The Role of Eddies in a Laboratory Study of the Antarctic Circumpolar Current

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***Abstract* - The Antarctic Circumpolar Current (ACC) is an eastward flowing current that transports on average 134 Sv around the Southern Ocean, dominating the dynamics of the region. Westerly winds drive the ACC, which roughly follows the path of the maximum westerlies at this latitude, as well as a geostrophic flow component set up by the presence of the Antarctic Polar Front (APF). The APF, characterized by strong density gradients, releases potential energy through baroclinic instabilities that cast off eddies poleward.**

We investigate the behavior of these instabilities, or eddies, in a laboratory setting by reproducing an idealized ACC system through a combination of mechanical and buoyancy forcing applied in a rotating cylindrical tank. We find that the eddies generated by the baroclinic instability of the buoyant current are important in setting the final stratification of the circumpolar front by determining the depth of penetration and strength of the current at equilibrium. We discuss the implications of our laboratory findings for understanding those processes that contribute to setting the stratification and transport in the ACC.

I. INTRODUCTION

The Antarctic Circumpolar Current (ACC) flows eastward in thermal wind balance with the strong lateral density gradients present in the Southern Ocean. On average, the ACC transports 134 Sv and plays an essential role in the global ocean circulation by interconnecting the three major ocean basins [8]. The Antarctic Polar Front (APF), characterized by sharply sloping isopycnals, releases its stored potential energy through baroclinic instabilities that cast off eddies poleward. This poleward flux of warmer water is required to offset the heat loss at the pole.

Recent laboratory experiments by [2] support the hypothesis that this eddy-shedding mechanism is essential in setting the equilibrium depth of the main thermocline. The balance between the eddy transfer and Ekman pumping determines the final depth and strength of the circumpolar current. Previous to these laboratory experiments, [6] has shown through numerical efforts, and [7] by a combination of theoretical and experimental results, that eddies do play a key role in the dynamics of the Southern Ocean, particularly in the APF region of the ACC. Fig. 1 illustrates these dynamics in a highly idealized, schematic fashion. The ACC flows cyclonically (out of the page for the Southern Hemisphere) in the frontal region marked by the sloping isopycnals. A weak, wind-induced Eulerian circulation, called the Deacon cell, enhances the frontal region through the associated Ekman pumping.

Observational evidence also exists that suggests the meridional transfer of heat transferred by eddies can balance the heat loss by evaporation at the pole, both from shipboard, traditional hydrographic sections across the ACC as well as satellite data, see for example [1], [4] and [5]. In this paper we extend the laboratory experiments of [2] utilizing a different set-up in an attempt to further elucidate the eddy transfer mechanism. The experimental apparatus is described in section 2; some preliminary results are presented in section 3, along with a few remarks about connecting the lab results with real ACC observations.

II. EXPERIMENTAL SET-UP

We attempt to elucidate the eddy transfer mechanism through a series of laboratory experiments in an idealized

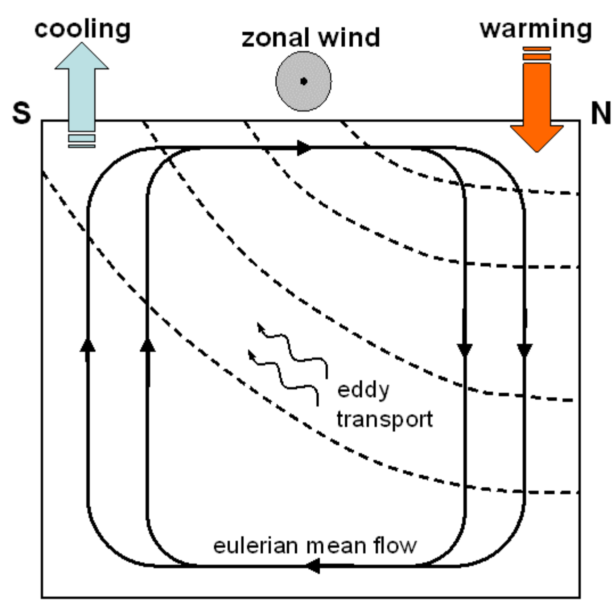

Fig 1. Schematic of the dynamics in the Southern Ocean. The sloping dashed lines represent isopycnal and mark where the ACC flows.

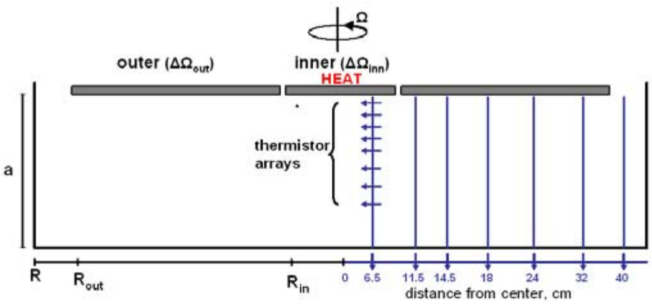

Fig. 2. The experimental apparatus used in all runs.

ACC system. The experimental apparatus, seen in Fig. 2, applies a combination of mechanical and buoyancy forcing to achieve the desired dynamics in a cylindrical Plexiglas tank of depth a = 17.5 cm rotating at an angular speed Ω (s^{-1}). The mechanical forcing is provided by two concentric differentially rotating disks of radii R_{in} = 10 cm and R_{out} = 35.5 cm, while the buoyant fluid is generated by heating elements on the underside of the inner disk. A buoyant current is set up by rotating the two disks to obtain a downwelling region below the outer disk. The lighter fluid, created below the inner disk and pumped upward by rotating cyclonically at a rate $\Delta\Omega_{in}$, is carried radially outwards by Ekman transport and then downwelled, so that it produces a circumpolar current in a similar fashion as the ACC is formed. The vertical velocity w_e induced by one disk is, according to Ekman theory [3],

$$w_e = \Delta\Omega_{in} / (\nu / (4\cdot\Omega + 2\cdot\Delta\Omega_{inn}))^{1/2} \qquad (2.1)$$

where $\nu = 0.01\ cm^2 s^{-1}$ is the molecular viscosity of water. The actual downwelling velocity of the fluid under the outer disk however, is a combination of the vertical velocities generated by rotation of the two disks separately.

Buoyancy forcing was applied by heating elements underneath the inner disk to generate a density difference (here done by temperature only) described by the reduced gravity, g', defined as

$$g' = g\cdot\alpha\cdot\Delta T / \rho_0 \qquad (2.2)$$

where α is the thermal expansion coefficient of water, g the gravitational acceleration, and ρ_0 the initial density of the fluid. We achieved the desired g' by supplying power to the heating elements determined by

$$W = Q\cdot\rho_0\cdot C_p\cdot\Delta T \qquad (2.3)$$

with W being the power in watts, $Q = w_e\cdot\pi R_{in}^2$ the flow rate, and C_p the specific heat of water at a constant pressure.

The stratification of the current was monitored using seven vertical temperature profilers, with 8 thermistors arrayed on each at different depths, positioned along a radial section, as in Fig. 2. These thermistors recorded temperature every 30 seconds, with a typical experiment lasting 4-8 hours. Visual observations of the fluid motion were made using potassium permanganate crystals ($KMnO_4$) that dye the water purple. The streaks made by the potassium permanganate qualitatively indicate the path of the current. A strong shear was observed in the vertical dye streaks due to the faster moving current, as well a swirling of the dye due to the presence of eddies.

III. PRELIMINARY RESULTS

Given the small downwelling velocities present in these experiments, on the order of $0.01 cm\ s^{-1}$ or less, the first test was to check if diffusive processes could significantly affect the results. The heat diffusion equation,

$$\partial T/\partial t = \kappa\nabla^2 T \qquad (3.1)$$

where T is temperature and $\kappa = 1.4\ 10^{-7}\ m^2 s^{-1}$ is the thermal diffusivity constant, governs how temperature changes with time. The solution to (3.1) in a form most useful to our system is

$$(T - T_0) = (T_1 - T_0)\cdot erfc(z / (4\kappa t)^{1/2}) \qquad (3.2)$$

where T_0 is the initial water temperature, T_1 is the temperature supplied by inner disk, z is the depth below the disk, and t is time. The temperature T_1 is calculated from relation (2.3) given a specified power, W, and flow rate, Q. Fig. 3 plots the predicted temperature due only to diffusion along with the actual temperatures recorded by the thermistors at a position

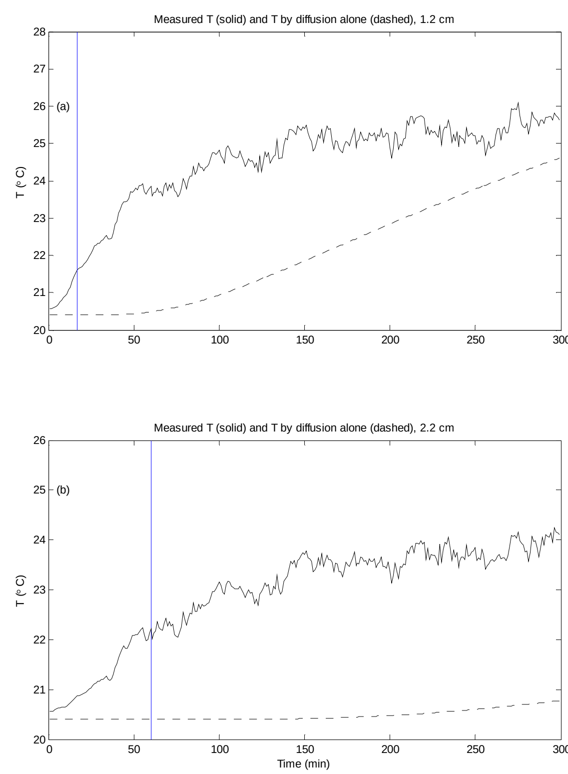

Fig. 3 Measured T (°C) and predicted T (°C) that would occur by diffusion alone for two depths, (a) 1.2cm and (b) 2.2cm at a radial distance 14.5cm. The vertical lines indicate the diffusive time scale at each depth.

14.5 cm from the tank center over the length of the experiment (about five hours). Clearly diffusion alone cannot account for the warming measured at the two depths plotted: 1.2 cm and 2.2 cm. At the 1.2 cm depth diffusion should start affecting the temperature after only seventeen minutes, calculated by using the characteristic thermal diffusion distance $(\kappa t)^{1/2}$, but significant warming occurs well before the seventeen minute mark. Similarly, warming occurs at the 2.2 cm depth much sooner than the diffusive timescale of about one hour. Thus we infer that there must be downwelling occurring that pumps water heated within the inner disk region down into the interior.

Shear instabilities at the disk edges, as discussed by [3], could lead to unwanted fluctuations as well. [3] found that these shear instabilities occur when both the Ekman number $E = 2\nu / (a^2 \cdot (\Omega + \Omega_{in})$, and a Rossby number, defined here as $\varepsilon = 2(\Omega - \Omega_{in}) / (\Omega + \Omega_{in})$, are small, i.e. E and ε are much less than unity. In particular, if $|\varepsilon| > \varepsilon_T$, where ε_T is a critical value determined empirically that depends on E, the behavior of the instabilities can be predicted. We take care in configuring our experiments in order to fall within the stable regime, $|\varepsilon| < \varepsilon_T$, so that no shear instabilities will form.

Still in progress, we will discuss only one typical run of the experiment so far, and leave further speculation and results for later publication. Table 1 lists the experimental parameters for this run, with $f = 2\Omega$ (s^{-1}) being the Coriolis parameter. The vertical velocity tabulated is the upwelling velocity predicted by (2.1) under the inner disk, while the negative sign in front of Δf_{out} denotes anti-cyclonic rotation. Fig. 3 displays a radial section of the temperature anomaly five hours after spinning up and shows the development of the frontal region. Sloping isotherms reveal the presence of a front at the inner disk edge, or poleward side, as desired. Relatively warmer water, marking the vertical extent h_e of the front, penetrates to a depth of about 4 cm near the inner disk edge and decreases its depth of penetration radially outward. The downwelling velocity should be a maximum at the boundary between the inner and outer disks, which corresponds to the largest h_e observed in this set-up. The enhanced flow is due to the velocity of a downward return flow inside a Stewartson boundary layer (thickness $E^{1/4}$) located there added to the downward velocity induced by the outer disk. Another set of sloping isotherms formed on the outer boundary of the tank around 35cm. This could lead to instabilities at the outer edge that could significantly affect the dynamics at play.

TABLE 1 - Experimental parameters

Exp. #	f (s^{-1})	Δf_{in}	Δf_{out}	g'	ΔT (°C)	w_e (10^{-3}cm s^{-1})
17	1.0	0.118	-0.03	2.16	11.0	4.16

Potassium permanganate streaks clearly showed anti-cyclonic eddies forming under the inner disk edge. This is inside the region predicted where eddies should grow and carry warmer water radially inward. Dye placed in the outer disk region demonstrated the presence of the cyclonically flowing current by shearing in the upper region of the streak.

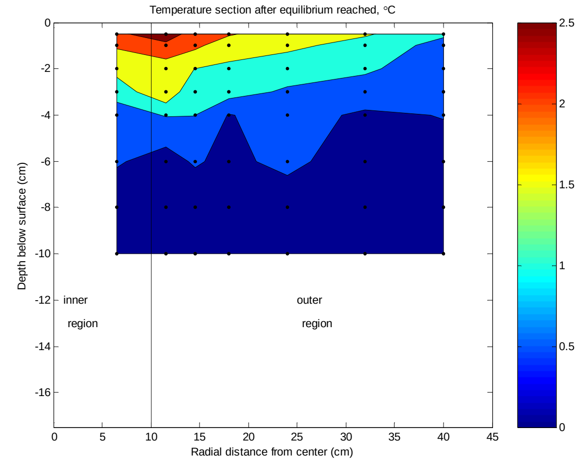

Fig. 3 Temperature anomaly (°C) section five hours into run. Black dots mark thermistor placements. The vertical line at 10cm divides the region underneath the inner disk from the outer disk region.

Concentrations of dye also collected directly underneath the inner disk and at the outer wall, slowly upwelling as predicted for those two regions. Future work will quantify the eddy flux and make an estimate of c, the eddy efficiency parameter, as well as estimate the speed of the buoyant current u_e by using particle tracking software. These estimates will allow the laboratory experiments to be compared to actual observations of the ACC region. Efforts will also be made to weaken the secondary front seen in the isotherms at the outer disk edge.

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