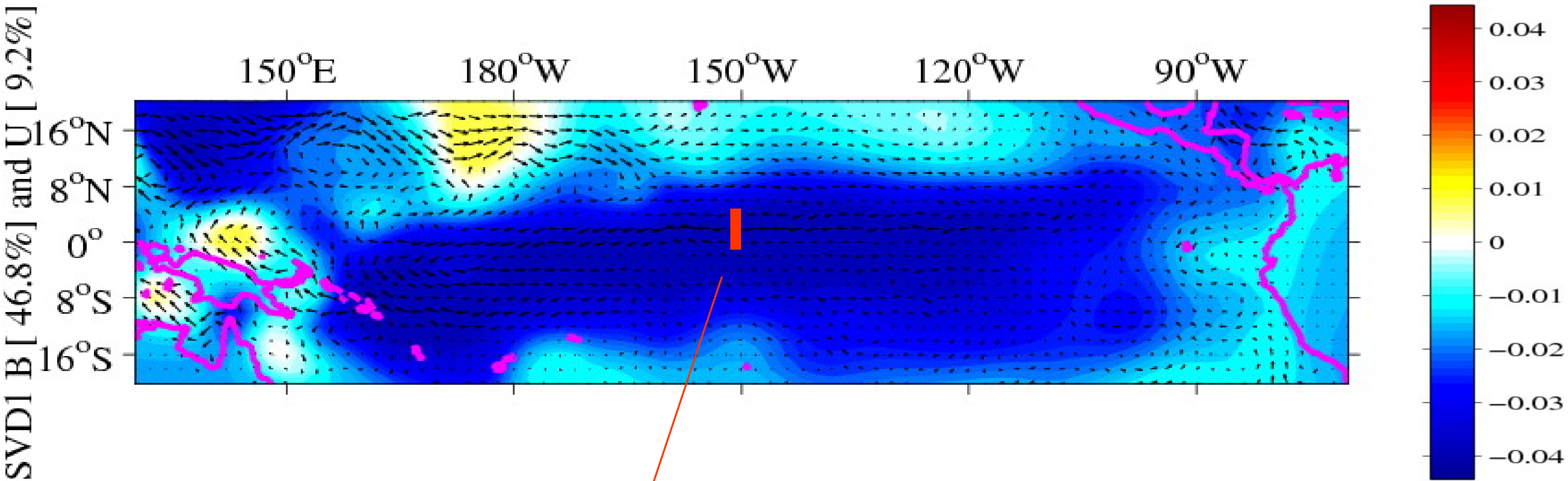
SVD1 (70%): **Br** vs **U**



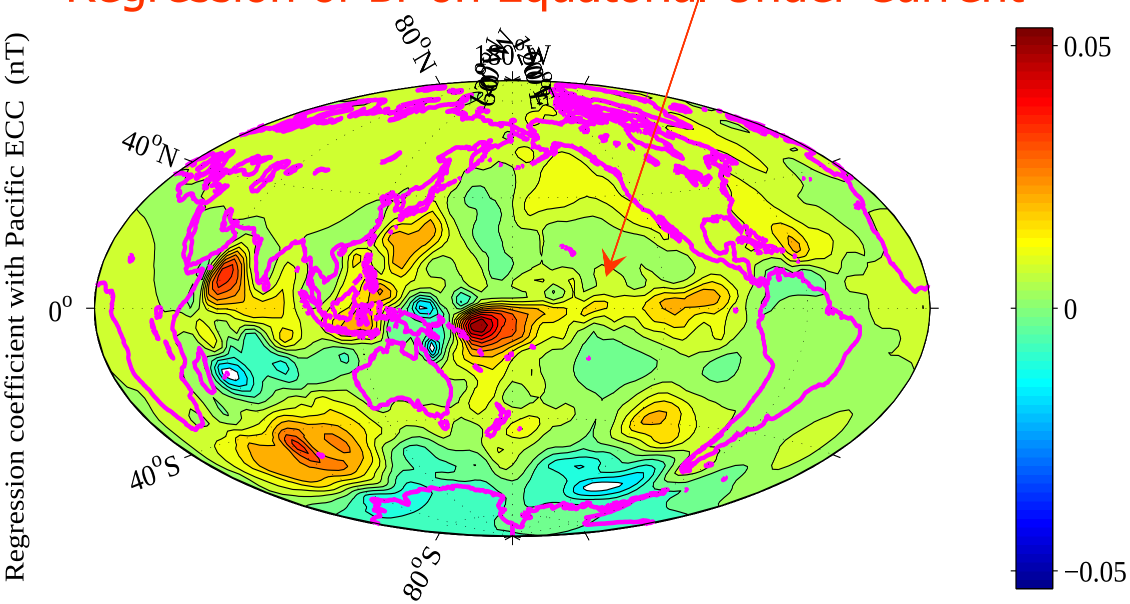


- SVD mode 1: 70% Squared Cov.
  - 52% of the variance of Br
  - 13% of U.
- Associates anticyclonic gyre with negatives Br anomalies and vice-versa
- Anomalies of >0.1nT (regression)
- Consistent with $\bar{u}_H^*.\nabla_H F_z$
- Weak direct signature of Somali current
  - Shorter spatial scales, hence attenuated at 400km
  - Or topographic influence: $F_z \nabla_H.\bar{u}_H^*$
- Immediate oceanographic interest
- Dominant annual period, like many external sources, but specific fingerprint.

Equatorial Pacific region: SVD

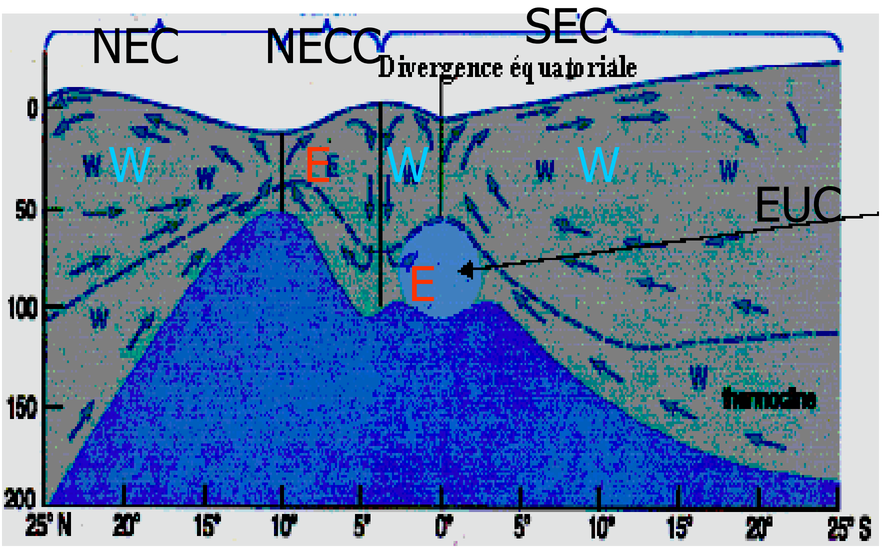


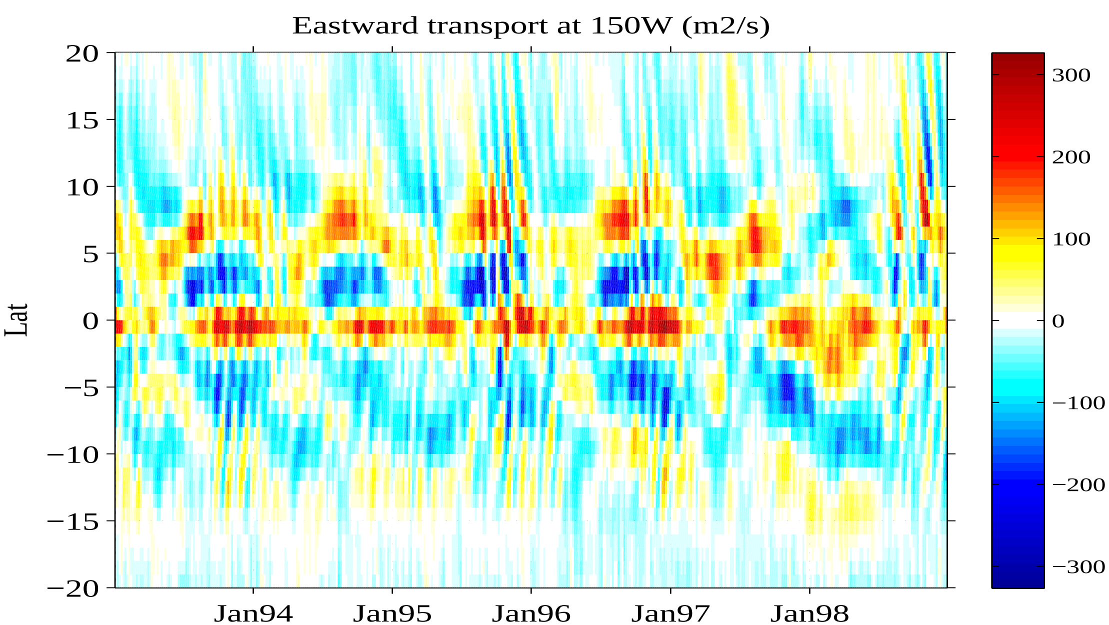
Regression of Br on Equatorial Under Current



- Annual cycle captured in first SVD mode: 68% of SC.
- Captures 50% of variance of Br, 10% for U
- Negative B anomaly is generated by decreased eastward flows, or increased westward flows
- Difficult to associate B anomalies with a specific current (eg, regression pattern with EUC is shifted to the West)

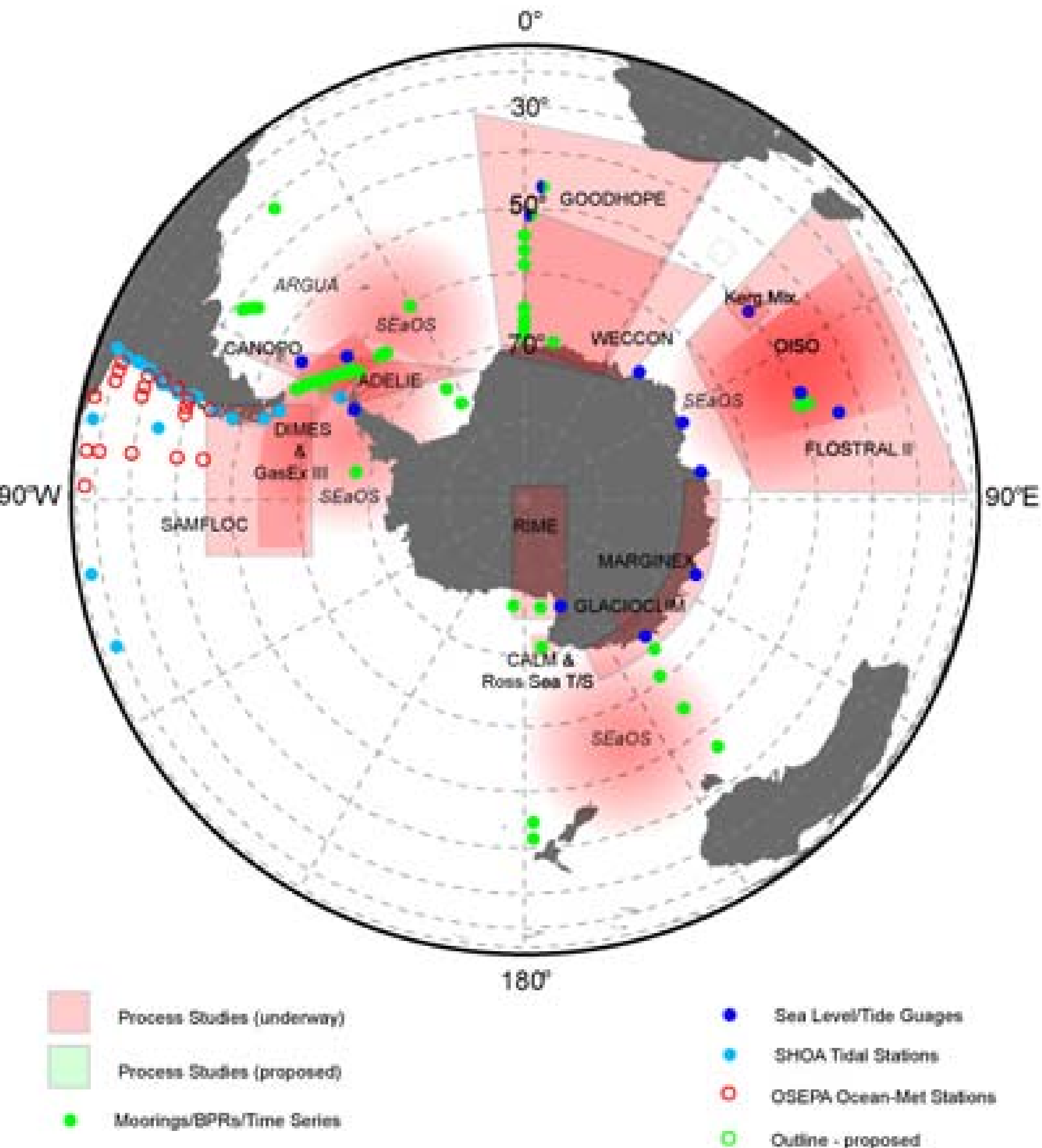
Equatorial Pacific region





- Complex system of currents, flowing in opposite directions
  - North Equatorial Current
  - N. Eq. Counter Current
  - South Equatorial Current
  - Equatorial UnderCurrent
- All have annual modulation in intensity and pathway.
- The meridionally integrated zonal transport has little seasonal cycle.
- Meaning of an integral measurement of the flow?

Monitoring the ACC transport: a high priority

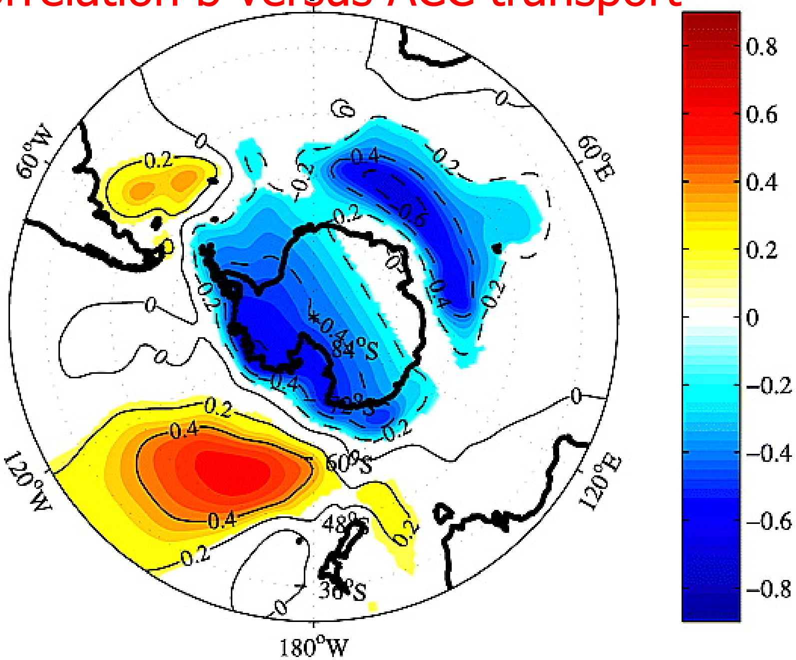


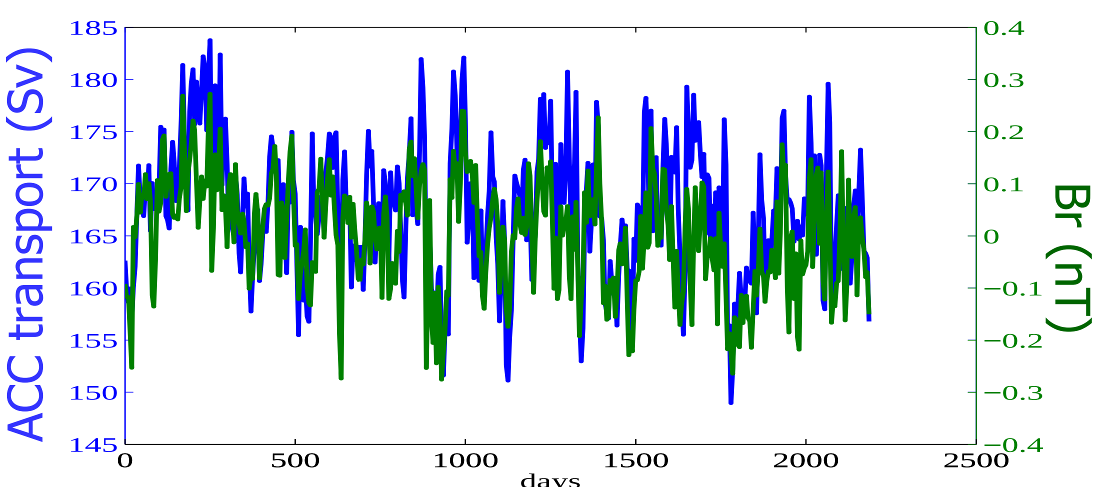
- ACC transport is a key climate index.
- Not satisfactorily monitored by current satellite or in situ programs
  - Altimetry (surface geostrophic velocity+ geoid inacurately known)
  - Gravimetry (large spatial scales).
  - In situ data (undersampling, difficulty to get integral measurements)
- Any attempt to get an ACC transport index is highly motivated.

The magnetic field as a proxy for ACC transport variations?

Vivier, Maier-Reimer, Tyler (2004)

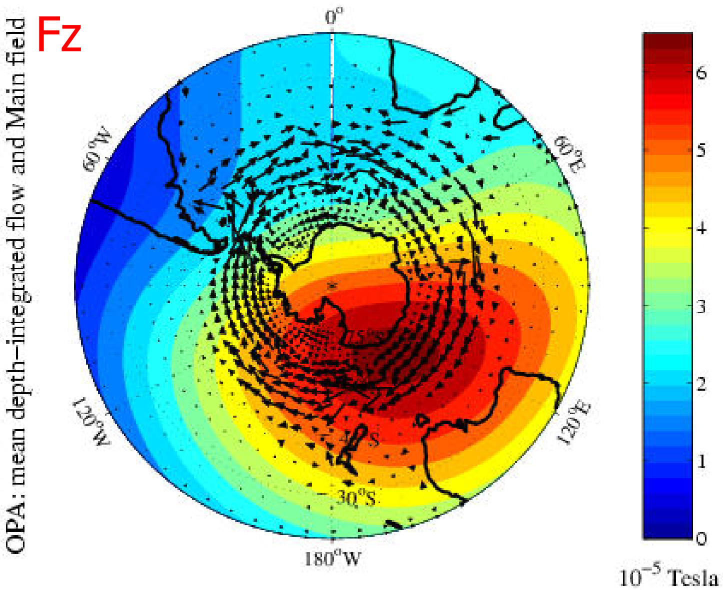
Correlation b versus ACC transport

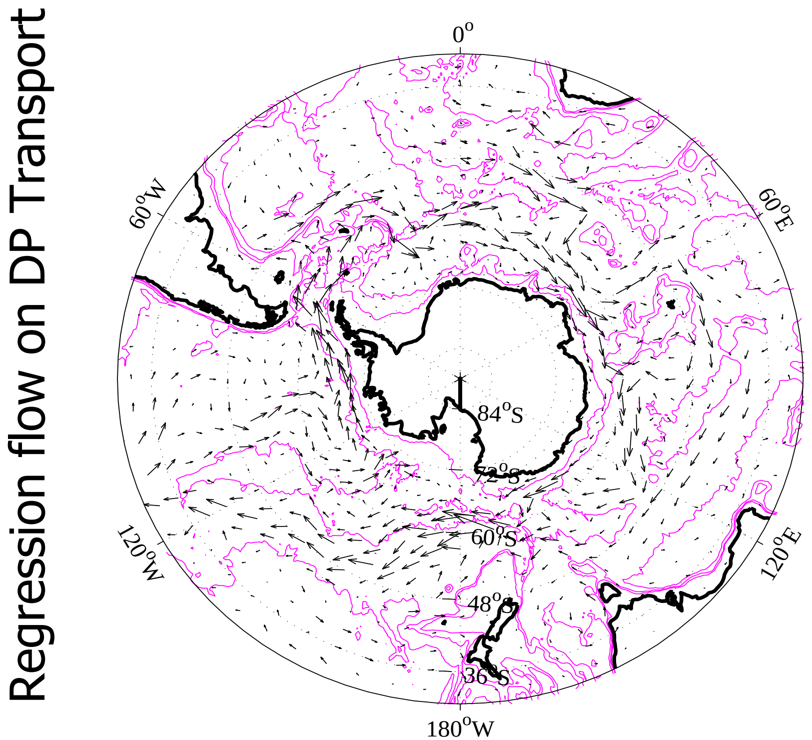




- Several areas of significant correlation between Drake Passage transport and Br
- Highest correlations when looking at the difference between Br in the Pacific and Indian oceans (0.72)
- Range of associated Br: 0.55nT (rms 0.1nT)
- Taking the difference between Br at two locations at the same latitude could be the beginning of an approach to separate the signal , since would filter axisymmetric external signal?

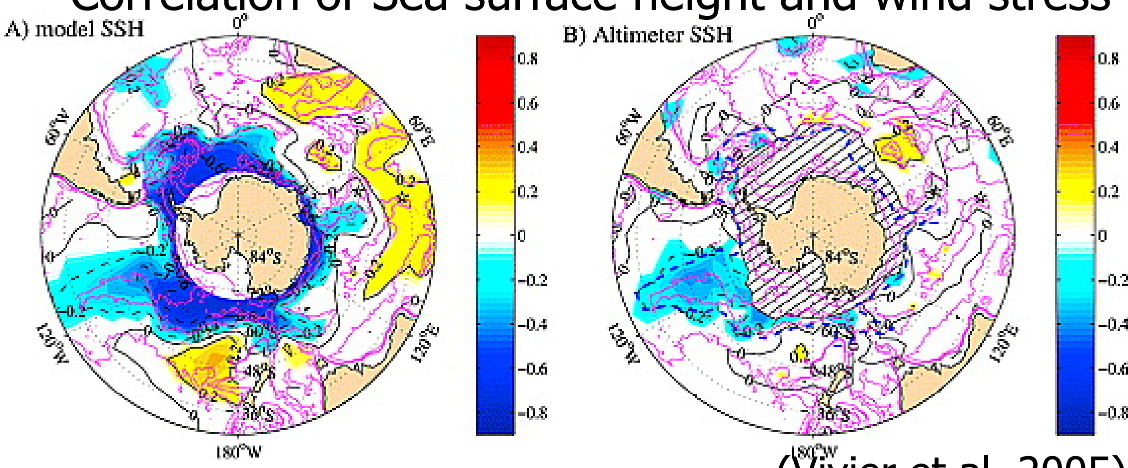
What explains the shape of the correlation pattern?





- Seasonal variation of ACC is not a modulation of the current amplitude along its pathway
- Barotropic flows are more much more constrained by topography and have a distinct pattern of variability
- "Southern" mode (Hughes et al, 99) forced by zonal wind stress

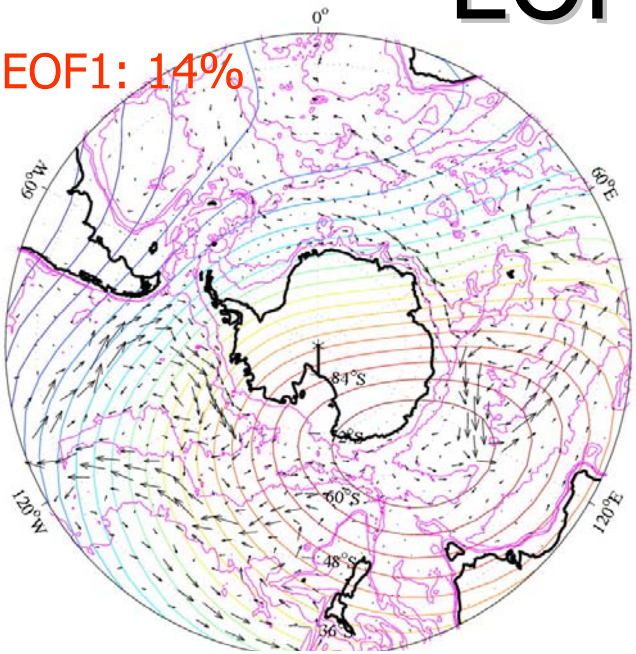
Correlation of Sea surface height and wind stress



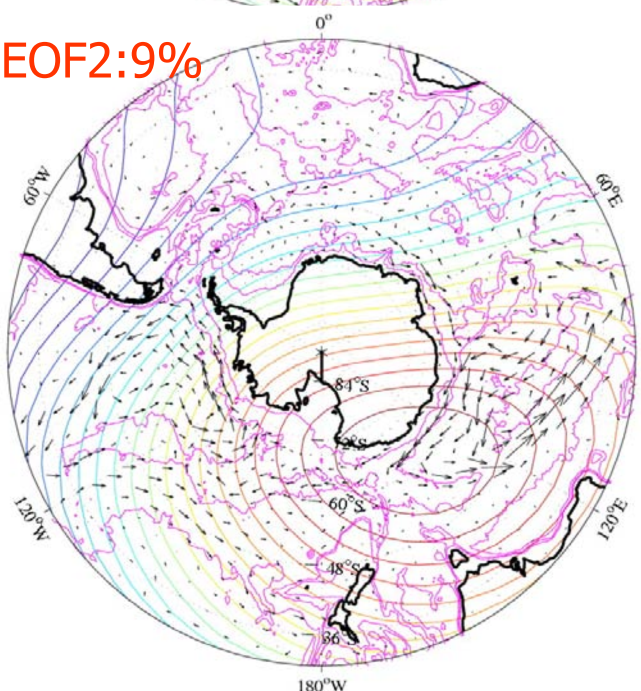
(Vivier et al, 2005)

EOFS analysis of flows

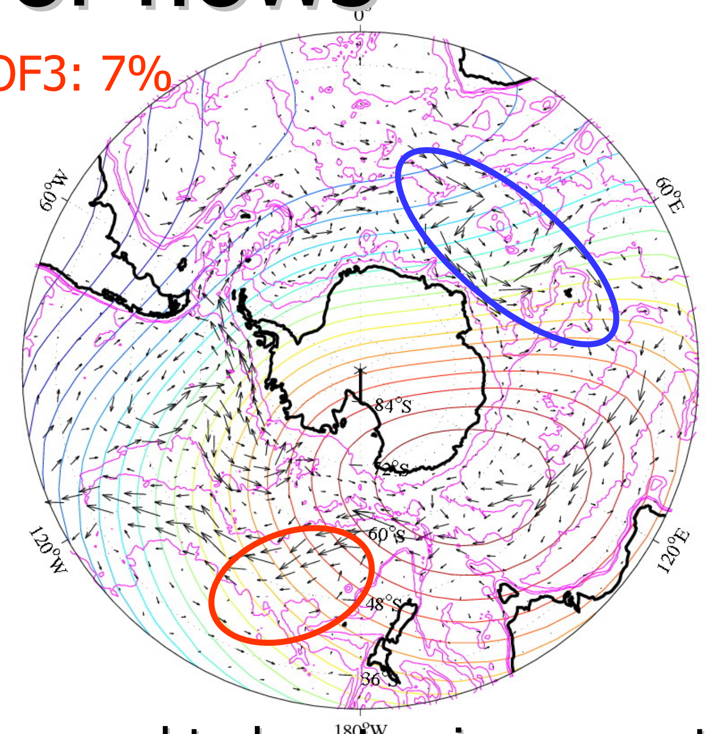
EOF1: 14%



EOF2:9%



EOF3: 7%



- EOF1 and 2 correspond to barotropic resonant basin modes, enclosed by topography, forced by the local wind stress curl (eg Vivier et al, 05) Little contribution to the circumpolar transport.
- “Southern” (circumpolar) mode shows up in EOF3, correlated with ACC transport (0.7)
- Magnetic field fingerprint of circumpolar mode shows up where the signal is not masked by the forcing due to EOF1 and 2:
  - South indian Ocean
  - East of New Zealand

Conclusion

- Br order of magnitude at 400km:
  - Mean: ~2 nT
  - Time variability RMS: up to 0.2 nT: range 0.9 nT detectable…(?)

- Could Br be used to measure the variability of flows?
  - Simple relationships in at least 2 cases:
    - Arabian sea gyre
    - ACC: strongly motivated (little direct measurements, no integral measurements)
  - Can the oceanic contribution to Br be separated?

    low SNR, no phase-locked frequency (unlike tides) but specific fingerprints of ocean signals that could be used to separate it.