Assessment of Temperature Structure in the Eastern Subarctic Pacific Ocean

by

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SUMMARY

Two structures are important in the upper 700 feet of depth in the Subarctic Pacific Ocean. A seasonal thermocline is formed between 100 and 200 feet depth in April. Its magnitude (ΔT) increases through the heating season until September while its dimensions and mean position remain fairly constant. The ambient variation of the depth of its upper and lower limits is 40 to 60 feet, and is due to internal waves. Above this seasonal thermocline small transient thermoclines occur in the potential layer depth during heating situations. They vanish during cooling situations or in the presence of strong winds. Convection, due to surface cooling, occurs from September through March. The potential layer depth becomes isothermal, cools, and the thermocline is eroded, sinks, and vanishes in February at about 330 feet depth. At this depth the temperature is determined in late March, when the waters are isothermal, and persists under the seasonal thermocline throughout the year. A permanent halocline exists between about 330 and 660 (±30) feet depth over the whole region throughout the year. Its temperature structure is constant in time although it varies over the area.

The primary variables in these structures are the temperature and occurrence of transients in the potential layer depth, the depth of the upper and lower limits of the seasonal thermocline and its magnitude (ΔT), and the ambient variation of the values. The OCEAN system of observation defines these limits and variations and presents them in a message form suitable for radio transmission in the weather code, for assessment, and for charting. An Oceanographic Information Service utilizing these researches and the OCEAN procedure has been established in the Naval Weather Centre, Esquimalt. Its efficiency is limited because there are not enough observing ships at sea, at any one time, to provide adequate data input, even though every use is made of historical and casual data.

The intensive research has shown that the temperature structure in the potential layer depth and the magnitude of the thermocline can be derived from continuous surface temperature observations, such as could be obtained from an airborne radiation thermometer.

An airborne radiation thermometer (FRB-1) especially designed for use in Neptune aircraft, and to exploit intensive research on the near surface temperature structure, has been built and successfully tested. It presents two graphical records. The Service Channel encompasses a range of 25 °F which can be set anywhere between 28° and 95° F, and can be read to the nearest 0.2 °F.

The Tactical Channel is a large scale presentation encompassing
2½, 5, or 10 °F which can be set anywhere in the temperature range. Relative temperature differences of 0.02 °F can be recognized with an estimated accuracy of 0.1 °F. The character of this record reveals the occurrence of transient thermoclines, and it is believed, waves. This channel has considerable tactical and research capabilities which should be explored by further testing.

It is proposed that the equipment should be flown on routine patrols of the Maritime Air Command, and the Service Record passed to the Information Service to supplement the OCEAN data input.

A second instrument (FRB-2) is required to ensure continuity of operation, allow surveys of large areas with two aircraft, and to finalize the design and packaging.
INTRODUCTION

There is a very real need in fisheries and military operations for assessment of the existing temperature structure in the oceans, and for frequent forecasts of the changes to be anticipated during the next half day to a week.

In the eastern Subarctic Pacific, an Oceanographic Information Service (Giovando, 1961) has been created to assemble daily radio reports of bathythermograph observations from ships, and produce charts of the definitive features of the temperature structure. However, there are not enough observing ships at sea at any one time to provide adequate data input. Even when the data are accumulated through a week they are too few for unaided contouring.

This situation was foreseen. Two researches were undertaken simultaneously: one to provide the oceanographic knowledge necessary to extend the interpretation of the meager data input; and the other to provide a means of increasing the data input.

From intensive research in the considerable historical data, rational definitions of the features of structure, their relation to weather, and the mechanism and sequence of the growth and decay of the seasonal thermocline, were derived. This model is applicable in any ocean region where the currents and turbulence are small and the temperature structure is primarily determined by local heating and cooling.

This research showed that considerable information about sub-surface structure could be obtained from continuous records (in time or space) of sea surface temperature. Such data can be obtained by an airborne radiation thermometer carried on regular ocean patrols by Neptune (or Argus) aircraft of the Maritime Air Command. Equipment was designed and built to suit the Service aircraft, fully exploit the environmental research, supplement the data income from ships, and have tactical value both for oceanographic research and the Maritime Air Command.

The airborne radiation thermometer FRB-1 is described by Pirart (MS, 1961). This report deals with its capability to assess the temperature structure in the oceanic (not coastal) regions of the central and eastern Subarctic Pacific. This capability depends on appreciation of the temperature structure and mechanism and manner of variation, and requires some bathythermograph data. Hence it is necessary to summarize the results of the oceanographic research, and the existing data resources.

OCEANOGRAPHY IN THE EASTERN SUBARCTIC PACIFIC OCEAN

The physical structure in the ocean depends on both the salinity and temperature structures. Usually one is limited or influenced by the other. Hence both must be considered.
Salinity structure

Dodimead (1961) defined the Subarctic region of the North Pacific Ocean (Fig. 1) by its unique salinity structure. As shown in Fig. 2 there is a marked halocline between about 330 and 650 feet (100 and 200 m) depth. It is permanent throughout the year, and provides a stability (density) boundary through which no surface effect can penetrate.

Below the halocline, the salinity increases slightly into the abyss. Here, both the temperature and salinity structure vary with location, but are almost constant with time.

Above the halocline there is a near iso-haline, low salinity zone, maintained by the excess of precipitation over evaporation in this region (Jacobs, 1951). In this zone, a small halocline (0.2% S) develops during the summer coincident with the thermocline (Dodimead, 1961). Its consideration is usually included with the thermocline. All seasonal variations of temperature structure are confined to this upper zone. Hence, the top of the permanent halocline (approximately 100 m, 330 feet) is the reference (base) level to which all seasonal temperature structures in this Review are referred.

The depth of the top of the halocline is arbitrarily taken as 100 m (330 feet) because this coincides closely with its mean value at Ocean Station "P". However, as shown in Fig. 3 the halocline is shallowest (80 m = 260 ft) in the northern part of the Gulf of Alaska and deepens gradually to about 140 m (= 460 ft) at the Subarctic boundary. The reference depth may be taken as 100 m (330 ft) through most of the region because the temperature gradient at this boundary are very small (Fig. 2).

South of the Subarctic boundary, in the Subtropic ocean, the halocline does not exist. Rather, the salinity decreases with depth to a minimum between 1500 and 3000 feet (500 to 1000 m). In this region the stability of the waters depends solely on the temperature structure. The reference level, at which the temperature ceases to be a marked seasonal function, deepens from the Subarctic to about 200 m (660 feet) in the Tropics. However, through most of the Subtropics it may be taken as 140 m (400 feet) depth (Robinson, 1957) because the annual variation at this depth is small.

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1For research purposes the data have been developed in metric units (depth in metres, temperature in centigrade degrees). These units will be retained here in the scientific part of the discussion. However, the applied products of the research will be shown in English units (feet, Fahrenheit degrees).
Currents and weather effects

In most oceanic regions, including the eastern Subarctic Pacific, the currents are slow, less than 10 miles per day, primarily zonal, and not visibly turbulent. Hence the weather conditions they experience during a month of transport (less than 300 miles) are similar, within the limits of assessment of oceanic weather, to the conditions they would experience if they remained stationary. Within these limits, the interaction between sea and atmosphere can be regarded as the dominant process determining temperature structure to the limiting depth of local effects. Below this depth, which varies during the year, temperature is a retained property and the structure is determined by internal processes, such as transport and internal mixing, no matter how slow.

Temperature structure

Figures 2 and 4 define the annual cycles of heating and cooling and temperature structures in the eastern and central oceanic Subarctic regions of the Pacific. Dodimead (1961) has observed that in March, at the end of the cooling season, the waters are virtually isothermal to the top of the halocline (about 100 m, 330 feet). With the advent of the heating season in April a thermocline is formed. The overlying waters continue to warm through the heating season until the end of August. Below the thermocline there is an unwarmed layer, which has been shown to be remnant of the cold isothermal structure formed during the previous winter. During the cooling season, from September, the surface layer cools and deepens. The thermocline is eroded, becomes abrupt, sinks and decays, and may vanish in February.

The mechanics of this growth and decay of the thermocline have been studied in the semi-daily bathythermograph observations at Ocean Station "P" (Lat 50° N, Long 150° W) and other extensive data from the oceanographic surveys conducted in the north Pacific Ocean since 1955 (Fig. 1). It has been concluded that the mechanics are similar in the central and eastern oceanic areas, differing from place to place and from time to time only in degree. This research is being prepared for publication. Meanwhile, it is convenient to summarize some of the principal conclusions. Patullo (1952) has shown that the sequence of events is similar in the Subtropics and the Subarctic Pacific.

Examination of the data show that in the non-turbulent oceanic regions (those away from the coasts) three dominant processes are involved in the growth and decay of the thermocline: heating, cooling, and wind mixing.

Heating is due mainly to radiant energy from the sun and occurs only during daytime. Cooling is due to evaporation, back radiation and conduction of heat from the sea surface, and is continuous day and night. Hence, there is usually a diurnal cycle of surface heating and cooling. During the heating season (Fig. 2) some of the daytime heat gain is retained through most nights. Hence there is a cumulative heat gain. Usually, there is some wind so that a shallow (3-15 ft) mixed layer is formed. Below this, there is a small negative thermocline separating the warmed surface waters
from the unwarmed deeper waters. The heat and the associated thermocline may vanish if the nighttime cooling exceeds the daytime heating. If the heat is not lost it is eventually mixed downward by the continuing winds, to the limiting depth of influence of normal strong winds in the region. This is defined as the potential layer depth. Any thermoclines above this depth are transient because they may be destroyed at any time by nighttime cooling or normal strong winds. Normally they cannot persist more than a few days. The potential layer depth is the depth of the top of the seasonal thermocline. This structure can be destroyed only by violent turbulence (Herlinveaux and Tully, 1961) or by a long continued process such as winter cooling.

These structures are illustrated in Fig. 5. The position of the seasonal thermoclines are shown by cross hatching. The positions of the transient thermoclines are shown by shaded transits through the potential layer depth. During the period indicated in the Figure, the transients first occurred in April, and a seasonal thermocline was formed at the end of the month. Thereafter, the transients occurred with increasing frequency throughout the heating season. Each transient provided a small increase in the temperature of the potential layer depth, and added to the magnitude (ΔΤ) of the seasonal thermocline.

Another aspect of the nature of these transients is shown in Fig. 6. During the summer of 1934, surface temperatures were observed every 4 minutes during parallel runs 1/8 and 1/4 miles apart. Although these observations required most of a day in each area shown, they were plotted as being synoptic. It is evident that there was considerable small scale variation of surface temperature. There were warm and cold areas with temperature difference as great as 1.5 C° (3 F°). It is believed that these correspond to the surface temperature differences associated with the transient temperature structures in the potential layer depth. Evidently the transient structures are of limited extent.

This may be explained on the basis of wind. Surface cooling is primarily due to evaporation which varies with wind force and difference of vapour pressure between sea and air (Tabata, 1961). Also winds occur as gusts which progress irregularly. Cooling is more rapid in the areas of strong gusts than between them. Hence there are patches of warm and relatively cool water. Also, as revealed by the spume trails, there are regions of convergence and divergence in the wind drift pattern of the sea surface. The surface waters would be warmer in the convergence areas. In either case it may be reasoned that during the heating season, transient negative gradients occur in the warm patches, and that the potential layer depth is more nearly isothermal in the cool patches.

As shown in Fig. 5 the depths of the upper and lower limits of the thermocline oscillate between 3 and 5 m (9 and 45 feet) from their mean depth. This is due to internal waves having a spectrum of periods from several minutes to at least half a day (Tabata and Boyce, 1962). Further, the waves at the top and bottom of the thermocline are not always synchronous, hence the thickness of the thermocline may vary by as much as 500%. Evidently, the position of the thermocline is best described by the mean depths of its limits and their standard deviations.
This ambient variability has a serious consequence. The magnitude and significance of temperature boundaries are usually defined by the gradient $\Delta T/\Delta H$. This definition cannot be maintained in the presence of the observed variability. A definition based on temperature difference ($\Delta T$) associated with the structure rather than the depth interval is used in this Review.

Aside from these ambient oscillations and variations, several sequences of events are illustrated in Fig. 5. The stable thermocline deepened through May in the presence of increasing winds. Then, at the end of June, in a period of light winds, a second thermocline was formed, overlying the old one. Thereafter, all heat additions (transients) contributed to the upper thermocline while the old thermocline remained constant. Such a double thermocline has only occurred during two summers (1956 and 1960) since 1955 at Ocean Station "P". During a period of very light winds, 9 to 17 August, 1956, a third, shallower thermocline formed. However, as soon as the wind increased this was driven down to the next level and joined the underlying thermocline. Three rules of behaviour may be deduced from these occurrences.

In such regions, a thermocline cannot ascend toward the surface. This would require the unmixing of the warmed and unwarmed waters which cannot be accomplished by any mechanical means. However, the mixed layer can deepen in the presence of any process which will increase the mixing, or remove the heat.

Heat cannot be transferred downward through a thermocline. Such transfer requires mixing, which must lower or destroy the thermocline. Hence, each thermocline forms a cover protecting the waters below it against further heating from the surface. The upper limit of a thermocline marks the limit of existing local surface influence. In and below the thermocline the temperature and structure can only be changed by internal processes, such as mixing or advection. In most oceanic regions such processes are slow, hence aside from internal waves the subthermocline temperature structure is constant, or changes slowly during periods of weeks or months.

Evidently the mean potential layer depth is a measure of the maximum winds that established the level. It may be reasoned that the resistance to mixing in the thermocline increases as its magnitude ($\Delta T$) increases. Hence the stability of the potential layer depth increases. This has been confirmed by the data. The mean potential layer depth becomes stable when the magnitude $\Delta T$ of the thermocline attains 3 °C (5 °F). This usually occurs about the end of June. Thereafter, the mean potential layer depth remains nearly constant until the beginning of the cooling season in mid-September.

At that time cooling and evaporation become dominant. The density of the surface waters increase, they sink, and convective mixing occurs. The waters above the potential layer depth become virtually isothermal. The process erodes the thermocline gradually through the cooling season, below the limit of any wind mixing, as shown in Fig. 4. In the Subarctic region the process stops at the depth of the permanent halocline (about 100 m, 330 ft) because its continuing stability precludes further downward mixing.
The effects of surface cooling usually reaches this depth in January or February. Thereafter the whole upper zone may continue to cool.

These discussions are summarized in Fig. 7. It shows, in generalized form, the sequence of structures throughout the year in the upper 700 feet of depth. There are four zones. The oceanographic structures in the potential layer respond to the current local surface processes (heating, cooling, wind mixing). The seasonal thermocline represents the cumulative effects of these processes and marks the limit of their influence.

The dimensions of the sub-thermocline zone vary during the year. The waters immediately above the halocline are exposed to surface influence (cooling) only during the short interval in late winter when the seasonal thermocline has vanished. The properties of these waters are established at this time. They are preserved, within reasonable limits, through the remainder of the year under the seasonal thermocline. Figure 8 shows the temperature at 100 m (330 ft) depth observed twice daily at Ocean Station "P". These data include the ambient variation due to internal waves. Aside from this, the data show in most years a slow regular cooling or warming which does not exceed 1 C° (2 F°) during the season.

In the northern part of the Gulf of Alaska the upper seasonal zone usually becomes colder than the waters in the halocline. A deep positive thermocline is formed in the upper part of the halocline (Fig. 2, first diagram). It is stable and usually persists throughout the following summer. This positive structure usually extends westward from Kodiak along the Aleutian Islands. Extreme winter cooling also occurs in the western Bering and Okhotsk Sea. The temperature minimum preserved under the seasonal thermocline is carried eastward in the West Wind Drift Current. It is diminished enroute (one to two years) and usually vanishes towards Ocean Station "P".

In the vicinity of Ocean Station "P" the upper waters usually cool to about the same temperature as the waters in the halocline. In this area the waters become isothermal to as much as 140 m (450 feet) depth, deep positive gradients are rare, and usually transitory. Further south, toward the Subarctic boundary, the upper zone seldom cools to the temperature of the halocline waters. Here there is a small residual negative thermocline at the end of winter.

The structure in the halocline zone is not affected by the local surface processes. It is subject only to internal processes (Tully and Barber, 1960)\(^2\). In most oceanic areas (except coastal and western boundary regions)

\(^2\)Tully and Barber (1960) showed that the halocline is a transition zone between the upper seasonal zones and the deep non-seasonal waters. However, the exchange is so slow that local and short-term fluctuations are integrated over one or more years. While the water is transported long distances, Hence the halocline structure in any locality may be considered constant for practical purposes.
these processes are steady and slow so that changes during a year are considerably less than at the upper limit of the halocline (Fig. 8).

**ASSESSMENT**

Present fisheries and naval operations require current assessment of the oceanographic structures in every part of the region. This assessment amounts to definitions of the occurrence and locations of boundaries, and definitions of the limits and magnitudes of the zones and their significant variations. The frequency of assessment must be adequate to define significant changes of structure.

**Fronts**

In the Subarctic Pacific the only fronts of any practical consequence are the boundaries of the region with the coastal waters, with the Subtropic waters (the Polar Front) (Fig. 1) and with the western boundary currents (Kuroshio and Oyashio). The mid and eastern oceanic regions are, for practical purposes, a single water mass.

Since 1955 oceanographic surveys have been conducted by United States, Japanese, and Canadian agencies each summer. Together these cover the Subarctic Pacific Ocean. The data have been published in Manuscript Data Records which have been analyzed to provide reliable assessments of the halocline and deeper waters each year. (e.g. Doe, 1955; Bennett, 1959; Dodimead, 1958). These data show that there is a consistent pattern of structure (Fig. 3) over the whole region in the deep waters, and within the limits of ambient variation due to internal waves, the structures and pattern are virtually constant throughout the year.

**Temperature structure**

Above the permanent halocline the significant variable is the temperature structure. This can be adequately defined for most purposes by the limits of the three zones; potential layer depth, thermocline, and sub-thermocline duct. An irregular structure such as shown in Fig. 9 may be used to define the features. The small variations within the zones may be regarded as transient. For operational purposes their individual positions and magnitudes may be ignored, and the structure approximated by trend lines (Giovando, 1962).

In most ocean areas where there is no sub-thermocline temperature maximum, the significant depth and temperature limits of the zones may be defined by:–

- $T_S$: Surface temperature
- $H_A$: Potential layer depth (PLD)
- $T_A$: Temperature at PLD
HB = Depth of bottom of thermocline
TB = Temperature at bottom of thermocline
HR = Reference level (330 feet in Subarctic Pacific)
TR = Temperature at the reference level

From this analysis the characteristics and magnitudes of the zones are defined by the differences:

TS - TA = Occurrence and magnitude of transients in the potential layer depth
TA - TB = Magnitude ($\Delta T$) of the thermocline
HA - HB = Thickness of the thermocline
TA - TB = Temperature gradient in the thermocline
HA - HB = Sub-thermocline temperature difference
TB - TR = Total temperature difference. In the eastern Subarctic Pacific this difference approximates the magnitude of the thermocline within 10%.

In those cases where there is a sub-thermocline temperature maximum it may be defined by the additional values:-

HM = Depth of sub-halocline maximum
TM = Maximum sub-halocline temperature
Hy = Depth of sub-halocline temperature minimum (seldom required).
Ty = Minimum sub-halocline temperature
Hx = Depth in the thermocline, of the sub-thermocline temperature maximum.

From this analysis the operationally important dimensions of the sub-thermocline duct are shown by the differences:

HM - Hx = Thickness of the duct
TM - Ty = Magnitude ($\Delta T$) of the duct

Ambient variability

In this identification of structure it is necessary to recognize the ambient variations due to transients and internal waves. Also there may be variations due to currents and large scale turbulence along water mass boundaries. It is concluded that no single observation (bathythermogram) can define the structure. Rather, it is necessary to make sufficient observations to determine the standard deviation and the fiducial limits.

The standard deviations are the limits above and below the mean value which include 2/3 of the data. It may be regarded as the limit of normal variation. Values beyond this will occur 1/3 of the time but will be short-lived. The fiducial limits are twice the standard deviation and include 95% of the data (probable variations). Values beyond these limits will be rare and transitory.
Usually it is simplest to determine the standard deviation, and anticipate (forecast) the fiducial limits.

Stability of structure

Except in boundary regions, the temperature and structure in the potential layer depth vary systematically in accord with the diurnal heating and cooling cycle. They also vary in short distances.

A system of forecasting the occurrence, persistence and depth of heating transients has recently been developed (Tabata, 1962; Tabata and Boyce, 1962). If the existing structure in the potential layer depth, and the probable weather are known, the probable structure in 12 or 24 hours can be forecast with reasonable accuracy at Ocean Station "P".

The temperature at the top of the principal thermocline changes only when a heat gain or loss is mixed completely through the potential layer depth. Between these events, which occur during strong winds, the temperature is constant. In consequence, the mean temperature at the top of the thermocline can be assumed constant over periods of two to three days.

The temperature at the bottom of the thermocline and below it is constant within the limits of ambient variation (internal waves) and advection while the thermocline exists (Fig. 4 and 5). It follows that temperature data in this zone (T_B and T_R) may be accumulated through most of the year, from April to January, in the Subarctic Pacific.

If the temperature at the reference depth (330 ft) is known from previous surveys, the magnitude (ΔT) of the thermocline may be derived within 10% as the difference from the surface temperature (T_S - T_R).

The mean potential layer depth is variable and uncertain when the first thermocline is formed during April and May. From mid-May till the end of June, while the magnitude of the thermocline is between 2 and 5 °F, the mean potential layer depth may descend slowly as shown in Fig. 5. During this period data may be accumulated for as long as a week. From the end of June till the advent of the cooling season, the magnitude of the thermocline is greater than 5 °F (Fig. 8). Then the mean potential layer depth is very stable, and data may be accumulated through this whole period. During the cooling season the mean potential layer depth sinks slowly and regularly. Its behaviour can be followed from very few data, and forecast with some confidence (Tully et al., 1962) by comparison with historical data, or extrapolating the trend.

The behaviour of the bottom of the thermocline appears to be similar to the top through the heating season. However, during the cooling season it does not start to descend until October, after the top has been eroded. Thereafter the thermocline becomes very abrupt (Fig. 2). In fact it is a discontinuity in the structure within the limits of ambient variation due to internal waves.
The OCEAN procedure is a method of observing, analysing and coding the temperature structure. It recognizes the ambient variations in the three seasonal zones, and presents the analyses in operational (fisheries and naval) terms. The procedure has been outlined in detail by Giovando (1961, 1962).

A group of 8 bathythermograms are observed at intervals of 5 to 15 minutes (depending on the locality and season). The depths and temperatures at the limits of the zones are recorded. The average (mean) values are determined and noted. Then the maximum and minimum values of each quantity are discarded. The standard deviation is taken as the greatest difference of the remaining values from the average. This difference includes $2/3$ of the data. Finally the averages and standard deviations are coded into a message which includes all the operationally pertinent information and is convenient for radio transmission or plotting.

True statistical analyses requires at least 20 observations. However, within the significance required for operational purposes this OCEAN procedure provides an assessment which can be assumed representative within a consistent water mass and within a region of consistent weather. In the eastern Subarctic Pacific Ocean the assessment may be considered representative over distances as great as 200 or 300 miles. However, if a water mass boundary is crossed, the situation must be reassessed. Water mass boundaries are usually revealed by a marked systematic change of surface temperature.

A similar assessment can be made from a continuous record of temperature or temperature structure in time or space. For example, the surface temperature record from an airborne radiation thermometer can be analyzed for ambient variation of surface temperature ($T_S$). As indicated in Fig. 6, such a record may also be used to assess the occurrence and magnitude of near surface structure (transients).

In fisheries and military operations it is necessary to know the surface temperature, whether or not there are transient thermoclines, the position and magnitude ($\Delta T$) of the principal thermocline, and the magnitude ($\Delta T$) and position of a sub-thermocline channel (Fig. 9) if it exists.

A system of OCEAN charts has been devised as illustrated in Fig. 10 through 14 to show this information throughout the area in convenient form. The format of the charts is consistent with the Meteorological charts of the area, and the size is chosen to fit existing radio facsimile transmission and receiving equipment.

The frequency of assessment is determined by the time rate of change of structure. In most oceanic regions this is determined by the surface weather and increases approximately as the logarithm of depth, from hourly
at the surface to annually at some depth between 300 and 500 feet. Below this depth the changes are usually long term. The required frequency of the charts in the Subarctic Pacific Ocean is shown in Table I.

Table I. Types of charts (cf. Fig. 10 through 14) and frequency or output necessary to provide adequate information for fisheries and military operations in the eastern North Pacific Ocean.

<table>
<thead>
<tr>
<th>Description of chart</th>
<th>Frequency of Output Desired</th>
<th>Attained (May-Sept, 1961)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface temperature and transients</td>
<td>daily</td>
<td>weekly</td>
</tr>
<tr>
<td>Potential layer depth</td>
<td>weekly</td>
<td>weekly</td>
</tr>
<tr>
<td>Magnitude (ΔT) of thermocline</td>
<td>weekly</td>
<td>weekly</td>
</tr>
<tr>
<td>Depth of bottom of thermocline</td>
<td>weekly</td>
<td>weekly</td>
</tr>
<tr>
<td>Temperature at 330 feet depth</td>
<td>annual</td>
<td>annual</td>
</tr>
</tbody>
</table>

OCEAN observations

Bathythermograph observations are made according to the OCEAN procedure once daily at Ocean Station "P" and from Canadian and United States naval and fisheries research vessels operating in the area of interest. Between 15 May and 30 September, 1961, 170 OCEAN observations were received.

Oceanographic surveys

In present Canadian practise a two-ship oceanographic survey (NORPAC) covers the Subarctic area (Fig. 1) during the period from mid-May to the end of June. These data are quite adequate to define the temperature structure.

In the western boundary regions, there are meridional ocean currents (Kuroshio, Oyashio, Gulf Stream, Labrador Current, etc.) which transport heat. There is marked turbulence in their regions of confluence. In coastal waters, over the continental shelf, estuarine and oceanic waters occur as discontinuous masses. Also there are strong tidal currents, and wind-induced upwelling of deep waters, or sinking of surface waters. In such regions as much as 50% of the heat content of the water may be due to transport rather than local heating or cooling. In such regions the rate of change of structure varies hourly, or at least semi-daily through the upper 500 feet. Below this the structure is more stable.
below the thermocline. The temperature pattern observed at 100 m (330 ft) depth is used as the reference level chart (Fig. 14). It is amended from time to time from the OCEAN data.

Sea surface temperature observations

Under the World Meteorological Organization (WMO) most large ships at sea observe the weather and the sea every six hours, and radio the information to the nearest Meteorological Centre. Sea surface temperatures may be obtained from these messages and used to augment the data input for OCEAN charts of surface temperature and magnitude (ΔT) of the thermocline.

Oceanographic Information Service

An oceanographic information centre has been established (May 1961) in the Fleet Weather Office of the Pacific Maritime Command (MARPA)C, H.M.C. Dockyard, Esquimalt, B.C. The OCEAN assessments are received there and combined with all other available oceanographic data into OCEAN charts. These charts are distributed to fisheries and military agencies as required.

The centre has been operating since May 1961. The frequency of output of OCEAN charts attained during the summer is shown in Table I. Both the quantity and quality of the Service was less than optimum because there have been too few observing ships at sea at any one time to provide adequate data input to the centre. During 1961 the OCEAN charts had to be prepared with the few data available and considerable bold interpretation based on familiarity with historical data, and appreciation of the heating and cooling processes.

If the number of ship observations are doubled, as they may be in the future the Information Centre can make a fair assessment of the thermocline and sub-thermocline zones. However, assessment of the surface temperature and occurrence of transients will require suitable observations daily, or at least semi-weekly. This requirement can only be met by airborne observation.

It must be recognized that the scope of individual fisheries and naval operations is limited within a radius of five miles. These small scale charts (Fig. 10 to 14) cannot show the detail necessary for such local appreciation. Rather, they provide a general assessment of temperature structures over the area, suitable for strategic planning. Tactical assessment in the local areas of operations is necessary if the features of the structure are to be exploited.

On-the-spot observation by the OCEAN procedure partly fulfills the requirement. However, it is usually desirable to scout a considerable area in the vicinity of a proposed operation prior to the ship's arrival. Airborne techniques would greatly facilitate such assessments.

The researches have shown that the features of the temperature structure below the thermocline are adequately represented by historical data.
and the annual surveys. The mean depths and the ambient variations of the limits of the thermocline can be deduced from historical data and few observations. The greatest variations are in the magnitude of the thermocline and the occurrence of transient gradients in the potential layer depth. Both of these can be evaluated from continuous surface temperature observations, such as would be provided by a suitably designed shipborne surface temperature recorder or airborne radiation thermometer. It was obvious that such airborne equipment was a primary requirement for a competent Information Service, hence its development was undertaken.

AIRBORNE RADIATION THERMOMETER (FRB-1)

The airborne radiation thermometer is a device which measures the long wave radiation (7 to 13 μm) from the surface over which it is flown. A detector (bolometer) looks through an optical system alternately at the surface, and at a reference black body, and compares the radiation from the two. This radiation is proportional to the fourth power of the absolute (K°) temperature.

The technique was first used in oceanography to track the edge of the Gulf Stream (Von Arx and Richardson, 1953; Von Arx, Bumpus, and Richardson, 1955). Temperature differences of the order of 1° to 3° F were readily recognized. A later, more sensitive instrument (Richardson and Wilkins, 1957) was used in the Caribbean by Malkus (1957) to study the small variations (0.04° F) of sea surface temperature associated with the formation of cumulus clouds.

This equipment was tested in eastern Subarctic Pacific (Tully, Pirart and Lane, 1960). Based on these feasibility trials the present equipment (FRB-1) was designed and built (Pirart, 1961).

Data presentation

The recorder (Fig. 15) is mounted adjacent to the navigation plot position in the (Neptune) aircraft. It presents two continuous graphical records on one chart of sea surface temperature as a function of time.

The temperature range on the paper chart contains 100 divisions in the 5½ inch width. The longitudinal time scale is marked in inches. The chart drive has 4 speeds; 240, 60, 12 and 4 inches per hour. The electrical noise level in the equipment is less than 0.02 F° hence the relative accuracy of the record is within the thickness of the ink trace, and can be recognized.

Service channel

This is a small scale-large range presentation showing 25 F° on full scale deflection (Fig. 16). Temperature can be read to about 0.2 F°, hence
intervals of $1^\circ F$ (4 divisions) can be accurately designated. The observation interval ($25^\circ F$) can be set anywhere in the range from $28^\circ F$ to $90^\circ F$. Normally the scale and range interval of this channel are set before a flight, to encompass the anticipated temperature range. It is desirable to operate the paper at slow speed (12 inches/hour) to facilitate analysis of the record.

**Tactical channel**

This presentation (Fig. 16) is independently variable and can be adjusted to show 2.5, 5, or $10^\circ F$ on full scale deflection. On the large scale ($2.5^\circ F$) presentation it is practical to recognize differences of 0.025 $^\circ F$. When using this channel the paper drive is often operated at high speed to allow close inspection of the detail of the record.

**Position-time**

Whenever the navigator fixes the position of the aircraft he annotates the record with an index (number or time) corresponding to the position on the plot of position. Later, the flight chart and the temperature record can be collated to prepare a temperature chart.

**Performance**

There have been two test flights in Neptune aircraft of #407 Squadron, Maritime Air Command, Royal Canadian Air Force, out of Comox, B.C. These flights - 4½ hours on 1 November and 9½ hours on 7 November - were undertaken to test the operational performance, rather than to collect data.

The Radiometer Head was positioned in the after camera hatch and the associated equipment grouped nearby. The thermometer was operated by the designers who communicated with the pilot and navigator by phone. The recorder was operated at high speed (240 and 60 inches per hour) to show the detail of performance. The instrument performed satisfactorily throughout the flights. Samples of the records are shown in Fig. 16.

To test the electrical noise level in flight, the instrument was operated for a time with the hatch doors closed while the reference black body was warming. This first trace confirmed the laboratory bench test. When the hatch was opened there was no evidence that the violent air turbulence had any effect on the stability of the reference temperature or the sensing element. These possibilities had been considered in the design and laboratory tested before flight.

During the first flight the aircraft flew over the Strait of Georgia. Then, being satisfied that the instrument was performing as planned, the aircraft crossed Vancouver Island and flew over the ocean coastal waters. The equipment recognized known water mass fronts (Fraser River Estuary, Active Pass) and shorelines, and ships. Traces 2 and 3 (Fig. 16) are samples from this flight.
The second flight was designed to test the endurance of the instrument on routine patrol (9½ hours). The temperature record was consistent throughout the flights. There was no apparent effect due to weather which included sunshine, overcast, rain and light fog, or due to variations of altitude from 50 to 1500 feet. These stabilities were anticipated in the choice of the radiation wave lengths (7-13μ) sensed. In this range, absorption of radiation by carbon dioxide and water vapour is small. It should be borne in mind that these assessments are qualitative. Satisfactory confirmation will require considerable observation of situations where the sea temperatures are checked by more ship observations than were available during these test flights.

The instrument appears to have all the required characteristics. However, some additional features are desirable, i.e. a time marker on the record. Also it should be possible to operate the Service channel at slow speed (12 inches per hour), independent of the tactical channel, because a short (10 foot) record is convenient for isotherm interpretation. The range of this channel should be variable (25 and about 10°F full scale deflection). It should be possible to operate the Tactical Channel at high speeds or stop it, without affecting the Service Channel. Evidently, two recorders are required. These are minor modifications which can be introduced into the present model.

INTERPRETATION OF DATA

Surface temperature charts

On most surface temperature charts the data are shown as isotherms at intervals of 1°F. These are taken from the record as the tangent to the regular side of the trace. In flight, the Service channel provides a continuous record of sea surface temperature, reveals the occurrence of fronts, and provides a reference basis for the tactical presentation. On return to base this Service Record is passed to the Information Service, for analysis and preparation of charts.

The first diagram of Fig. 17 shows the flight track and the observed sea states during the second flight. It also shows the position of a weak cold weather front. The whole area was influenced by a cooling moist air flow from the southwest along the coast toward drier air associated with a higher pressure region over British Columbia.

The lower diagrams are vertical sections along the flight track showing the varieties of weather encountered (clear, rain, fog) and the aircraft altitudes.

Figure 18 shows surface temperature data interpreted by the Meteorological Officer (B.V. Benedictson) at the Comox Air Base. The first diagram shows the isotherms derived from the Service Channel of the ART record.
The second diagram shows these same isotherms (1°F°) superimposed on an interpretation (2°F°) of five days accumulation of surface temperatures from ships' weather reports. There were 8 reports in the area, but the interpretation is supported by surrounding data. The principal feature of the two sets of data are in agreement. There is a northward intrusion of relatively warm water into the region. They differ in that the ART data shows the intrusion closer to the coast and bounded by a more marked temperature gradient. Also the ART shows a virtual temperature front lying normal to the southern end of Vancouver Island.

Considering the sparsity and questionable reliability of ships' observations, and having considered historical data in the region it is concluded that the ART data are much more reliable and should be accepted as a true presentation of surface temperature distribution.

Magnitude (ΔT) of the thermocline

The Tactical channel was designed to show the magnitude (ΔT) of the thermocline directly. The temperature at the reference level (HR = 330 ft) at any position in the area may be read on the HR chart prepared by the Information Service (Fig. 14). This value may be offset on the tactical channel. Then the record, usually on the expanded scale (2.5 or 5°F°) shows the difference between the temperature at the surface and at the reference level. This defines the magnitude (ΔT) of the thermocline, usually within 1°F°. An example of this chart was not prepared from present data because the principle has been demonstrated already.

Transients

When the ART is flown over an area where transient thermoclines are present, the associated surface temperature variability (Fig. 6) is revealed by erratic variability of the temperature record. This is most noticeable on the expanded scale of the Tactical Channel. In this situation one side of the trace is fairly regular and represents the background temperature. The amplitude of the peaks on the other side are irregular. If the irregular peaks are warmer than the background a heating situation exists at the sea surface. If the peaks are cooler than the background (Fig. 16) a cooling situation is revealed.

During the heating season it may be assumed that the transient gradients are negative. Thus the minimum temperatures represent the areas where the transients are least, and the potential layer depth is nearest to being isothermal. Thus the tangent to the minimum temperatures on the record can be assumed to represent the temperature (T_A) at the potential layer depth. Then the range of the erratic variations is a measure of the magnitude of the transients (T_S - T_A). Their extent and horizontal gradient is shown by the length of the deviation.

During the cooling season it may be assumed that the transient gradients are positive. In this case the tangent to the continuous maximum reveals the temperature at the potential layer depth. The variable
minima reveal the degree and extent of the transients.

During both test flights a marked cooling situation existed. Sea surface temperatures from ship observations indicated that the water was cooling 2 to 4 °F per week. This is reflected in the records (Fig. 16) in which the transients are colder than the background temperature.

It must be borne in mind that the ART senses radiation from the uppermost few millimetres of surface. Hence it is sensitive to any small variations on rather than in this surface.

Heating occurs at the surface, and the downward transfer depends on mixing. Mixing is usually somewhat slower than heating. Hence there must usually be a considerable temperature gradient in the upper few centimetres of depth. This is most difficult to observe in situ since all sampling devices (pails, etc.) and sensing elements (thermometers) penetrate the surface and in fact recognize the average temperature through some depth, 10 to 100 cms.

Also, rain occurring over the ocean creates a very thin layer (or patches) of brackish water. Because of this salinity stability, surface water may be cooled relative to the underlying water. This may give the appearance of transients in the trace (Fig. 16) which are purely surface effects.

There is some uncertainty in these records as to how much of the transients are due to real sub-surface positive thermoclines, and how much is due to purely surface cooling. It is believed that they can be distinguished if the airborne observations can be compared with adequate coincident bathythermograms. Such comparison is planned.

Waves

The Tactical records (Fig. 16) show regular small amplitude (0.1 °F) temperature variations. These have been interpreted as waves. This recognition was not anticipated originally. However, in retrospect it is reasonable because of the stability and the very fine resolution (±0.02 °F) of the equipment.

It may be reasoned that, in the presence of wind, the evaporation and therefore the cooling is more rapid on the wave crests than in the troughs. Hence, there should be a slight temperature difference. Also it may be reasoned that the peaks and troughs are regions of convergence and divergence. Hence, if there are any near surface temperature gradients these regions must be distinguished by temperature differences. It will be difficult to prove these theories by in situ observation, because there is no suitable equipment. Meanwhile, indications from comparison of records from various sea states is offered.

The waves (sea and swell) were not observed critically during either test flight. However, during the first flight there were strong winds (40 knots) and the fully arisen sea was rough and whitecapped. The wave features
in the record of the first flight indicate a wave length of about 400 feet, which is consistent with the calculated wave length (440 feet). During the second flight the winds were small (10 knots) and very few whitecaps were observed. However there was a noticeable swell. The fourth record (Fig. 16) indicates a wave length about 225 feet, which appears reasonable. Furthermore, this length varied when the circling aircraft was travelling with and against the direction of the waves.

Considerable further observations are required to define and exploit this feature.

**AIRBORNE TEMPERATURE SURVEYS**

It requires six weeks for two oceanographic research vessels to survey the area of interest (Fig. 1) making observations at intervals of 50 or more miles. For economic reasons such surveys can only be made once a year. During the remainder of the year the Information Service depends on OCEAN observations from transiting ships which can never be adequate to provide frequent assessments (Table I) of the surface temperature structure.

Neptune aircraft of the Maritime Air Command fly regular patrols over various and considerable parts of the area of interest. If equipped with airborne radiation thermometers they can provide frequent continuous records of surface temperature and structure. These records supported by the anticipated bathythermogram data, would provide the basis for an effective Oceanographic Information Service.

It is desirable, that whenever possible an airborne radiation thermometer be carried on patrol, and the record and plot be made available to the Weather Centre for analysis immediately on return to base. From there, the information can be passed to the Information Centre and incorporated on the current OCEAN charts.

At least two instruments are required to provide an effective service. Usually, when one patrol returns to base another takes off, and there is not sufficient time to transfer equipment. Both instruments may be flown concurrently to provide synoptic surveys of large areas of ocean. Maintenance requirements are anticipated but not known. In any case, two units are required to ensure continuous service.

**PROPOSALS**

It is proposed that some additional operational aids be added to the present unit (FRB-1) and that it be put into Service as soon as convenient.

With this equipment, the significance of the temperature records
should be exhaustively compared with concurrent bathythermograms, so that the records can be exploited to the utmost to evaluate temperature structure. In particular the capabilities of the Tactical Channel should be examined.

A second unit should be provided as soon as possible to finalize the design, ensure continuity of service, and allow use in two aeroplanes to cover large areas of ocean.

Equivalent shipborne surface temperature sensing and recording equipment should be provided to observing vessels, to aid their operations and augment the Information Service.

REFERENCES


Malkus, J.S. 1957. Trade cumulus cloud groups. Tellus, 9, pp. 33-44.


Figure 2.
NORTH PACIFIC OCEAN
DEPTH (Metres)
At Top of Halocline
MAY-JUNE, 1961

NORTH PACIFIC OCEAN
TEMPERATURE (°C)
At Top of Halocline
MAY-JUNE, 1961

Figure 3.
Figure 4. Growth and decay of the thermocline
Figure 5 Features of the thermocline
Surface temperature (°C) 1934

Figure 6
Oceanographic structures in the Subarctic Pacific Ocean
(Ocean Station "P" Lat. 50°N, Long. 145°W)

Figure 7
Figure 8
Figure 9.

GENERAL MODEL OF TEMPERATURE STRUCTURE
Figure 10. "Ocean" chart - surface temperature
Figure 11. "Ocean" chart - potential layer depth
Figure 12 "Ocean" chart - magnitude of the thermocline
Figure 13 "Ocean" chart - depth of the bottom of the thermocline
Figure 14 "Ocean" chart - temperature at 330 feet
Figure 15. Components of Airborne Radiation Thermometer (FRB-I)
Operational records, Airborne Radiation Thermometer, FRB-1

Figure 16
FLIGHT TRACK
7 NOV. 1961

WEATHER AND ALTITUDE

THIN UCST  UCAST  IN CLD

RAIN  RAIN  RAIN  RAIN  RAIN

Figure 17
SEA SURFACE TEMPERATURE
FROM AIRBORNE RADIATION THERMOMETER (FRS-I)
7 NOV. 1961

Figure 18