Monsoon-Frontal-Wave Interactions Drive Cyclone Biparjoy's Wake Recovery in the Arabian Sea

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Kerhalkar et al. (2025), GRL

Pham et al. (2026), GRL

INTRODUCTION

- **Cyclone-induced upwelling** and **mixing** create **cold, salty wakes**. Earlier observations link their **recovery** to **atmospheric forcing** and **advection**, but numerical models also highlight the impact of **submesoscale dynamics**.
- **In-situ observations** of **submesoscale processes** affecting the **wake recovery** are lacking. **Autonomous instruments** typically lack sufficient **spatio-temporal resolution** even in highly networked field campaigns.
- Understanding **wake recovery** is critical for quantifying **ocean heat transport** and improving the **predictability** of subsequent **cyclone intensity, tracks**, and **sub-seasonal monsoon variations**.

CYCLONE BIPARJOY OVERVIEW

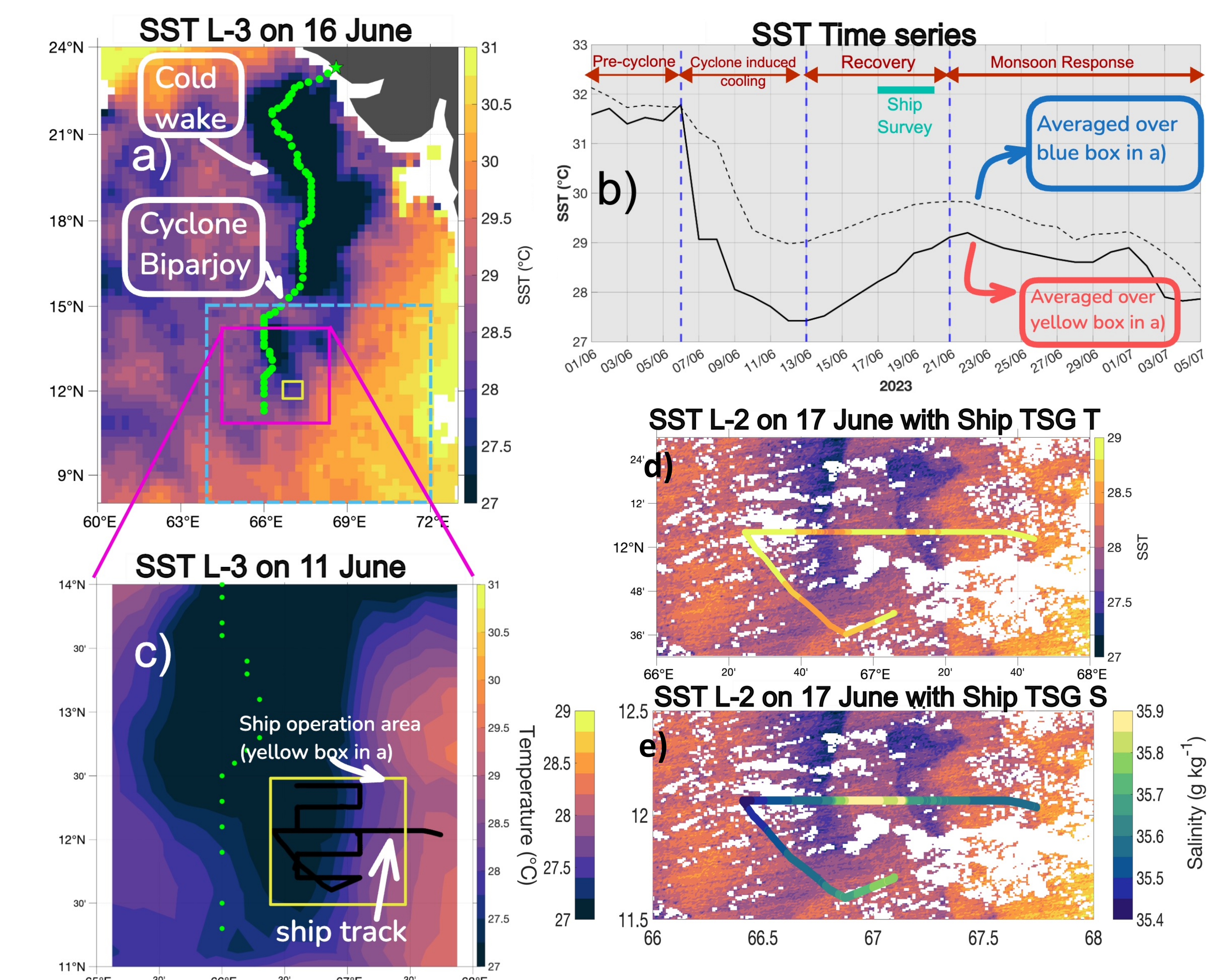

Figure-1: (a) SST from AMSR-2 on 16 June 2023. (b) Time series of mean SSTs from AMSR-2 between 1 June and 5 July 2023. The ship surveyed the wake between 17-20 June (c) SST from AMSR-2 over the solid magenta box on 11 June 2023. (d) SST from L2 VIIRS-NPP with in-situ SST data overlaid on 17 June 2023. (e) Same as (d) but with in-situ Sea Surface Salinity (SSS) overlaid.

The slow movement of Cyclone Biparjoy (**1–2 ms^{-1}**) suppressed **near-inertial wave generation** within the survey region.

WAKE SURVEY REVEALS COMPLEX STRUCTURE

- Survey reveals an **asymmetric vertical structure** around the **wake**.
- The MLD is **slightly shallower** in the west of the wake compared to within the wake itself. This region is characterized by **weak eastward** and **stronger southward flow**, with **strong horizontal shear** at the front.
- **East** of wake is characterized by **deeper MLD** than the wake. The flow in the eastern edge of the wake is **weakly westward and northward**.
- **Edges of the wake** are characterized by **colder waters** (a difference of **0.72°C**) compared to those in the vicinity of the wake. However, the **core of the wake** is **slightly warmer** than its edges. The core is also **saltier** (a **0.45 g kg^{-1}** difference) and **denser** (a **0.39 kg/m^3** difference).

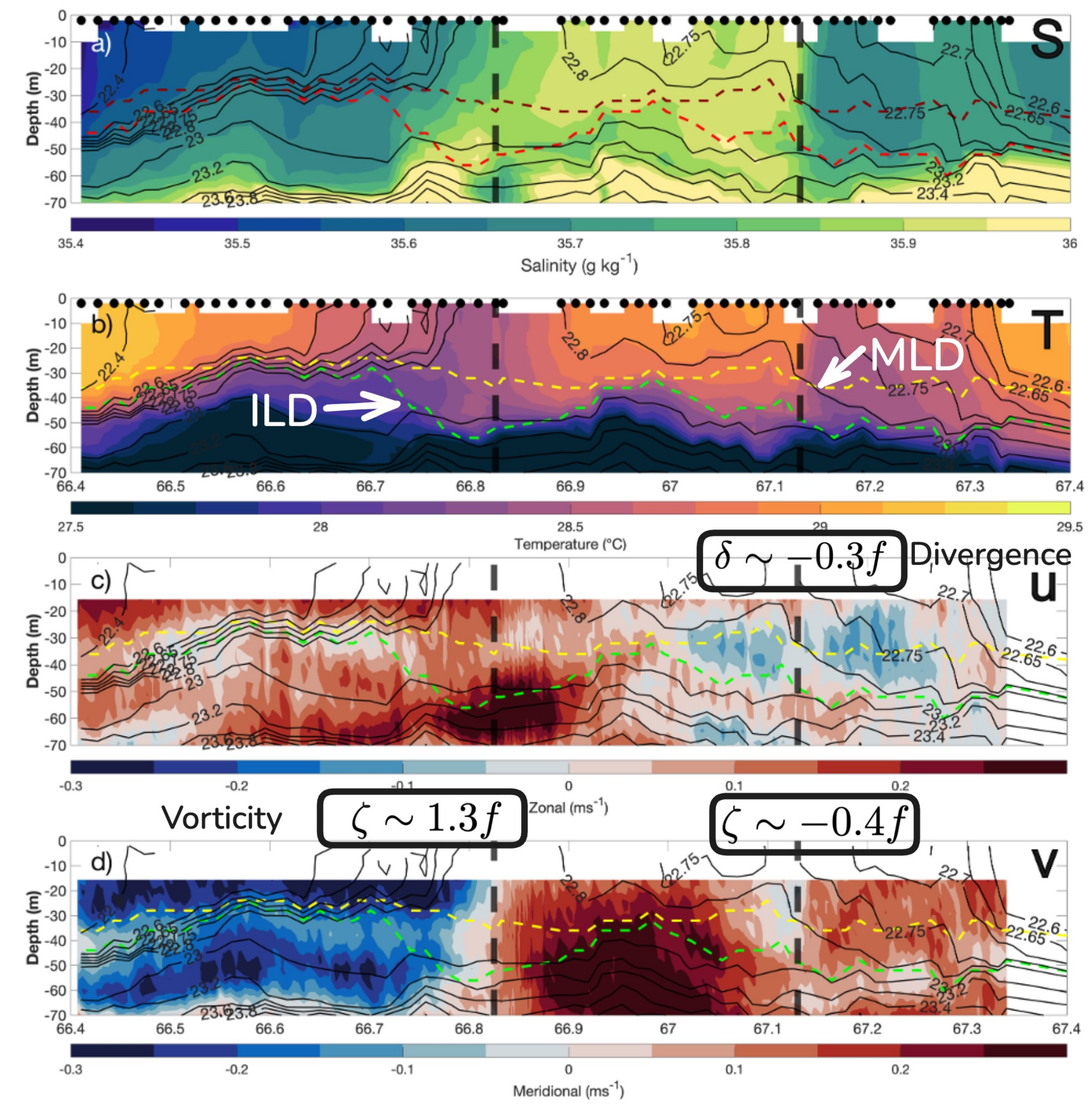

Figure-2: Vertical sections of (a) salinity, (b) temperature, (c) zonal velocity and (d) meridional velocity.

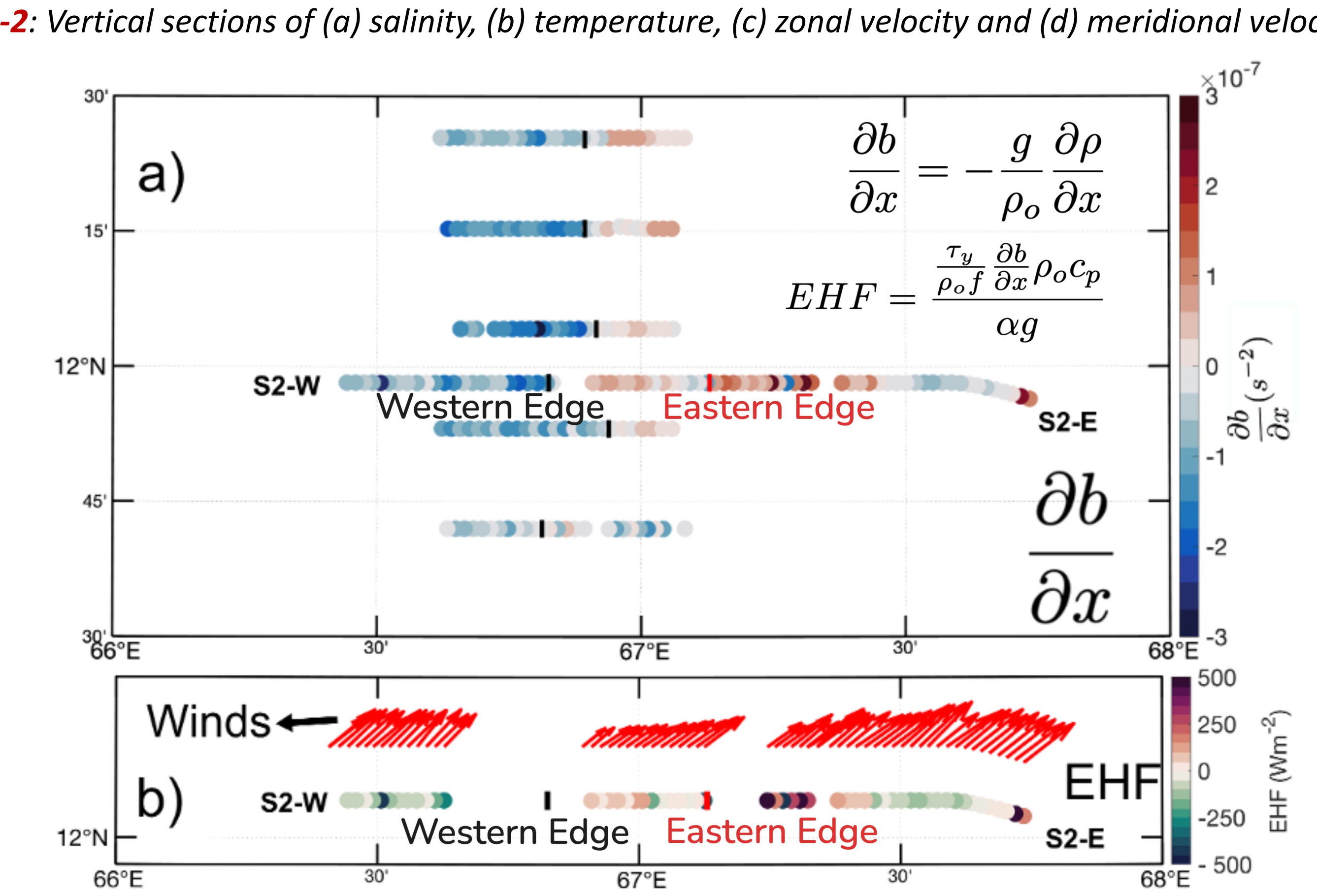

Figure-3: (a) Surface buoyancy gradients (b) Ekman heat flux (EHF)

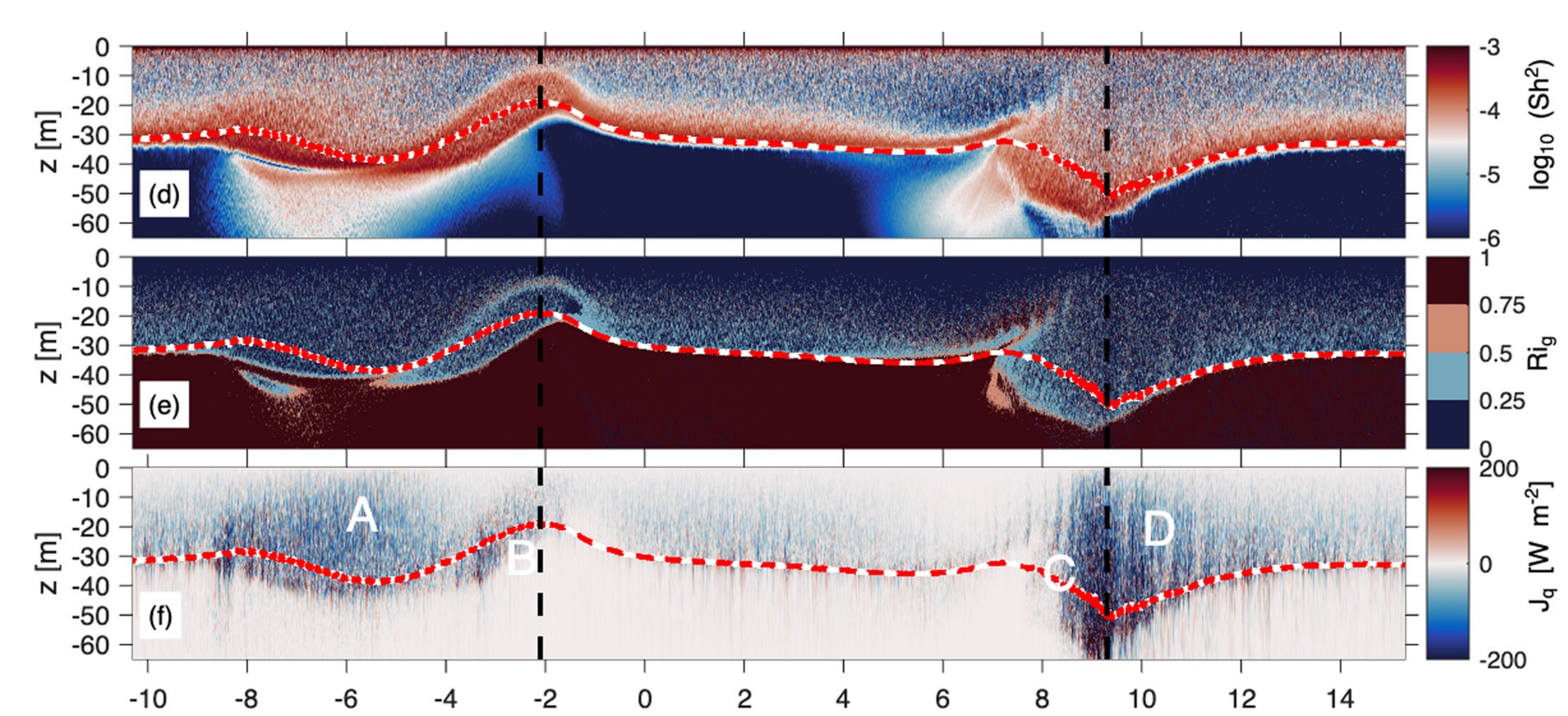

Figure-4: Asymmetric evolution of the dense water filament (DWF) using LES at time t = 17.2 hr. (d) squared shear, (e) gradient Richardson number and (f) turbulent heat flux. Vertical dashed lines mark the DWF edges, where buoyancy gradient peaks. Red dashed lines denote the mixed-layer depth. The fields are along-front averages.

- **Asymmetrical** surface buoyancy gradients (**O(10^{-7})**) are observed with the **eastern edge being 1.7 times stronger.**
- Significant EHF (heat flux equivalent of **Ekman Buoyancy Fluxes [EBFs]**) of around **500 W/m^2**, and **O(1)** Rossby/Richardson numbers indicate **submesoscale-driven recovery.**

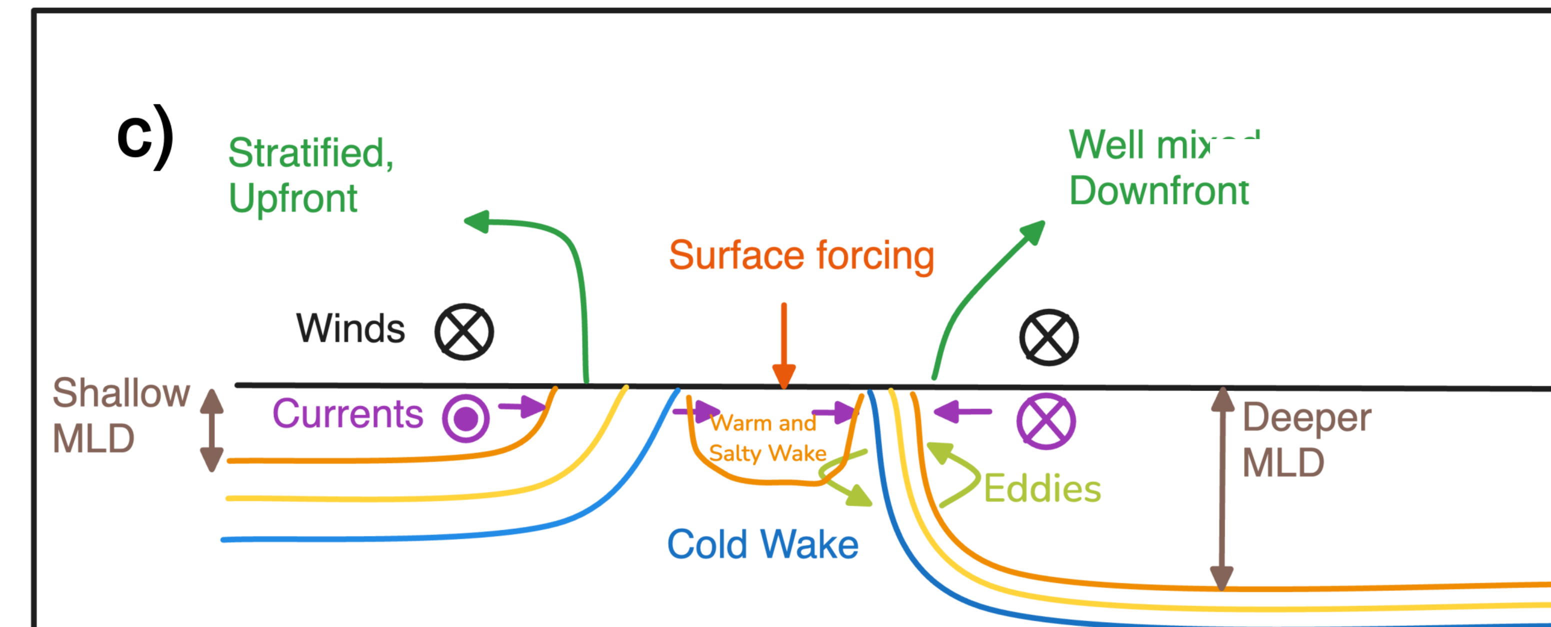

Figure-5: Schematic explaining the forcing conditions and the asymmetric response of the cold wake

The **wake** shows contrasting responses to **south-westerly monsoon wind forcing**. **Upfront winds** on the **western edge restratify** the front, creating a **shallower mixed layer**. On the **eastern edge**, **downfront winds** would typically cause **destratification**, but **mixed layer eddies (MLEs)** provide a **competing restratifying** effect.

THEORETICAL ESTIMATES OF WAKE RECOVERY

Mechanisms	Recovery timescale (in days)
Surface forcing only (SF)	29.6 ± 7
EBFs only	25.4 ± 6
MLEs only	38.4 ± 8
Surface forcing + EBFs	9 ± 2
Surface Forcing + EBFs + MLEs	**7 ± 1**
Remote Sensing	**8**

IMPACTS OF WIND-WAVE MISALIGNMENT ON RECOVERY

Wind–wave misalignment impacts **wake recovery scaling** by altering the **effective drag** and hence **wind stress**.

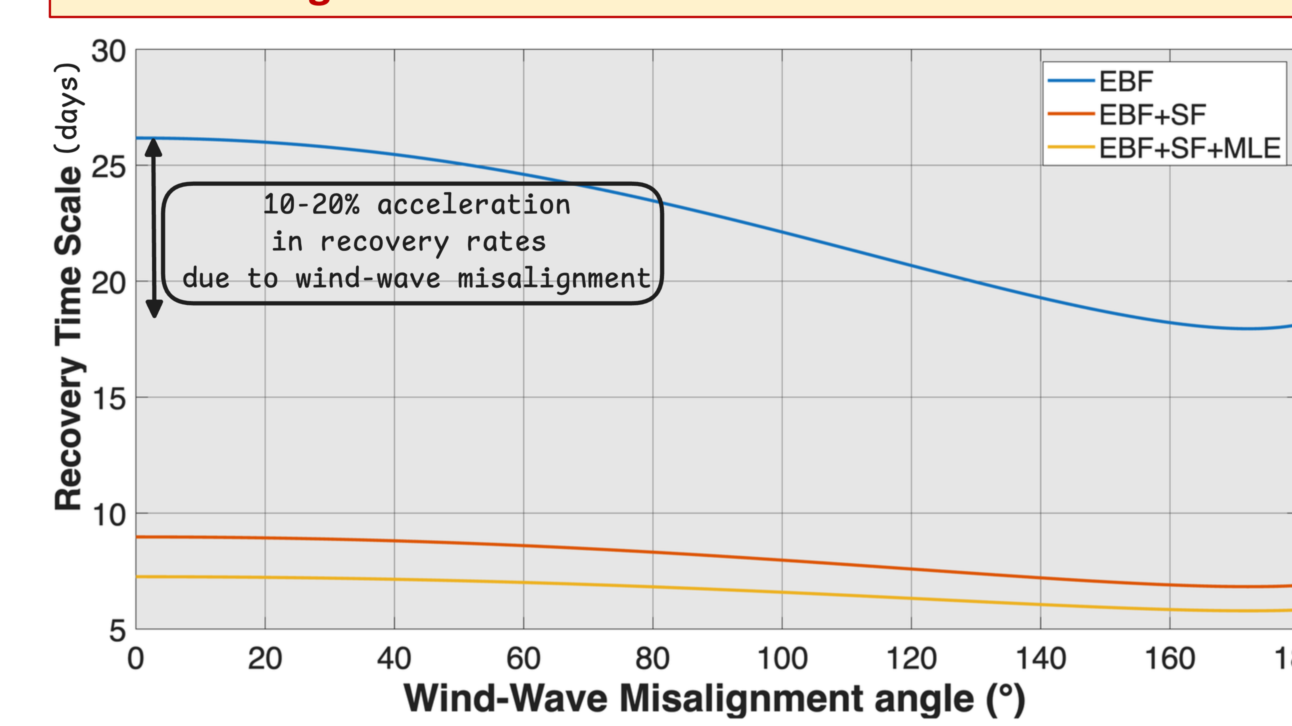

Figure-6: Recovery time scales due to EBFs, and its combination with other processes as a function of wind-wave misalignment.

CONCLUSIONS

- **In-situ observations, remote sensing, LES and theoretical estimates** highlight the presence of **submesoscale processes** within the wake, which accelerate the **wake recovery. Wind-Wave misalignment** also accelerates recovery.
- Interaction between **monsoon winds** and the **underlying 3-D submesoscale fronts** cause the **wake of a slow-moving cyclone** to be **asymmetric**.