ADVECTION—A CLIMATIC CHARACTER IN THE MID-PACIFIC

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In an attempt to discover oceanographic changes in the Hawaiian Islands region which may be associated with the seasonal nature of the skipjack fishery and its annual fluctuations, we have been looking into what might be described as the "oceanographic climate" of the region. This involves a study of the time and space distribution of surface variables which by means of budget considerations will yield some information regarding the processes associated with these distributions. The following notes describe partial results of this study and may be of interest during the second portion of this Symposium.

Since the temperature is of primary interest in any climatic study, the following will deal with the heat budget of the surface layer. On the basis of conservation of heat one can say that at any locality in the ocean the net heat exchange across the sea surface must be balanced by the change in heat content of the water column, heat diffused through the sides of the column, and the heat carried in or out of the column by means of currents. Such an expression can become rather complicated. However, since this is to be a climatic study, interest lies with the gross seasonal changes and therefore some simplifying assumptions can be made for the Hawaiian survey region (10°-30°N., 150°W-180°).

In this area the mixed surface layer is generally well defined and since it has neutral stability one can say that heat exchanged across the sea surface is uniformly distributed throughout this layer. Furthermore, because of high stability in the thermocline just below the mixed layer, and small horizontal temperature gradients, vertical and lateral diffusion are assumed negligibly small compared to advection and heat exchange across the sea surface. With these assumptions the heat budget and the volume budget of a column of water of unit cross sectional area can be expressed by

$$\frac{\partial z}{\partial t} = -\nabla(z\bar{v}) \quad \text{and} \quad \frac{\partial(C_p z\theta)}{\partial t} = H - \nabla(C_p z\theta\bar{v})$$

which after expanding and combining reduce to

$$\frac{\partial \theta}{\partial t} = \frac{H}{zC_p} - \bar{v} \cdot \nabla\theta$$

In the above equations H is the net heat exchange across the sea surface (insolation less evaporation less back radiation less conduction), θ is the surface temperature, C_p is the specific heat at constant pressure which can here be considered constant, z the depth of mixed layer, $\bar{v}$ the velocity, and ∇ the operator

$$\bar{i}\frac{\partial}{\partial x} + \bar{j}\frac{\partial}{\partial y}$$

The last equation, the temperature budget, states that the time rate of change of temperature and not the absolute temperature is of importance when processes are considered. The equation also points out that in order to understand the advection term $(\bar{v} \cdot \nabla\theta)$ the horizontal distribution of temperature about the locality of interest must be known. In other words, by knowing the horizontal temperature gradient, one can obtain a measure of the velocity component perpendicular to the isotherms. Finally, heat advection cannot give any information about the velocity component parallel to the isotherms.

A similar expression for the salinity budget in the surface layer is as follows:

$$\frac{\partial s}{\partial t} = \frac{s}{z}(E-P) - \bar{v} \cdot \nabla s$$

Here s is the salinity and $(E-P)$ the evaporation minus precipitation.

The above discussion as well as the approximate values of $\frac{\partial \theta}{\partial t}$ and $\frac{H}{zC_p}$ used below, will be presented with more detail in the climatic atlas which is in preparation for publication.

Of interest now are the graphs obtained when $\frac{\partial \theta}{\partial t}$ and $\frac{H}{zC_p}$ are plotted versus time as shown in figure 47A. The solid line shows the mean seasonal variation of the rate of change of surface temperature in the vicinity of Oahu, Hawaii, and the dashed line the seasonal rate of change of surface temperature due to the net heat exchange across the sea surface only. The difference between the two curves indicates advection.

Thus, when $\frac{H}{zC_p} > \frac{\partial \theta}{\partial t}$, the component of flow across the isotherms is from cold to warm, indicating cold advection. When $\frac{H}{zC_p} < \frac{\partial \theta}{\partial t}$, warm advection is indicated. No advection $\frac{H}{zC_p} = \frac{\partial \theta}{\partial t}$, indicates either flow parallel to the isotherms or no flow.

Figure 47A shows what may be called characteristic advection features for the vicinity of Oahu: low advection from February to May, and considerable advection for the remainder of the year.
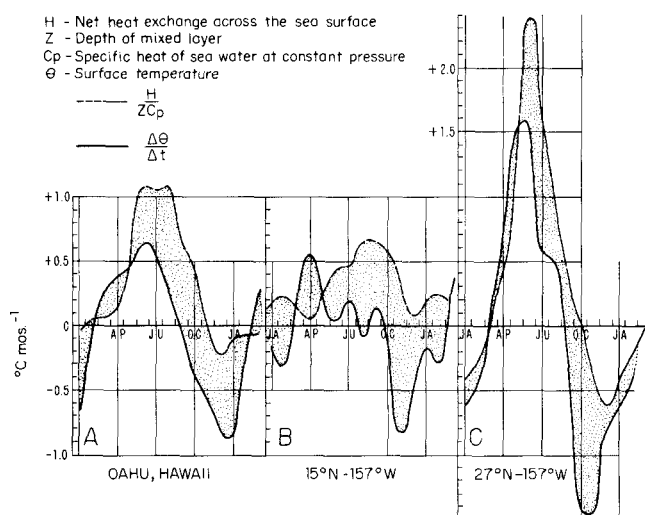
H - Net heat exchange across the sea surface
Z - Depth of mixed layer
Cp - Specific heat of sea water at constant pressure
Θ - Surface temperature

$\dfrac{H}{ZC_p}$

$\dfrac{\Delta\Theta}{\Delta t}$

OAHU, HAWAII   15°N -157°W   27°N-157°W

FIGURE 47. Characteristic heat advection curves.

Similar graphs can be drawn for other locations. For example, figures 47B and 47C show the "characteristic heat advection curves" for 15°N. and 27°N. to the south and north of Oahu, respectively. At 15°N. warm advection occurs during March to May, the $\dfrac{\Delta\theta}{\Delta t}$ max and $\dfrac{H}{zC_p}$ max are four to five months out of phase, and even the $\dfrac{\Delta\theta}{\Delta t}$ fluctuations between June and October are believed to be characteristic of the location.

The characteristic heat advection curve for 27°N. (Fig. 47C) shows that the period of low advection extends from February to May and high advection from October to December, approximately as in the vicinity of Oahu. However, the curves also reveal that the heat exchange across the sea surface plays a greater role in determining the surface temperature than it does farther to the south. In other words, advection is relatively less important in determining the temperature than is the heat exchange across the sea surface.

To illustrate how the characteristic advection curves may be used to interpret local temperature anomalies, the mean Oahu temperatures and rates of change of temperature (solid lines) are drawn in figure 48 together with the Koko Head values for 1956 and 1957 (dashed line). Of interest in figure 48A are the below normal temperatures February to June 1957, and again from December 1957 to April 1958. Also of interest are the below normal temperatures during November and December of 1955.

Figure 48B deviations from the mean pattern are brought out in terms of processes. For the sake of clarity the mean $\dfrac{H}{z}$ curve has been omitted from the graph. The $\dfrac{\Delta\theta}{\Delta t}$ curve shows that in December 1955 and January 1956 it was higher than the mean curve which can be interpreted as less cold advection. Then from February to April of 1956, the curve is below the mean which indicates an increase of cold advection during that period. September and October of 1956 indicated reduced cold advection. The $\dfrac{\Delta\theta}{\Delta t}$ curve for 1957 shows colder than normal advection between January and April and then, during May and June, considerable warmer than normal advection. Finally, during November and December colder than normal advection is again indicated.
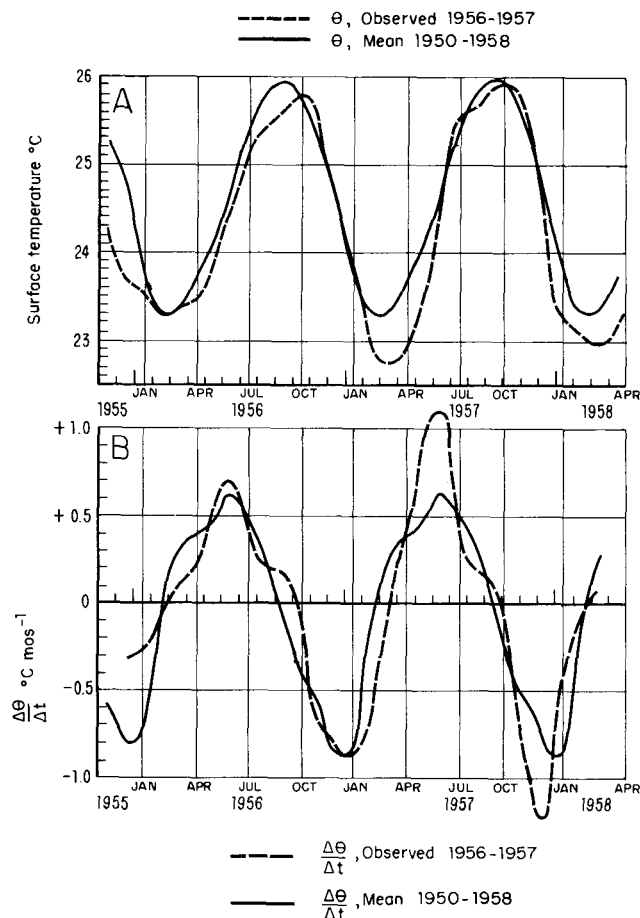
Θ, Observed 1956-1957
Θ, Mean 1950 -1958

$\dfrac{\Delta\theta}{\Delta t}$,Observed 1956-1957

$\dfrac{\Delta\theta}{\Delta t}$,Mean 1950-1958

FIGURE 48. A. Mean and observed surface temperatures, Oahu, Hawaii. B. Characteristic and observed rates of change of surface temperature, Oahu, Hawaii.

When the 1957 $\frac{\Delta\theta}{\Delta t}$ curve is now compared to the mean or characteristic curve at 27°N. (Fig. 47C), a striking resemblance in the shape of the two curves becomes apparent. This suggests a southward shift of the oceanographic climate. Or, during 1957, Oahu found itself in an oceanographic climate normally to be found a few degrees of latitude to the north. This observation is in agreement with the salinity observations presented by Murphy et al.

Similar salt advection curves could add significantly to the climatic picture of a region. Unfortunately, our salinity data are too incomplete to enable an interpretation of the 1956, 1957 salinities in terms of salt advection at this time.

To summarize, characteristic heat advection curves illustrate two important climatic features:

1. Deviations from the mean $\frac{\Delta\theta}{\Delta t}$ curve as in 1956 can explain temperature anomalies in terms of heat exchange and advection, and, if the temperature gradients are also known, changes in the component of flow normal to the isotherms.

2. Changes in the characteristic $\frac{\Delta\theta}{\Delta t}$ pattern as in 1957 can reveal shifts in the oceanographic climate.

GENERAL REMARKS

The shortcomings in the above discussion lie in experimentally unverified interpretation of the $\frac{\Delta\theta}{\Delta t}$ curves and not in the use of such curves as tools in interpreting monitoring data. This is primarily due to the fact that one or more members of the budget equation are usually absent.

In order to be able to interpret characteristic advection curves with confidence, temperature and salinity measurements are insufficient to begin with. In the Hawaiian Islands region, the magnitude of the year-to-year variation of H and z must be determined as well as changes in the horizontal temperature and salinity gradients. In order to be able to verify the results, the velocity must also be determined.

We may discover that because of the buffering action of the sea the heat exchange across the sea surface shows little annual variation. We may also discover that the same is true for the horizontal gradients in many areas. We may find that although diffusion is not entirely negligible, the year-to-year variation of diffusion would be. Thus, characteristic advection curves could be used to interpret temperature and salinity anomalies in terms of shifts in oceanographic climate or changes in flow perpendicular to the iso-

pleths. They could also be used to interpret past records where adequate time series are available.

ADDENDUM

In the discussion of figure 48B the deviation of the 1956-1957 observed $\frac{\Delta\theta}{\Delta t}$ curve from the mean $\frac{\Delta\theta}{\Delta t}$ curve was explained in terms of advection. This implies that $\frac{H}{z}$ and diffusion do not show year-to-year variations which, of course, is not reasonable. There are, however, data which suggest that year-to-year changes in these are insufficient to account for the $\frac{\Delta\theta}{\Delta t}$ deviations during 1956 and 1957.

In the vicinity of the Hawaiian Islands examination of the vertical temperature gradient below the mixed surface layer reveals no seasonal change. This suggests that the stability also remains constant and that therefore significant changes in the vertical diffusion are unlikely even if the diffusion is not negligible as assumed in the above discussion.

The seasonal range of the calculated heat losses from the sea surface (evaporation, back radiation, and conduction of sensible heat) is only about 5 percent. It is expected that the year-to-year changes in the heat lost from the sea surface are less.

Remaining is the incident radiation which can vary considerably due to changes in cloud cover. Although no observations are available at sea, the incident radiation has been measured on Oahu by the Hawaiian Sugar Planters Association and the Pineapple Research Institute.

Between 1943 and 1957 the greatest deviation of the incident radiation from the mean for the month of June has been less than ± 10 percent. Therefore, in June one might expect a change in $\frac{\Delta\theta}{\Delta t}$ of .1°C. due to a change in incident radiation. In winter when $\frac{H}{z}$ is small the year-to-year fluctuations in $\frac{H}{z}$ would result in a negligible change of $\frac{\Delta\theta}{\Delta t}$.

Going back to figure 48B, the deviations of the observed from the mean $\frac{\Delta\theta}{\Delta t}$ curve were approximately as follows:

December 1955—January 1956	+ .5°C.
February—April 1, 1956	− .15°C.
September—October 1956	+ .3°C.
January—April 1957	− .4°C.
May—June 1957	+ .5°C.
November—December 1957	+ .5°C.

These are well in excess of changes to be expected from changes in $\dfrac{H}{z}$ so that advection remains as the most likely process responsible for the 1956-1957 sea-surface temperature changes in the vicinity of the Hawaiian Islands.

DISCUSSION

Charney: Before opening the discussion from the floor, I wonder if I might use my prerogative as chairman to ask a number of questions. Since I do not have the proper background for absorbing oceanographic data in such large quantities, I feel that I have just about reached my saturation point and should like to hear some explanations. Quite a number of events have been reported and, as has been pointed out, we may be talking about phenomena on different scales. The examples presented by Mr. Murphy are a very good documentation of oceanographic changes. Attention has been concentrated on the temperature anomalies. May I ask questions about these anomalies? It seems to me that temperatures in the ocean can be changed by a number of mechanisms, some of which have already been mentioned by Mr. Murphy. Anything that would interfere with the net heat flux at the ocean surface would produce temperature anomalies. But variations in surface-heat flux do not in themselves determine the anomalies. You have to know what is happening beneath the surface. In the central regions of the oceans the heat that is being absorbed at the surface is at least partially balanced by the downward flux into deep water: if you increase the downward flux of heat beneath the surface, the temperature will fall, and conversely, if you decrease the downward flux of heat, the temperature will rise.

Anything that would decrease the anticyclonic curl of the wind stress would immediately, everything else being constant, decrease this downward flux of warm water and produce a warming. This is one mechanism. How important is it?

The next question is suggested by the data that Professor Isaacs so kindly provided beforehand. At Woods Hole we looked at the NORPAC current velocities and temperature distributions and asked ourselves, "Can one account for the temperature increases, which are of the order of 2° or 3° F., in a relatively short period, by advection of warm water?" I gather from Mr. Murphy's remarks that there is a possibility of this too.

A third question is suggested by Mr. Namias' reference to a possible correlation between anomalous temperature changes in the oceans and anomalous temperature changes in the atmosphere, although he carefully avoided the implication of a direct causal relationship. One can at least ask the question: to what extent are the temperatures in the ocean determined by the atmospheric temperatures? I am under the impression that the direct transfer of heat between the atmosphere and the ocean is small and could not account for the changes. If this is so, the influences must be more roundabout.

I do not presume to answer my own questions. They are questions, however, that I think are pertinent to the problems with which we are dealing here. And, I wonder if it makes any sense at this point, before we try to assimilate more data, to try to get some answers. Those who have presented the data have, of course, thought about answers to these or similar questions. By observation they have tried to establish direct physical relationships or to suggest the possibility of some mechanism or another. After all, we do have something to explain: enormous changes—anomalies of up to 6°F over a very wide area in the Pacific. These changes are rather sudden. From December to January, there are changes of 4 to 6°F. How does one account for these changes? Can one account for them by advection?

Fleming: Can I point out here that, in terms of total heat budget for the year, the changes in the heat of water are very, very small, compared to the other process of heat exchange. In other words, back radiation is so large compared say, to heat in the water, that I think you have to look for some process that is altering incoming radiation or evaporation. As has been said before, many of these are feedback mechanisms. I think you have to remember that you are looking at something that is probably a consequence, more than a cause.

Reid: Referring to one of your mechanisms—the temperature change which can be accounted for by wind curl—we do have measurements of temperature change but no computations of wind curl. We do have an index of pressure changes. When we consider the circulation of the winds and the known temperatures, we have found what appears to be in many cases, a relation between wind variations and temperature variations. We have a theory in mind but it is not necessarily a correct one.

Stommel: When you strengthen the California Current you do it by decreasing the wind curl.

Reid: And increased temperatures might be caused, among other things, by weaker winds as well as decreased wind curl.

Stommel: When you increase wind you have an increase in current and therefore a convergence to the right, and both of these could possibly change the water surface temperature.

Reid: Increasing the thickness of the mixed layer by stirring would cause cooling. In part of the Northern Pacific region, the wind strength is *inversely* related to the temperature, but in the Kuroshio it is *directly* related, in some seasons.

Charney: It would depend on how far down the mixing went.

Reid: We do have vertical sections across the California Current which show that in 1957 there was great warming in the mixed layer, and in some cases there appears to be a maximum in the extent of the warming just below the thermocline. The heat has not been merely redistributed so that the water is cooler below the thermocline than above. Enough additional heat has come in by some advective process to have warming below the thermocline as well as above.

Charney: Why do you say some advective process?

Reid: Because I have in mind a tentative hypothesis involving advection, which is consonant with the recent changes in the California Current system.

Charney: What about the stirring downwards of the heated layer?

Munk: I was going to say that maybe to some extent you can reason from an analogy with the seasonal effect as we are talking about a three months abnormality of weather. Dr. June Pattullo, for a doctor's degree, tried to work out a heat budget of the world on a seasonal basis and found out that for most of the world, the changes in heat content are limited to the upper layers. One can use the flux and ignore advection, and come out quite well. That tends to bear out Dr. Fleming, in that there is plenty of flux in and out.

Fleming: Also, I think while we are discussing this, a number of people have tried to evaluate these processes and they never succeed. You really can not evaluate all the factors. We have tried to account for the annual cycle of temperature. Gunter Seckel has been working with data around Honolulu, but you really cannot evaluate these things because there are too many unknowns. For example, in terms of the advection, you nearly always have horizontal gradients, but you do not know the direction of the flow well enough to know what component to put in to evaluate the advection.

Charney: But I gather from those remarks that if you simply made the assumption that there was a little advection, you could account for the changes.

Fleming: If you take the whole North Pacific.

Munk: If you could take the heat content (not temperature) of all oceans, then, of course, you have no advection. Only the flux through the surface is important—evaporation, radiation, etc. For even small units, advection might be a comparatively small factor. Dr. Pattullo took one gyre at a time and did pretty well by simply assuming no advection in and out of the gyres.

Charney: If you consider the seasonal mean, would it be possible to take the wind data and compute the mean Ekman convergence, which would give the flux of heat through the bottom of the wind-stirred layer? It seems to me that other things being equal, this would then give the anomalous temperature changes as well as the heat content changes. Of course we are only talking about superficial aspects. In other words, I do not think of this mechanism as determining the heat supply but only as determining changes in the surface layers. It may have little to do with the overall heat budget of the oceans.

Schaefer: If you know the change in heat content because you have measured it, from what do you compute this flux?

Charney: I may be all wrong and I hope someone will correct me if I am, but here is my reasoning: assume that the Coriolis force in the wind-stirred layer

is balanced by the pressure force and the force of friction due to vertical eddy transfer of momentum:

$$f \vec{k} X \rho \vec{v} = - \nabla_h p + \frac{\partial \vec{\tau}}{\partial z}.$$

Take the curl and integrate through the entire depth h of the windstirred layer. One obtains approximately

$$f \int_{-h}^{o} div_h (\rho \vec{v}) \, dz = \text{curl } \tau_o;$$

From continuity

$$div_h (\rho \vec{v}) \cong - \frac{\partial(\rho w)}{\partial z}.$$

Whence

$$f(\rho w)_{z = -h} = \text{curl } \vec{\tau_o},$$

which states that the mass transport ρw at the bottom of the stirred layer is equal to the curl of the surface wind stress divided by the Coriolis parameter. If the temperatures at this level are assumed to be known, the heat transport is thereby determined. This is essentially a mid-ocean up or downwelling effect.

Schaefer: Are you going to measure this quantity on the right from the pressure charts, and compute the vertical flux of heat?

Stommel: From a dynamic point of view, would it not be more constructive if you could use mixed layer depth rather than surface temperatures? That is what Seckel did.

Isaacs: But there was an increase in heat below the thermocline off California, and one of Seckel's assumptions was a negligible heat transfer vertically through the thermocline.

Schaefer: Rather than depend on a wind stress to compute heat transfer, Seckel used the total heat content of the water column. He measured this directly. One factor is bothersome here. You have three processes—advection, changes in incoming and changes in back radiation. The bothersome thing is back radiation. You either have to assume it to be a constant or measure it. For incoming radiation and back radiation, you wind up using some average for the Northern Hemisphere—values that do not apply to the particular area you are working with.

Charney: Is this a small difference between two large terms?

Schaefer: It is the difference between two relatively large terms. You do not know them for the exact data you are working with, and you assume some sort of average.

Saur: Roden, did you not make some calculations on the heat transport of the California Current? And did these not show a loss of up to 400 gram calories per day per square centimeter?

Roden: On an annual average the incoming radiation is about 400 cal per cm² per day. The back radiation is about 100 cal per cm² per day. The loss of heat through evaporation is about 100 cal per cm² per day.

This leaves 200 cal per cm^2 per day for the advection term, and the advection must be of cold water. Since radiation varies only by a factor of two in different years, and wind by as much as a factor of five (and stress as the square of this, Eds.), I think that heat changes are more likely to be caused by wind changes than by radiation changes.

Namias: One of the effects perhaps resulting from vertical motion, particularly in some of the areas of figures 21 and 22, was a particular dramatic change to a sharp negative anomaly in a short period of time. Associated with this was a sharp increase in cyclo-genesis, which might account for a lowering of surface temperature. Over the easternmost area the temperature rise is confined, as I see it, mostly to the east side of a negative air pressure anomaly (Fig. 7) where there are these anomalous southerly components of wind presumably, resulting in warm water throughout the mixed layer. On the other side of the negative anomaly no such increase is true, as the anomalous components are from the other direction.

Roden: I think that the negative pressure anomaly will have opposite effects on opposite sides of the ocean. We have observed an increase in surface temperatures in the Northeastern Pacific and a decrease in the Northwestern Pacific.

Takenouti: North of the Kuroshio zone in Japan in 1955, there was also high temperature at this point. (1955 was a year of cold in the eastern North Pacific. Eds.)

Munk: In Hawaii do you observe great changes in salinity? I thought they were greater than temperature. In 1958 there was a marked rise in temperature, and a rise in salinity more marked than the rise in temperature. It must mean advection does it not?

Murphy: This was our interpretation.

Reid: And, further strengthening our belief in advection off California, we had significant decreases in sub-thermocline oxygen. There were extremely low oxygens off the coast of California, about 0.5 milliliters per liter less than average, and it is difficult to account for these subsurface changes in oxygen except by advection.

Favorite: I am wondering if insolation would account for the change you attribute to advection. Do you have that much confidence in the insolation values?

Reid: What we have here is too primitive for that. We have temperature measurements which allow us to make temperature anomaly charts over a certain area of the ocean. And there exists a somewhat similar distribution of the pressure anomalies for the period. We put these two sets of charts together—the pressure anomalies and temperature anomalies, and conclude that the pressure anomalies indicate an anomalous wind, which might result in moving water to effect the observed temperature anomalies.

Schaefer: The supposed changes in advection are so great that I do not think that they could be accounted for by errors.