Vertical-mode decomposition as a dynamic description of the Atlantic meridional overturning circulation

Zoltan Szuts

Jochem Marotzke

Max-Planck-Institut für Meteorologie, Hamburg

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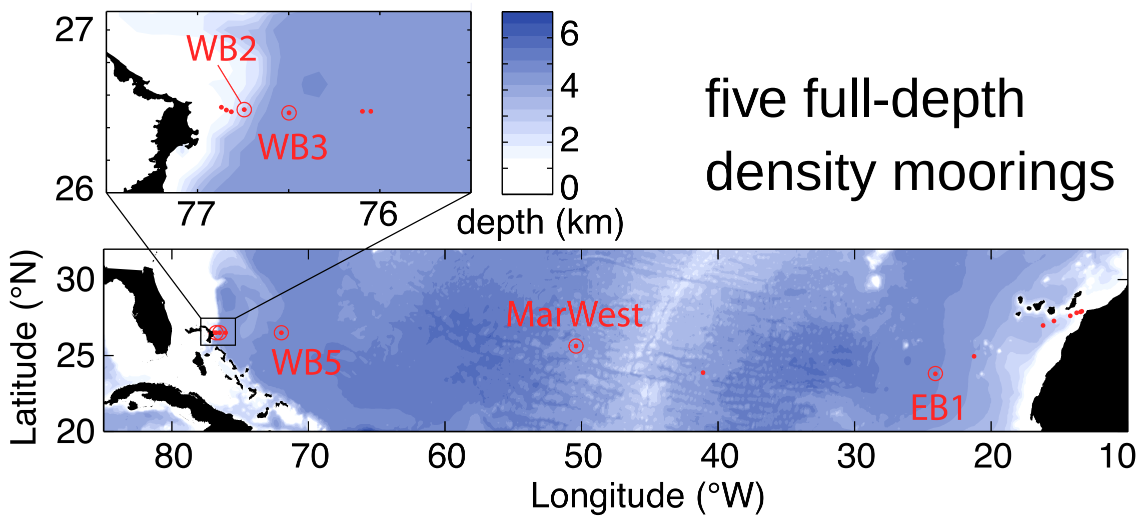
Max-Planck-Institut für Meteorologie

What processes does the RAPID/MOCHA array measure?

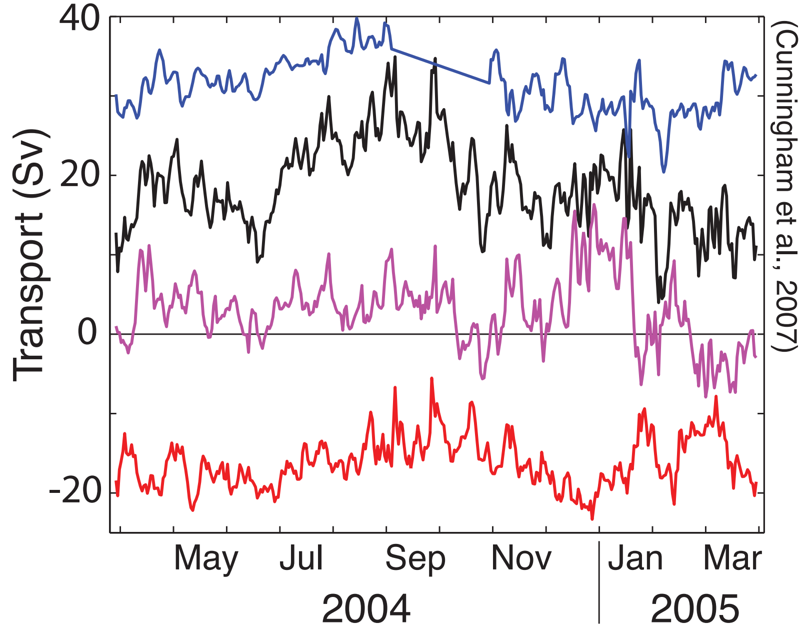
RAPID/MOCHA array



five full-depth density moorings

AMOC Components

$$T_{AMOC} = T_{MO} + T_{FC} + T_{Ek}$$



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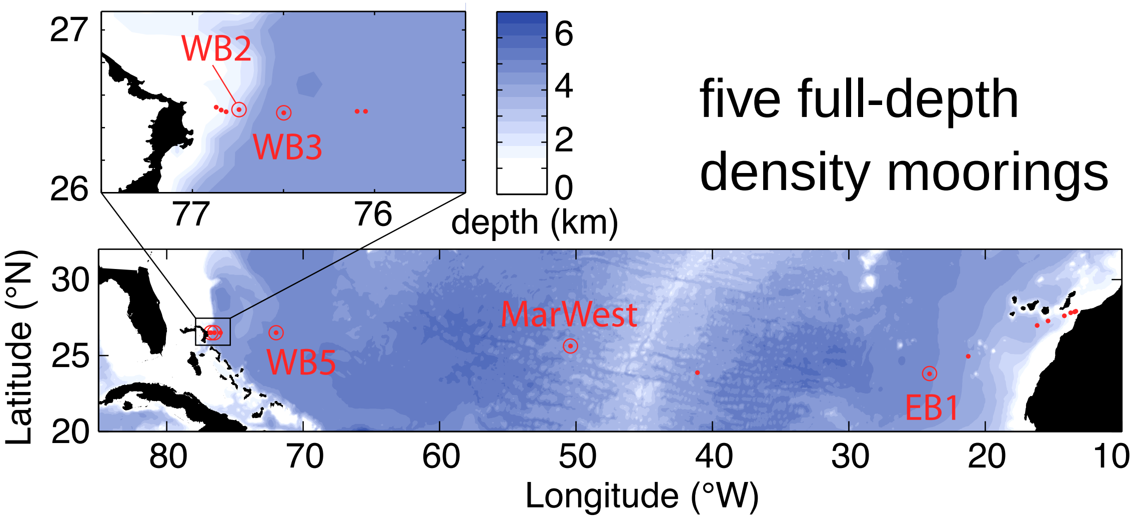

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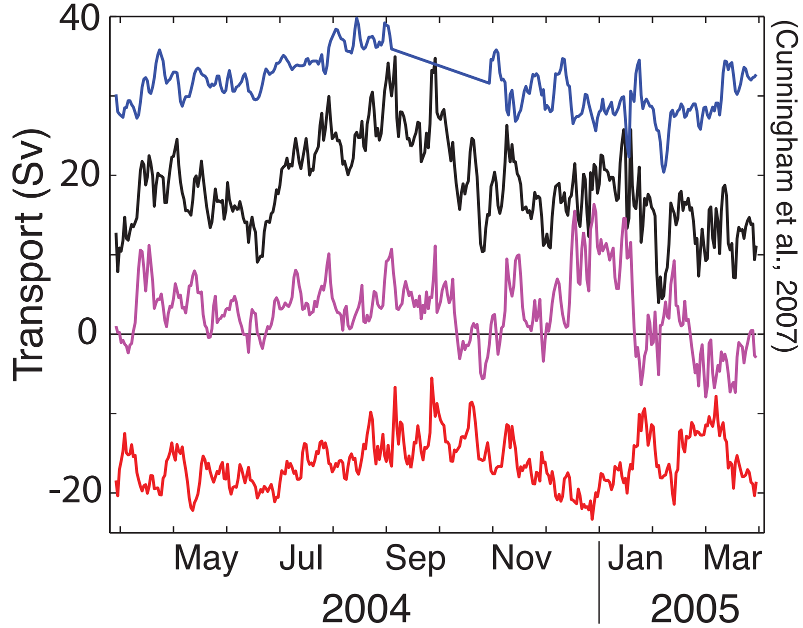


To understand the basin-scale signal (AMOC), we must also understand the local signal.

Test whether **simple** dynamics explain **vertical** **density** fluctuations.

- Test: use *a priori* shapes, not EOFs
- simple: vertical modes
- vertical: certain forms implicitly assumed by Wunsch (2008) or for SSH
- density: profiles of local geopotential anomaly

Methodology and Organization

1. **Decompose vertical structure at each mooring into modes.**
   Fit modes to 2-day low-pass filtered moored CTD measurements:
2. **How useful is the decomposition and what does it show?**
   Compare it with the original signal and with SSH.
   – local signal at each mooring
   – transports between moorings, across basin
3. Summary

How to obtain modes from our observations?

In a motionless and flat-bottomed ocean, vertical modes depend on $N^2(z)$.

$$u' = \sum_n U_n(x, y, t)\, F_n(z)$$

$$p' = \rho_0 \sum_n P_n(x, y, t)\, F_n(z)$$

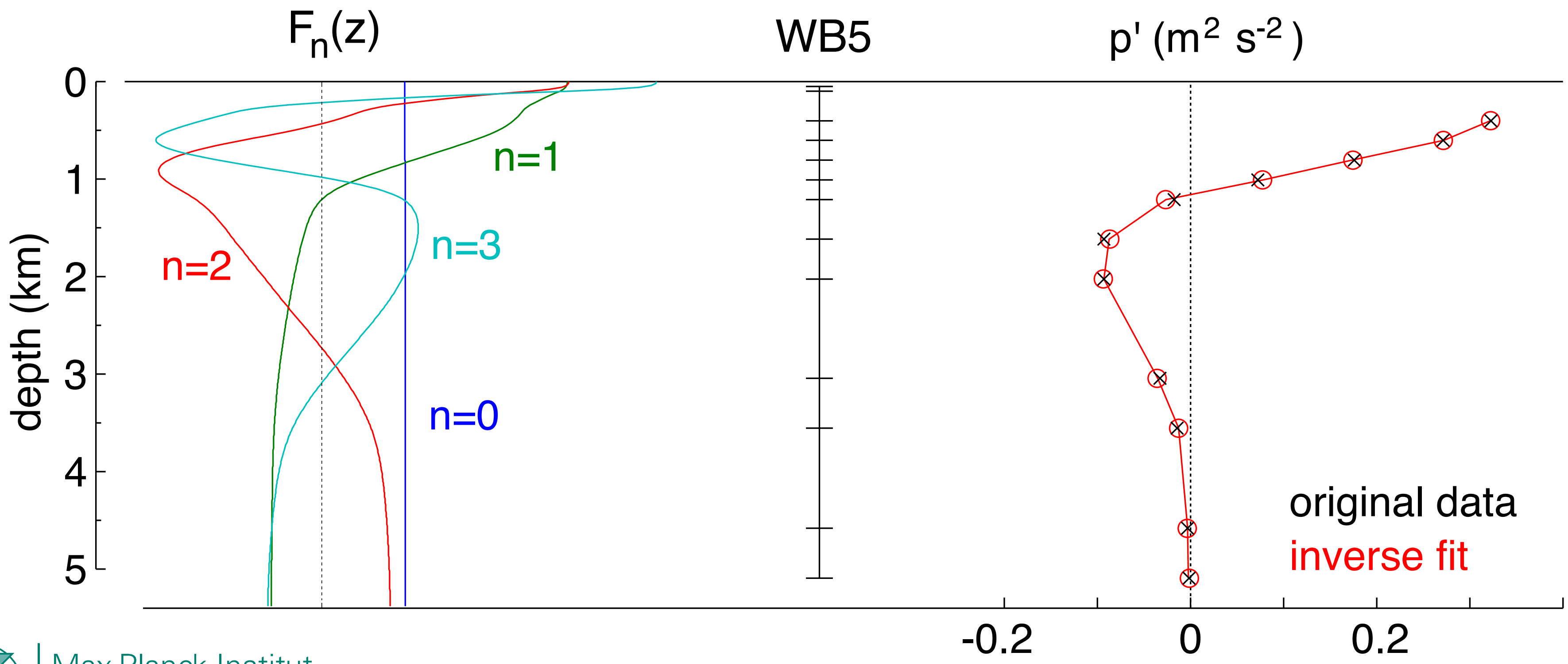
From moored density measurements:

(1) calculate $\rho(z, t)$ with climatology (RAPID)

(2) calculate pressure perturbation

$$p'(z, t) = \frac{g}{\rho_0} \int \rho'(z, t)\, dz$$

(3) use Gauss-Markov inversion to fit 8 modes at each time-step (Wunsch, 1996)



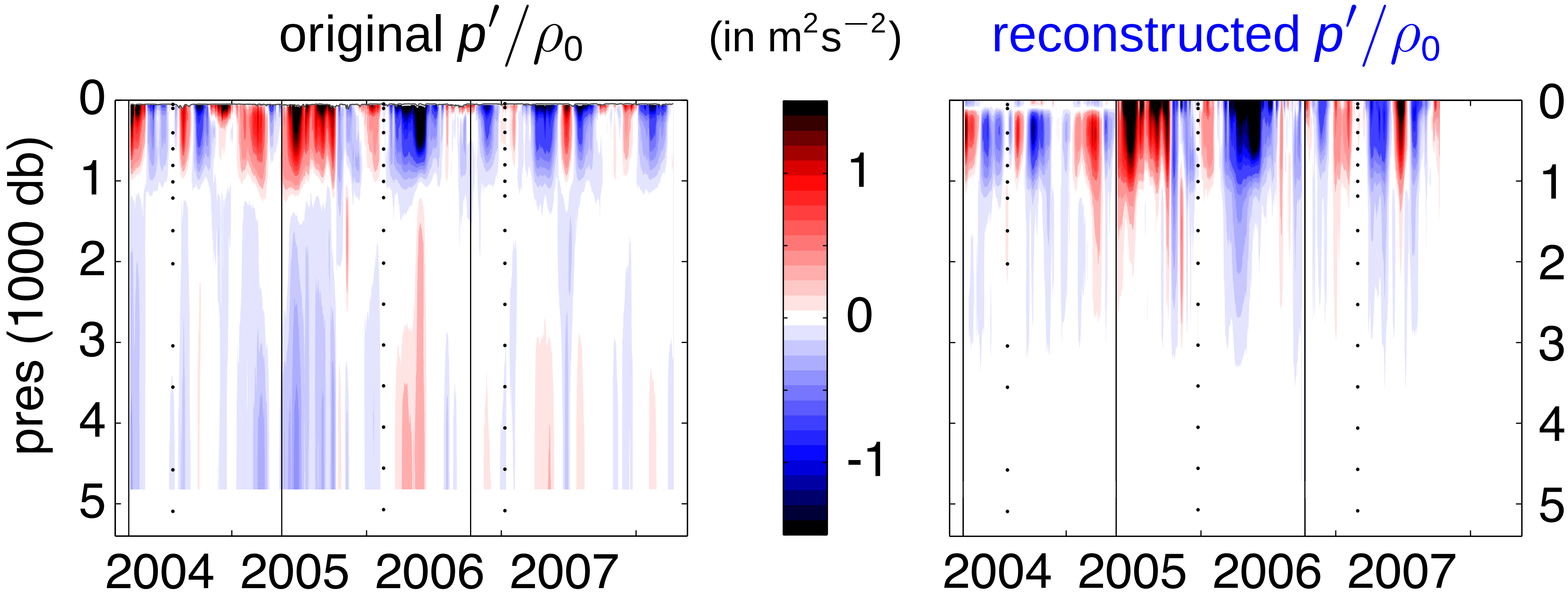
Compared quantities

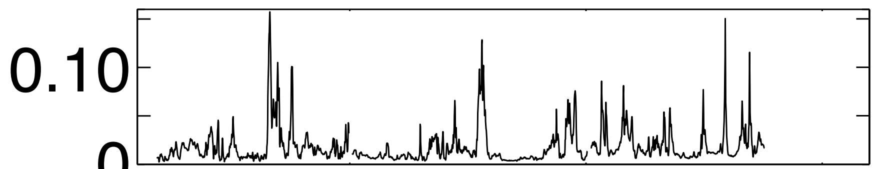
For remainder of talk, compare these three quantities in units of $\mathrm{m}^2\mathrm{s}^{-2}$:

	geopotential anomaly perturbation:	ϕ'
Original	or	
	reduced pressure perturbation:	p'/ρ_0
Reconstructed	reconstructed pressure perturbation:	$\sum_n \mathrm{P}_n(x,t)\,\mathrm{F}_n(z)$
SSH	altimetric SSH anomaly times gravity: (with zonal average removed)	$g\eta$

Because these quantities are all time-perturbations, for geostrophic transport calculations we must add back the time-averaged geopotential anomaly $\overline{\phi}(z)$.

Is the full-depth signal recovered at WB5?





fractional residual

– data from three deployments

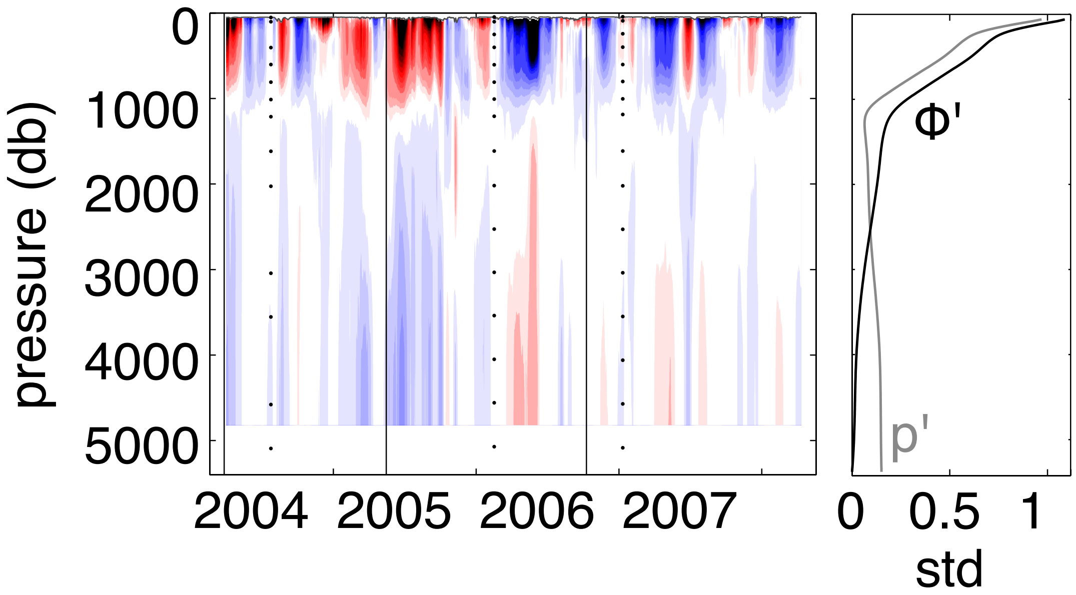
– only use data at sensor depths (dots)

– don’t use observations above 200 m

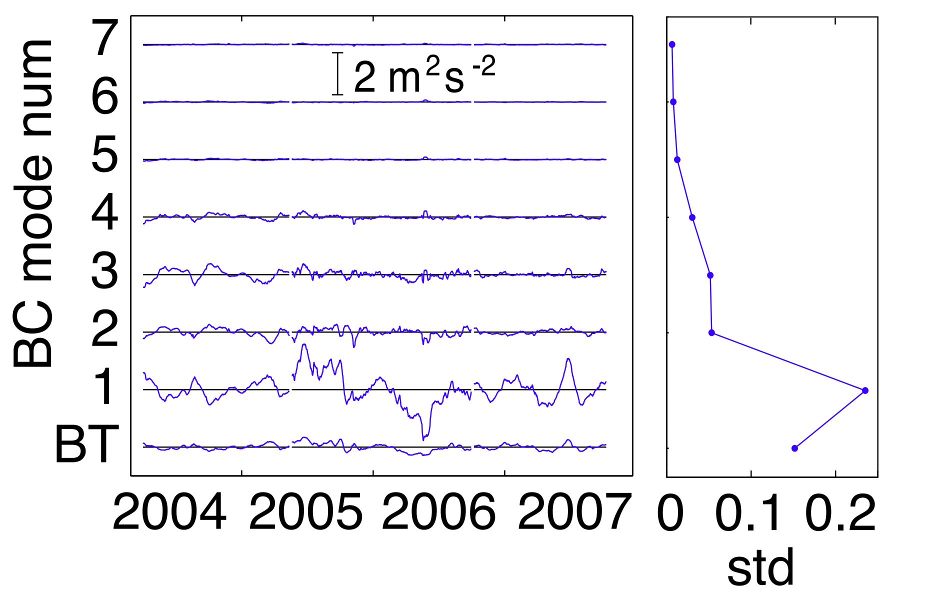
– recovered signal using 8 modes

Variance against depth or mode number

original p'/ρ_0 (in $m^2 s^{-2}$)



$p'_n F_n(z = 0)$ (in $m^2 s^{-2}$)



– p' is intensified above 1200 m

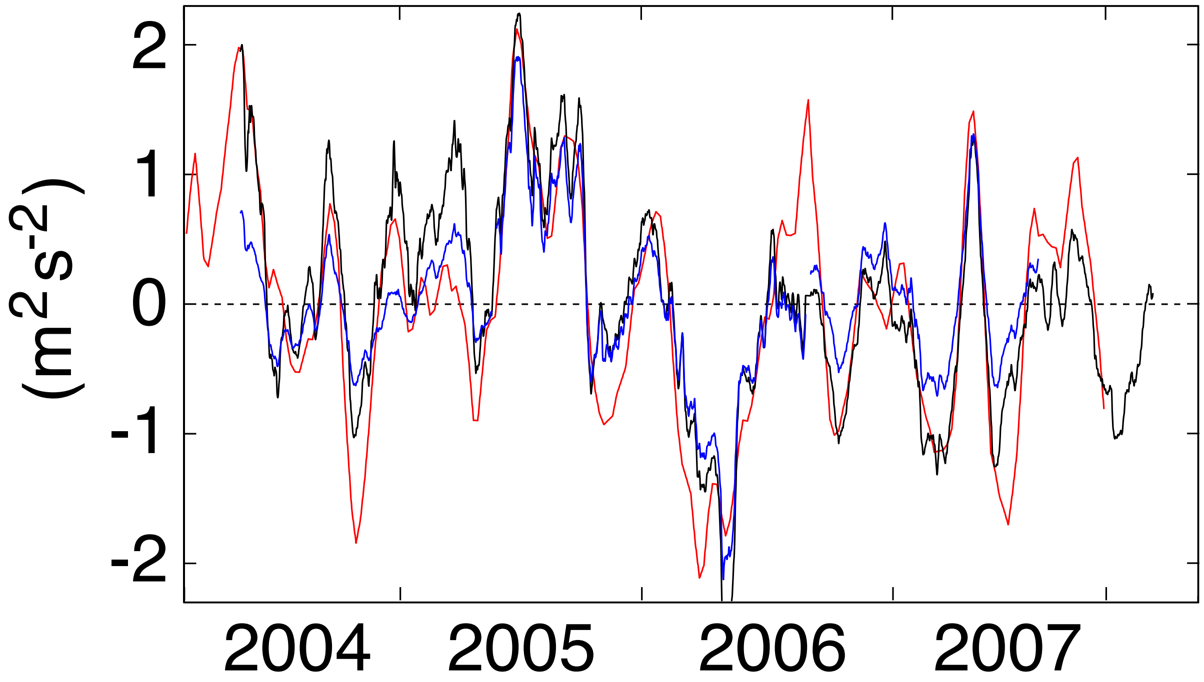
– weak signal below 3000 m

– first baroclinic mode (BC1) dominates

– barotropic mode (BT) is retained, as it's unclear whether enforcing a condition of 'no forcing' is appropriate (Kunze *et al.*, 2002)

Is the local signal at WB5 recovered?

geopotential anomaly (Φ) at 200 db
BC1 reconstruction (p_1'/ρ_0) at 200 db
SSH ($g\eta$) from altimetry



correlation (r)

	Φ	p_1'/ρ_0	$g\eta$
Φ	1	0.87	0.85
p_1'/ρ_0		1	0.93
$g\eta$			1

there's good agreement:

– BC1 recovers 76% of variance

– of which almost all (86%) is coherent with SSH

(the signal at 200 db is considered to avoid surface seasonal heating and cooling)

Is the transport between WB5 and MarWest recovered?

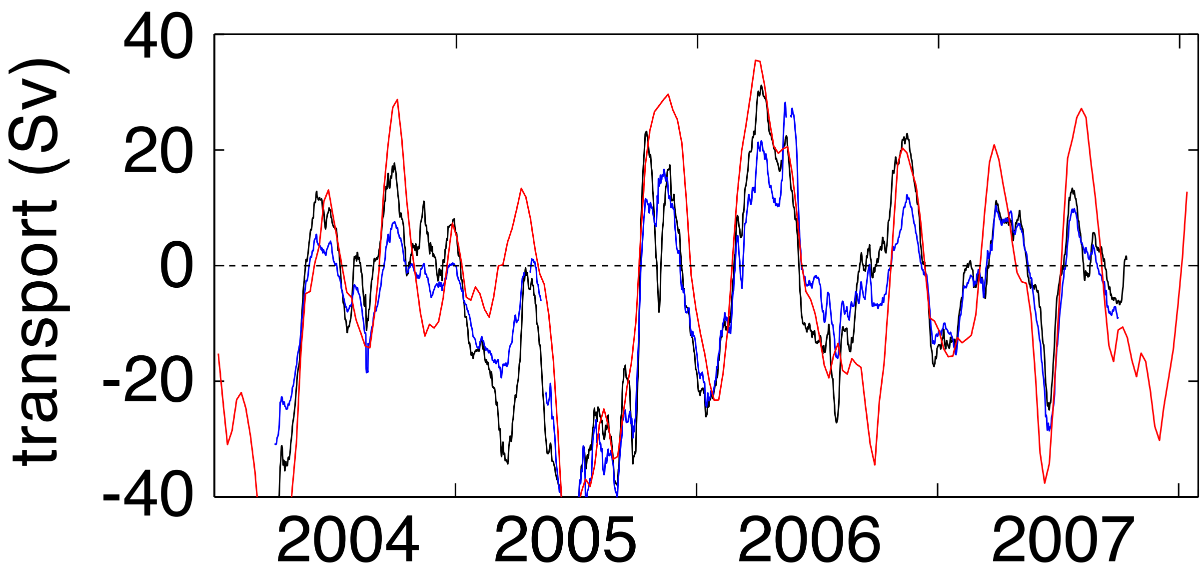
Geostrophic transport relative to bottom

directly measured (T_Φ)

reconstructed from BC1 mode (T_{BC1})

reconstructed from SSH and BC1 (T_{SSH})

std (Sv)	correlation T_Φ	T_{BC1}	T_{SSH}
17	1	0.91	0.80
24		1	0.83
20			1



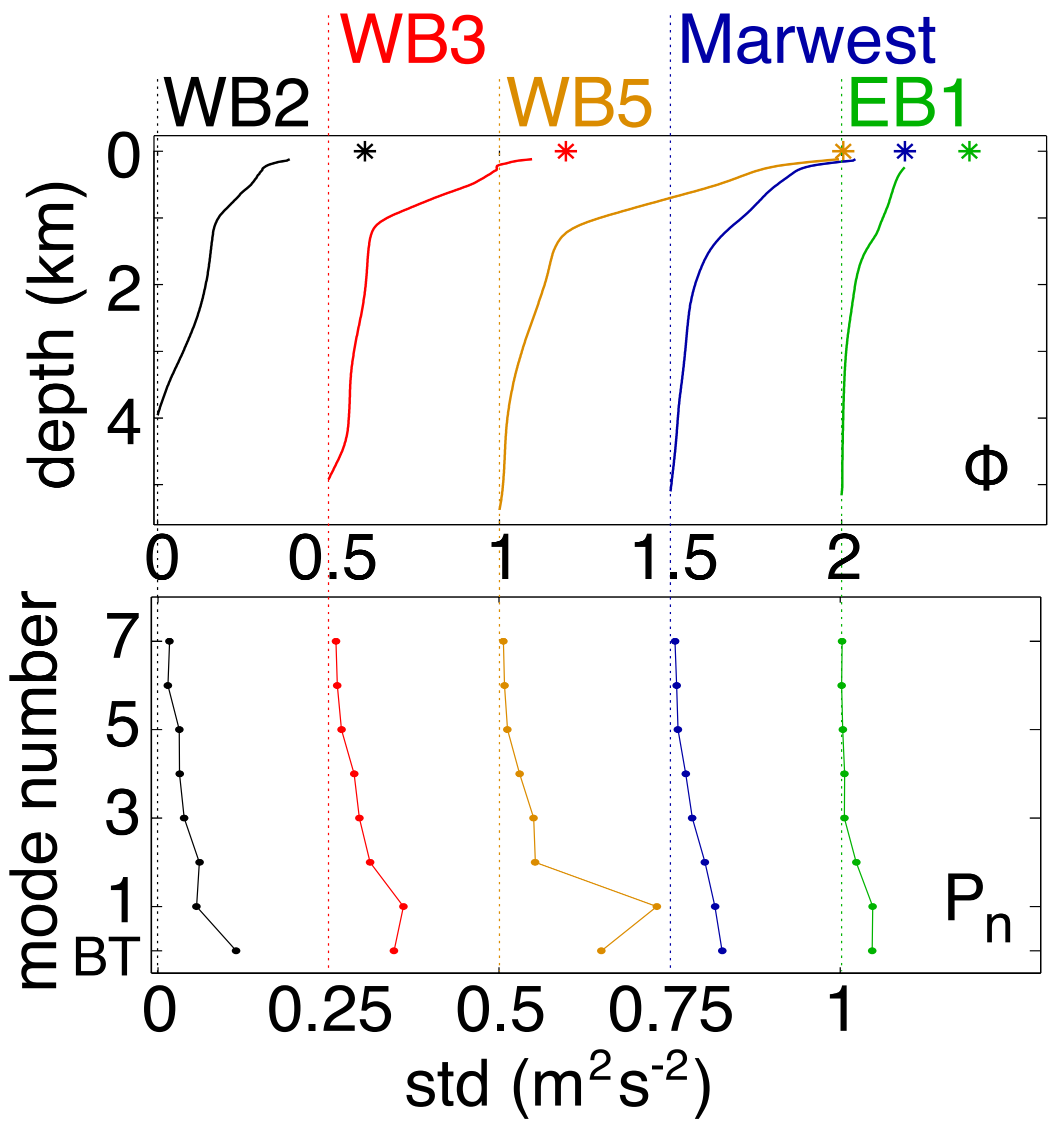
there's still good agreement:

of the variance in T_Φ,

– T_{BC1} recovers 83%

– T_{SSH} recovers 64%

How does mode decomposition vary across 26.5°N?



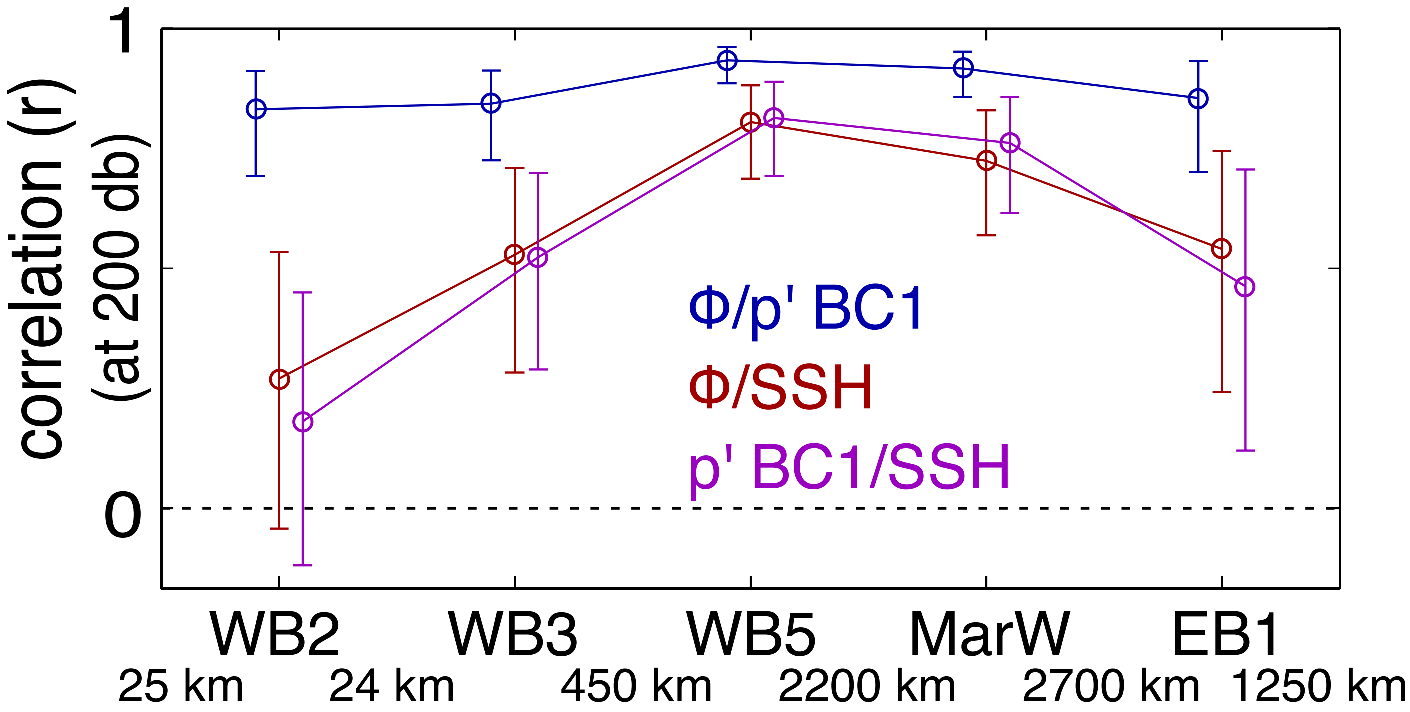
– std in upper 1000 is large and surface-intensified away from boundaries

– Surface intensification is weak at boundaries

– BC1 mode dominates away from boundaries

– WB2 and EB1 have different distribution of variance among modes

Correlations of the local signal across 26.5°N

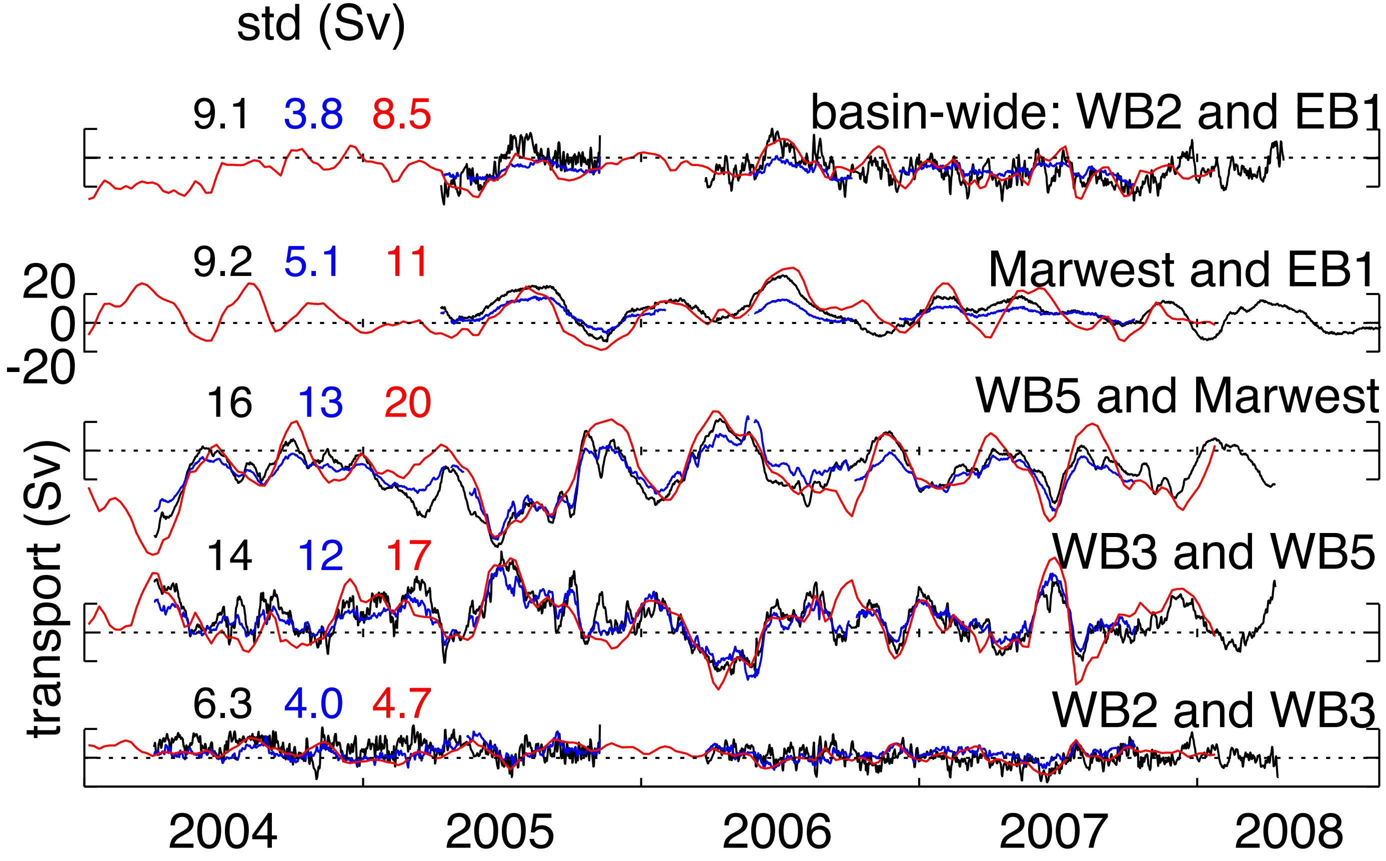


– the BC1-reconstruction and **Φ** agree well at 200 db

– In the interior (WB5, Marwest), the BC1-reconstruction and SSH agree well with **Φ**

– At boundaries, although the BC1-reconstruction recovers the **Φ** signal that is correlated with SSH, neither is well-correlated with **Φ**.

Transports between moorings (T_{Φ}, T_{BC1}, and T_{SSH})



correlations (r) of:

	T_{Φ} T_{SSH}	T_{Φ} $T_{p'}$
basin-wide: WB2 and EB1	0.63	0.68
Marwest and EB1	0.83	0.95
WB5 and Marwest	0.80	0.91
WB3 and WB5	0.77	0.89
WB2 and WB3	0.45	0.29

– The local BC1 signal is also the dominant transport away from boundaries

– At boundaries, only 40% of the transport variance is recoverable from BC1 or SSH

Conclusions

We characterize the variance measured by density moorings in terms of the vertical mode structure.

– The first baroclinic mode dominates in ocean basin . . .
  . . . but not within 25–50 km of W or 1000 km of E boundaries.

– Transport at the boundaries is poorly explained by the first baroclinic mode
  . . . and so wave perturbations there do not have the simple form expected.

– This vertical structure offers a clear explanation of the limitations of recovering transport from SSH at this latitude.

Modal Decomposition Theory

A motionless reference state $\overline{\rho}(z)$ defines the perturbations, and its stratification N^2 defines F(z) and G(z)

$$\frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{1}{N^2}\frac{\mathrm{d}F}{\mathrm{d}z}\right) + \gamma^2 F = 0$$

and

$$\mathrm{G}(z) = \frac{i\omega}{\mathrm{N}^2(z)}\frac{\mathrm{d\,F}(z)}{\mathrm{d}z}$$

there are two vertical shapes (Gill, 1982; Wunsch and Stammer 1997):

$$u' = \mathrm{U}(x,y,t)\,\mathrm{F}(z)$$
$$v' = \mathrm{V}(x,y,t)\,\mathrm{F}(z)$$
$$p' = \rho_0\,\mathrm{P}(x,y,t)\,\mathrm{F}(z)$$
$$w' = \mathrm{P}(x,y,t)\,\mathrm{G}(z)$$
$$\xi' = \mathrm{H}(x,y,t)\,\mathrm{G}(z)$$

The equivalent geopotential anomaly modes ϕ'_n are calculated with 1) hydrostatic balance to obtain ρ'_n, 2) vertical integration to obtain ϕ'_n, and 3) the Boussinesq approximation:

$$\Phi'_n = \int_0^{p_0} \delta'_n\,\mathrm{d}p \approx \int_0^{p_0} \frac{-\rho'_n}{\overline{\rho}^2}\,\mathrm{d}p = \int_0^{p_0} \frac{-1}{\overline{\rho}^2}\frac{\partial p'_n}{\partial z}\,\mathrm{d}p = \ldots = \frac{1}{\rho_0}p'_n$$