# Simple Method for Measuring Relative Humidity, Water and Air Temperatures Within a Few Millimeters of Wind-Generated Water Waves

Allen H. Schooley

*Naval Research Laboratory, Washington, D. C. 20375*

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## ABSTRACT

A very short time-constant thermistor, mounted on a streamlined strut, was placed to alternately measure the water and air temperatures during the passage of wind-driven water waves in the laboratory. The results were preserved by using a high-speed recorder. A thin film of water was found to cling to the thermistor upon emerging from a wave and its evaporation recorded the wet-bulb temperature, followed immediately by the dry-bulb temperature when evaporation was complete. Thus, the relative humidity within a few millimeters of the wavy water surface was determined. Under the set of conditions used, it was found that molecular diffusion is important in the first few millimeters from the actual water surface before the transition to turbulent diffusion predominates.

## 1. Introduction

According to Roll (1965), "The boundary layer next to the sea surface is of crucial importance . . . for the exchange of heat and water vapor between the ocean and atmosphere, since it is here that the basic processes occur . . . At sea the laminar layer is scarcely accessible for measuring and, therefore, the question arises whether or not we are entitled to extrapolate from measurements taken in the turbulent region downward into the layer immediately at the sea surface."

During the past several years there has appeared a small amount of literature on average molecular sublayer thicknesses associated with air and water momentum transfer, heat conduction, and water vapor diffusion (Osborne, 1964; McAllister and McLeish, 1969; Wu, 1970; Schooley, 1971; Hill, 1972; Omholt 1973). There is still need for new tools to make direct relative humidity, and water and air temperature measurements within the molecular sublayers with respect to the actual air-sea interface, when wind waves are present.

This paper gives some preliminary measurements using a simple device that makes it possible to directly explore the region that Roll (1965) said is scarcely accessible for measuring.

## 2. Apparatus

Fig. 1 shows a commercial 0.013 cm diameter thermistor (small dot at the left center) supported vertically by 0.0013 cm diameter platinum-irridium leads. They are soldered to 0.05 cm diameter nickel wire that are embedded in a plastic streamlined spar (leading edge on the right). The horizontal distance between the spar edge and the thermistor is about 1.5 cm.

Fig. 2 is a picture of the 1.6 m short-fetch water-wind tunnel used in developing the device. For the experiments the water and air depths averaged 15 cm each (water was not introduced for this picture). Air was drawn from left to right by a variable speed blower, outside the picture to the upper right. The air inlet at the left was shaped to induce turbulent air immediately, thus simulating a considerably longer fetch than the actual length of the water-wind tunnel. The air was withdrawn directly upward on the right which minimizes end reflections, and water reaching the blower.

The streamlined spar is shown held at the 85 cm fetch point with the thermistor upwind at a height where it alternately samples both the water and air temperatures at and near the interface when wind waves are present. The thermistor is a part of a simple bridge circuit, connected to the amplifier of the commercial recorder in the foreground of Fig. 2. The time constant of the thermistor-recorder combination, under the conditions used, was about 0.004 s. The thermistor dissipation was about $6\times10^{-5}$ W. For the wind and water velocities used, the thermistor was sensitive to temperature only.

## 3. Experiments

The experiments yielded some unexpected results. For example, it was found that after the thermistor

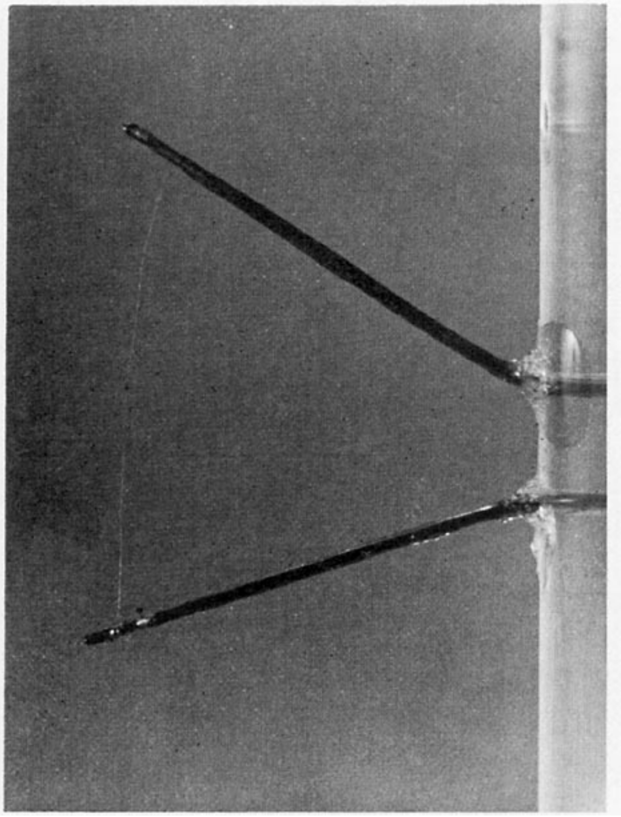

FIG. 1. Thermistor (0.013 cm diameter) supported 1.5 cm in front of thin streamlined spar.

emerged from the water it carried with it a thin film of water that quickly evaporated in the air, thus recording the wet-bulb temperature on the calibrated recorder tape. After evaporation, this was followed immediately by recording the dry-bulb air temperature at substantially the same height above the water. Thus, it was possible to make relative humidity measurements very close to the water surface.

Fig. 3 shows the average wind field immediately above a smoothed, average, short-fetch wave profile. The average wind-field vectors were obtained by tracing the trajectories of many small helium-filled, substantially neutrally buoyant, soap bubbles (Schooley 1963). The thermistor first may be considered to plunge into the water just before the crest strikes (on the left) and emerge somewhere between the crest and the trough as the wave passes. After emerging into the air the water film covering the thermistor starts to evaporate. It continues to evaporate as its distance above the water surface increases until all the water has evaporated. At this point the thermistor quickly changes from the wet-bulb temperature to the dry-bulb temperature. From these data the relative humidity may be determined by using a psychrometric slide rule.

Fig. 4 is one frame from a 500 frame per second, 16 mm cine film. The leading edge of the streamlined strut is on the right with the supports for the thermistor projecting into the wind. The thermistor bead is visible as a dark spot very near the center of the frame. The

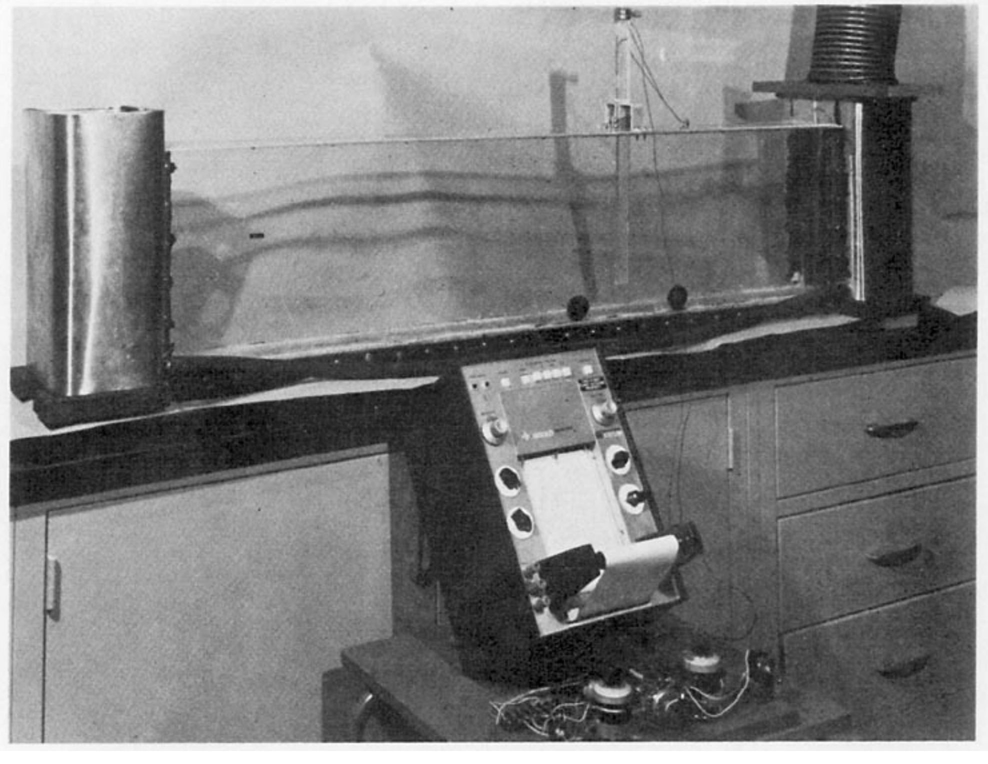

FIG. 2. Spar, with thermistor mounted in short-fetch water-wind tunnel at waterline (when filled) and connected to bridge circuit, amplifier and fast-response recorder.

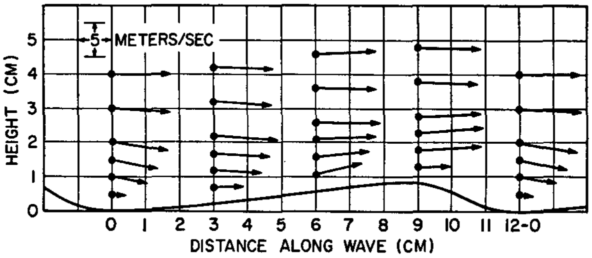

Fig. 3. Wind field immediately above and along an average short-fetch wind-wave profile.

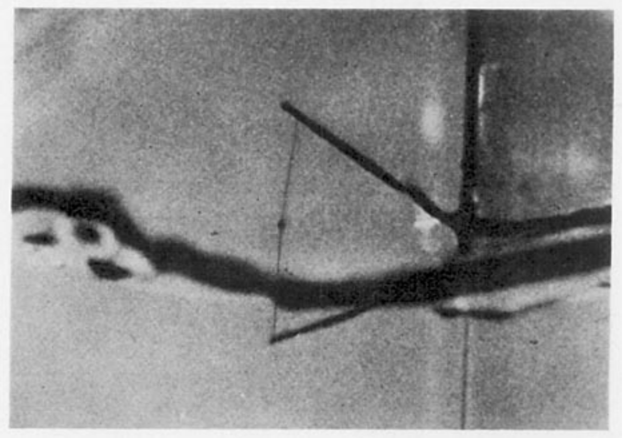

Fig. 4. One picture from a 500 frame per second cine film showing thermistor in the air and about to be undulated by the oncoming wave at the left. (Thermister retouched for reproduction.)

frame covered an area about 3 cm high by 6 cm long. At the time of this frame the thermistor is in the air and soon will be submerged by the oncoming wave crest which is approaching from the left. The water surface is the irregular dark shadow separating the water below from the air above. The measured mean wind speed at 5 cm above the average water surface was $\bar{U}_{5\,\mathrm{cm}}=8.6$ m s$^{-1}$.

Fig. 5 is a section of the recorder tape, showing how the thermistor bead changes temperature with time as it passes through the air-water interface of three successive waves. The tape was pulled horizontally from left to right in 0.8 s between the side lines. For ease of explanation it will be assumed that the recorder tape was stationary, and it was the recorder pen that moved at the same speed as the tape but in the opposite direction, i.e., from right to left. It is this time scale that is shown on the figure.

The vertical temperature calibration was 2.4°C per large division with a bottom line reference of 15.6°C.

Starting at the right-side temperature minimum the thermistor bead is in relatively cool 18.0°C water. After this minimum it measures an increasing temperature until it reaches a plateau of 19.7°C. (The small waves in the trace are due to 60 Hz power line pick-up by the recorder amplifier.)

At the start of the plateau the thermistor has just emerged from the water and is covered with a film of water that starts to evaporate; as the water evaporates the thermistor is held at substantially the same temperature as it rises in the air with respect to the water surface. When the water film on the thermistor is completely evaporated the thermistor quickly adjusts to the dry-bulb air temperature as is indicated by the sudden jump to 21.4°C from the wet-bulb temperature of 19.7°C. These dry- and wet-bulb temperatures represent a relative humidity of 86%. Use of high-speed cine pictures made it possible to estimate that the point of relative humidity measurement was about 0.21 cm above the actual wavy water surface.

After the jump to the dry-bulb reading the thermistor reaches a maximum and then drops in temperature with a reversal of curvature, probably coincident with entering the crest of the next oncoming wave. The inflection point appears to be at about 18.9°C. As time progresses, the next minimum temperature reached in the water is about 17.8°C. It is interesting to note that there is no sudden change in temperature at the transition from air to water even though the "bulk" air temperature was 39.5°C and the "bulk" water tempera-

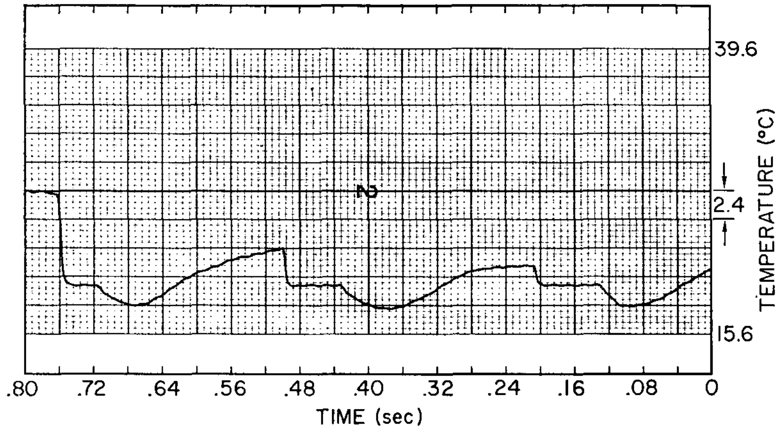

Fig. 5. Recorder graph of temperature vs time during the passage of three waves.

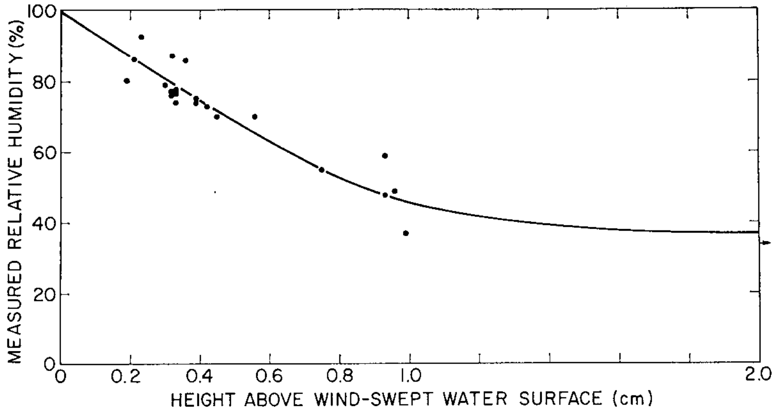

FIG. 6. Measured relative humidity as a function of height above the upwind slope of a group of 21 waves under one set of conditions.

ture 15.6°C. This unexpected result suggests that very near the naviface, eddy and molecular diffusion tend to moderate temperature difference.

Continuing to the left there are two more evaporation plateaus followed by sudden jumps to the respective air temperatures. In these cases the relative humidity was measured to be 76% at a height of 0.39 cm above the wind-swept water surface, and 49% at 0.96 cm above the wavy surface.

## 4. Summary of results

Fig. 6 shows 21 points, derived from 21 temperature signatures from 21 waves similar to the three described previously. The measured relative humidity is plotted as a function of height above the actual wind-swept water surface. A conventional psychrometer was also held at a mean height of 10 cm above the same point as the thermistor had been located. It indicated a relative humidity of 34% in the turbulent region above the water. The arrow on the right margin is at the 34% relative humidity ordinate. However, an extrapolation of the best-fit curve would require a fivefold increase in the horizontal scale to reach this value. This off-scale point to the right may be considered an asymptotic point in the turbulent air, for the mean curve drawn through the other points closer to the wavy water surface. (It was assumed that the relative humidity was 100% at the water surface.)

It appears from Fig. 6 that the mean relative humidity is a linear function of height up to about 3–4 mm and therefore appears to be significantly influenced by molecular diffusion under the conditions that have been described.

It is possible that similar measurements made at sea may show similar results. It is likely that the small mass and small cross section of the thermistor will withstand considerable buffeting by the sea if flotsam is absent. However, considerable refined engineering design will be required for a suitable streamlined spar mounting for use at sea. Two or more thermistors, displaced vertically by a few millimeters, will probably be required to estimate the height of each from the water surface by comparing the phase of the time-temperature recordings.

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