Lagrangian Simulations in the Tropical South Atlantic

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1 Introduction

Veneziani et al. (2014) mentions the results of a two-way nested ROMS-AGRIF simulation of the tropical South Atlantic. The model was run with three successive grids nested inside a grid of $1/4^0$ resolution (1/3 resolution of previous grid); 9km, 3km and 1km respectively. Learning about the distinct seasonality in the mixed layer depth across the domain from this study, we decided to probe its affect on particle dynamics. Lagrangian particles were thereafter simulated in the 9km and 1km runs by Ashwanth Srinivasan.

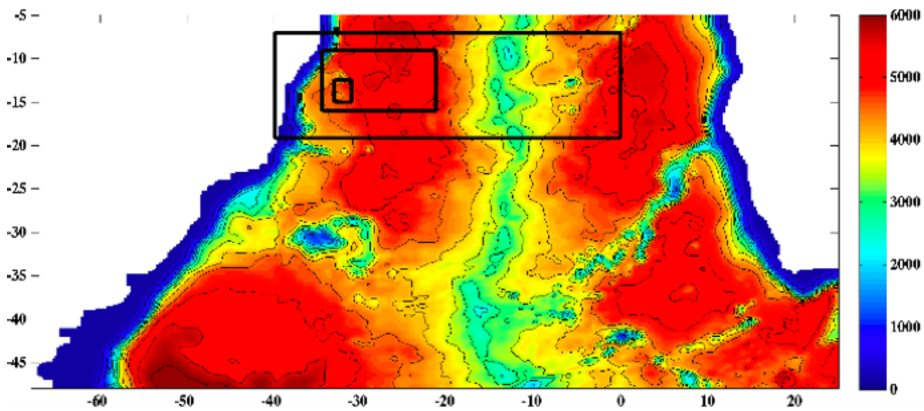


Figure 1: Model domain with nested domains inset, overlaid on local topography.

I could not find a higher resolution version of this plot in color, stand in for now

(Veneziani et al., 2014)

1.1 Lagrangian Model Setup

Lagrangian particles were advected offline with 6-hourly model velocities from the 9km (LR) and 1km (HR) runs. Particles were simulated using an RK-4 numerical integration advection code (by Ashwanth). Particles were released every 3 grid points with a spacing of 27km in LR (6482 particles) and 3km in HR (4980 particles). The particles were advected for a year from August 1999 to August 2000. In LR particles were released every 3 months for a total of three separate releases, whereas in HR particles were released every month for a total of 12 releases.

Add details about numerical simulation of particles, time-step, interpolation of model velocity fields etc

There were five sets of particle releases:

1. 2D particles: constant depth at 15m (within the mixed layer)
2. 3D particles:
   (a) 15m
   (b) 30m, within the mixed layer throughout the year
   (c) 60m, at the base of the mixed later in the winter
   (d) 150m, below the mixed layer throughout the year

Note: New HR re-release runs do not have 2D 15m

1.2 Coverage and Mean Flow

In conjuction with mean flow seen in Figure 4 differences in coverage (Figure 2) across resolution can be explained. In LR mean flow is southwestward in most of the domain except the boundary current region, where we can see convergence of particles at 150m. General circulation changes drastically upon crossing the mixed layer depth, for instance the flow bifurcation point along the coast of South America (not seen here) shifts southward.

add mean flow for other depths

Generally better coverage is seen at depths below the mixed layer where the particles are trapped in mesoscale flow structures, and generally flow with longer decorrelation timescales (see Figure 3). In HR the mean flow is southward and varies greatly by season, coupled with low coverage tells us the Lagrangian statistics are skewed by local flows during each of the release times (also seen in individual release coverage maps not shown here).

In HR, due to a lack of sufficient coverage of the domain and limited particle lifetime (Figure 5) additional particles were released every grid point with a nested region of $1^o \times 1^o$ where particle spacing went down to 500m and for increased temporal coverage every 5 days. These are in the process of being analyzed.

Add coverage plots for newHR run and discuss improvement in coverage

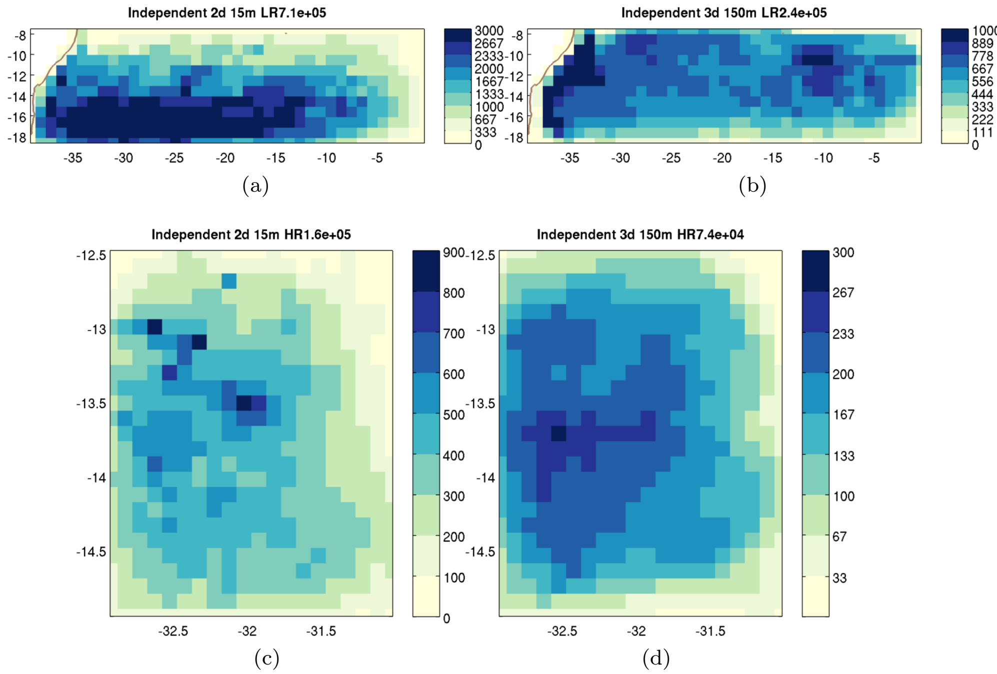
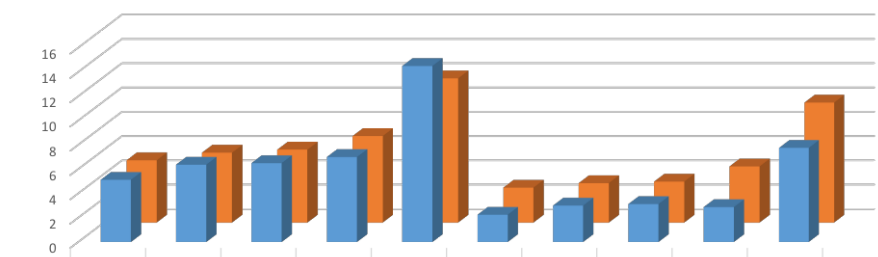
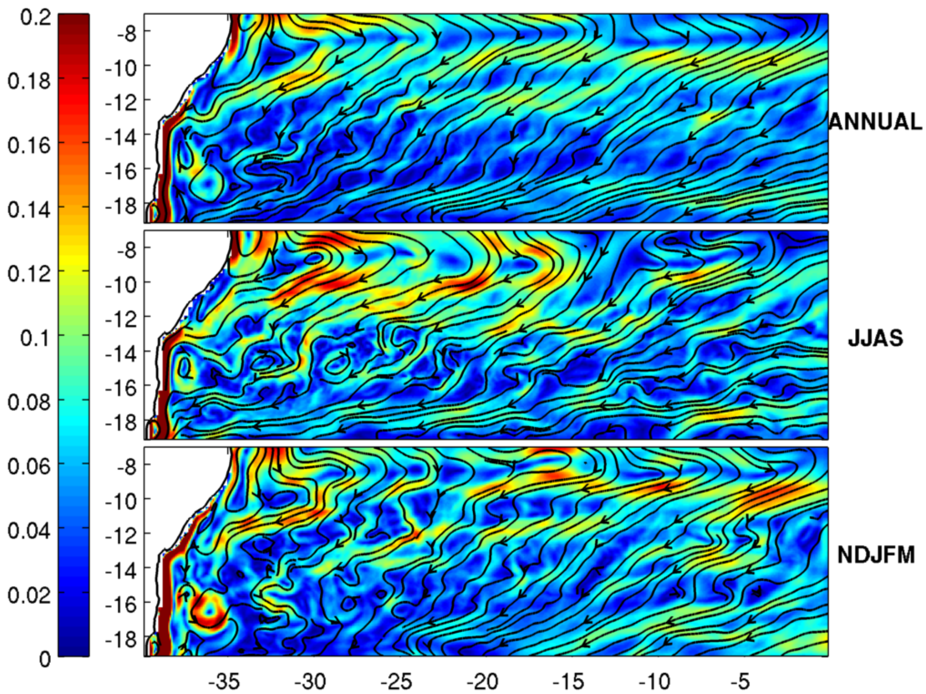


Figure 2: Number of statistically independent observations in 2D 15m and 3D 150m release at both resolutions. Independent observations signify number of observations divided by the number of particles that would be co-moving based on the auto-correlation timescale of the flow

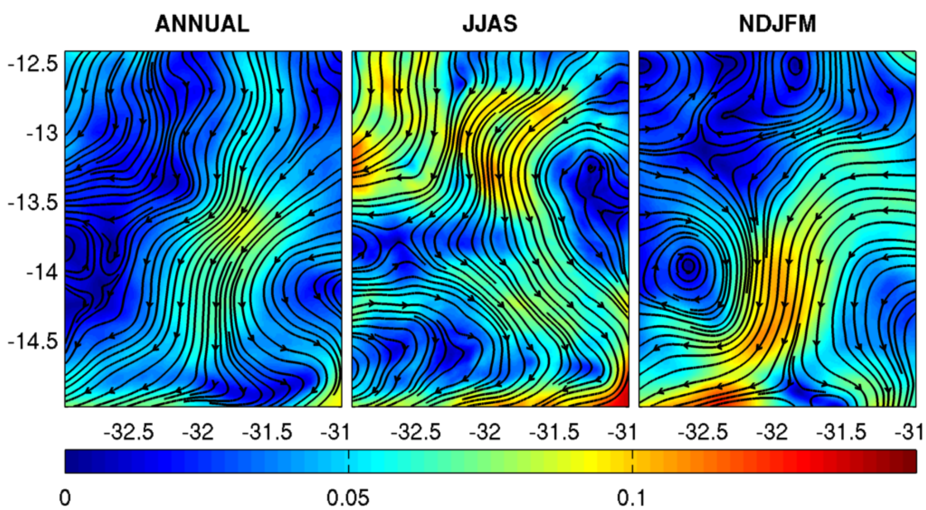


	LR 2D 15m	LR 3D 15m	LR 3D 30m	LR 3D 60m	LR 3D 150m	HR 2D 15m	HR 3D 15m	HR 3D 30m	HR 3D 60m	HR 3D 150m
JJAS	5.125	6.375	6.5	7	14.5	2.25	3	3.125	2.875	7.75
NDJFM	5.125	5.75	6	7.125	11.875	2.875	3.25	3.375	4.625	9.875

Figure 3: Auto-correlation timescales across all releases, both resolutions and seasons

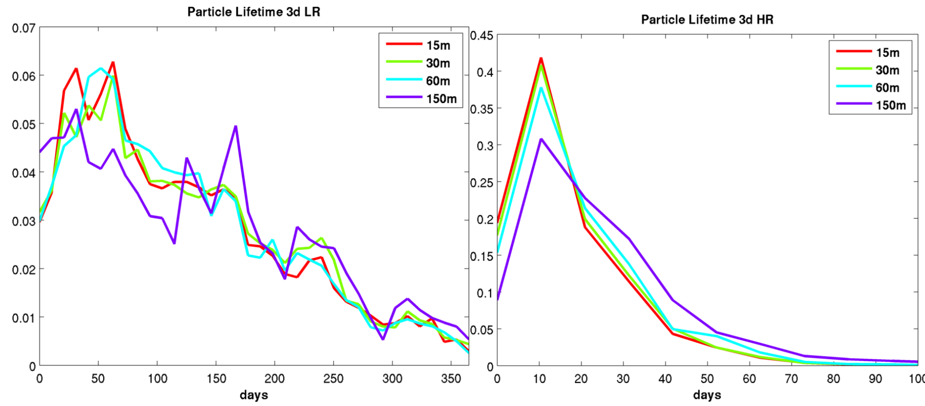


(a) 9 km



(b) 1 km

Figure 4: Mean Flow at 15m in both resolutions across seasons



(a) (b)

Figure 5: 3D release particle lifetime in domain

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2 Analysis

2.1 Methodology

The mixed layer is deeper in winter as a result of intensified winds lending energy to submesoscale motions (1-10km length-scales), as opposed to the summer where larger mesoscale features dominate. Based on this seasonality of the mixed layer observed in the earlier simulation see Figure 6, seasons chosen for further comparison: JJAS(6:9) & NDJFM(11:3); winter and summer respectively (southern hemisphere). All further particle analysis is broken into averages over these two seasons. The goal of the study being how the seasonality of the mixed layer depth affects particle dynamics manifested in Lagrangian particle statistics.

In our time-series analysis, we use residual velocities i.e., Lagrangian particle velocities with seasonal components removed. We must also be wary that inertial periods vary greatly in the LR domain due to its latitudinal extent: 1.5 3.6 days in LR and 1.9 2.3 days in HR. We applied a bandpass to remove all power in the inertial range from the spectrum of particle u,v component time-series. The submesoscale/eddy timescales overlap with the inertial period and performing a bandpass to remove inertial oscillations is not a trivial endeavour. As per suggestion from Philip Wolfram we can try to make rotary spectra to separate eddy oscillations from inertial ones and possibly their timescales. To make a better comparison between HR and LR, we used a subsection of the LR run, where the boundary current did not dominate dynamics.

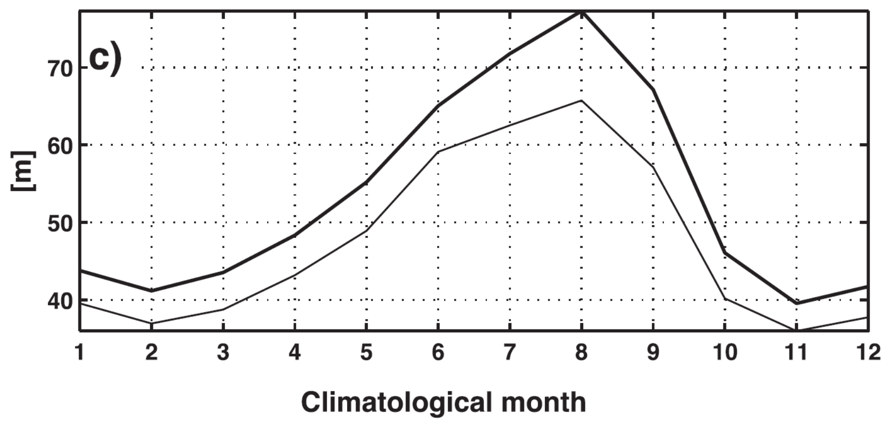


Figure 6: Seasonality of Mixed Layer Depth in South Atlantic based on 3-year; 1999-2002; ROMS AGRIF run. Thin line: mixed layer depth, thick line: isothermal layer depth

Clarify the relationship between EKE/Re no. (any other independent variables) of the flow and dispersion statistics; absolute and relative. See (Poje et al., 2010) where they normalize relative dispersion with OKW > 0 of each model to get a nice collapsed curve. OKW > 0 signifies regions of flow dominated by strain and deformation that result in most of the spreading of particles. OKW < 0 corresponds to coherent eddies that trap particles.
As a result figure out if comparing two resolutions with different dynamics is appropriate?

2.2 Trajectories

Qualitatively (as seen in spaghetti trajectory plots and videos of particles, not shown here) there is little difference to be seen in seasons across LR releases. However in HR we can clearly see the different scale of structures in different seasons as seen in Figure 7. In the summer months most of the particles are trapped in one large eddy with size commensurate with the domain, as a result our statistics will be skewed by this one large eddy, hence the new re-release of particles. On the other hand in the winter the plot is much less coherent with smaller structures guiding the particles. These can be better seen with two-pair statistics based FSLE/FTLE plots shown later.

Before we delve into dispersion statistics we can take a look at few basic statistics. We have already looked at auto-correlation timescales and how they increase with lower resolution, higher depth and change with season (Figure 3). These timescales were controlled by structures, which also controlled the lifetime of particles in the domain (Figure 5). Most of the particles in HR left

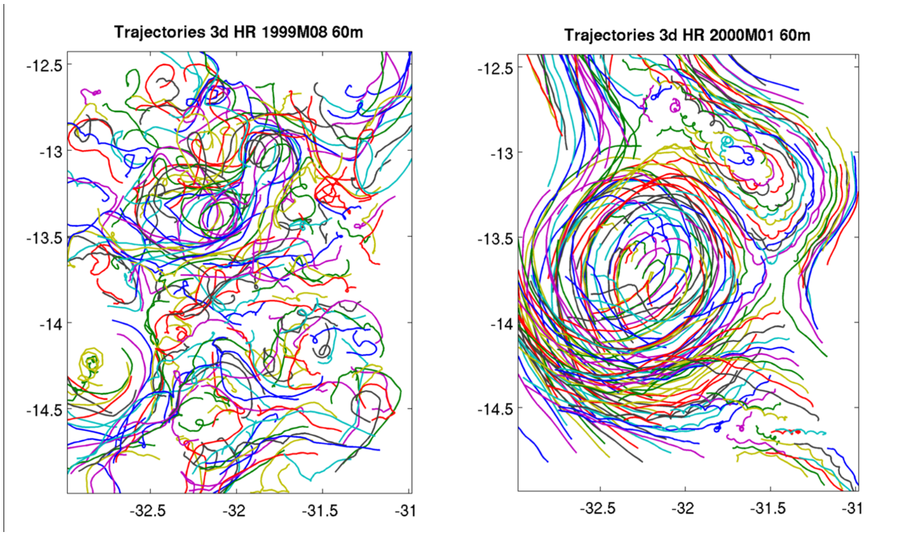


Figure 7: Particle positions from release to 10 days. Particles are released at 60m, in different seasons: winter (left) and summer(right)

the domain within a month, due to the size of the domain. Whereas LR had good coverage for most of the simulation, though skewed by the mean flow. The average depth of particles averaged over all particles still remaining in the domain can be seen in Figures 9 & 8. It is important to remember the lifetime of particles when judging these plots as they are averages of particles remaining in domain, thus the sample size is decreasing with time. Near the top of the mixed layer (15m in the summer) particles tend to sink, whereas near the bottom of the mixed layer (30m in the summer and 60m in the winter) particles tend to rise. Any other relationships are not qualitatively clear from these plots. We can also have a look at Figure 10 to see the distribution of particles across or below the mixed layer averaged over all releases.

Calculate OKW for the eulerian flow fields: especially important for relative dispersion, qualitative characteristics of OKW should be captured by FSLE and FTLE plots

Redo power spectra weighted by variance, or power spectra with statistical significance calculated as well. W power spectra is interesting, shows a broad spectrum larger than 2f, Figure 11

Rotary spectra to separate trajectories into submesoscale and mesoscale/inertial components?

Another useful thing to measure are Eulerian and Lagrangian seasonal means of parameters such as EKE and OKW

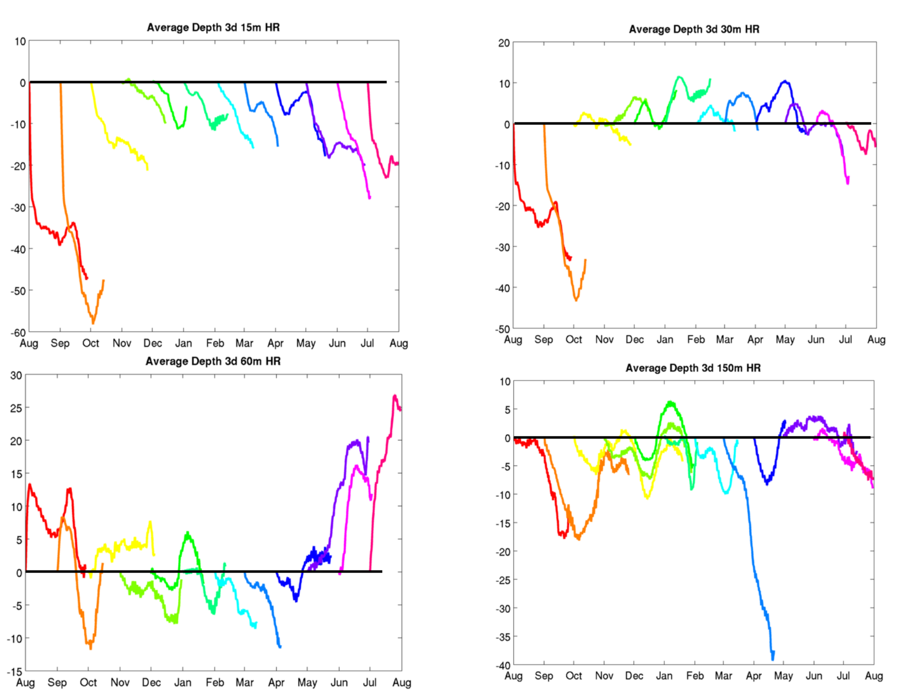


Figure 8: Average depth of particles (greater than 200) remaining in domain across several releases and depths, relative to release depth, in the HR run

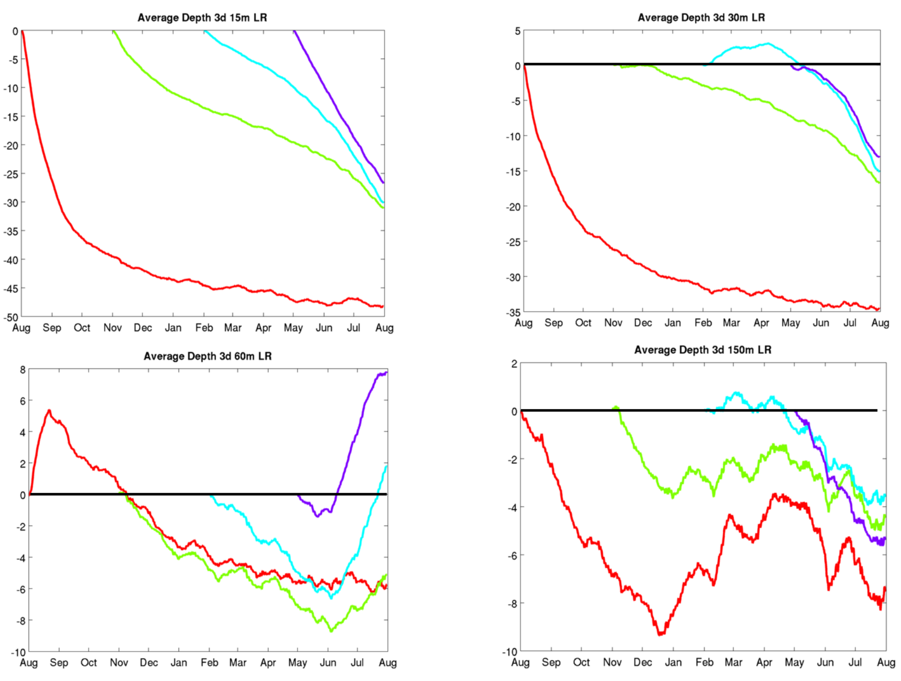
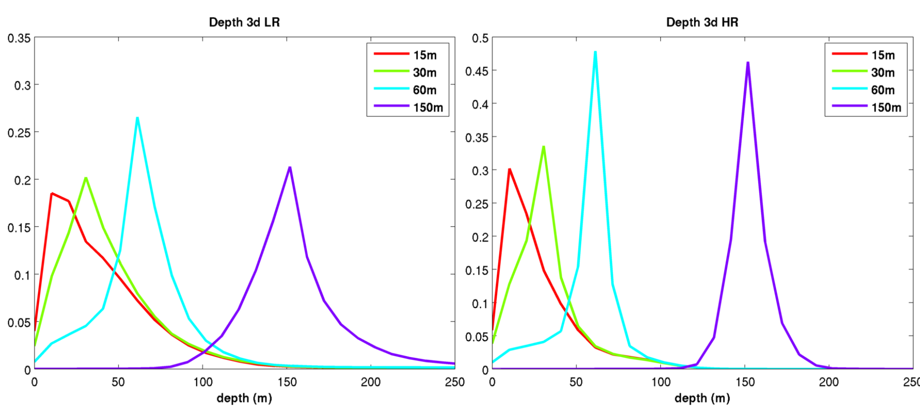


Figure 9: Average depth of particles (greater than 200) remaining in domain across several releases and depths, relative to release depth, in the LR run



(a) (b)

Figure 10: 3D release particle lifetime in domain

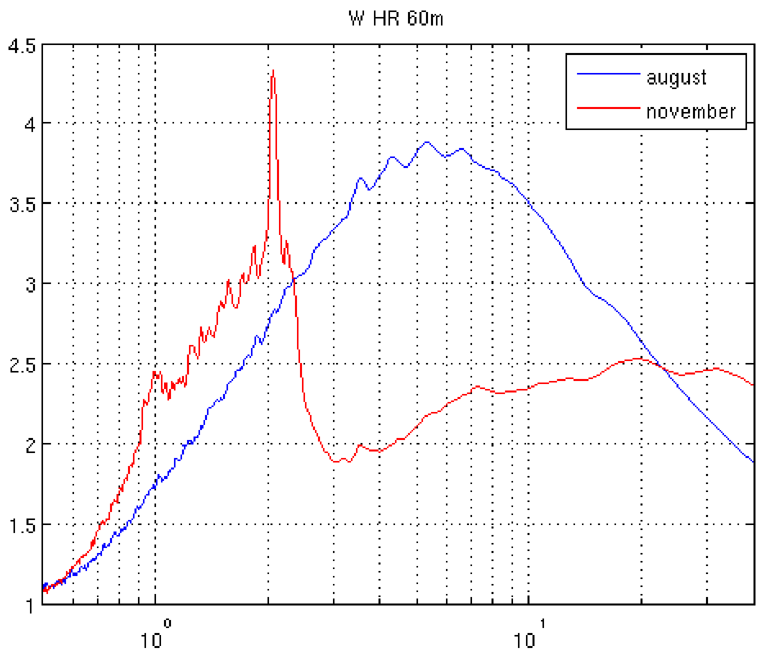


Figure 11: Power spectra of vertical velocity of all particles released at 60 m by month

2.3 Dispersion Statistics

Theory of dispersion statistics: LaCasce paper

2.3.1 Single-Particle

Using the particle timeseries of residual velocity dispersion statistics were calculated for both seasons and aggregated over all releases. Inertial frequencies were also removed from the timeseries using a bandpass filter (whose need/effectiveness is still in question). Dispersion curves without bandpass were also calculated but they included the high boundary current coastal velocities in LR and therefore skewed the curves. Absolute dispersion was calculated as follows:

$$D(\delta t) = \sum (x(t_0 + \delta t) - x(t_0))^2 \quad (1)$$

$$x(t_0 + \delta t) = x(t_0) + \int_{t_0}^{t_0+\delta t} \bar{v}(t)\ dt \quad (2)$$

$\sum$ over all particles in season, where $\bar{v}$ is the residual velocity component and $x(t_0)$ is the initial position of the particle

Figure 12 shows absolute dispersion in all cases. For ease of reading the curves: red(zonal) and blue(meridional) are LR curves, and purple(zonal) and green(meridional) are HR. Only focusing on LR there is more dispersion in the summer, in both zonal and meridional directions. This difference is not as easily visible in HR dispersion curves, which are fairly similar until about 15-20 days and then diverge. There is also anisotropy at depth, zonal dispersion grows much larger at longer times in the summer. Comparing the resolutions against one another shows that HR dispersion is larger initially, upto around 15 days and is not significantly different thereafter. Most particles in HR have left the domain after 20-30 days. Therefore dispersion at times O(1 month) or larger can be explained by particles trapped in a coherent structure. Hopefully the results from the new runs will be more conclusive.

Vertical residual velocities were also used for calculating vertical dispersion, no bandpass filter was applied . Vertical dispersion, as seen in Figure 13, is much larger in the winter in both resolutions. In addition HR vertical dispersion is significantly larger than LR. Below the mixed layer both resolutions converge to the same vertical dispersion.

it is not clear what the inertial frequencies would be for vertical motions

2.3.2 Two-Particle

Relative dispersion was calculated as per (Poje et al., 2010):

$$D(t) = D_0 + \sum_{ij}^{all\ pairs} (x_i(t) - x_j(t)) \quad (3)$$

$$(x_i(t) - x_j(t)) = \int_{t_0}^{t_0+\delta t} \bar{v}_i(t) - \bar{v}_j(t)\ dt \quad (4)$$

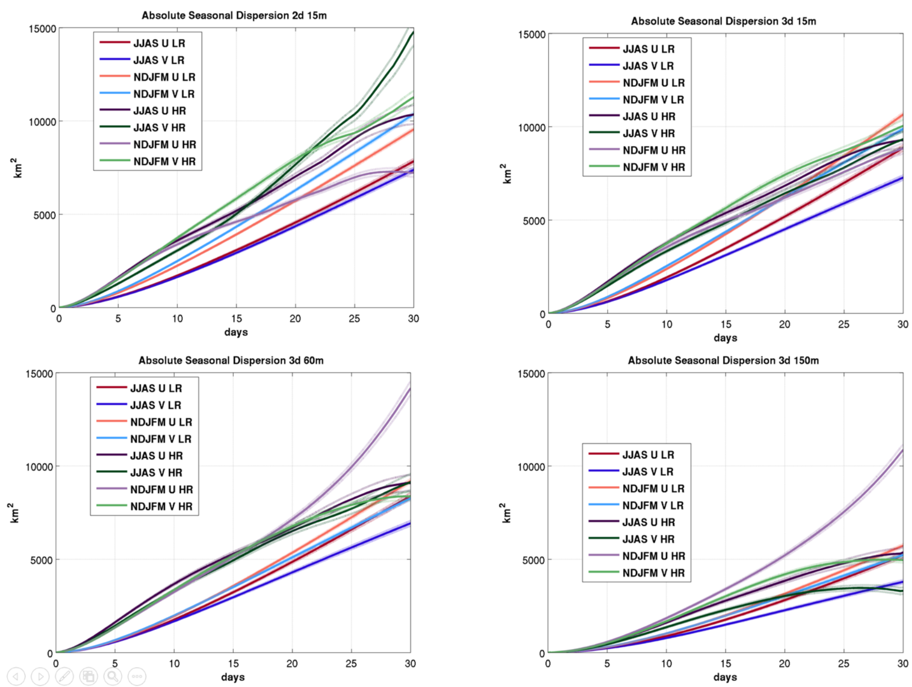


Figure 12: Absolute seasonal dispersion for all depths and resolutions: zonal and meridional

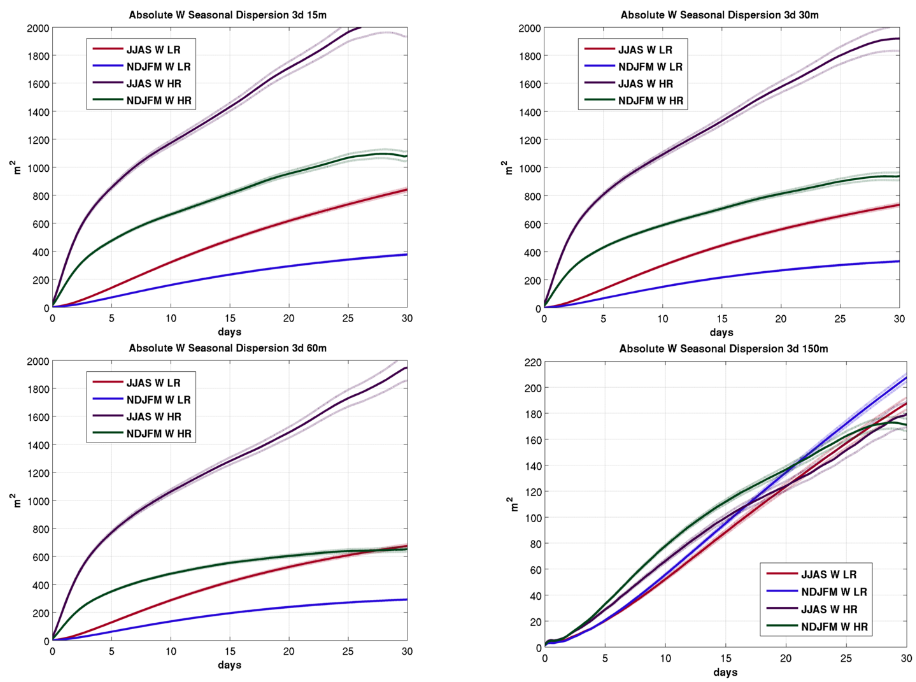


Figure 13: Vertical absolute dispersion at all depths and resolutions

where D_0 is the initial separation of the particle pairs and x_i and x_j are their positions
Careful comparison of the relative dispersion curves still needs to be done.

Helpful plot: Particle position movies overlaid on FSLE/FTLE contours, visualize the lagrangian coherent structures

FSLE and FTLE maps/curves were also calculated as per following:

$$FTLE_\tau(x,y) = \log\left(\frac{r_i(\tau) - r_j(\tau)}{r_i(0) - r_j(0)}\right)/|\tau| \tag{5}$$

$$FSLE_d(x,y) = \log\left(\frac{r_i(\tau_d) - r_j(\tau_d)}{r_0}\right)/|\tau_d| = \log(n)/|\tau_d| \tag{6}$$

above calculates FTLE for finite time τ, where $r_i - r_j$ is pair separation at different times and FSLE for finite distance d, where τ_d is the minimum time required for a particle pair to reach separation $r_0 \times n$
Figure 14 is an example of FTLE showcasing the seasonal difference in the flow. Larger values indicate regions of stretching and high relative dispersion, whereas smaller values are converging structures. In the winter the structures are submesoscale and 'noisier' than the summer.
These 2D maps of lyapunov exponents can be averaged over all particles (positions) to gain traditional lyapunov exponent curves.

3 Future Work

Important conclusions to make/finalize:

- 2D vs 3D HR dispersion
- Vertical dispersion seasonal and resolution difference
- HR vs LR horizontal dispersion: differences in sampling EKE of flow leading to different dispersion statistics
- Differences in flow within the mixed layer and below; qualitative and quantitative
- Relative dispersion vs resolution (validation of Poje et al. (2010) and other results)
- Eulerian vs Lagrangian frequency spectra

Todo list

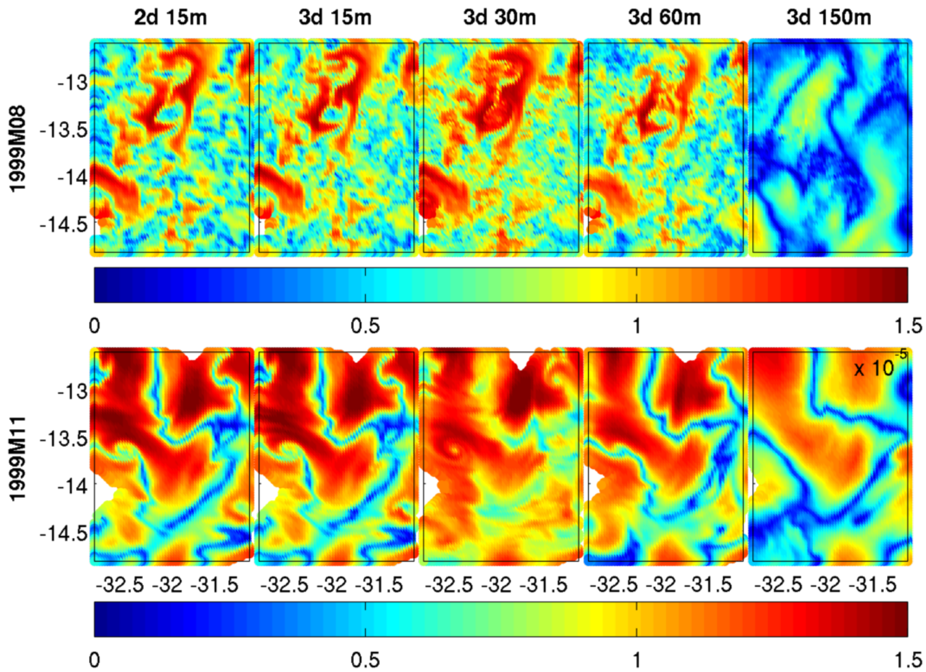


Figure 14: FTLE 3 days, difference between the seasons in HR

References

Andrew C Poje, Angelique C Haza, Tamay M Özgökmen, Marcello G Magaldi, and Zulema D Garraffo. Resolution dependent relative dispersion statistics in a hierarchy of ocean models. *Ocean Modelling*, 31(1):36–50, 2010.

Milena Veneziani, Annalisa Griffa, Zulema Garraffo, and Jean A Mensa. Barrier layers in the tropical south atlantic: Mean dynamics and submesoscale effects. *Journal of Physical Oceanography*, 44(1):265–288, 2014.