REGULAR ISSUE FEATURE

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THERMAL FOOTPRINTS OF WHALES

Figure 1. Photo of a north Atlantic right whale and calf, showing smooth footprints, each surrounded by a ring of rougher water that scatters more sunlight. *Courtesy of P. Duley, NOAA NMFS*

UNDER THE RIGHT meteorological conditions, whales can leave a trail of cool spots on the ocean surface that are detectable in infrared images. When the wind is light and the sun is shining, the surface water warms to produce a thermal gradient in the top few meters of the ocean. Under these conditions, whales swimming near the surface produce a jet of cooler water with each upward motion of the tail fluke. When this jet reaches the surface, it will produce a temperature difference that can persist for several minutes. In this paper, we report the first observations of these thermal footprints; we discovered them in infrared images made by a camera mounted in a light twin-engine airplane. We also describe their formation and dissipation.

An infrared camera that could detect whales from an aircraft when they are not visible by eye could be a useful tool for research and management. Already, visual detection of whales from low-flying (300 m or less) aircraft is an important technique. For example, ship strikes are a major source of mortality for the highly endangered (~ 300 individuals remaining) north Atlantic right whale (*Eubalaena glacialis*), and aerial surveys are used to direct shipping around individual whales (National Marine Fisheries Service, 2005). However, these surveys can only be done during the day, only animals at the surface can be observed, and the low-altitude flights over the ocean can be dangerous. An infrared camera could extend the conditions under which whales can be detected. It would also allow surveys at altitudes up to several thousand meters.

Whales have been detected in infrared images taken from the surface (Cuyler, et al., 1992; Perryman, et al., 1999; Thomas and Thorne, 2001). The clearest signals were from the blow and the blowhole, although centimeter-scale resolution is required to detect the latter. The blow is more detectable looking out from the surface than down from the air because of the lower background emissivity.

Whale footprints have often been seen and photographed during visual surveys. In Figure 1, the footprints show up as two slick spots behind a north Atlantic right whale and her calf. Whales propel themselves with an up-and-down motion of a demarcated caudal tail fluke that forms reverse von Kármán vortex streets in their wakes (Motani, 2002). The turbulence associated with the decay of these vortices damps surface waves, producing the visible slick. The turbulence decays rather quickly, and only a few footprints can usually be seen.

We discovered the thermal footprints following aerial surveys designed to locate fish in the vicinity of Steller sea lion haulouts near Kodiak Island, Alaska, in August 2001 and 2002. The primary tool of these surveys was a lidar, but the infrared camera was flown along with it for spotting sea lions directly, especially at night. Although whales were not the object of the surveys, it is a region where they congregate to feed in the summer. We were using an infrared video camera with a spectral response of 7–14 μm, a sensitivity of about 0.1 K, and a spatial resolution of 34 cm from our flight altitude of 300 m. Each frame of the video output covered a region 109 m by 82 m on the surface. During the day, we also recorded visible images with a spatial resolution of 20 cm. Species identification was by visual observation. As expected, the warm bodies of birds and of sea lions were clearly seen in the infrared images. We did not observe direct infrared images of whales or of whale blows and were pleasantly surprised to find evidence of the whales in the thermal footprints.

One of the most striking examples of a thermal whale wake (Figure 2a) occurred when we came up behind a pair of humpback whales (*Megaptera novaeangliae*) that were part of a group of about 12 animals observed to be feeding in the area. The length of the longer track is over 300 m, with about 4.9 m between the first three spots. The diameters of the first three spots, at the top of the track, are 3.7, 6.2, and 8.4 m. The length of the whale, taken from the visible camera, was 13.9 m, a typical length for a female

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humpback (Winn and Reichley, 1985). Its fluke width, 3.9 m, was about the same as the width of the first spot. The maximum contrast in the thermal image was about 1.3°C, which is consistent with previously published values for solar heating of the surface (Stuart-Menteth et al., 2005). Sea-surface temperature in the area, measured with an infrared radiometer, was 15.3°C.

The length of this track suggests that the thermal footprints must persist, but we would need to know the swimming speed of the whale to infer the persistence from the length of the track. Although we cannot estimate the speed directly from a single pass of the aircraft, we can make some inferences based on previous studies of the hydrodynamics of this type of propulsion. The approach is similar to estimating the speed at which a person was walking from the distance between footprints and the person's height. First, we noted that a study of seven species of odontocete cetaceans observed peak-to-peak fluke amplitudes equal to 0.21 ± 0.03 times body length (Rohr and Fish, 2004). Then, we used an empirical relationship between the power generated by the tail and the Reynolds number for the motion of the body through the water (Motani, 2002) to infer a swimming speed of about 2.4 m s^{-1}. This speed is reasonable for feeding humpback whales (Jurasz and Jurasz, 1979; Fish, 2004). The inferred fluke beat frequency is about 0.5 Hz. From the length of the track, it is clear that the thermal footprints must persist for at least two minutes if our estimated speed is close to the correct value. If the whales were traveling at closer to their migration speed of about 1.2 m s^{-1} (Corkeron and Connor, 1999), the same track would have to persist for over four minutes.

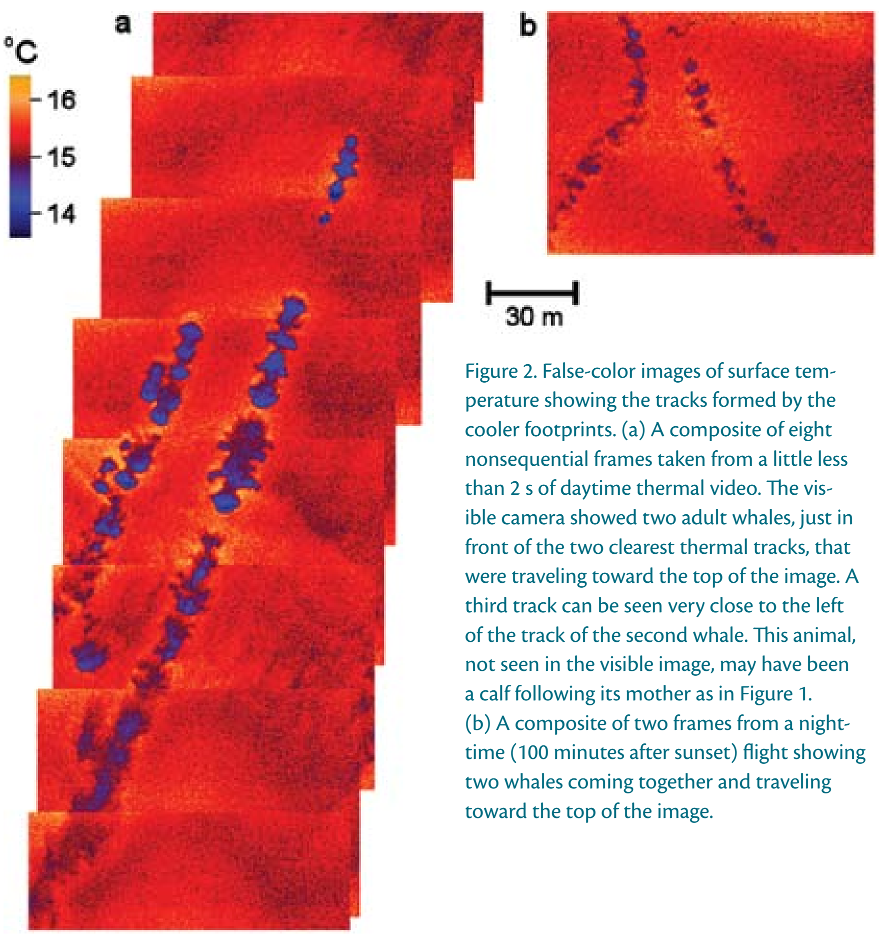

Figure 2. False-color images of surface temperature showing the tracks formed by the cooler footprints. (a) A composite of eight nonsequential frames taken from a little less than 2 s of daytime thermal video. The visible camera showed two adult whales, just in front of the two clearest thermal tracks, that were traveling toward the top of the image. A third track can be seen very close to the left of the track of the second whale. This animal, not seen in the visible image, may have been a calf following its mother as in Figure 1. (b) A composite of two frames from a nighttime (100 minutes after sunset) flight showing two whales coming together and traveling toward the top of the image.

We can explain this persistence with a relatively simple hydrodynamic model, in which we assume that each footprint starts as a jet with the same width as the fluke. This jet hits the surface and spreads, with turbulent mixing of the initial cooler water with the warmer water near the surface. Mathematically, we use the semi-empirical equations for average velocity and turbulent energy density of a jet (Monin and Yaglom, 1971). These are solved numerically, and temperature is assumed to be a passive additive quantity.

This model predicts that the magnitude of the temperature change at the center of the footprint should still be at about 0.5°C after two minutes. In fact, the calculated temperature difference out to 200 s is well approximated (within 0.01°C rms) by

$$\Delta T = 0.48^\circ \exp\left(-\frac{t}{14\mathrm{s}}\right) + 0.81^\circ\left(1 - \frac{1}{2}\sqrt{\frac{t}{300\,\mathrm{s}}}\right). \quad (1)$$

Thus, we have a rapid initial decay with a time constant that is similar to reported values for the time constant associated with the thermal signature of breaking waves (Jessup et al., 1997). This rapid decay is followed by a very slow decrease with a time constant of 300 s. Figure 3 shows this function, along with the measured contrast at the center of a number of spots along the track.

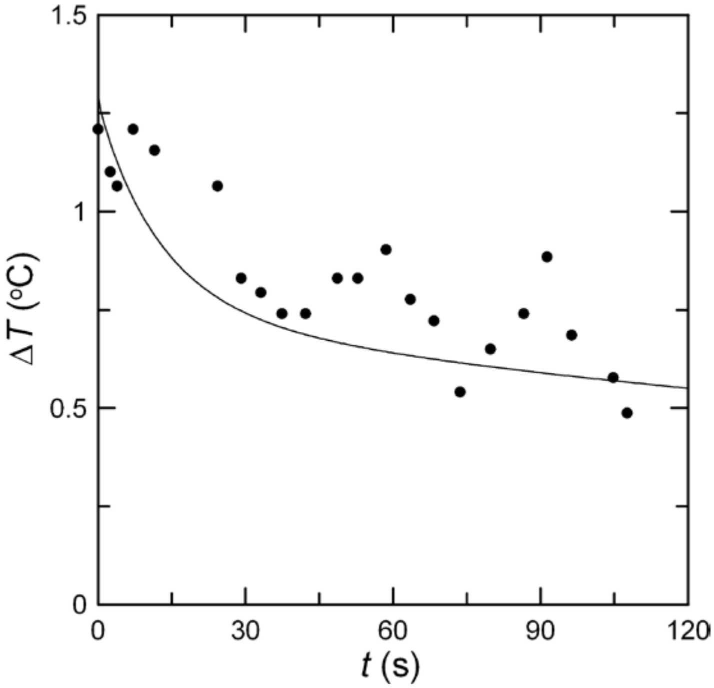

Figure 3. Plot of temperature contrast ΔT as a function of time t from Equation 1 (line) and measured values at the center of the spots in the right-hand track of Figure 2a.

The tracks can also provide some information on the interactions between whales. For example, the whale on the left in Figure 2a appears to be trying to catch up with the one on the right. The position of the track places the one on the left about 70 m behind the other, and the greater spacing of the first three footprints (6.7 m compared with 4.9 m) implies a greater speed. The tracks in Figure 2b tell us that one whale has met with another, and the two have continued on together.

The reliability with which whales can be detected in this manner remains to be determined, although thermal tracks were detected on any day that we visually detected more than four or five whales. We seldom saw the whales that left the tracks, so the persistence could not often be estimated. Numerous segments corresponding to about 30 s of travel by the whale were captured, and few of these had a noticeable difference in contrast between the leading and trailing ends of the track. The absolute water temperature does not affect the contrast, but a temperature gradient near the surface is required. The minimum temperature gradient would probably be several times the camera sensitivity, or 0.3–0.5°C m^{-1} for our camera. The maximum winds to get a detectable track were above 5 m s^{-1}; both examples in Figure 2 were obtained when the wind was 4.1 m s^{-1}. Contrast and persistence both tended to be higher during the afternoon on a clear day, as in Figure 2a, than at night after a cloudy day, as in Figure 2b.

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