MIXED-LAYER FRONTS IN THE CALIFORNIA CURRENT

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ABSTRACT

Observations of the structure of the mixed-layer in regions of large horizontal shear are presented. Cyclonic shears of order f were found to be associated with strong surface convergences. Several possible driving mechanisms are proposed and scaled.

1. INTRODUCTION

The summer-time mesoscale flow off Central and Northern California consists of narrow seaward baroclinic jets emanating from the coastal upwelling region, embedded in a field of cyclonic and anti-cyclonic eddies. These jets transport cold coastal water offshore, and appear as cold filaments on satellite infrared images. Some typical scales of the jets are: width 20 to 50 km, surface velocity 0.5 to 0.8 m/s, velocity e-folding depth 150 m, total flow 0.5 to $2 \cdot 10^6 m^3/s$ and alongshore spacing 50 to 500 km. These features have been discussed by Davis (1985), Flament et al. (1985), Kosro and Huyer (1986) and Rienecker et al. (1985).

The surface layer processes associated with the jets are asymmetric: at the anticyclonic boundary, the transition from cold to warm water is often spread over 20 km, whereas the cyclonic boundary corresponds to a front generally sharper than the 1-km resolution of the infrared images. This asymmetry seems to be an ubiquitous characteristic of the filaments and has been qualitatively observed in all the images analyzed.

A series of cruises was organized from 1982 to 1985 to study the small-scale structure of the filaments and the mechanisms maintaining the sharpness of the cyclonic front despite turbulent diffusion. The results of these cruises have been presented in details by Flament et al. (1985) and Flament (1986), and are summarized in section 2. Several possible frontogenetic mechanisms are discussed in section 3.

2. OBSERVATIONS OF THE FRONTAL STRUCTURE

The filament rooted near Point Arena was studied in 1982. A 10 m/s northwesterly wind prevailed during this experiment, deepening the surface mixed-layer to 35 m. The width of the sharp front was 350 m. It extended only to the bottom of the mixed-layer: there was no corresponding thermal front in the thermocline. The fronts observed in the satellite images were thus shallower than the velocity field.

Two results suggested that a strong cross-frontal convergence was responsible for the sharp front. In a sequence of satellite images, a "lucky streak" was observed to coalesce with the front. The cross-isotherm convergence was 18 cm/s over a distance of 20 km. Thermohaline layers were found to originate at the front and extend ˜20 km into the thermocline underneath the anticyclonic region, consistent with a subduction of the denser frontal waters presumably forced by the convergence. Similar subducted layers were observed near Point Conception in 1983.

However, it was not possible to estimate the rate of divergence in the along-isotherm direction from the satellite images, and thus to distinguish between convergence ($\nabla \cdot u \neq 0$) and confluence ($\partial_x u \neq 0$ with $\nabla \cdot u = 0$). The subducted layers were the only indirect evidence suggesting that $\nabla \cdot u \neq 0$.

In July 1985, the hypothesis $\nabla \cdot u \neq 0$ at the sharp front was tested by deploying clusters of surface drifters at several positions across the filament rooted near Point Sur. This experiment was conducted during a period of light wind (<2 m/s), following a 10 m/s northwesterly wind event which lasted two days.

In the anticyclonic region, the flow was non-divergent within the sampling errors and the shear was $-0.3\ f$ ($f = 9 \cdot 10^{-5}\ \mathrm{s}^{-1}$ is the planetary vorticity). At the cyclonic front, the flow was discontinuous at the 1-km resolution of the cluster. The shear was larger than $4.5\ f$ and persisted for at least one week. It was associated with a cross-frontal surface convergence of 6 cm/s, visible as a 20 m wide accumulation of debris of seaweeds commonly found on the shelf. Thermohaline layers were again found to originate at the front and to extend under the anticyclonic region. The vertical scale of the layers was smallest near the front. However, a simple interpretation in terms of subduction was not possible, perhaps because a well-developed surface mixed-layer was lacking.

The convergence at the cyclonic front is a robust finding of this work: it has been consistently observed remotely from satellite images, in situ using clusters of drifters, and by the accumulation of kelp. The associated water subduction is more complicated to infer when there are many water types in presence, although thermohaline intrusions are clearly associated with the fronts.

3. POSSIBLE MECHANISMS DRIVING THE CONVERGENCE

Since the fronts were generally confined to the mixed-layer and were shallower than 35 m, it is tempting to interpret the convergence in terms of mixed-layer processes. Several possible ones discussed and scaled below could cause the convergence. A jet $U(y) < 0$ flowing westward will be assumed.

1. The simplest interpretation is a difference in the turbulent layer thickness H across the jet. Variations of H are likely because the mixed-layers on either side of the front have different deepening histories and because the rate of deepening is affected by the local vorticity (Klein and LeSaos, 1986). Assuming slab mixed-layers, the cross-frontal Ekman velocity v_e is

$$v_e = -\frac{\tau_x}{\rho f H(y)} \qquad (1)$$

where τ_x is the x-component of the wind stress. A surface convergence is induced where $\partial_y H$ and τ_x have opposite signs. For a 10 m/s wind, an initial 10% change of H induces a convergence of only 0.5 cm/s at the latitude of our experiments. This process seems to require unreasonable mixed-layer depth variations to account for the observed convergence.

2. A convergence of the Ekman transport can also be caused by the horizontal shear, through the non-linear terms of the momentum balance (Niiler, 1969; Stern, 1975; Flament, 1983). The cross-frontal Ekman velocity

$$v_e = -\frac{\tau_x}{\rho(f - \partial_y U)H} \tag{2}$$

is decreased on the cyclonic side and enhanced on the anticyclonic side. Since a shear of order f exists at the cyclonic front, this coupling results in large variations of v_e across the jet, and, for a wind with an eastward component, the most frequent in the region studied, in a convergence along the axis of the jet. For the vorticities found during the 1985 experiment, the anticyclonic and cyclonic regions would converge at 9 cm/s with a 10 m/s wind. This mechanism should be tested by correlating the frontal gradients with the wind direction in existing infrared images archives.

3. The marine atmospheric boundary layer is modified when advected across a temperature front and a change of the drag coefficient results (Businger and Shaw, 1984). This can also create an Ekman convergence. For a mixed boundary layer of height h initially in thermal equilibrium with the water, the e-folding distance for recovering equilibrium is h/k where $k = 1.2 \cdot 10^{-3}$ is the sensible heat exchange coefficient (Friehe and Schmitt, 1976). For $h = 200$m, this distance is 170 km, an order of magnitude larger than the width of the filaments: this process does not seem important in the present case (see also Hanson, 1987).

4. Refraction of surface waves by the shear is another candidate for driving the convergence. Such sharp refractions have been observed off California by Sheres et al. (1985). A relevant theory on the effect of surface waves on mean flows is found in Garrett (1976). For waves propagating at a small angle with the axis of the jet, the dominant effect is a near-surface stress oriented to the right of the wave ray when the shear is cyclonic, and given approximately by

$$F = \frac{E_o \partial_y U}{c_o} \tag{3}$$

in which E_o and c_o are the energy density and the phase speed of the waves. The stress induced by a typical westerly swell of 6 s period and 1 m amplitude refracted by the cyclonic shear found in 1985 is 0.2 Pa, to be compared with a wind stress of 0.15 Pa for 10 m/s wind. A convergence at the southern edge of the cyclonic region and a divergence on the axis of the jet result.

5. The convergence may simply be a frictional effect on the quasi-geostrophic flow $U(y)$. Assuming an exponential velocity profile of e-folding depth $D = 150\text{m}$, the frictionally driven secondary circulation is

$$V = \frac{K_v U}{D^2 f} \tag{4}$$

where K_v is the vertical eddy viscosity. A convergence towards the southern edge of the cyclonic front results. For a typical mixed-layer eddy viscosity $K_v = 0.1\text{m}^2/\text{s}$, the convergence corresponding to the shear observed in 1985 would be 2 cm/s over a scale of 1 km. This process is also consistent with the lack of front below the mixed-layer, since the vertical eddy viscosity is much smaller there.

All these processes may contribute to the convergence, some may be more important when the wind is strong (the 1982 experiment), other may dominate when the wind is weak (the 1985 experiment) and the data presently available is not sufficient to single out any. A parallel shear flow has been assumed here; other effects may be play a role when the streamlines of the mean flow are curved. Further work is clearly needed to understand the dynamics of mixed layers in regions of strong horizontal shear.

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