Toward an improved understanding of frontal dynamics in the vicinity of the Gulf Stream

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Abstract

In this study, we present preliminary efforts to quantify the importance of frontal curvature in the vicinity of the Gulf Stream, a first step in a greater effort to better understand how centrifugal forces might affect parcel motion within ocean fronts. Motivated by upper ocean observations, we focus on realistic numerical simulations of the North Atlantic during winter that, roughly-speaking, permit mixed layer baroclinic instability and therefore resolve eddy scales of interest—i.e. mesoscale and submesoscale eddies and fronts. We use this analysis to motivate a future characterization of such flows from anticipated satellite measurements.

Motivation & Background

At horizontal scales of *O*(1-10 km) and time scales of hours to days, referred to as the **oceanic submesoscale regime**, frontal shears are elevated and stratification reduced to an extent that gradient Rossby and gradient Richardson numbers, Ro and Ri, approach one. As a result, frontal instabilities are more common. Since such instabilities are believed to impact energy, buoyancy, and tracer budgets in the upper ocean, any process that elevates or diminishes the prevalence of these phenomena in the upper ocean merits attention. One possible factor is centrifugal accelerations experienced by parcels in curved fronts & vortices [1-3].

Symmetric instability (SI) is a unique form of parcel motion found in low-stratified fronts and vortices [4,5]. While gravitationally stable ($N^2 > 0$) and inertially stable ($\zeta/f > -1$), fluid parcels in these fronts can still be unstable to motions at angles to the horizontal. In the surface mixed layer (SML), **SI is most prominent in winter** (**Fig. 1**), as reduced vertical stratification N^2 admits Ri near one [6,7].

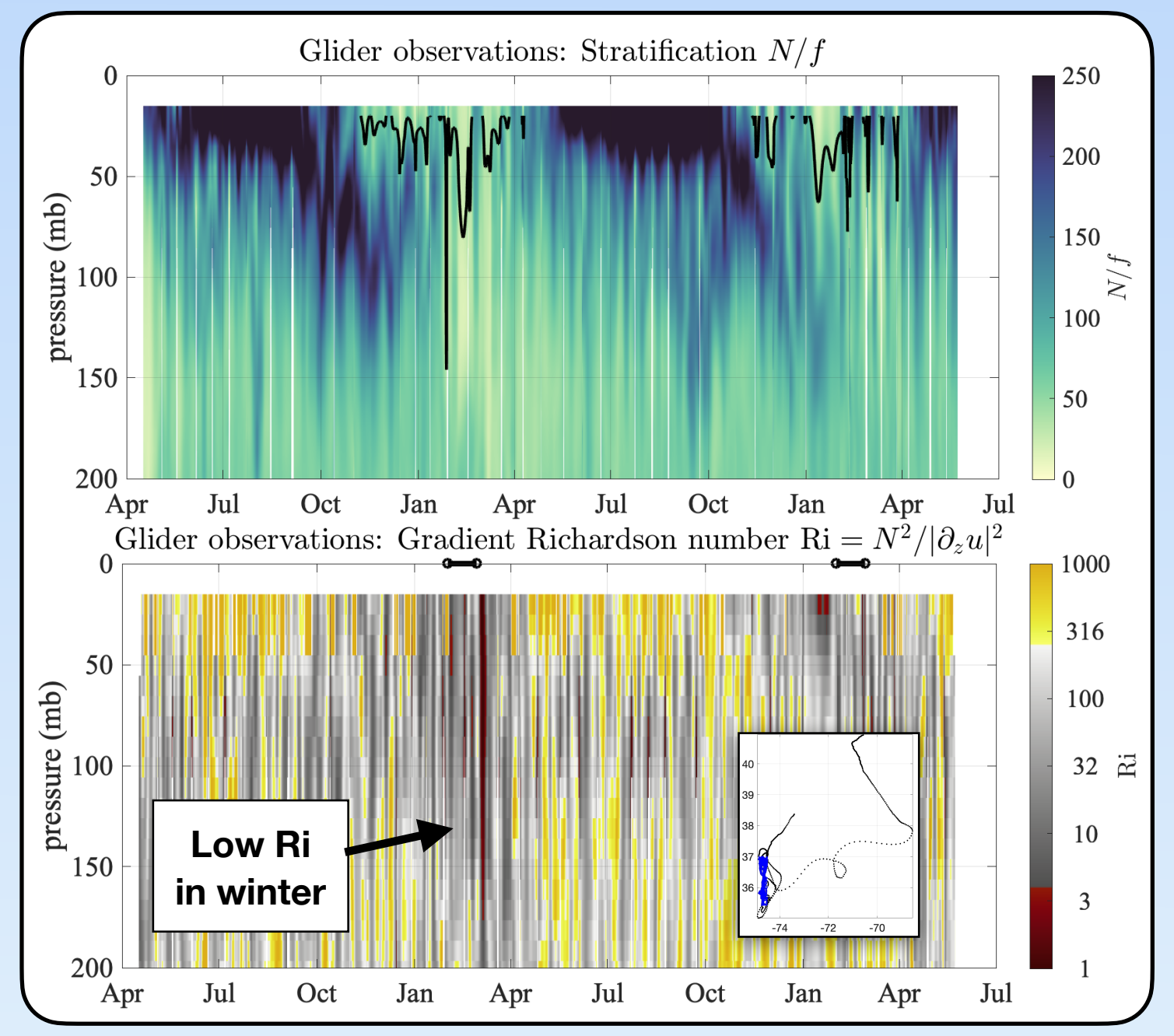

Fig.1: Observations of the upper ocean in the vicinity of the Gulf Stream [8].

Methods

1. Stability/instability of fluid parcels on the sphere

- Local stability on the sphere is determined by the sign of the product of absolute angular momentum L and Ertel potential vorticity q [9,10]: $\Pi = Lq \gtrless 0$
- For positive stratification away from the Equator ($f^2N^2 > 0$) and assuming a geostrophic (without curvature) or cyclo-geostrophic (with curvature) balance, we can write the stability discriminant Π in non-dimensional form (**Fig. 2**) [1,2]:

$$\boxed{\Pi' = L'q' = (1+\mathrm{Cu})(1+\mathrm{Ro}) - (1+\mathrm{Cu})^2\mathrm{Ri}^{-1} \gtrless 0}$$

$\mathrm{Ro} = \bar{\zeta}/f$ is the gradient Rossby number
$\mathrm{Ri} = N^2/|\partial_z \bar{\mathbf{u}}|^2$ is the gradient Richardson number
$\mathrm{Cu} = 2|\bar{\mathbf{u}}|/(fR)$ is the curvature number

negative values of Π' indicate instability

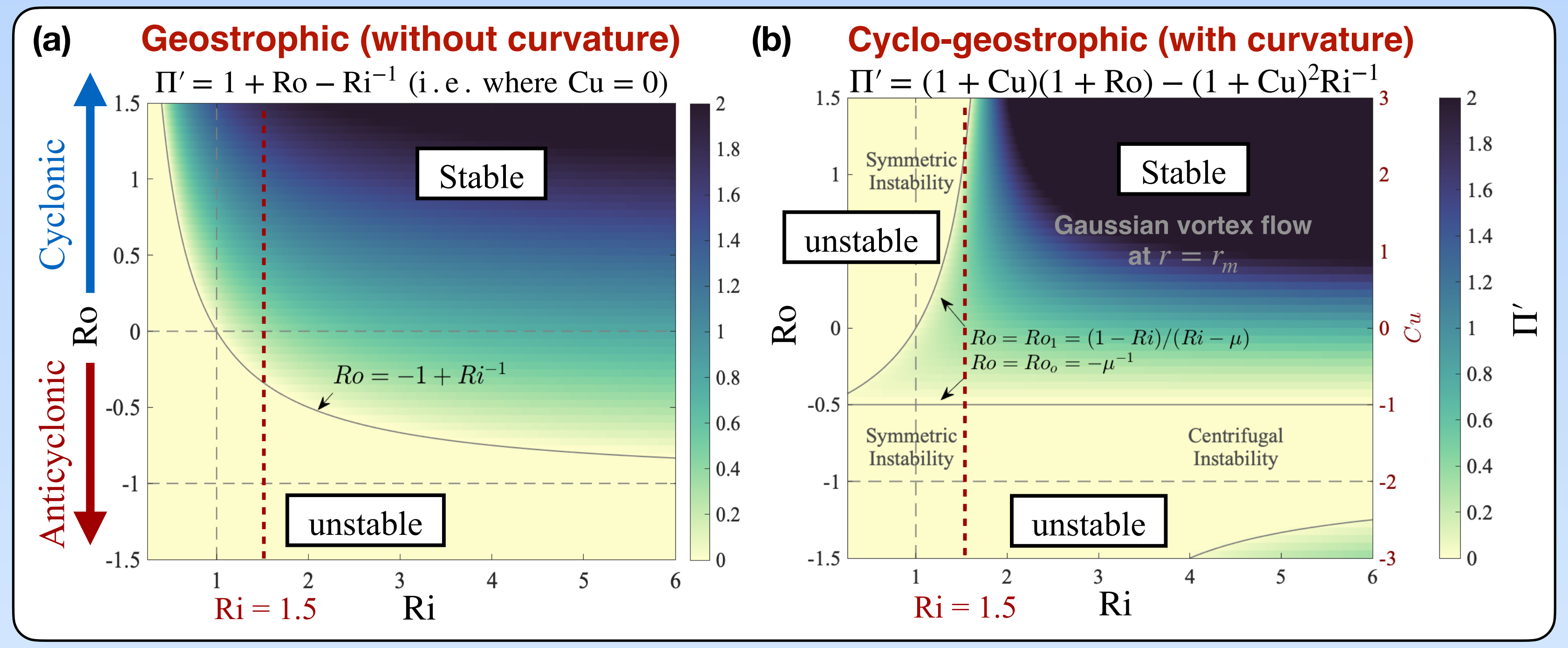

Fig.2: Stability regime diagrams at low gradient Richardson numbers, $\mathrm{Ri} < 6$, when (a) not accounting for and (b) accounting for curvature effects. One main conclusion drawn from this graphic is that curvature stabilizes anticyclonic ($\mathrm{Ro} < 0$) flow and de-stabilizes cyclonic ($\mathrm{Ro} > 0$) flow at low Ri. Adapted from [1,2,10].

2. Realistic, submesoscale-resolving simulations (NATL60)

- Evaluate Π' in SML (0-300m) using fine-scale ($\Delta x \sim 1$ km) simulations of the North Atlantic (NATL60; non-assimilating; absent tides) in winter (**Fig. 3**)
- Estimate Ro and Cu from $\bar{\mathbf{u}}$ (e.g. [11]). Instead of estimating Ri from model output (N^2 is crudely resolved), we set $\mathrm{Ri} = 1.5$ in the SML and evaluate Π' **with** and **without curvature** (i.e. Π' and $\Pi'_{\mathrm{Cu}=0}$). Average Π' across the SML: $\langle \Pi' \rangle = \int_0^{-h} \Pi' dz$
- Estimate *relative stability* $\langle \Pi' - \Pi'_{\mathrm{Cu}=0} \rangle$ to determine where curvature Cu matters

Results

- $|\langle \mathrm{Cu} \rangle| \gg 0.1$, revealing considerable departures from geostrophy (**Fig.3c**)
- Both mesoscale & submesoscale fronts are affected (**Fig.3e,f**)
- **Curvature reduces *persistent* stability** of cold-core rings, Gulf Stream (GS) meanders, & SML dynamics modified by seamount wakes (**Fig.3g**)
- **Curvature enhances *persistent* stability** near GS separation (**Fig.3g**)

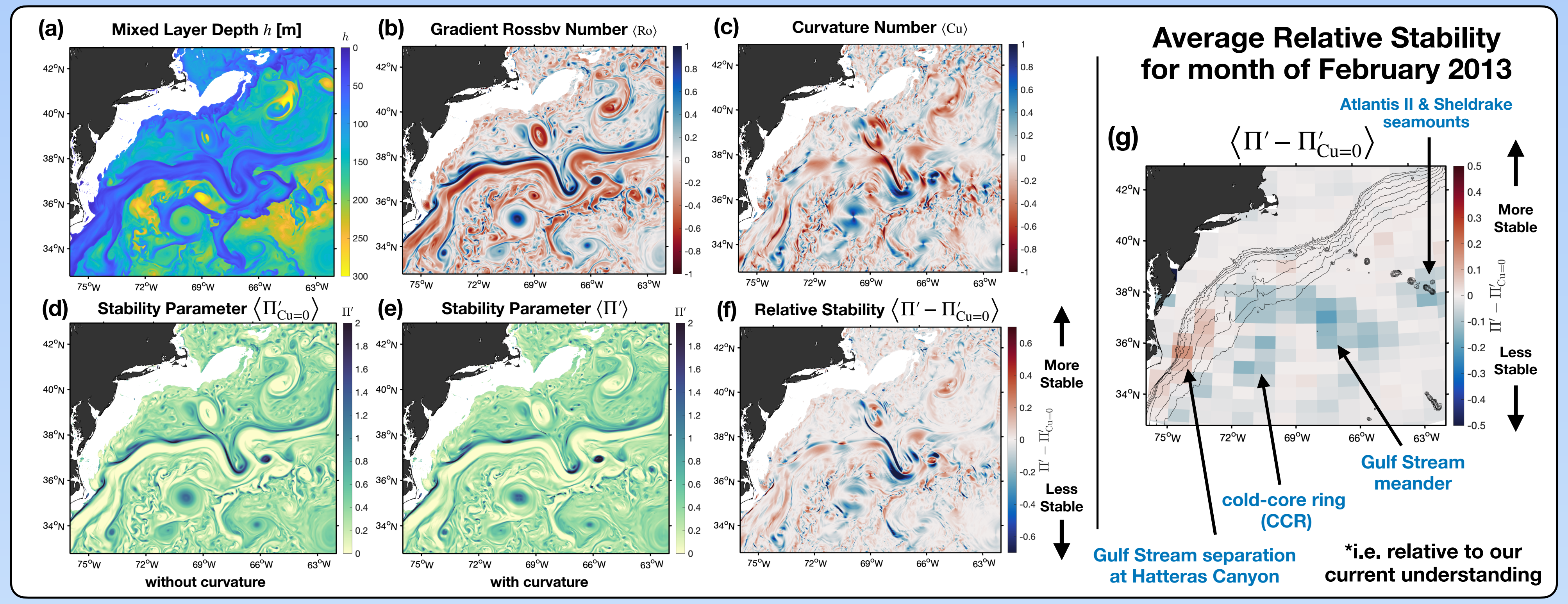

Fig. 3: Upper ocean properties in the vicinity of the Gulf Stream from NATL60 (CJM-165): (a) SML depth, (b) gradient Rossby number, (c) curvature number, (d) stability without curvature, (e) stability with curvature, (f) stability with curvature relative to that without curvature (i.e. relative stability) and (g) average relative stability for February. All variables in (b)-(g) are averaged over the SML ($\langle \cdot \rangle$) and (a)-(f) are valid on 1 Feb. The ML base is defined as the depth at which density exceeds its value at $z = -10$ m by 0.03 kg/m³ and in (g) bathymetric contours are every 500 m.

Conclusion

To the extent that $\mathrm{Ri} \sim 1.5$ in the SML, curvature is a leading factor in determining the stability of fluid parcels in the Gulf Stream region!

References

1. Buckingham, C.E. *et al.*, 2021, Part 1. *JPO*, doi:10.1175/JPO-D-19-0265.1
2. Buckingham, C.E. *et al.*, 2021, Part 2. *JPO*, doi:10.1175/JPO-D-20-0258.1
3. Singh, S. & M. Mathur, 2021. *JFM*, doi:10.1017/jfm.2021.793
4. Hoskins, B.J. 1974. *QJRMS*, doi:10.1002/qj.49710042520
5. Thomas, L.N. *et al.* 2013. *DSR*, doi:10.1016/j.dsr2.2013.02.025
6. Stone. P.H. 1966. *JAS*, 23, 390-400.
7. Buckingham, C.E. *et al.*, 2016, *GRL*, doi:10.1002/2016GL068009
8. Todd, R.E. 2020. *JGR*, doi:10.1029/2019JC016006 / 10.21238/S8SPRAY0880
9. Kloosterziel, R.C. et al., 2007. JFM, doi:10.1017/S0022112007006325
10. Buckingham, C.E. 2021, Part 3. *JPO*. https://arxiv.org/abs/2110.11200
11. Balwada, D. *et al.*, 2021. JPO, doi:10.1175/JPO-D-21-0016.1

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