# 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

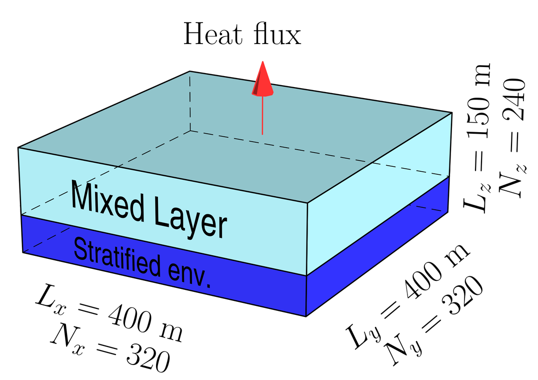


Table 1: General parameters for all the simulations in this work. $|h|$ is the absolute value of the mixed-layer depth and $w_* = (B_0|h|)^{1/3}$, where $B_0$ is the buoyancy flux at the surface.

| Parameters | Value |
|---|---|
| Large-scale convective time-scale | $T_* = \|h\|/w_* = 4.5 \times 10^3$ 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, 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)

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

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

## Profiles of vorticity statistics

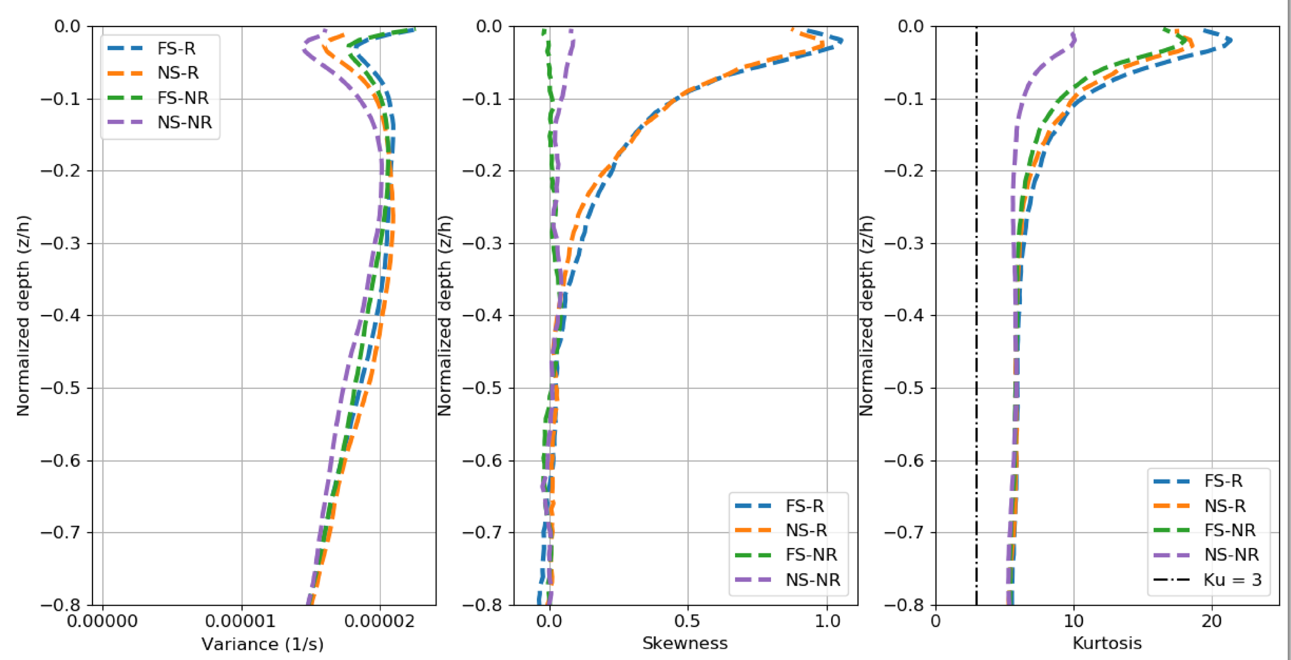


Figure 1: Vertical profiles of variance (left), skewness (middle) and kurtosis (right) for vorticity for all simulations considered in this work.

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 there Rossby number of the flow is Ro $\approx 50$ and there is no mean flow.

The main question raised by these results is: why is vorticity impacted by rotation?

## Statistics of DDVs

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

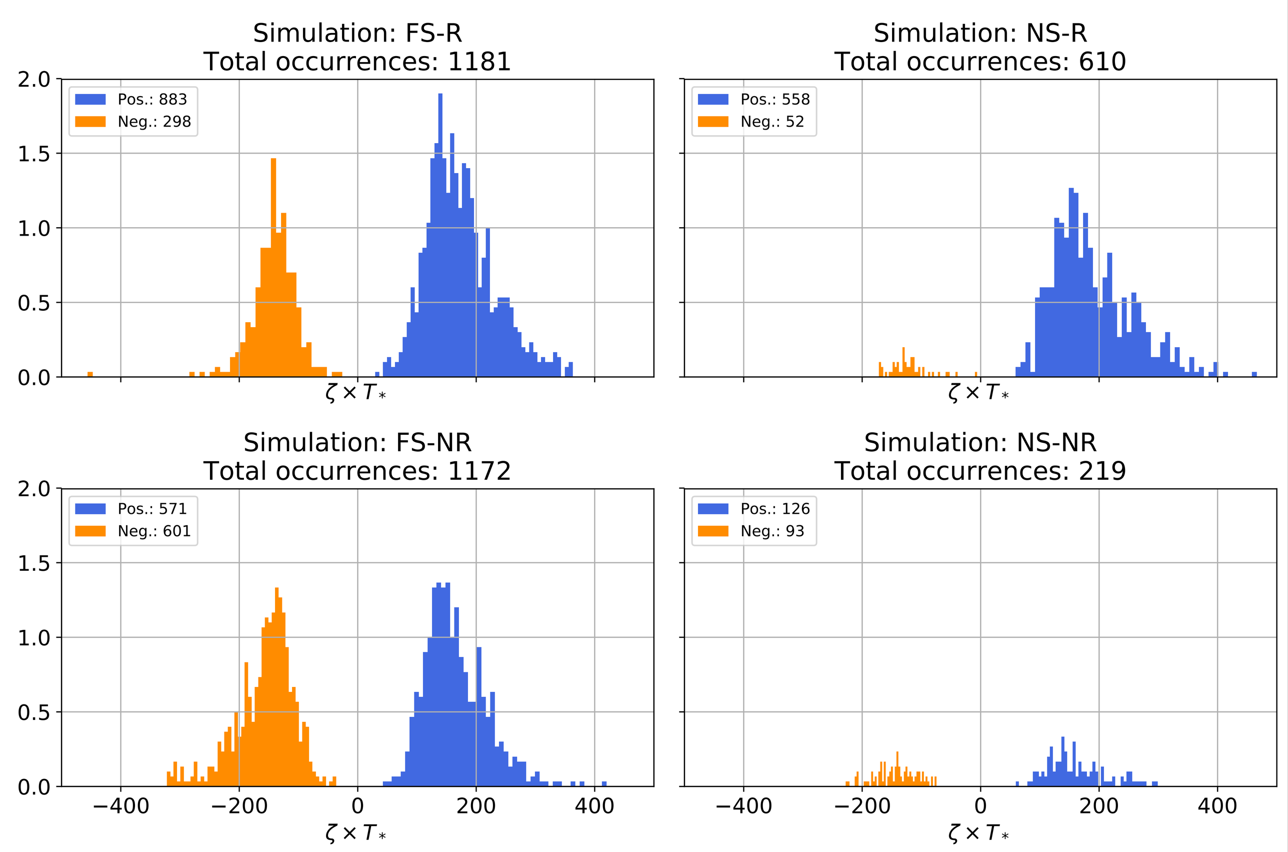


Figure 2: Average number density of DDVs in any given snapshot of the simulations in this work. Blue bars are cyclonic DDVs and orange bars are anti-cyclonic DDVs. The average was taken using 30 snapshots.

- In non-rotating simulations, 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-slip cases, but not their total numbers.
- 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.

There is also significant skewness in the circulation of individual DDVs, which 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 does not appear to be important in our simulations.

M2 Vortex stretching due to size asymmetry between areas of horizontal convergence and divergence near the surface [2, 3]:
- M2 in not a localized phenomena and should then depend on 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. Plot divergence and coarsened divergence in Figure 3 as a way to visualize the local and large-scale flows.

In Figure 3, we can see DDVs as roughly circular spots of high absolute vorticity (red for cyclonic vorticity and blue for anti-cyclonic).

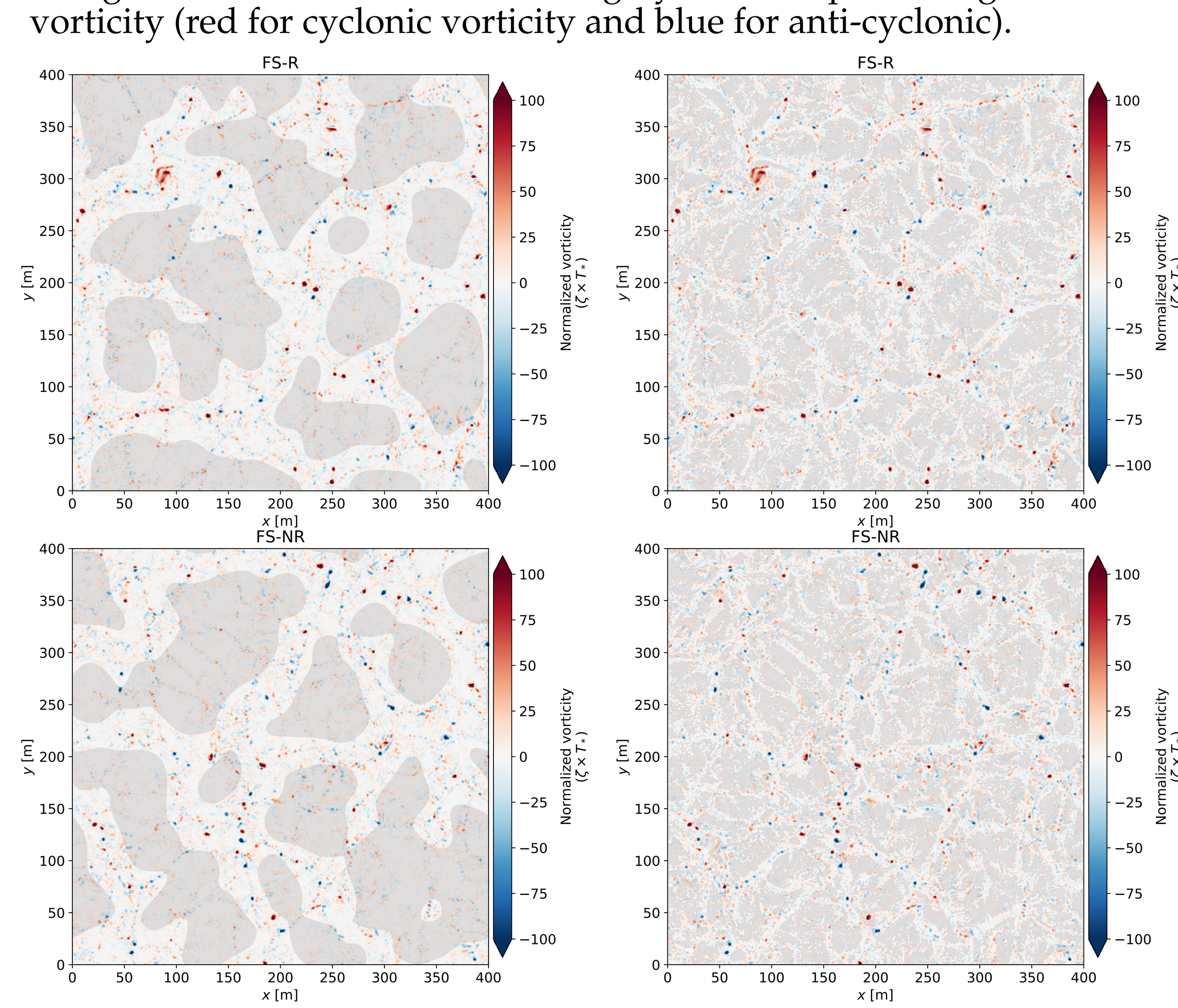


Figure 3: Vorticity normalized by the convective time-scale $T_*$ for simulations FS-R and FS-NR near the surface. The shaded areas correspond to horizontal divergence areas after a gaussian filter (left) and without the gaussian filter (right). The gaussian filter has a 50 m width, but the results aren't 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 3 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

In order to have a better statistical view of the preferential locations for DDV formation, we plot the Joint PDF of local horizontal divergence and large-scale (i.e., coarsened) horizontal divergence in Figure 4 along with points corresponding to individual DDV occurrences.

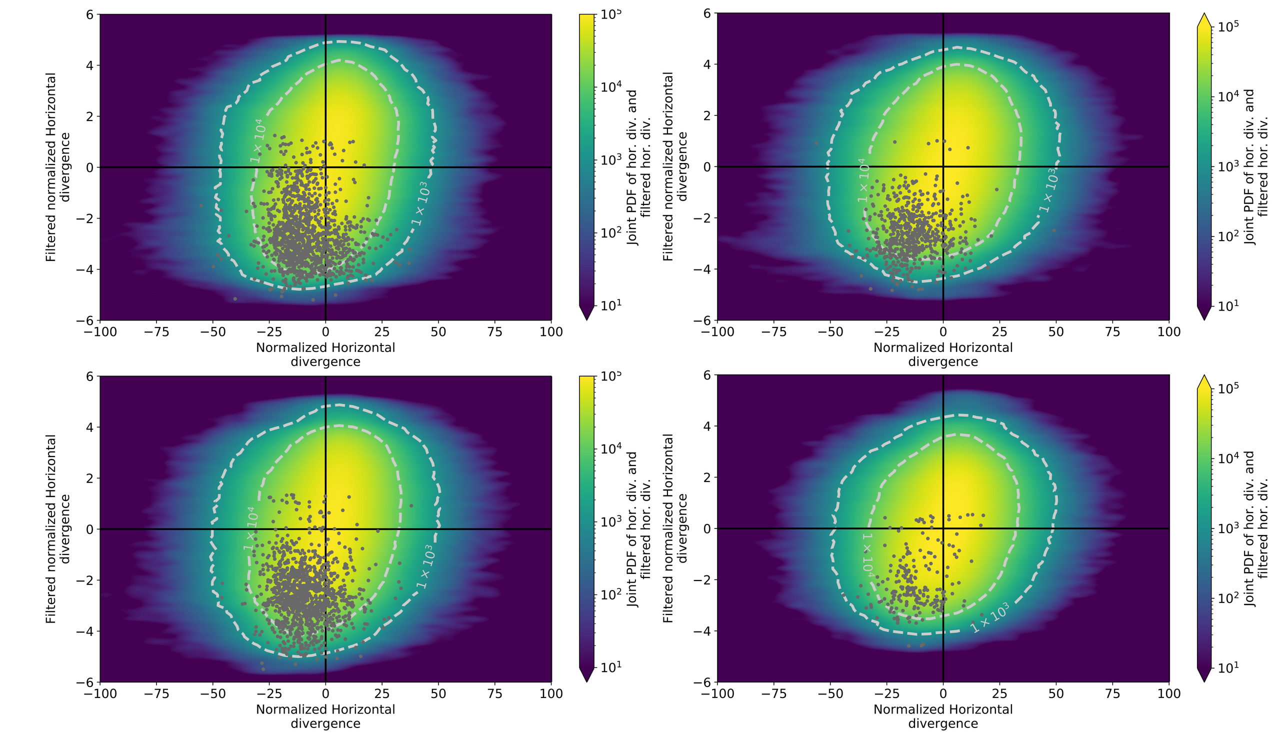


Figure 4: The colormap is the Joint Probability Density Function (PDF) between divergence and coarse-grained divergence (or large-scale divergence). Each point is a DDV.

- 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 3)

This analysis (which used 30 snapshots for each simulation) supports 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 a mixed layer environment and investigated their dynamics.

- Their formation appears to be controlled by the large-scale fluctuations in horizontal divergence
- 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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