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

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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

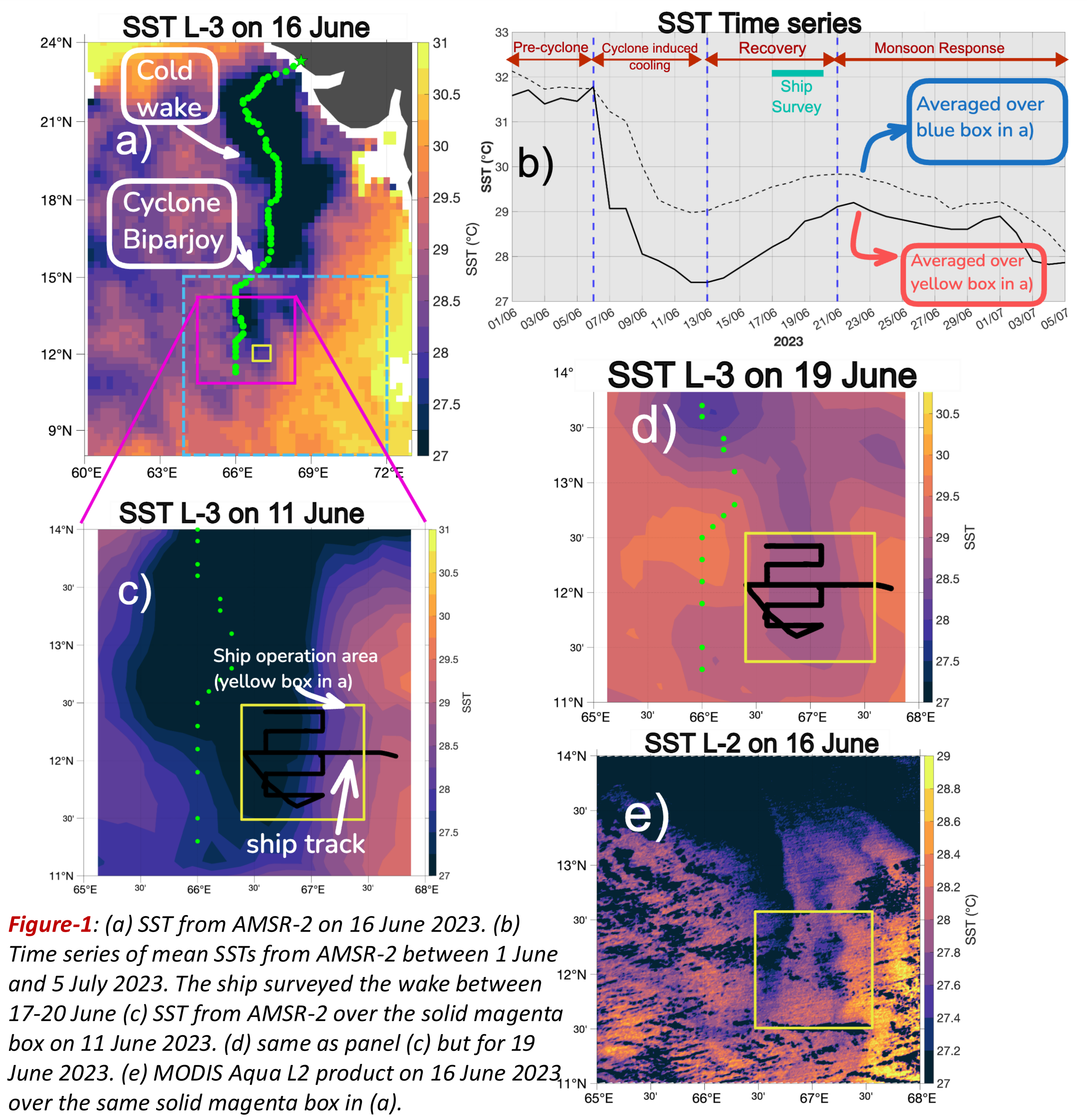

Figure-1: (a) SST from AMSR-2 on 16 June 2023. (b) Time series of mean SSTs from AMSR-2 between 1 June and 5 July 2023. The ship surveyed the wake between 17-20 June (c) SST from AMSR-2 over the solid magenta box on 11 June 2023. (d) same as panel (c) but for 19 June 2023. (e) MODIS Aqua L2 product on 16 June 2023 over the same solid magenta box in (a).

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**.
- Upon eliminating the effects of the background flow, evidence of **convergence** (**$^{\delta}/_{f}\sim$ -0.3**) is observed at eastern edge of the wake.

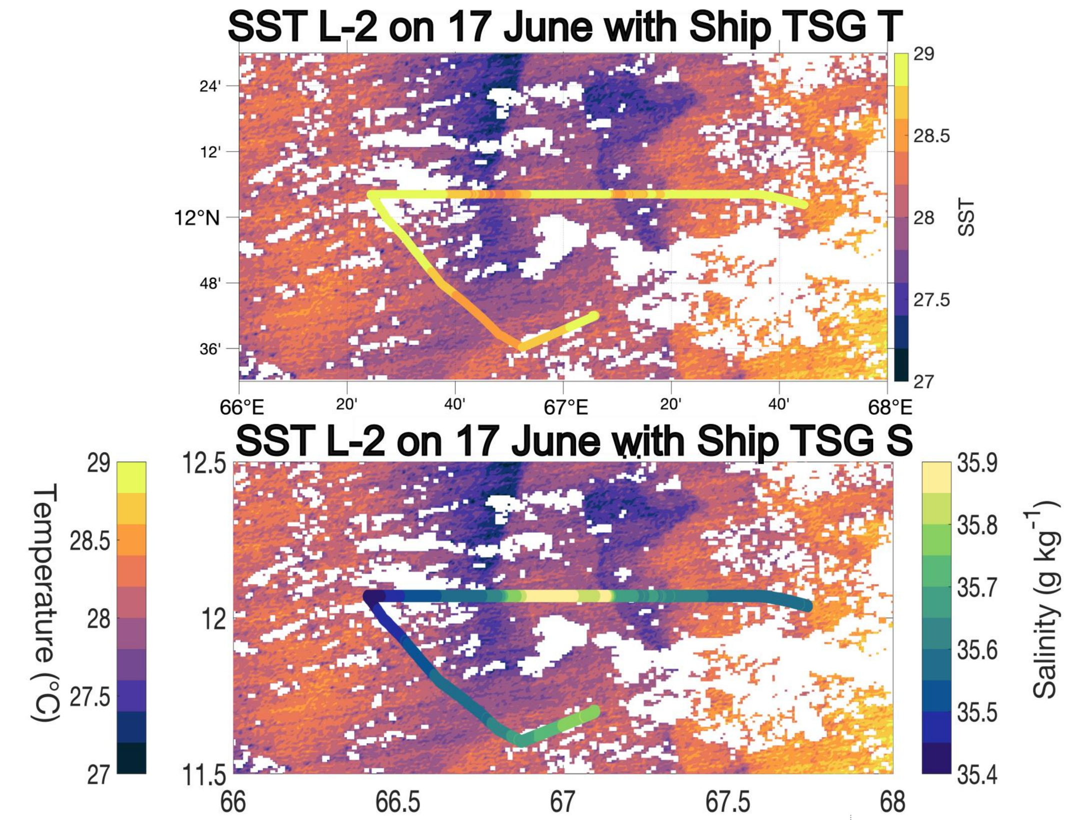

Figure-2: (top) SST from L2 VIIRS-NPP with in-situ SST data overlaid. (bottom) Same as (top) but with in-situ Sea Surface Salinity (SSS) overlaid.

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).

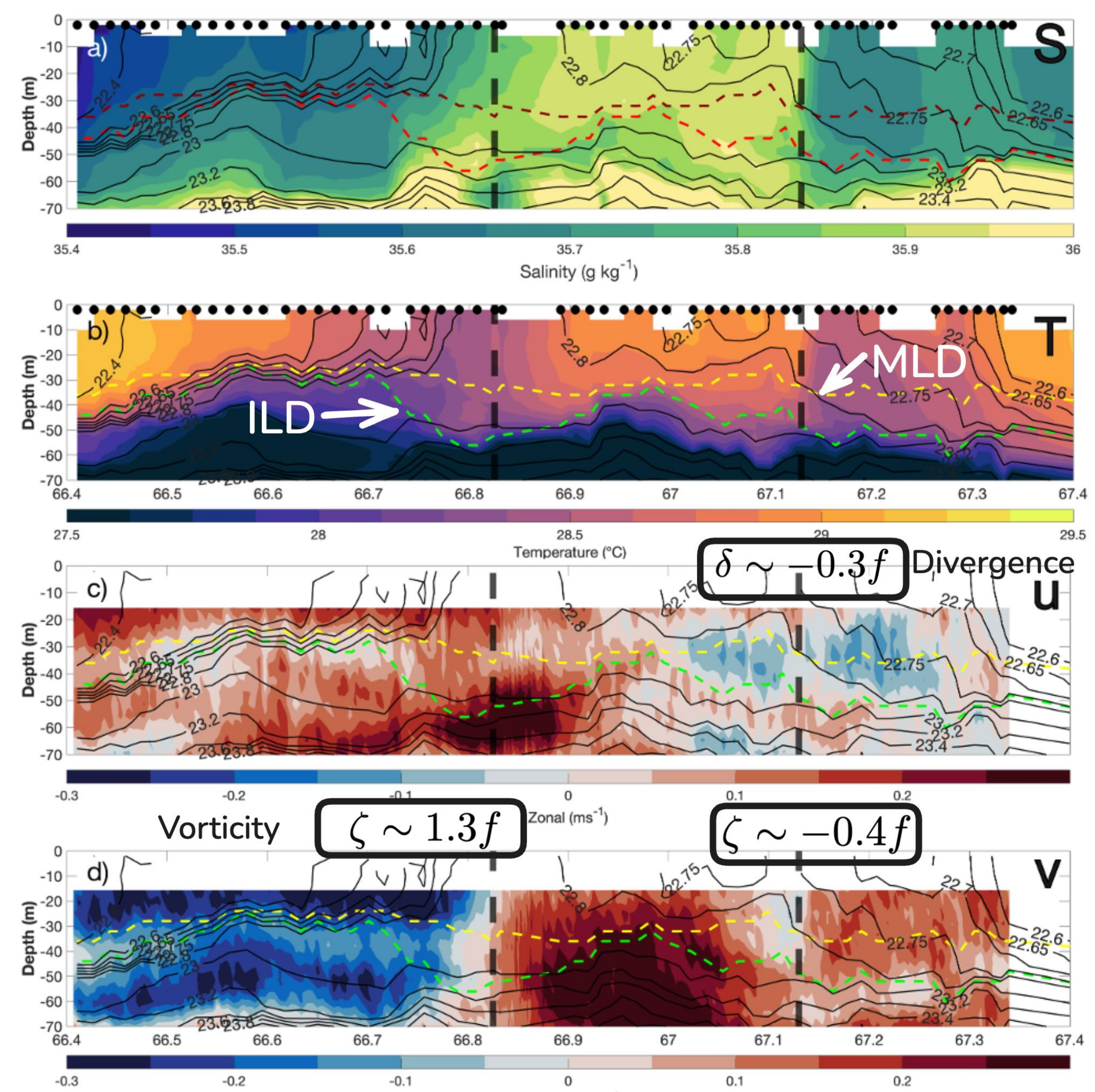

Figure-3: Vertical sections of (a) salinity, (b) temperature, (c) zonal velocity and (d) meridional velocity.

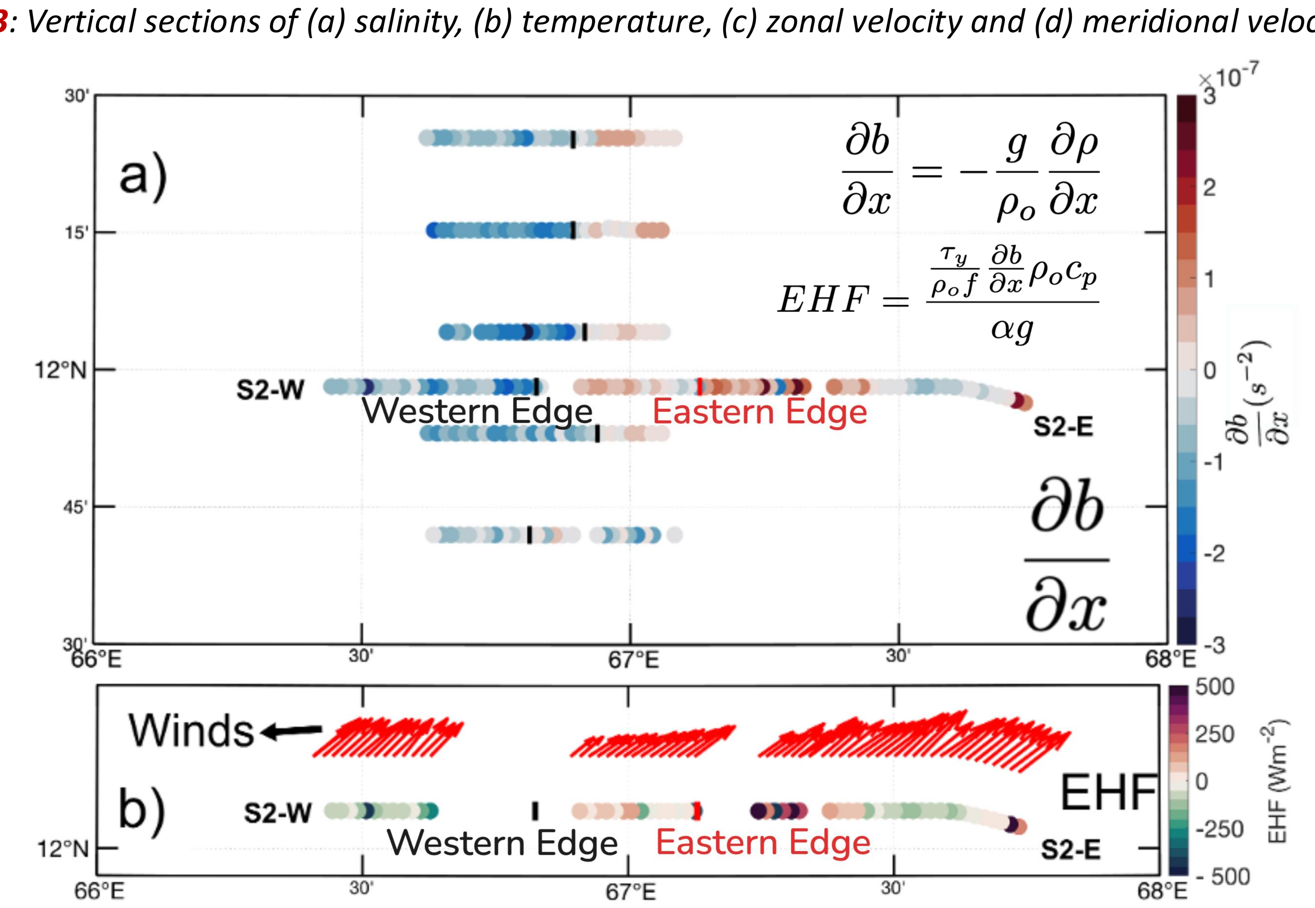

Figure-4: (a) Surface buoyancy gradients (b) Ekman heat flux (EHF)

- **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/m²**, and **O(1)** Rossby/Richardson numbers indicate **submesoscale-driven recovery**.

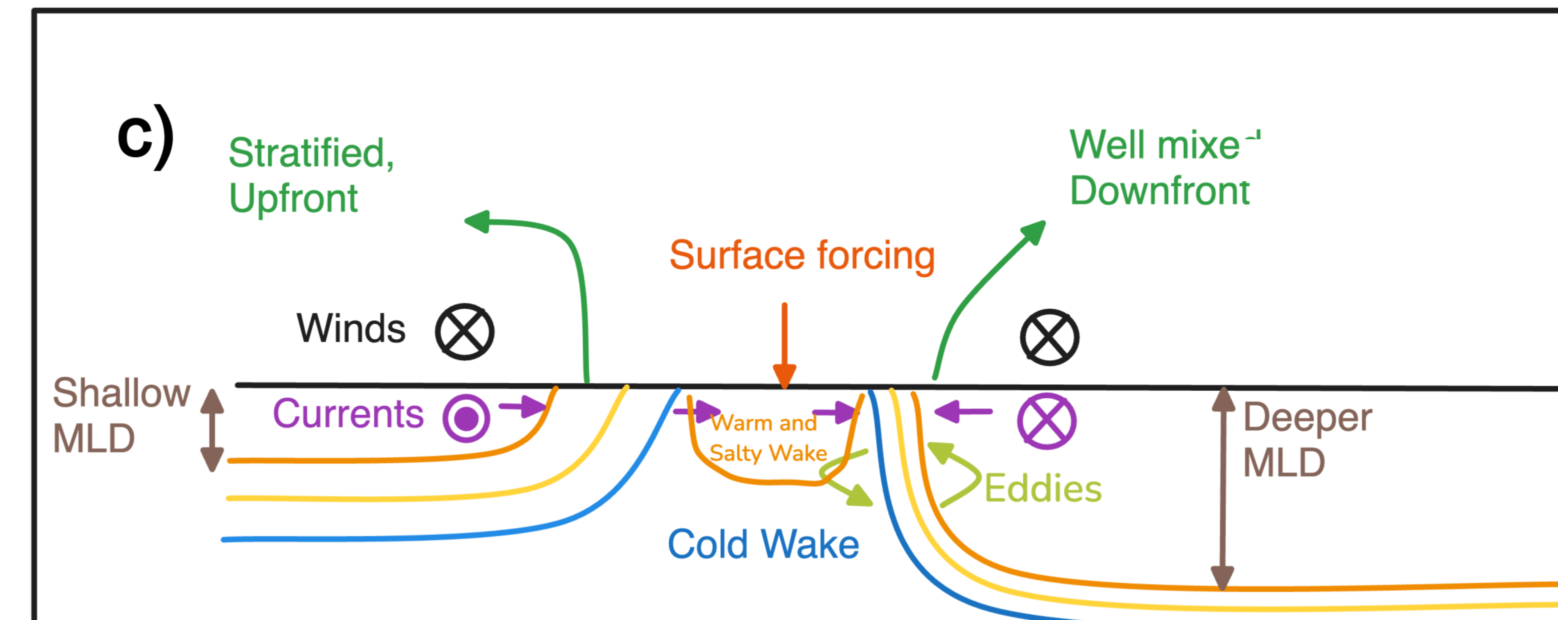

Figure-5: Schematic explaining the forcing conditions and the asymmetric response of the cold wake

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

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

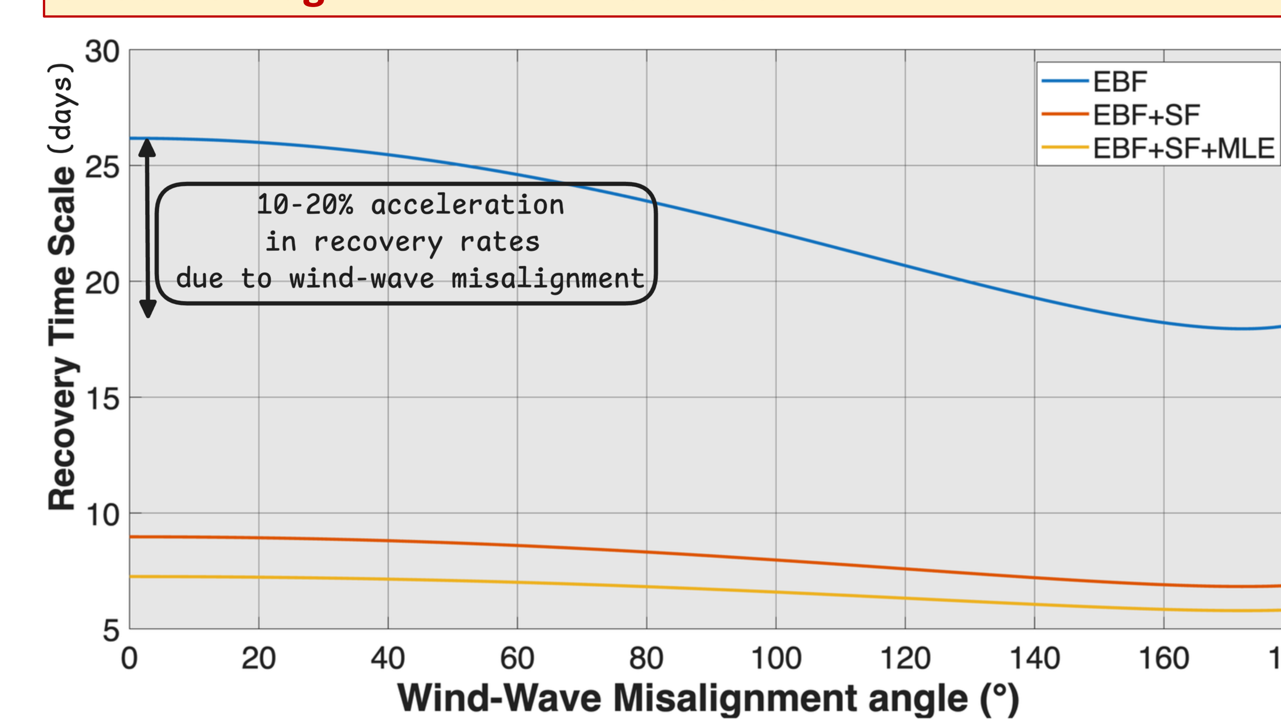

Figure-6: Recovery time scales due to EBFs, and its combination with other processes as a function of wind-wave misalignment.

CONCLUSIONS

- **In-situ observations, remote sensing 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**.