XXXX: Dust-devil-like vortices in the oceanic mixed layer

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Introduction

- Vortices similar to dust-devils were identified in oceanic simulations of free-convection
- They have been shown to impact surface distribution of buoyant materials [1] but have not been studied in detail
- We conduct an investigation to identify formation mechanisms and effects of dynamical settings

We refer to these vortices as dust-devil-like vortices (DDVs) as a common nomenclature for both the atmosphere and the ocean phenomena. A brief definition of a DDV is a vertical vortex-like coherent structure attached to the surface, with a vertical vorticity that is significantly higher than the background vorticity.

Objectives

- Investigate potential differences between DDVs in the atmosphere and ocean in free-convection conditions
- Investigate the general formation mechanism for DDVs
- Investigate effects of rotation on DDVs

Numerical set-up

We base our approach on large-eddy simulations (LES) of an ocean-like mixed layer in free-convection

- Zero wind shear
- No waves
- Periodic conditions in the horizontal directions

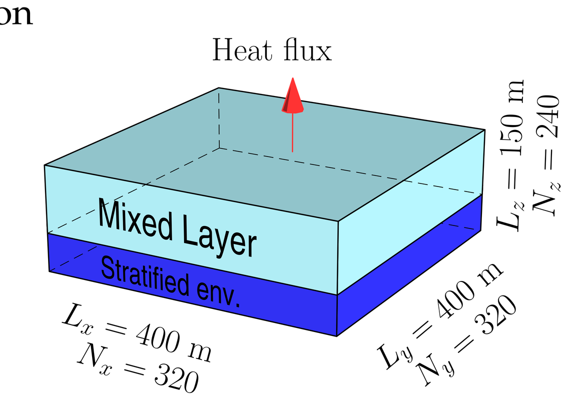

Figure 1: Schematic of simulation domain

Table 1: General parameters for all the simulations in this work.

Parameters	Value
Large-scale convective time-scale T_*	$= 4.2 \times 10^3$ s
OML depth	80 m
Horizontal domain size	400 m
Vertical domain size	150 m
Horizontal resolution	1.25 m
Vertical resolution	0.625 m

Since the main fundamental dynamical difference between the atmosphere and the ocean is the boundary condition (BC) at the surface (free-slip for the ocean and no-slip for the atmosphere), we run

- rotating and non-rotating simulations with a free-slip condition at the surface to represent the ocean (FS-R and FS-NR, respectively),
- rotating and non-rotating simulations with a no-slip BC as a proxy for the atmosphere (NS-R and NS-NR)

Details on each simulation can be found in Table 2.

Table 2: Simulations used in this work and their specific parameters.

Simulation	BC at $z = 0$	Coriolis freq. (s^{-1})
FS-R	Free-slip	1×10^{-4}
NS-R	No-slip	1×10^{-4}
FS-NR	Free-slip	0
NS-NR	No-slip	0

Profiles of vorticity statistics

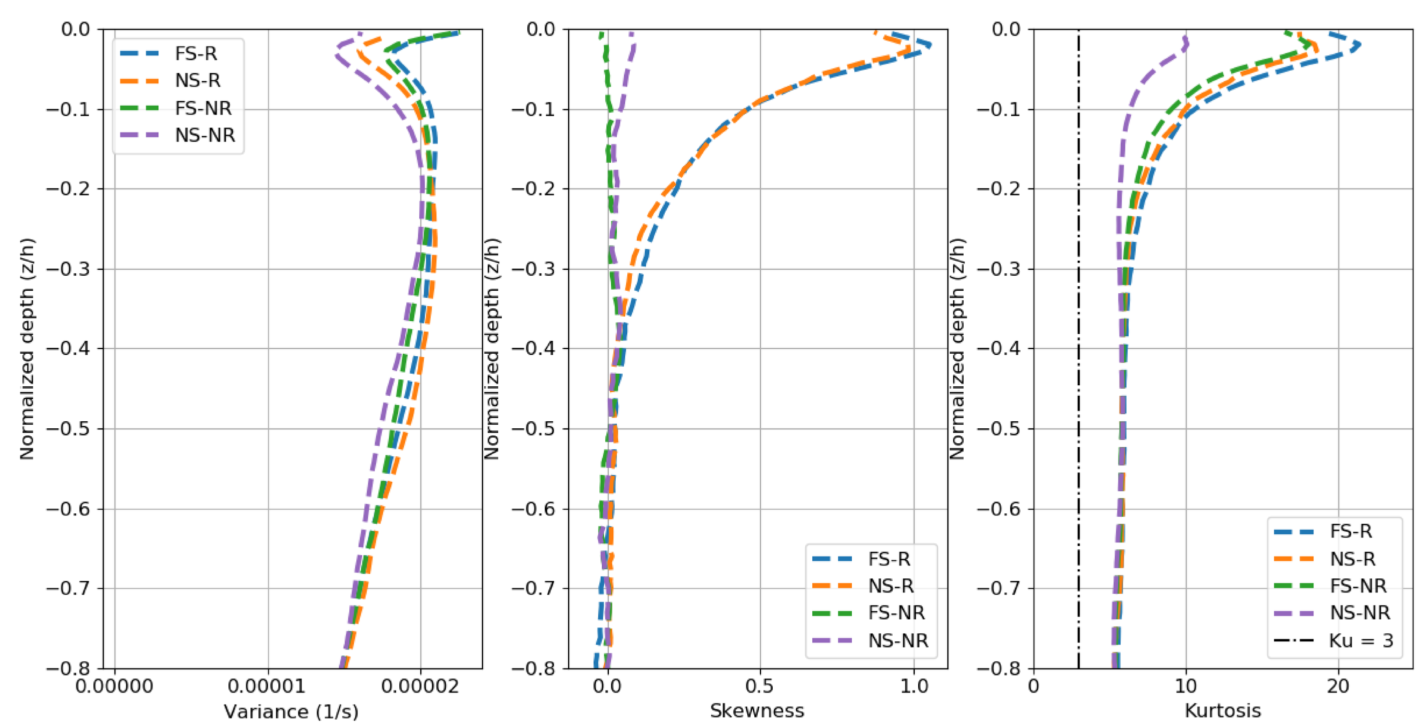

Figure 2: Vertical profiles of variance (left), skewness (middle) and kurtosis (right) for vorticity for all simulations considered in this work.

Noteworthy aspects of Figure 2 are

1. The variance generally increases towards the surface for all simulations, with the no-slip simulations having generally smaller variance at the surface.
2. The distributions of the rotating cases (FS-R and NS-R) become skewed towards cyclonic values close to the surface. This is surprising, since the Rossby number of most DDVs is $O(100)$ and there is no mean flow.
3. All simulations have an intermittent distribution (kurtosis higher than 3), and it becomes even more intermittent close to the surface.

The main question raised by these results is: why is small-scale vorticity (which has a high Rossby number) impacted by rotation?

Statistics of DDVs

We employ a modified particle detection algorithm to identify DDVs based on vorticity near the surface.

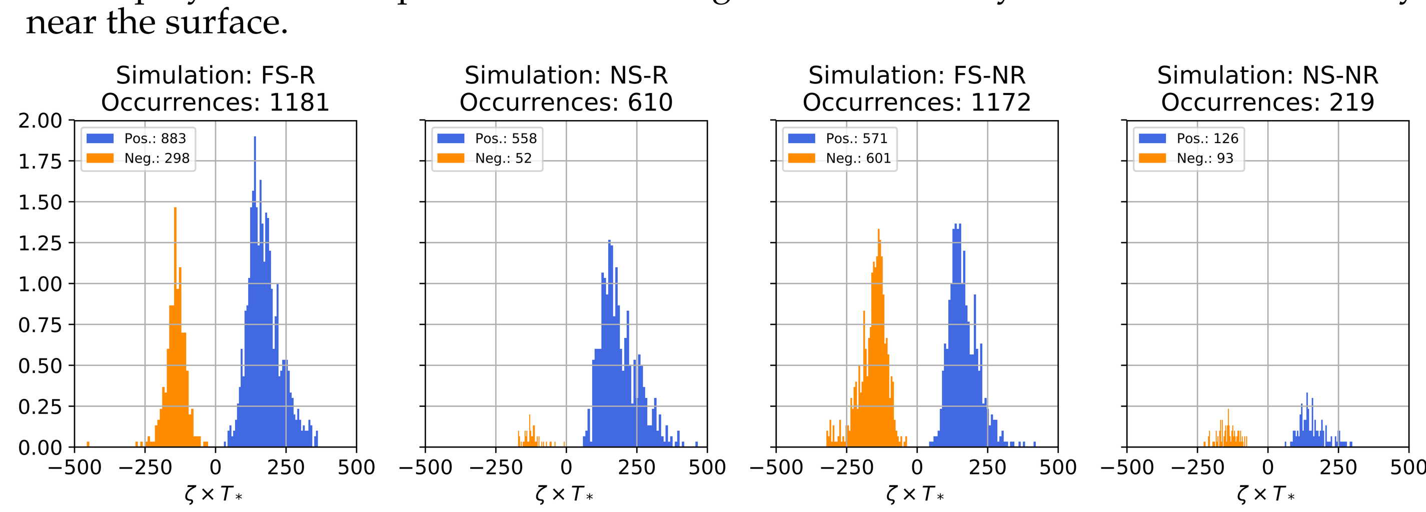

Figure 3: Average number density of DDVs in any given snapshot of simulation FS-C (left) and simulation FS-C-NR (right). Blue bars are cyclonic DDVs and orange bars are anti-cyclonic DDVs. The average was taken using 30 snapshots.

Some noteworthy aspects of this figure:

- In non-rotating simulation, cyclonic and anti-cyclonic vortices are equally likely, as expected.
- Large asymmetry in vortices in rotating simulations (FS-R, NS-R) even though their Rossby number is $O(100)$.
- Rotation appears to impact the distribution of vortices in the free-slips cases, but not their total numbers.
- However, in no-slip conditions, rotation does impact the number of DDVs identified. This points to stretching of planetary vorticity being important for no-slip conditions, since the vorticity at the surface may be smaller due to the no-slip at $z = 0$.

Again there is a skewness in vorticity even when considering individual DDVs (instead of every grid point). The effects of rotation in the formation of DDVs was found to be much smaller in other studies [5].

Formation mechanism

In the context of the atmosphere, two proposed mechanisms of DDV formation are generally accepted:

M1 Vortex tilting [4, 2]: initially horizontal vortices are tilted upwards.
- M1 can only be relevant in simulations NS-R and NS-NR, since the free-slip BC inhibits much of the horizontal vorticity.
- M1 should preferentially occur in the vertices of the convective cells.

M2 Vortex stretching due to size asymmetry between areas of horizontal convergence and divergence near the surface [2, 3]:
- M2 can happen in all the simulations in this work.
- M2 in not a localized phenomena and should then depend on large-scale features of the flow.

M1 doesn't appear to be important in our simulations, thus, we focus on M2, which depends on the large-scale features of the flow.

Most DDVs are located in an area of convergence, but many areas of convergence do not produce any DDVs. Thus, DDVs appear to be produced in preferred areas. What controls these areas of preferential DDV formation?

Raasch and Franke [5] argue that DDVs depend on the large-scale flow because they preferentially form in the vertices of cells. We argue that DDV formation depends on an even larger scale since there are many cell vertices that also do not produce DDVs. To study the influence of these large-scale features we

1. Coarsen the divergence field with a gaussian filter to obtain the large-scale circulation of the flow
2. Separate coarsened divergence and coarsened convergence areas as a way to visualize the large-scale circulation in Figure 4 on top of the vorticity field.

We plot a snapshot of vorticity in simulations FS-R and FS-NR in Figure 4, where we can see DDVs as roughly circular spots of high absolute vorticity (red for cyclonic vorticity and blue for anti-cyclonic).

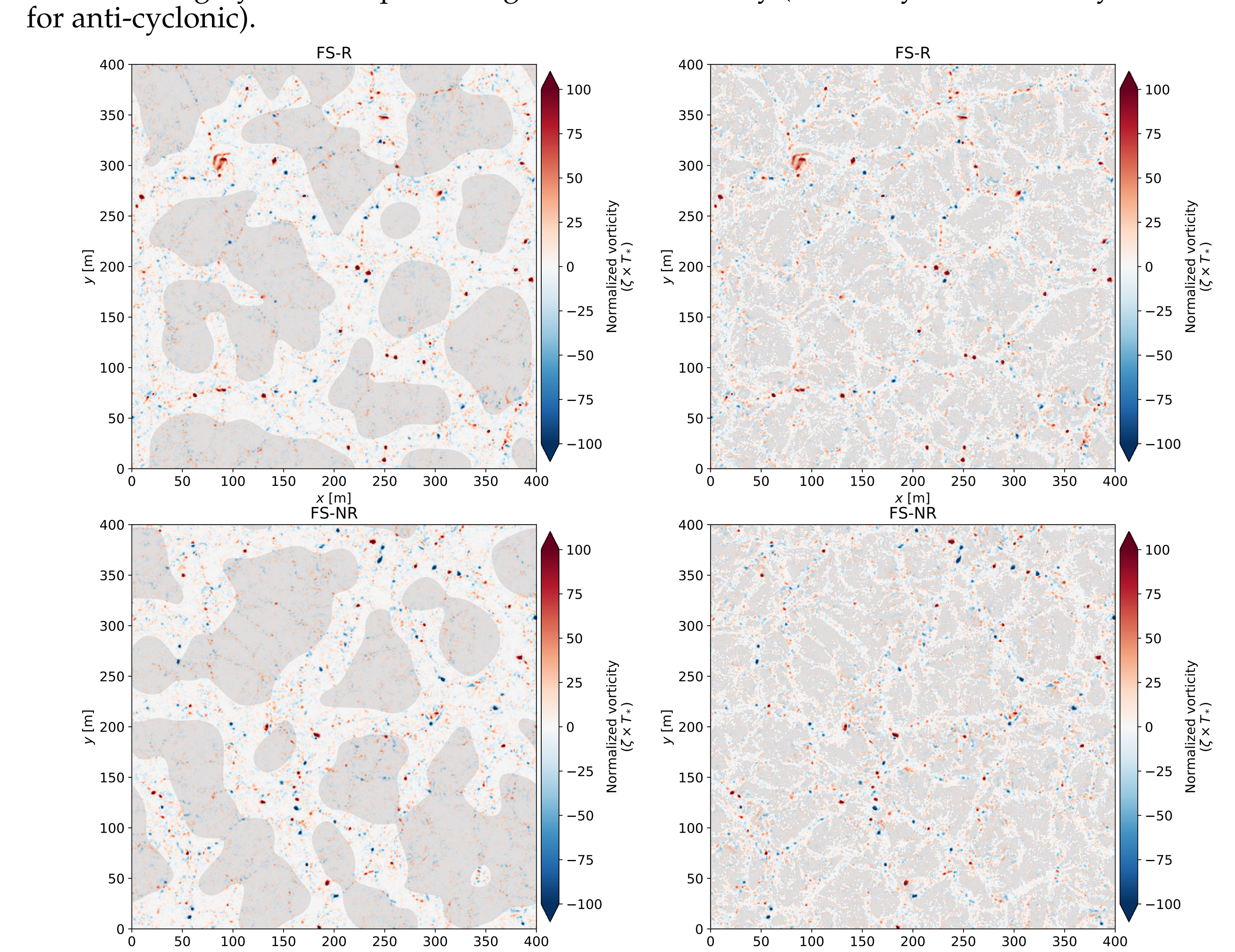

Figure 4: Vorticity normalized by the convective time-scale T_* for simulations FS-R (top) and FS-NR (bottom) near the surface. The shaded areas correspond to horizontal divergence areas after a gaussian filter (left) and without the gaussian filter (right). The gaussian filter has a 30 m width, but the results aren't sensitive to the precise choice of width.

Comparing the location of DDVs with the large-scale (left) and local (right) patterns of horizontal divergence in Figure 4 we see that

- the large majority of the DDVs are located in areas of large-scale convergence;
- there are many vertices and lines of local convergence that are outside areas of large-scale convergence and those do not produce vortices.

Formation and the impact of Rotation

Although Figure 4 is illustrative, it is only one snapshot and is not statistically reliable. Thus, in order to have a better statistical view of the preferential locations for DDV formation, we plot the Joint Probability Density Function of local horizontal divergence and large-scale (i.e., coarsened) horizontal divergence in Figure 5 as a colormap. On top of the colormap are points, each of which corresponding to an individual DDV occurrence.

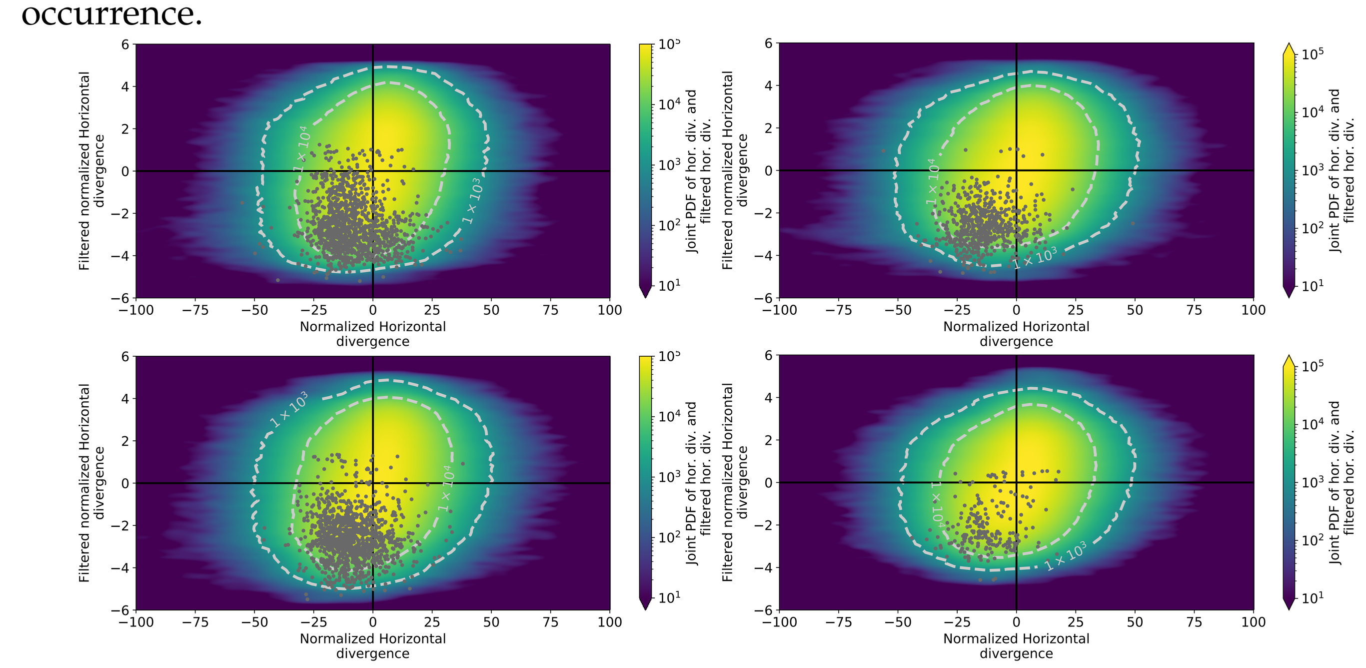

Figure 5: The colormap is the Joint Probability Density function between divergence and coarse-grained divergence (or large-scale divergence). Each point is a DDV.

From the Figure above we see that

- Most DDVs fall within regions of local convergence (as expected from previous studies)
- More importantly, most DDVs also fall within regions of large-scale convergence (as expected from Figure 4)

This analysis (which used 30 snapshots for each simulation) confirms our hypothesis that the large-scale patterns in divergence also matter for DDV formation.

Summary and conclusions

We have reported on dust-devil-like structures in the Oceanic Mixed Layer and investigated their dynamics.

- Their formation appears to be controlled by the large-scale fluctuations in horizontal divergence
- Since the number of DDVs decreases with a no-slip BC (in comparison to the free-slip cases), it appears that vortex tilting is not important. This is in accordance with the findings of Ito, Niino, and Nakanishi [3].
- Although the Rossby number of individual DDVs is very high, rotation appears to influence their formation and distribution
  - Rotation impacts the number of cyclonic versus anticyclonic vortices in all simulation (especially simulations with no-slip BC)
  - Rotation also impacts the total number of vortices in simulations with no-slip BC (but not for free-slip cases)

The main question raised is: What is the mechanism by which rotation impacts the distribution of DDVs? Further studies are needed to answer this question appropriately.

Scan the QR-code to access an animation of the results.

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This research was made possible by a grant from The Gulf of Mexico Research Initiative