AVHRR observations of the horizontal structure of the surface layer of the ocean under low wind conditions

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Abstract. Diurnal warming layers that form in low wind display coherent horizontal structures in the form of streaks at least 50 km long, with a wavelength of 4-8 km and an amplitude of 0.5-1.5°C. These features have been observed in the California Current in three different occasions using a combination of satellite and in-situ measurements. It is hypothesized that their scale is set by planetary boundary layer circulations.

1. Introduction

Large diurnal warming of the surface layer of the ocean occurs in low wind and low cloud cover conditions (e.g. Bruce and Firing, 1974). The diurnal amplitude of surface temperature can then reach several °C, over regions that have been shown to correspond closely to anticyclonic ridges (Stramma *et al.*, 1986; Cornillon and Stramma, 1985). In contrast, when a well-developed wind-driven mixed layer is present, the diurnal amplitude seldom exceeds a few tenths of °C.

We present here 1-km resolution AVHRR infrared images and in-situ CTD profiles that suggest the existence of coherent horizontal structures in these warming layers, at scales of 3 to 10 km.

2. Satellite images

The area studied is shown in Fig.1. An anticyclone was centered at 135°W 40°N during July 1985, resulting in low winds off the coast of California. Three AVHRR images were acquired on 8 and 9 July, at about 14:00, 19:00 and 08:00 local (UT-8) time. Band 4 (10.8 µm) will be used for sea surface temperature.

Surface temperature on 8 July at 19:00 is shown in Fig. 2. Cold water due to coastal upwelling and offshore advection of coastal water is seen in the east of the image. Over most of the image, the temperature field consists of large nearly isothermal patches, separated by fronts a few km wide. For example, near [x=200,y=160] km, surface temperature does not vary much over a radius of ~30 km. This structure is typical of infrared images of the California Current.

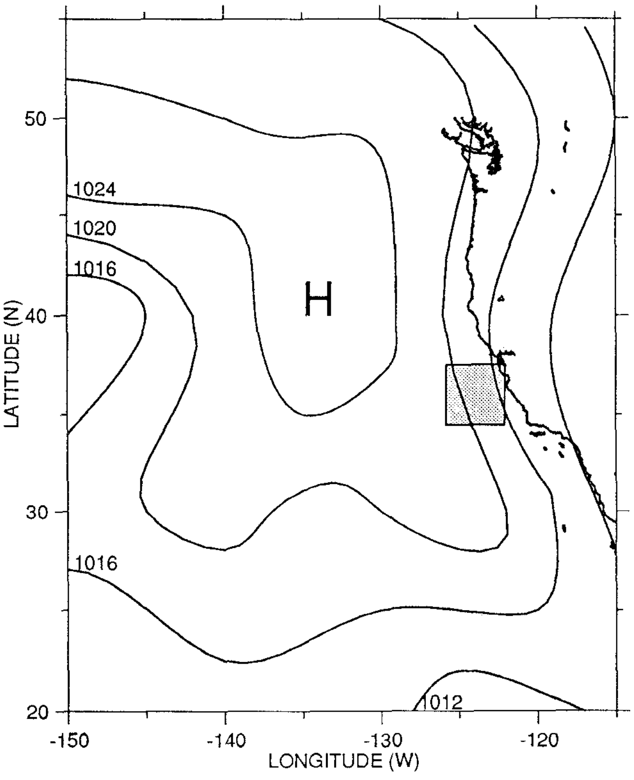

Fig. 1. Map of the area studied, with the surface pressure field on 11 July at 16:00 (UT-8). Note the anticyclonic ridge extending southeastward from 135°W 40°N. The position of the image shown in Figs. 2 and 3 is outlined.

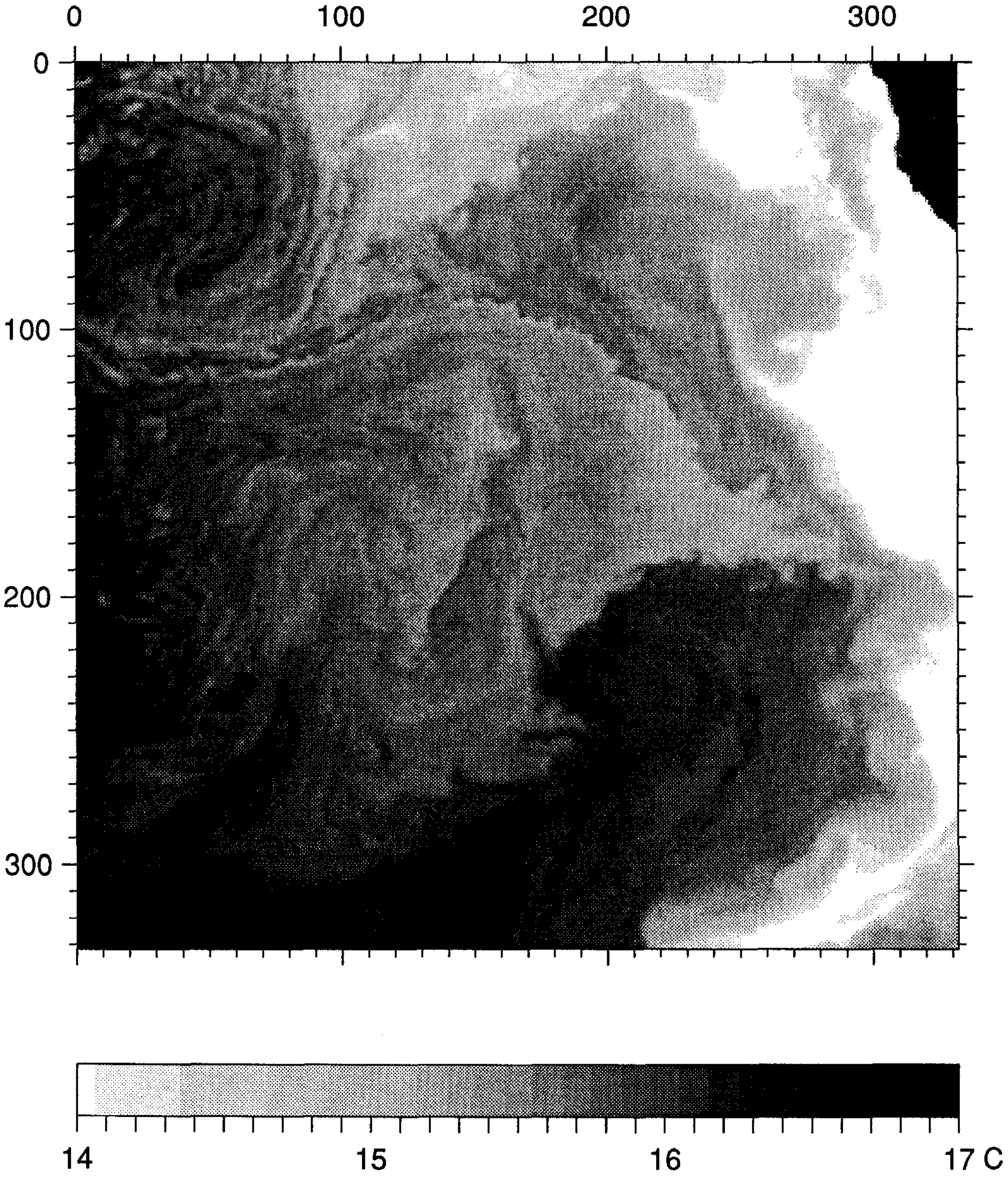

Fig. 2. Thermal infrared AVHRR image on 8 July 1985 at 19:00 (UT-8). Cold water is coded in white and warm water in black; the temperature scale is labeled in °C. The grid is labeled in km. The origin is at 125°48 37°30N.

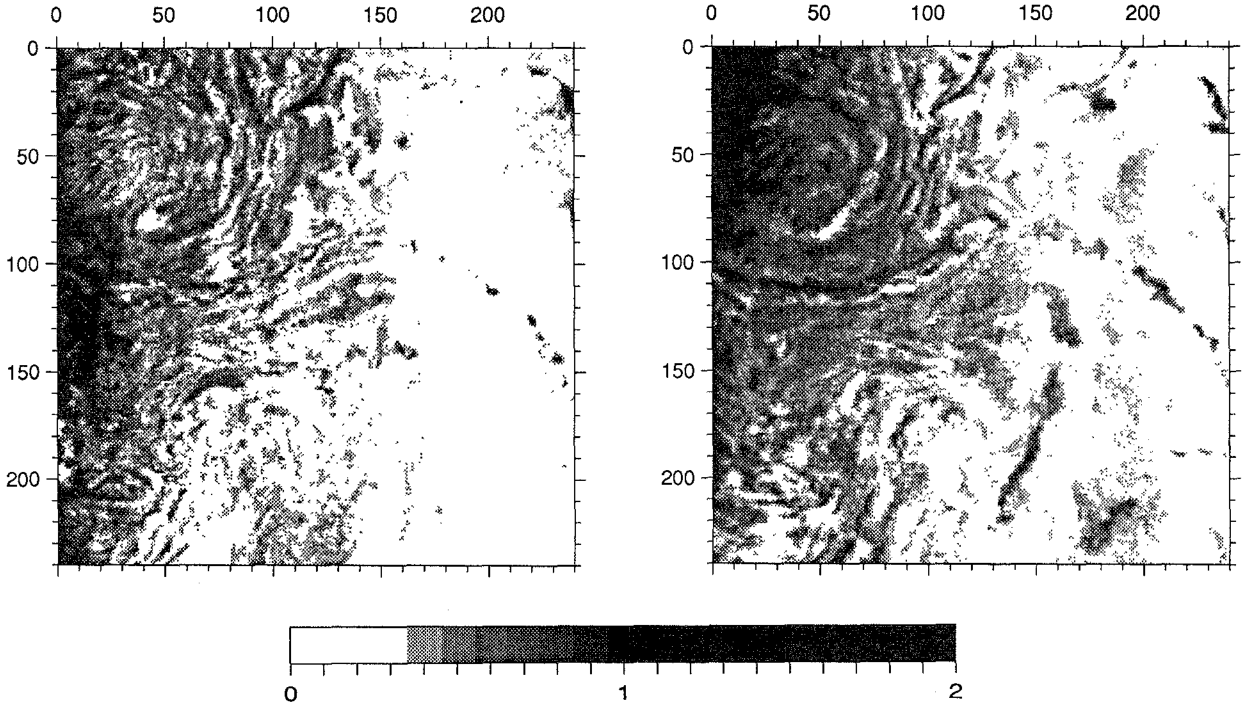

Fig. 3. (a) difference between the images on 8 July at 14:00 and at 19:00 (UT-8); (b) difference between the images on 8 July at 19:00 and on 9 July at 08:00 (UT-8). Differences smaller than 0.3°C are white; larger differences are shown in gray.

However, a very different structure is seen in the northwest of the image. In that area, surface temperature varies rapidly, and displays numerous streaks ~50 km long with a typical wavelength of 5-6 km and amplitude of 0.5 to 1°C. They are most clearly seen near [x=80,y=90] km. They seem to align preferentially along the streamlines of the mesoscale flow. These streaks are also seen in the preceding and following images, but seem most intense in the image shown. Although they are visually reminiscent of clouds, they are not clouds: the difference between brightness temperatures at 3.7 μm and 10.8 μm was negligible, unlike clouds which have a smaller emissivity (0.7) at 3.7 μm.

Fig. 3 shows the differences between the 14:00 and 19:00 images, and between the 19:00 and 08:00 images. Over the center and east of the images, the differences are very small. They are less than 0.3°C, except near fronts where advection dominates. Over the area of the streaks, however, the signature of a large diurnal warming event is clearly seen, with differences of the order of 0.5 to 1.3°C between pairs of images and a decrease of temperature from the afternoon image to the morning image.

3. In-situ measurements

Two weeks after these images, we had the opportunity to sample diurnal warming layers from ship. The wind was less than 1 m/s and the sea surface was glossy. On 25 July at 23:00, our attention was caught by periodic variations of intake temperature while steaming at about 2.5 m/s. A mixed-layer drifter drogued at 5 m was deployed and a 3-hour survey was conducted along the track shown in Fig. 4. The position of this survey is [x=260,y=200] km in Fig. 2. The motion of the drifter corresponded to a mean flow less than 10 cm/s, indicating that the area was not in a jet or mesoscale front.

Fig. 5 shows surface temperature and salinity at 50 cm depth, measured at an intake on the side of the ship. Salinity was virtually constant through the survey, but temperature varied between 14.9 and 15.7°C, with features identifiable at scales of 2 to 8 km. There is a clear symmetry at the southeast turning point of the survey, suggesting that the temperature variations were the expression of streaks running northeast to southwest.

A CTD was yow-yoed between the surface and 40 m depth during the survey. Using a winch

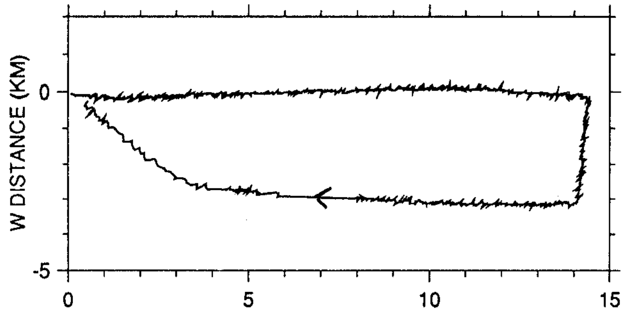

Fig. 4. Ship track over ground on 25 July at 23:00 (UT-8). The origin is at 122°20W 35°45N.

rate of about 40 cm/s, 80 vertical profiles were obtained. The profiles at km 1 and km 5 are shown in Fig. 6; the other profiles were in all aspects similar. Both profiles reveal a "fossil" mixed-layer about 29 m deep, capped by a near-surface restratification. The amplitude of the restratification varied between 0.3 and 1.3°C and its thickness between 3 and 8 m. Salinity was constant from the surface to 29 m (the small salinity anomaly near the surface is caused by inappropriate matching of the conductivity and temperature cell responses; it is not real).

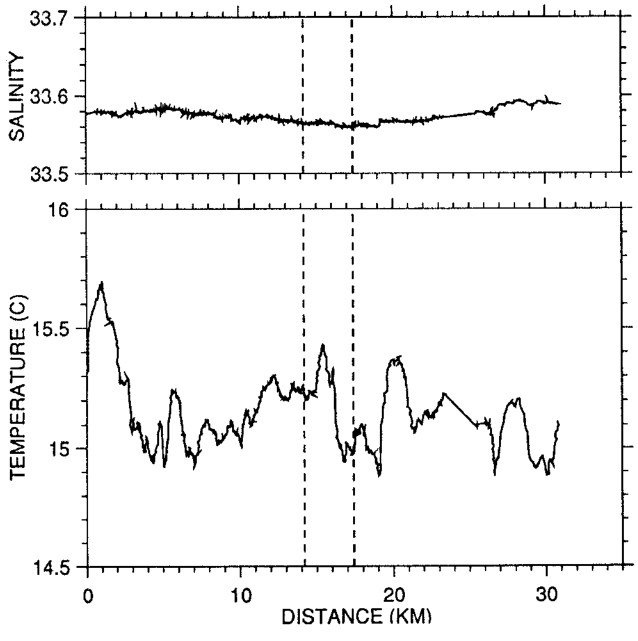

Fig. 5. Surface temperature and salinity sampled along the ship track, as a function of distance run. The turning points are shown by dashed lines.

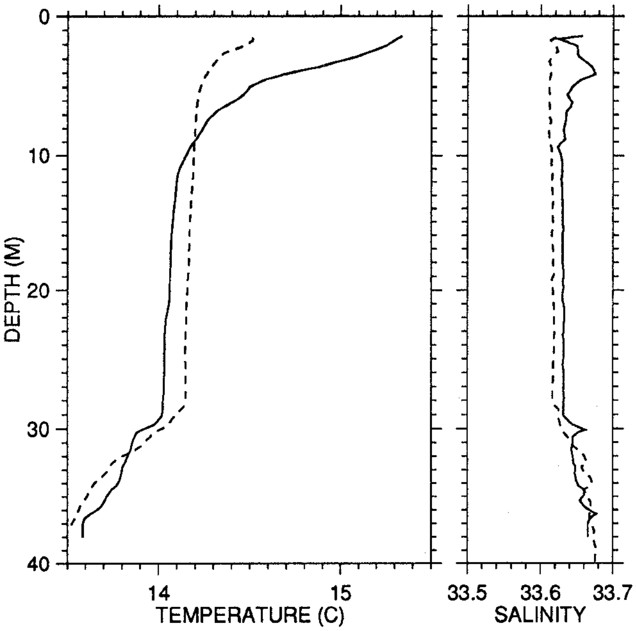

Fig. 6. Temperature and salinity profiles at approximately 1 km (solid) and 5 km (dashed) distance run.

4. Conclusion

We have shown, using a combination of satellite images and CTD profiles, that diurnal warming layers display coherent horizontal structures in the form of streaks at least 50 km long, with a wavelength of 4-8 km and an amplitude of 0.5-1.5°C. Although the survey was located 200 km to the southeast of the streaks seen in the images and was conducted 2 weeks later, we have all reasons to believe that the features observed were similar, given the steadiness of weather patterns during this period.

We have identified two similar events from satellite images and mooring data in April 1982 and in July 1988, which will be documented in a forthcoming paper. The coherent streaks appear quite common under low wind conditions in the California Current.

What processes may be responsible for these variations of surface temperature? The 4 to 8 km-wavelength scale of the streaks seems inconsistent with processes involving the upper ocean alone (i.e. Langmuir cells, interfacial waves, convective cells), which would scale with the mixed-layer thickness. Rather, this scale points to a coupling between the ocean and the planetary boundary layer, which may have a thickness of the order of a kilometer.

Helical circulation rolls occur frequently in planetary boundary layers (Brown, 1980). In general, they derive their energy from a combination of convective forcing and instability of the vertical shear. Their wavelength is typically 2 to 4 times the boundary layer thickness. Assuming preexisting rolls in the atmosphere, the surface windstress is maximum underneath the axes of the rolls and minimum at the stagnation lines between adjacent rolls. Two scenarios are possible.

If surface temperature is principally governed by one-dimensional entrainment of a warm surface layer, cold anomalies will form underneath the axes of the atmospheric rolls and temperature streaks at one-half the wavelength of the rolls will appear. On the other hand, if surface temperature is principally governed by convergent and divergent advection of a thin warm surface layer, cold anomalies will form underneath the divergent stagnation lines and temperature streaks at the wavelength of the rolls will appear.

Since the cold (divergent) lines form underneath the downdrafts and the warm (convergent) lines form underneath the updrafts, the second scenario leads to an interesting feed-back mechanism further enhancing the atmospheric cells. Thus it is possible that the streaks are ultimately caused by a coupled ocean-atmosphere instability, without the need for pre-existing circulations. This conjecture, of course, will have to be tested by a purposely designed experiment.

References

Brown, R.A., "Longitudinal instabilities and secondary flows in the planetary boundary layer: a review," *Rev. Geophys. and Space Phys.*, vol. 18, pp. 683-697 (1980).

Bruce, J.G. and E. Firing, "Temperature measurements in the upper 10 m with modified expandable bathythermograph probes," *J. Geophys. Res.*, vol. 79, pp. 4110-4111 (1974).

Cornillon, P. and L. Stramma, "The distribution of diurnal warming events in the Western Sargasso Sea," *J. Geophys. Res.*, vol. 90, pp. 11811-11815 (1985).

Stramma, L., P. Cornillon, R.W. Weller, J.F. Price, and M.G. Briscoe, "Large diurnal sea surface temperature variability: satellite and in-situ measurements," *J. Phys. Oceanog.*, vol. 16, pp. 827-837 (1986).

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