Chaotic Advection in the Alboran Sea: Lagrangian Analysis of Transport Processes in and out of the Western Alboran Gyre

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INTRODUCTION & MODEL

Alboran Sea

- East of the Strait of Gibraltar, **SG**
- Atlantic water enters the Mediterranean as the Atlantic Jet, **AJ**
- Major feature is the Western Alboran Gyre, **WAG** – persistent anticyclonic mesoscale eddy
- Past studies of Finite-Size Lyapunov Exponents highlight the WAG edge, implying it has **chaotic flow**— aperiodic stirring with exponential stretching and folding of fluid parcels.

Questions

How large is the Atlantic Jet-Western Alboran Gyre exchange?
Where do chaotic advective fluxes occur?
How large are advective fluxes in budgets for volume, heat, and salt?

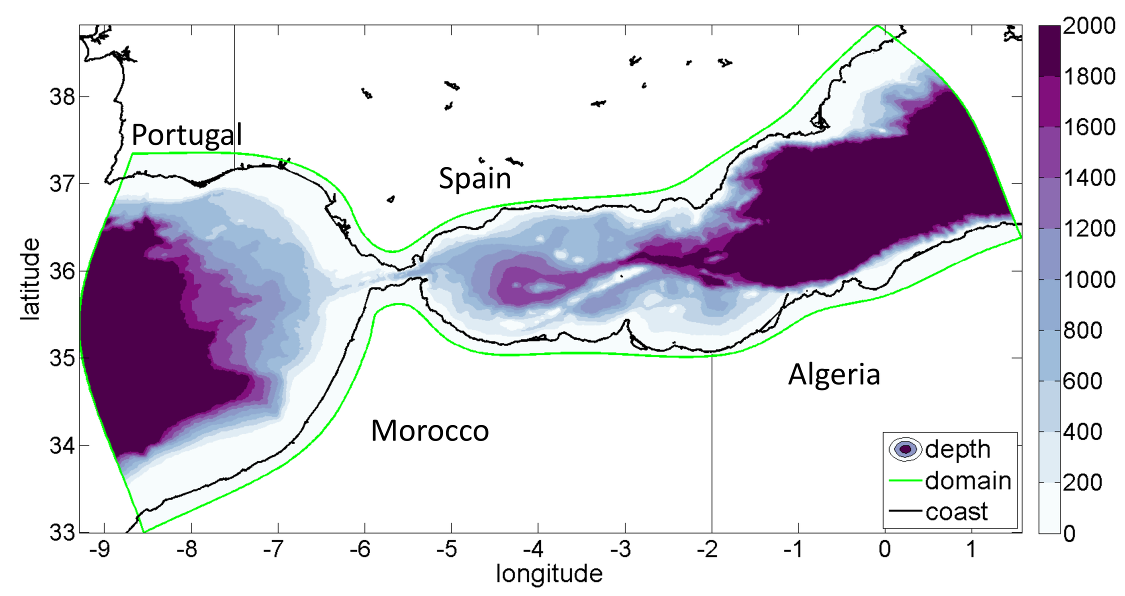

Figure 1: model domain and topography

MIT general circulation model

- Domain includes the Strait of Gibraltar (figure 1) with **1km horizontal resolution** and 46 vertical levels.
- Full simulation runs November 1 2007- March 28 2008 after 130 days spinup.
- SSH matches AVISO measurements well.

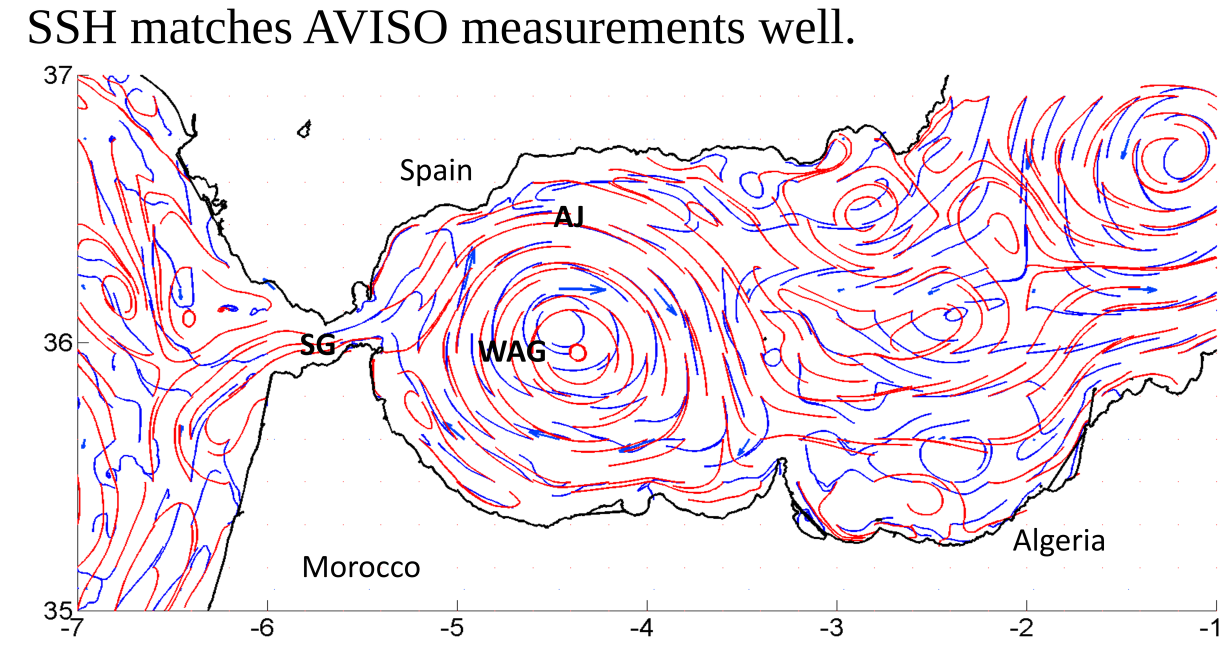

Figure 2: Mean circulation at the surface (red) and along the σ=28.5 isopycnal surface (blue). Note shift in WAG position and that the lower surface has outflow through the strait.

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METHODS

Manifolds

- Lagrangian gyre boundary
- Ridges of the FTLE (strain) field
- Reach hyperbolic points asymptotically in time
- 3D surfaces connecting the 2D material curves on the surface and isopycnals
- Grown via advection over 8-30 days with 2-5km curve resolution.

Lobes

- Bounded by intersecting manifolds
- Flux water across the WAG boundary
- Example in figure 4

Gate

- Joins manifolds at set location
- Creates continuous WAG boundary

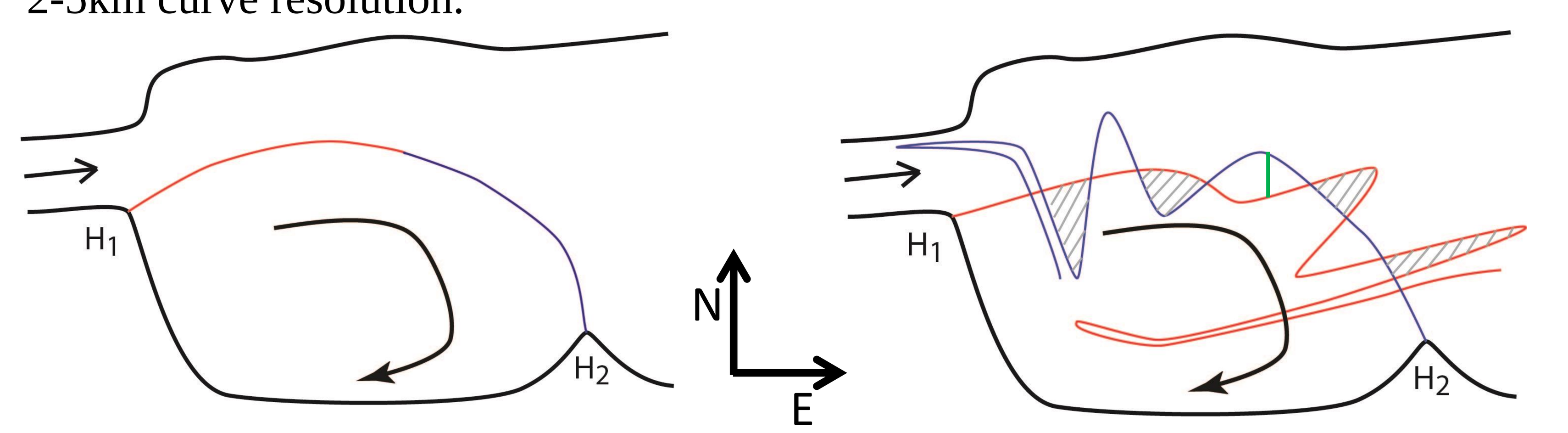

Figure 3: Unstable and stable manifolds and gate. Hyperbolic points H1, H2. **Left**, steady. Water is trapped in the gyre for all time. **Right**, periodic. Shaded lobes map to each other in time and flux water out of WAG. Unshaded lobes flux into WAG. WAG boundary from H1: unstable manifold, gate, stable manifold, H2, coast.

RESULTS

Manifolds and Lobes

Manifolds bound the WAG; intersections delimit lobes. The region covered by manifolds is the stirring region **where chaotic advective fluxes can occur**. The **center region** of the WAG is where no manifolds reach: water is retained for at least 8 days.

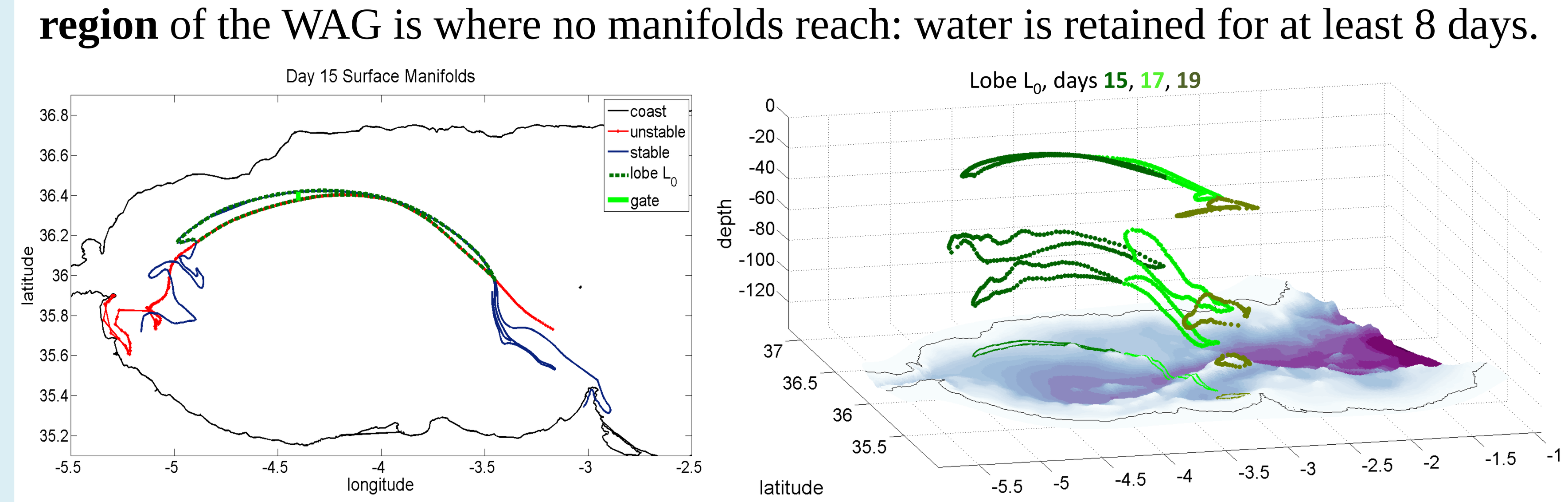

Figure 4: Lobe example. Left, surface manifolds and gate, day 15. Right, points from the manifolds at the surface and isopycnals σ=26.5, 27 on days 15, 17, 19.

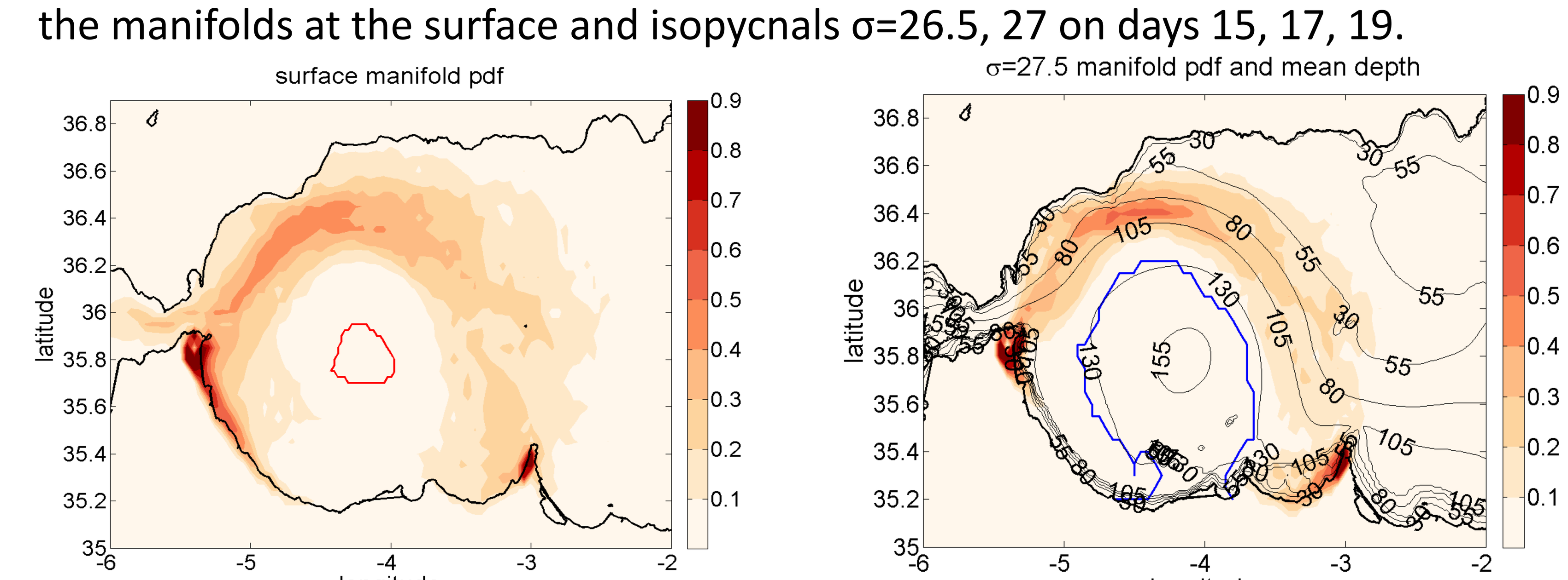

Figure 5: Probability density function (reds) of manifold location on a given day; color curve is the zero contour. Density surface mean depth is contoured in black.

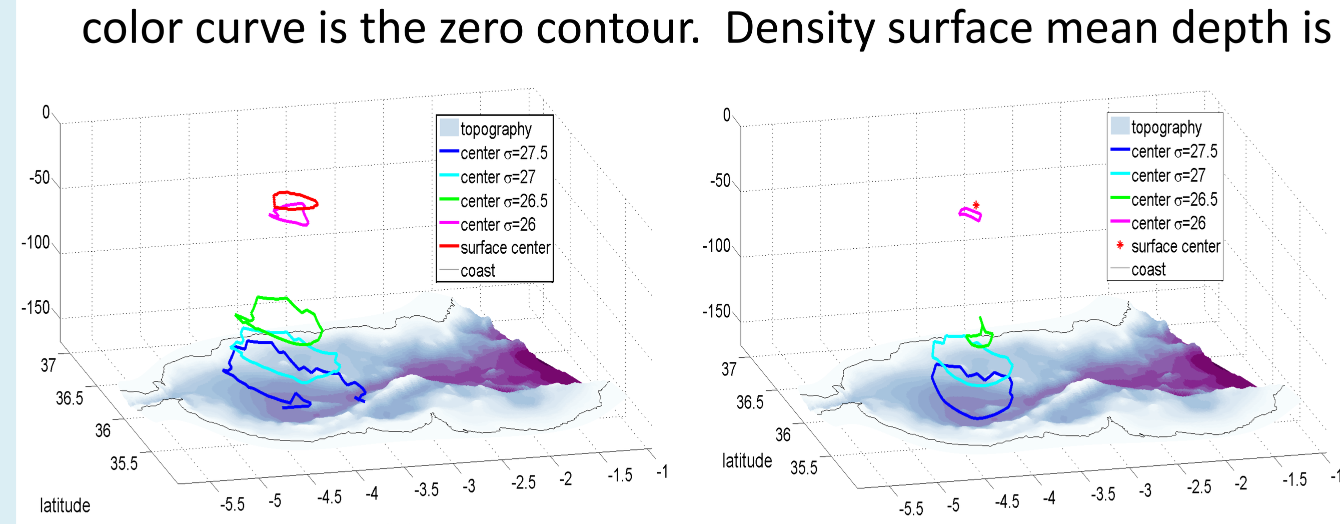

Figure 6: Center region of the WAG. Zero contours of the manifold pdf from the surface and 4 isopycnals. Left, 8 days; right, 14.

Volume, Heat, Salt Budgets

Lagrangian budgets include advective fluxes through the gate, sea surface forcing, estimates of diffusion, and changes in storage (not shown). The WAG is bounded horizontally by manifolds, gate, and coast, and vertically by the sea surface and the σ=27.5 isopycnal.

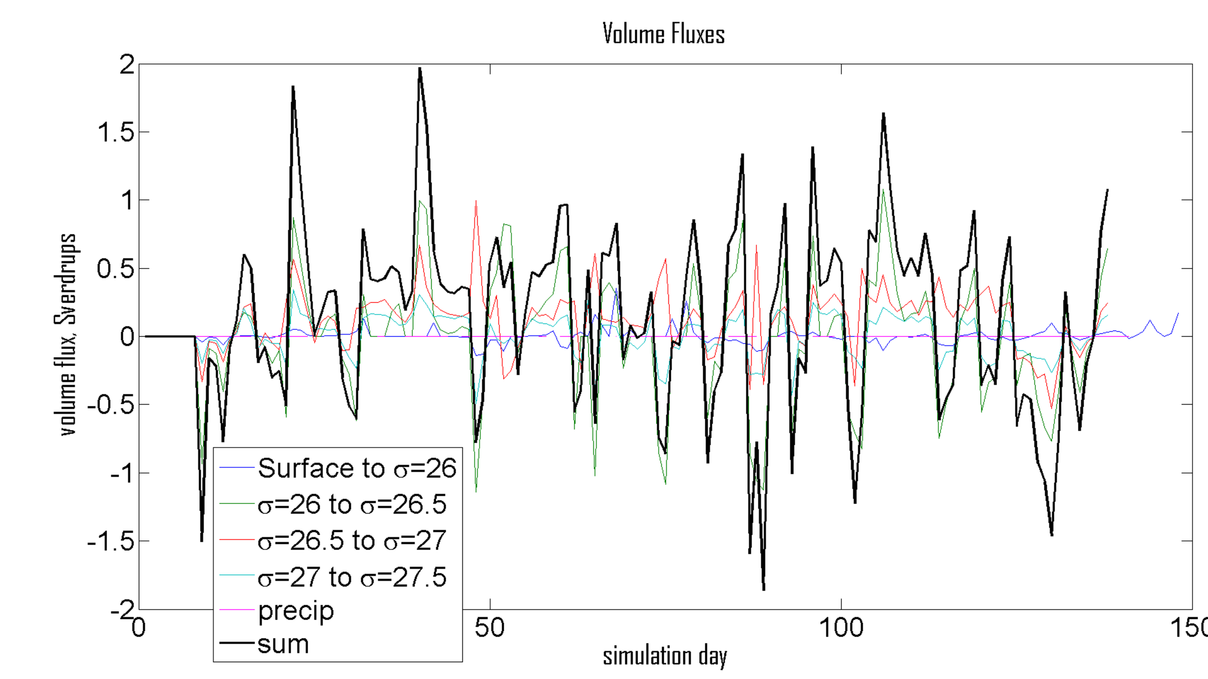

Figure 7: volume budget. Each isopycnal layer's advective fluxes are separate. Sea surface fluxes are negligible. Changes in WAG volume are the correct order of magnitude to close the budget.

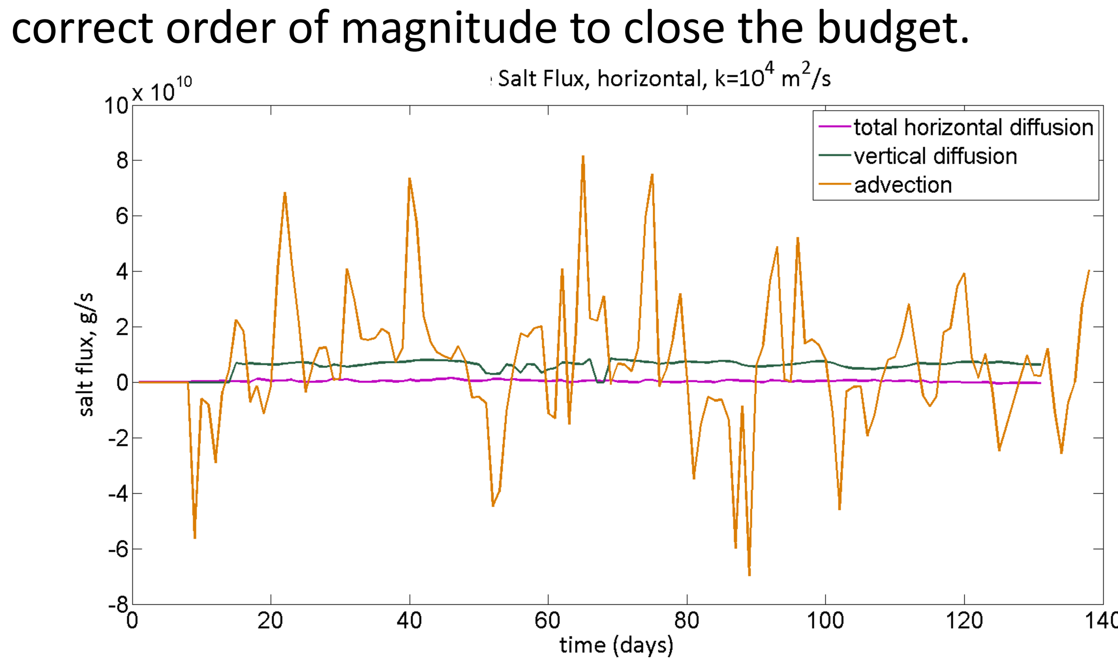

Figure 8: salt budget. Advection is water of salinity close to 36. Vertical diffusion is similar to salinity 38 water at mean advective volume flux.

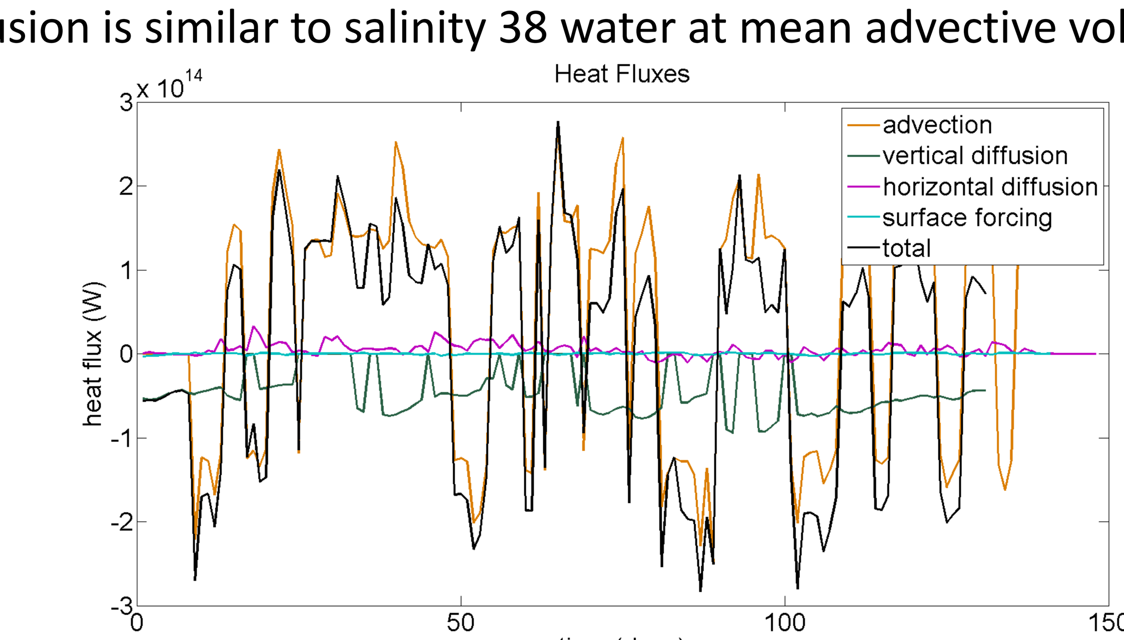

Figure 9: heat budget. Surface forcing is negligible. Vertical diffusion balances advection and horizontal diffusion.

CONCLUSIONS

Chaotic advection does occur around the edges of the Western Alboran Gyre. Direct calculation of manifolds shows a **stirring region which reaches the northern coast** and a **core region, larger with depth, where fluid is retained** on timescales of 1-2 weeks. We also show the structure of a lobe with depth and time. Advective fluxes show that, sporadically, **up to 100% of the Atlantic Jet** (typically 1Sv) **can be entrained into the WAG**, although the time average is about 10%. **Advective fluxes comprise the majority of the volume, heat, and salt budget for the WAG**; these are balanced by storage in the volume budget and vertical diffusion in the heat and salt budgets.