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# THE OCEANIC HEAT BUDGET AS AFFECTED BY HURRICANE AUDREY (1957)

by

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During 26-27 June, 1957, hurricane Audrey passed northward over the northwestern Gulf of Mexico approximately along 94 deg. W. It is of interest to determine the effects of this intense tropical cyclone on the heat budget of the superthermocline water; further, to investigate the restoration of thermal equilibrium after the hurricane.

For these purposes the affected area may be defined as the northwestern Gulf north of latitude 24N and west of longitude 90W. Sea surface temperatures from ship reports were **studied** from 23 June 06Z through 6 July 12Z. Study of air temperatures was carried out for the "recovery period" only, defined as beginning 27 June 18Z. The ship reports were subdivided into the following significant time groups.

| Name | Time Limits | Storm Behavior |
|---|---|---|
| Before | 23 June 06Z to 26 June 00Z | Had not yet entered area |
| During | 26 June 06Z to 27 June 12Z | Traversing area |
| After I | 27 June 18Z to 30 June 12Z | Had left area; gone inland |
| After II | 30 June 18Z to 3 July 12Z | Had left area; gone inland |
| After III | 3 July 18Z to 6 July 12Z | Had left area; gone inland |

Since the area is small and since ocean properties are nearly homogeneous within it during summer, averages of variables may be formed simply by taking the arithmetic mean of all observations. Results are shown below.

| Period | Sea Temp °F | No. Reports | Air Temp °F | No. Reports |
|---|---|---|---|---|
| B | 84.3 | 59 | | |
| D | 83.6 | 34 | | |
| A I | 82.0 | 30 | 82.8 | 37 |
| A II | 83.3 | 29 | 83.7 | 36 |
| A III | 84.3 | 23 | 83.6 | 26 |

Passage of the hurricane resulted in an area-averaged surface temperature drop of at least 2.3 F (1.3 C), probably more, since the three-day average temperature for period AI, a period of undoubted warming, should exceed the temperature at the start of this period.

Fuglister's (1947) thermocline data indicate an average thermocline depth over the area of only 15 meters. This shallow depth suggests the assumption that temperature reduction was uniform through the super-thermocline layer. Greater cooling at the surface than at the thermocline, given constant temperature above the thermocline as initial condition, would have resulted in gravitational instability. If, in the first approximation, the thermocline depth may be treated as constant and if vertical heat flux due to mixing below the thermocline may be neglected, the water mass affected by the hurricane was 1500 gm $\text{cm}^{-2}$ with use of mean thermocline depth in lieu of synoptic data.

Hurricane passage: The energy extraction by the hurricane may now be computed as

$$-1.3\ ^{\circ}\text{C} \times 1\ \text{cal gm}^{-1}\ ^{\circ}\text{C}^{-1} \times 1.5 \times 10^{3}\ \text{gm cm}^{-2} = -1950\ \text{cal cm}^{-2}.$$

The hurricane affected the area for 1½ days. Thus, the energy extraction rate averaged 1300 ly/day or .90 ly/min. Under hurricane conditions the Bowen ratio is known to be considerably enhanced over the value typical for the undisturbed trades. Choosing 0.25 for the ratio and using 582 cal/gm for the latent heat of evaporation, a water depth of 2.7 cm was evaporated and the evaporation rate was 1.8 cm/day, a conservative value.

Recovery period, first phase: Subsequent to the hurricane, the subtropical Atlantic anticyclone built westward over the north-central Gulf, with fair skies over the area of computation (about 2.5 2 oktas total cloudiness from inspection of surface charts). From the ship data we assume that a sea surface temperature of 82.0 F occurred at approximately 29 June 06Z and that this temperature had warmed to the air temperature (83.7 F) by about 3 July 11Z. Then sea surface temperature rose 1.7 F (0.9 C) in 4.2 days. If this warming was uniform in the super-thermocline layer, the net heat input rate was

$$\frac{1.5 \times 10^{3} \text{ gm cm}^{-2} \times 0.9\ ^{\circ}\text{C} \times 1 \text{ cal gm}^{-1}\ ^{\circ}\text{C}^{-1}}{4.2 \text{ days} \times 1.44 \times 10^{3} \text{ min day}^{-1}} = 0.222 \text{ ly/min.}$$

Since the air layer just above the ocean surface was gravitationally stable, we may try the hypothesis that no sensible or latent heat exchange occurred between sea and air. If so, the heat budget of the layer was determined mainly by radiative heat fluxes; the period is too short for lateral advection of water masses to enter as a factor. We then have:

Net heat input = short-wave incoming radiation from sun and sky -

- infrared outgoing radiation from sea surface.

For an estimate of the radiative fluxes, we turn to Sverdrup's "The Oceans" (1942). Table 25 on p. 103 lists average incoming solar and sky shortwave radiation reaching the surface as a function of location (latitude and longitude belts) and month. Interpolating suitably between latitudes 10 and 30N and between June and July, the incoming radiation may be estimated as .301 ly/min. for average cloudiness and as ~~.39~~ .35 ly/min for actual cloudiness. It is assumed here that, in the first approximation, the constant used to estimate the climatic effect of cloudiness can be applied to short periods. In future work, this assumption will be eliminated through use of pyrheliometer observations when possible.

Sverdrup's fig. 25 on p. 111 yields effective infrared back radiation from the sea surface to clear sky as a function of sea surface temperature and ambient relative humidity of the air. Given the mean-period sea surface temperature of 82.8 F (28.2 C) and relative humidity of 77 per cent (air temperature 83 F, dewpoint 75 F), the back radiation is .167 ly/min. Cloudiness may be taken into account with the empirical formula on p. 112 of Sverdrup's text

$$Q_{net} = Q_{clear} (1 - 0.083C)$$

where C is cloudiness in deciles. For the cloud cover of ~~2~~ 2.8 oktas (~~2.5~~ 3.5 deciles) the net infrared radiation is ~~.13~~ .12 ly/min. This calculation should be replaced with measurements by net radiometer.

For calculation of the net heat input into the Gulf we now have ~~.39~~ .35 - ~~.13~~ .12 = .23 ly/min or almost exactly the required quantity. In view of the computational uncertainties, all fully stated, not too much significance can be attached to this result. Nevertheless, it is of interest that use of a mean thermocline depth and climatic formulae for radiative fluxes a fit to the observed temperature rise is obtained when sea-air heat exchange is taken as zero because of prevailing gravitational stability near the surface.

<u>Recovery period, second phase:</u> Let us now consider the period from 3 July 11Z to 5 July 06Z, the midpoint of period AIII, duration 1.8 days.

During this period the sea temperature gradually rose above the air temperature so that heat transfer from sea to air should have resumed. At first, we shall compute the heat budget without such heat transfer in order to determine whether a positive imbalance, available for transfer from sea to air, is obtained.

As 7 hours of the present period occurred in AII and 36 hours in AIII, the weighting formula of .16 (AII) + .84 (AIII) was used for each quantity. It may be noted immediately that extension of this calculation over a longer time interval with three more days AIV would have been preferable, for better stabilization of mean values and time increments. Using the above weighting formula, the mean cloudiness was 3.6 oktas (4.5 deciles) and the relative humidity 79 per cent. Proceeding as before, the net downward flux of insolation was .34 ly/min, the outgoing radiation was .11 ly/min, net downward heat flux .23 ly/min as for the previous period.

The sea surface temperature rose from 83.7 F to 84.3 F, an increment of 0.6 F or 0.3 C. Again holding the super-thermocline temperature at a uniform value, the required net heat flux down is .17 ly/min. With this, an excess of downward heat flux over required heat flux is obtained. Its value is .06 ly/min. Since this is a rather small residual between two larger numbers, its reality is open to some doubt. Nevertheless, the residual has the correct sense, and in the following we shall compare it with values of sea-air heat exchange computed from the turbulence approach.

In view of lack of precipitation and small air-sea temperature differences, we may now neglect sensible compared to latent heat transfer. The latter, following the turbulence method, has been expressed as

$$Q_e = \text{const x } \overline{(q_s - q_a)\ V},$$

where $q_s$ is saturation specific humidity at the sea surface, and $q_a$ and V are specific humidity and wind speed at ship's deck level, respectively. The bar denotes area averaging. From previous computations (unpublished) the area average of a product may be replaced by the product of area averages, when ship reports in a small region and over a limited time period are considered under synoptic conditions as described. In fact, the product of area averages may be preferred, since it eliminates the effect on the computation of occasional spurious ship data input.

The following additional quantities were available for computation.

| Period | Wind Speed (knots) | No. Reports | Dewpoint ($^{\circ}$F) | No. Reports |
|---|---|---|---|---|
| AII | 11.8 | 16 | 76.9 | 11 |
| AIII | 9.6 | 13 | 74.7 | 9 |

The report density is less than in our first table since the above means were obtained (later) from The Northern Hemisphere Daily Bulletin, which lists 12Z data only, while the previous means came from comprehensive teletype reports.

All interest centers on the value of the constant in the evaporation equation, since this constant is known not to be absolute, but dependent at least on air-sea temperature difference and wind speed. Indeed, as such seen, the whole equation may lose its meaning when the air is warmer than the sea surface (cf. also Riehl 1954). For mean trade wind conditions with wind speed of 13-15 knots and air-sea temperature difference with order of 1 F, the constant has been computed as $3 \times 10^{-3}$, when $q$ is expressed in g/kg, $V$ in knots and $Q_e$ in ly/min. Use of this constant would result in evaporative heat flux of .21 ly/min from the present data which is too large by a factor of three. A constant of $1 \times 10^{-3}$ is appropriate, implying a different eddy structure and transfer effectiveness near the suface under present compared with mean trade wind conditions.

Conclusion: In this report, an initial effort to investigate transfer processes at the sea-air boundary under varying atmospheric and oceanic conditions in the tropics has been described. The main purpose was to see whether use of ship data with all their faults, plus computational techniques and climatic data taken from the literature, would yield something of sufficient interest to pursue these calculations in a variety of situations. The conclusion is that the results presented offer encouragement in the direction of continuation of the experiment. Assume, for the sake of argument, that the results are really trustworthy. Then it should follow, for instance, that impact of a similar hurricane on an ocean area with thermocline depth of 50 - 100 meters would produce a correspondingly smaller temperature drop and that the recovery period should also occupy much more time, with further reaction on weather disturbances passing subsequently over such an area. If, however, the temperature rises rapidly during the recovery period, then lack of effective mixing throughout the super-thermocline layer under conditions of slight stability must be postulated. Calculations from other hurricanes, and from non-hurricane situations, are presently under way.

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