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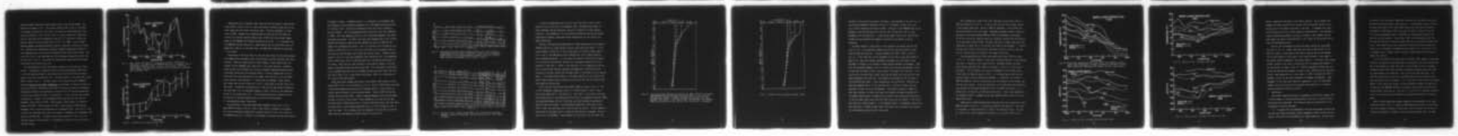

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

ONE-DIMENSIONAL MODEL PREDICTIONS OF OCEAN TEMPERATURE ANOMALIES DURING FALL 1976

by

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20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

The hypothesis that upper ocean temperature anomalies that developed over the North Pacific Ocean during the fall-winter of 1976-77 were primarily generated by vertical mixing processes was tested using the Garwood (1977) mixed layer model. A series of points along 175°W and along 38°N were chosen

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for use in this preliminary study. Atmospheric forcing for the one-dimensional ocean model was derived from the surface heat budget calculations in the Fleet Numerical Weather Central (FNWC) atmospheric prediction model. The suitability of the FNWC heat flux calculations was evaluated through comparison with the upper ocean heat content changes derived from the TRANSPAC analyses. The comparisons showed better agreement along 175°W than along 38°N. A series of ocean thermal structure predictions from 15 September to 31 December 1976 were made using the time series of the atmospheric forcing and the initial profile from the September TRANSPAC analysis. In the central region near 38°N, 165°W the predicted thermal structure agreed very well with the TRANSPAC analysis for December 1976. Near the southern and western ends of the domain, the temperature predictions were systematically lower than the analyzed values between the surface and 200 m.

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LIST OF FIGURES

Fig. 1 Points along 38°N and along 175°W within the ADS grid for which calculations were made.

Fig. 2 Atmospheric forcing from 1 September to 31 December 1976 at 38°N, 165°W including wind speed (m s^{-1}), total heat flux (cal cm^{-2} hr^{-1}) and solar radiation (cal cm^{-2} hr^{-1}).

Fig. 3 Similar to Fig. 2 except at 38°N, 135°W.

Fig. 4 Heat content (10^{4} cal cm^{-2}) relative to the 200 m temperature calculated along 38°N from the TRANSPAC analyses in September (solid) and November (dashed) 1976. Vertical lines between 175°E and 135°W indicate the cumulative surface heat flux between 15 September and 15 November 1976.

Fig. 5 Similar to Fig 4 except along 175°W.

Fig. 6 Predicted mixed layer depth changes relative to initial values on 15 September 1976 at points along 38°N. Longitude 215 corresponds 135°W and the initial spacing between adjacent traces at 10° longitude intervals corresponds to 100 m change in depth.

Fig. 7 Similar to Fig. 6 except along 175°W. The initial spacing between adjacent traces at 2° latitude intervals corresponds to 100 m change in depth.

Fig. 8 Initial (circles) temperatures profiles at 38°N, 165°W from September 1976 TRANSPAC analysis and mean predicted values at 10m intervals for months of October (triangle), November (horizontal dash) and December 1976 (cross). Verification data from December 1976 TRANSPAC analysis are given at 0, 30, 60, 90, 120, 150 and 200 m (diamond).

Fig. 9 Similar to Fig. 8 except at 32°N, 175°W.

Fig. 10 Mixed layer temperature (°C) along 175°W from TRANSPAC analyses (solid) during September, October, November and December 1976 and model predictions (dashed) during October, November and December.

Fig. 11 Similar to Fig. 10 except for mixed layer depth.

Fig. 12 Similar to Fig. 10 except along 38°N.

Fig. 13 Similar to Fig. 12 except for mixed layer depth.

1. Introduction

The overall goal of the North Pacific Experiment (NORPAX) has been to study the large-scale variability in the ocean thermal structure (Anomaly Dynamics Study, 1978). Some of the temperature anomalies have spatial scales of thousands of kilometers and persist for months. The largest thermal variability in the mid-latitude Pacific occurs between 30-50°N and 140-180°W, which is a region of strong atmospheric variability. Several physical mechanisms have been proposed to explain the development of near-surface temperature anomalies, including:

a) Horizontal divergence of the surface layers produced by wind stress curl;

b) Horizontal advection by surface Ekman flow and geostrophic flow;

c) Anomalous heat flux at the surface; and

d) Anomalous entrainment heat flux at the base of the mixed layer generated by wind stirring and convective overturning.

Whereas these mechanisms would develop anomalous thermal structure in situ, other mechanisms have been proposed which would result from the propagation of waves from adjacent regions. These will not be considered here, as only the local processes represented in c) and d) above are examined.

The basic hypothesis of this paper is that near-surface temperature anomalies in the North Pacific Ocean during the fall-winter of 1976-77 were primarily generated by vertical mixing processes. An anomalous surface heat flux can contribute to a net change in the heat content of the upper ocean, whereas the vertical mixing processes redistribute the heat content in the column. The monthly analyses of the TRANSPAC data (White and Bernstein, 1978) indicate anomalies in which the upper layers were 2°C lower than normal whereas the lower layers were 0.5°C higher than normal. Several mixed layer models (e.g. Camp and Elsberry, 1978) demonstrate that an anomaly which is cold near the surface and warm below can result from the passage of an atmospheric storm. Documentation of the upper ocean response to atmospheric cyclones on the time scale of days suggests a natural extension to the development and dissipation of upper ocean temperature anomalies with longer time scales. One of the long-range objectives of this research is to determine what fraction of the surface and subsurface anomalies may be related to the local surface forcing processes versus the other hypotheses being tested by the Anomaly Dynamics Study (ADS) group of NORPAX.

We represent the vertical mixing process through the Garwood (1977) oceanic mixed layer model. This model requires the atmospheric forcing fields of wind, solar radiation and surface heat flux on time scales of hours, even though we are attempting to explain anomalies with time scales of months. It is clearly impossible to monitor the heat and momentum fluxes each hour over the entire ADS region (30°-50°N, 130°W-170°E). Our approach is to use the results of the surface heat budget calculations from the heating package of the Fleet Numerical Weather Central (FNWC) atmospheric prediction model. In addition to calculations of the effect of clouds on the radiative fluxes, the FNWC fields incorporate the synoptic scale storm effects that have been found to be important in prior studies (Johnson, 1977; Paulus, 1978).

In the second section of this paper we evaluate the suitability of the FNWC heat flux calculations through comparison with the heat content changes derived from the TRANSPAC analyses. In the third section we initialize the Garwood model with the TRANSPAC analyses and predict the evolution of thermal structure changes caused by surface processes alone. The period of the simulation is from September, 1976, through the end of December, 1976, which is similar to the study of Haney, et al (1978). Significant cold anomalies in the central Pacific and warm anomalies in the eastern Pacific developed during this period.

In this preliminary study we consider only the points along 38°N and along 175°W shown in Fig. 1. These cross-sections through the ADS region allow us to test the forcing and model predictions over the latitudinal and longitudinal range. Later studies will consider the complete ADS domain.

2. Atmospheric forcing functions

The bulk mixed layer of Garwood (1977) predicts the evolution of the oceanic thermal structure profile at a geographical location. Values of the wind speed, solar radiative flux and the total surface heat flux must be provided at hourly intervals. As indicated above, these values were extracted from the FNWC historical data files. S. Pazan of NORPAX provided the data tapes for the September to December 1976 period. These included the east and west wind components at 6-h interhals, and the solar and total heat (latent plus sensible plus back radiation minus solar) flux values at 12-h intervals. Details of the reformatting, and editing of these files and of the extraction of time series at particular points may be found in Gallacher (1979). The wind fields were interpolated to hourly values using cubic splines.

A special treatment was required for the heat flux components. An instantaneous solar flux estimate each 12 h provides normally only one daytime value. The 0000 GMT value will correspond to local noon at 180°W, but will be 1500 local time at 135°W. The procedure for computing the hourly solar fluxes during the remainder of the daylight hours is given by Gallacher (1979). Milankovich's formula is used to estimate the hourly solar flux on the basis of the value of the solar flux closest to local noon, and the time of local sunrise and sunset. This procedure assumes that the moisture and cloudiness effects that are implied in the known solar flux value persist throughout the daylight hours. It should be noted that the FNWC atmospheric prediction model resolves only the large scale features that are slowly varying in time. It would of course be preferable

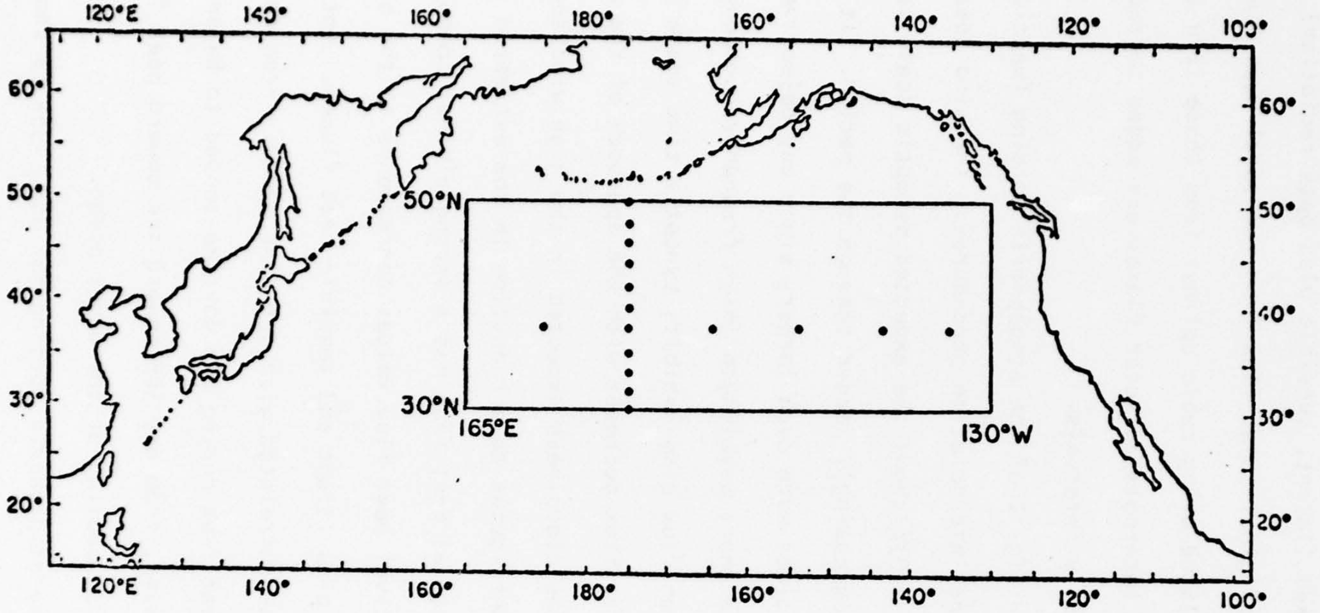

Fig. 1 Points along $38^{o}N$ and along $175^{o}W$ within the ADS grid for which calculations were made.

to have the solar flux integrated over 12 h, or more frequent estimates of the instantaneous flux, but these were not archived at FNWC during this period. The 12-h surface heat fluxes (latent, sensible plus back radiation) are determined by subtracting the original solar flux from the total heat flux values. Hourly values are interpolated using cubic splines from these 12-h surface heat fluxes. Finally the interpolated solar fluxes are added to reconstruct the total heat flux at hourly intervals.

An example is shown in Fig. 2 of the atmospheric forcing functions derived by the above extraction and interpolation procedures. The wind speed from 1 September to 31 December 1976 shows the expected synoptic scale variability. Peak wind speeds become increasingly larger through the period. It is likely that the actual maximum values were even larger, since any objective analysis scheme tends to smooth the short wavelength (high frequency) components. The envelope of solar radiation flux also exhibits synoptic time scale fluctuations. Maximum values of the solar flux decrease with the approach of the winter solstice. It appears that the cloudiness expected in the high wind speed events from 305-365 days also contributes to a reduction in the estimated solar flux at the sea surface. The total heat flux has a strong diurnal component. The envelope of upward (positive) heat flux values corresponds to the night-time values of back radiation plus latent and sensible heat fluxes. Note that these fluctuations were somewhat correlated with the wind speed. From days 245 to about 275 the downward heat flux during the daytime tended to balance the upward heat flux at night. However, from day 305 onward the upward heat flux clearly dominated, leading to a net cooling of the upper ocean.

Another example of the atmospheric forcing for 38N, 135W is shown in Fig. 3. Whereas the location of Fig. 2 was near the center of maximum storm activity, the location of Fig. 3 was under an upper level ridge, which contributed to

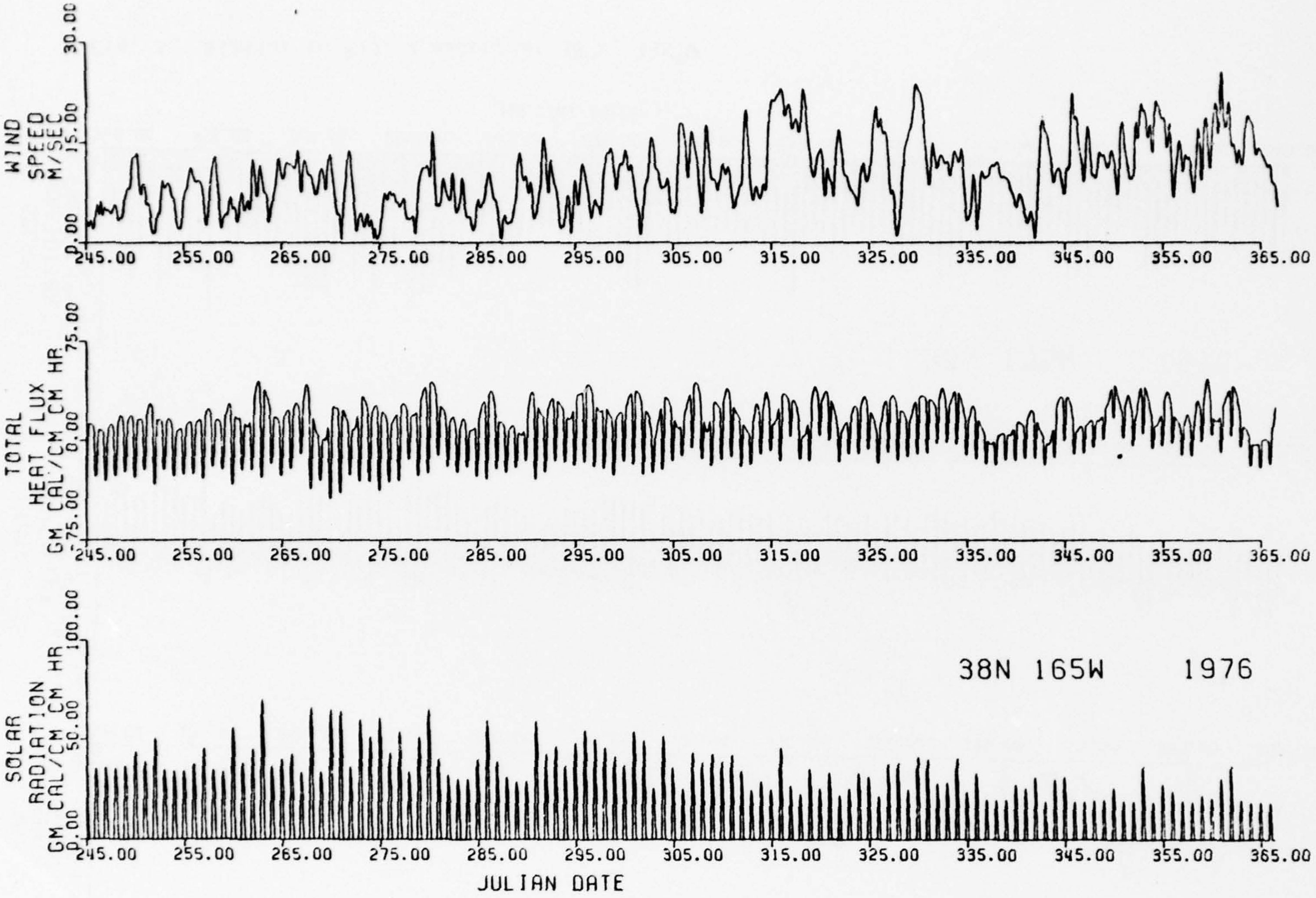

Fig. 2 Atmospheric forcing from 1 September to 31 December 1976 at 38°N, 165°W including wind speed (m s^{-1}), total heat flux (cal cm^{-2} hr^{-1}) and solar radiation (cal cm^{-2} hr^{-1}).

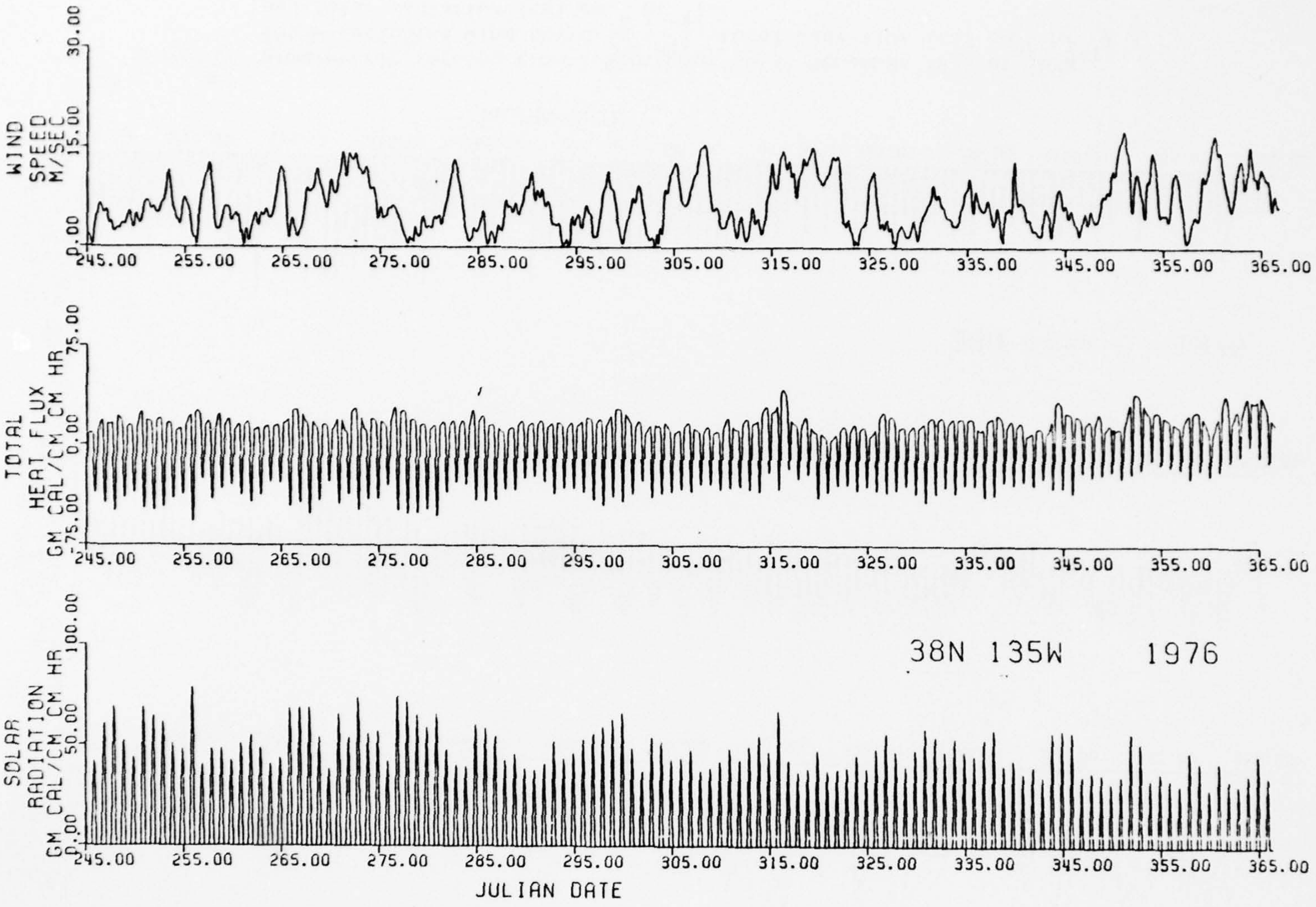

Fig. 3 Similar to Fig. 2 except at 38°N, 135°W.

extreme drought conditions along the west coast of the United States. The maximum wind speeds in Fig. 3 are clearly smaller than in Fig. 2, and there are extended intervals of light winds. By contrast, the maximum solar flux values are greater in Fig. 3 than in Fig. 2. This is especially true after day 315, when peak values exceeding 50 cal cm^{-2} h^{-1} occurred at 135°W, compared to maximum values of about 30 cal cm^{-2} h^{-1} at 165°W. Thus the FNWC heating package introduced physically realistic east-west variations in solar flux. Whether the interpolation procedure produced reasonable estimates of the integrated solar flux can not be determined from these figures alone. The total flux (Fig. 3) was dominated more by the downward (negative) values than was the case in Fig. 2. Only after day 345 does the upward heat flux exceed consistently the daytime solar flux.

The one-dimensional mixed layer model considers only the vertical fluxes of heat. Consequently a necessary condition for accurate model predictions is that the observed change in heat content during the period must be nearly equal to the total surface heat flux. The heat content in the upper 200 m along 38°N is shown in Fig. 4. The heat content is calculated from the TRANSPAC analyses _relative to the 200 m temperature_, which tends to remove the effect of vertically coherent fluctuations which may be related to non-mixing processes. Nevertheless there are considerable oscillations with 10° longitude wavelength in each trace, especially west of the dateline. In this case the oscillations are generally in phase, with the November 1976 trace smaller than that for September 1976, except at 125°W. The decrease in heat content is a maximum between 155-175°W. Thus the zonal minimum in heat content at 165°W during September 1976 is even more pronounced during November 1976. The vertical lines indicate the integrated total heat flux between 15 September and 15 November 1976 based on the FNWC data. In general these values agree fairly well with the analyzed change in heat content--if allowances are made for the oscillations in the heat content.

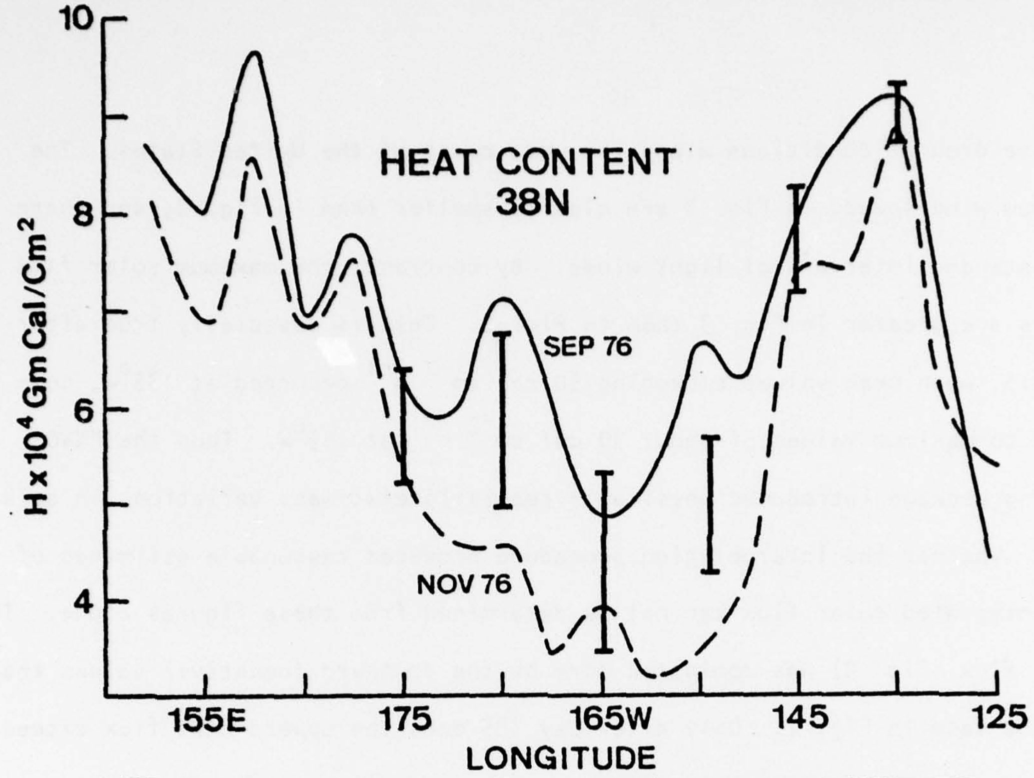

Fig. 4 Heat content (10^4 cal cm^{-2}) relative to the 200 m temperature calculated along 38°N from the TRANSPAC analyses in September (solid) and November (dashed) 1976. Vertical lines between 175°E and 135°W indicate the cumulative surface heat flux between 15 September and 15 November 1976.

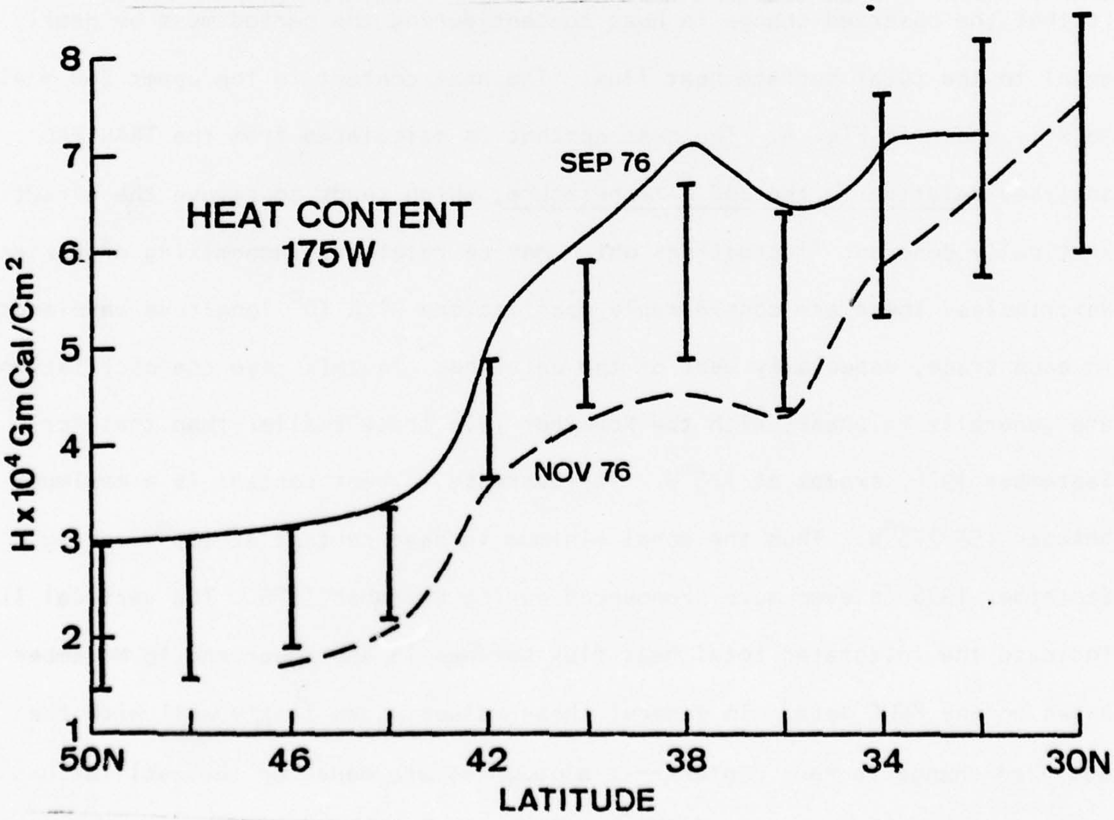

Fig. 5 Similar to Fig 4 except along 175°W.

Comparison of the integrated total heat flux and the change in heat content along 175°W is shown in Fig. 5. Both calculations indicate a heat loss in the upper ocean over the 30-50N latitudinal band. Excellent agreement is found north of 36°N. Whereas the integrated heat flux derived from the FNWC historical files attains maximum values south of 36°N, the heat content change based on the TRANSPAC data becomes progressively smaller. It is possible that the TRANSPAC analyses were poor in these regions due to insufficient ship- of-opportunity reports; on the other hand, the FNWC heat fluxes may be too large in this region.

Comparisons of the total heat flux and the heat content during other periods also showed better agreement along the meridional sections than along the zonal sections. Some very large month-to- month changes in heat content were calculated from the TRANSPAC data, especially in the zonal sections. Evidently these are due to the movement of vertically coherent temperature patterns that are perhaps associated with mesoscale eddies. The best comparisons with the total heat flux were achieved with the longer time intervals (up to the three-month intervals were examined). In these cases the changes in heat content were larger and the oscillations as in Fig. 4 constituted a smaller fraction of the signal. Considering the uncertainty in both of the heat content change and the total heat flux, the agreement suggests a major fraction of the change may be due to the surface heat flux. In the following section we examine the redistribution of the heat content due to vertical mixing processes.

3. One-dimensional model simulations

The predictions of the mixed layer depth changes at the points in Fig. 1 along 38°N are shown in Fig. 6. Each of the traces is separately calculated with the one-dimensional model and is plotted relative to the initial depth in the TRANSPAC analysis. A display in this manner illustrates the east-west extent of changes in depth. A deepening event is in progress on 15 September 1976. There appears to be an eastward propagation with the deepening ending earlier at 175 than at 195. Following the deepening event the trace is marked by daytime retreats. The first deepening event lasted only a few days (269-272) at 135°W. Much less deepening occurs at this longitude compared to the other longitudes considered. At 175°E, the mixed layer deepened 100 m (one interval between the traces) by around day 342, whereas the trace at 135°W did not deepen 100 m throughout the period. This is consistent with the smaller wind speeds at 135°W (see Fig. 3), and may be explained by the northward track of the storms around the upper level ridge near the west coast. Another notable feature in Fig. 6 is the rapid deepening event around day 315. Less deepening occurs farther east, which illustrates again the limited east-west extent of this event. Note also the layer retreats to much smaller depths in the four western longitudes around days 335 through 345. This shallowing is consistent with an extended period of low wind speeds and near-zero total heat flux from days 335 to 339 in Fig. 2 (see Elsberry and Raney, 1978, for a discussion of this type of shallowing event).

Mixed layer depth changes predicted by the Garwood (1977) model at points along 175°W in Fig. 1 are illustrated in Fig. 7. North of 40°N there are periods of sustained deepening alternating with extended periods in which there are regular daytime retreats to quite shallow depths. South of 36°N the daytime retreats are quite persistent. Gradual seasonal deepening occurs during these periods, with only a few periods of rapid deepening (e.g. days 315 and 329). Note that both of these events have a limited north-south extent, and that there are other cases in which marked deepening occurs at high latitudes but not at lower latitudes. This indicates that the atmospheric forcing derived from the FNWC files has considerable horizontal variability/structure.

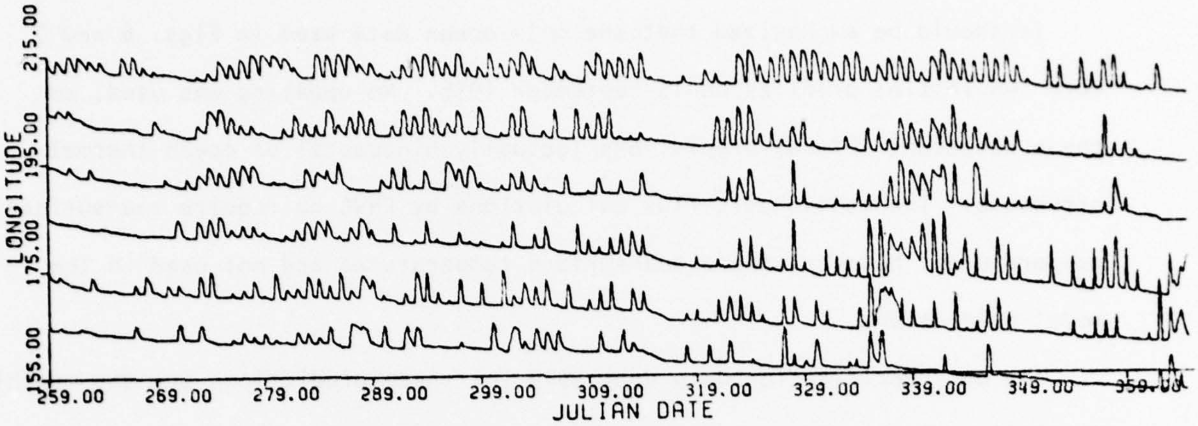

Fig. 6 Predicted mixed layer depth changes relative to initial values on 15 September 1976 at points along 38°N. Longitude 215 corresponds 135°W and the initial spacing between adjacent traces at 10° longitude intervals corresponds to 100 m change in depth.

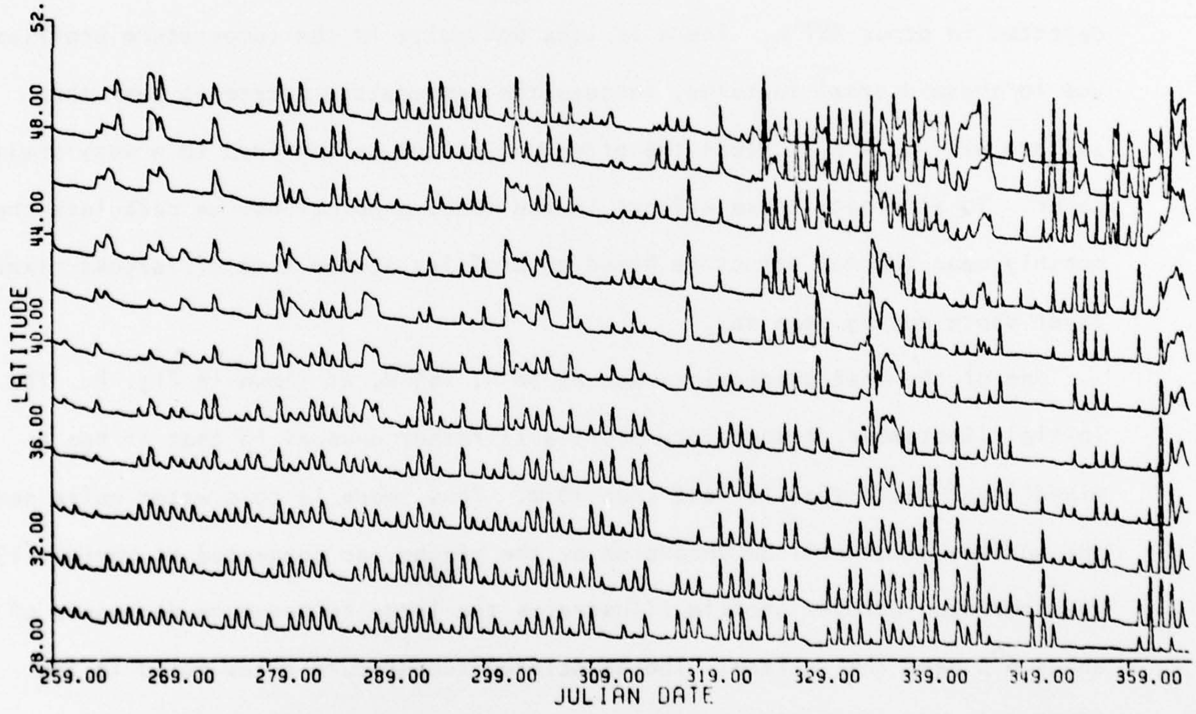

Fig. 7 Similar to Fig. 6 except along 175°W. The initial spacing between adjacent traces at 2° latitude intervals corresponds to 100 m change in depth.

It should be emphasized that the only ocean data used in Figs. 6 and 7 were the initial profiles on 15 September 1976. No updating was used, so these represent 107-day predictions (actually hindcasts) of ocean thermal structure. The atmospheric flux calculations by FNWC do require sea-surface temperatures; however, these sea-surface temperatures are not used in the model predictions.

The only verification data available for these predictions are the monthly TRANSPAC analyses of ocean thermal structure and mixed layer depth. If the actual temporal variability in mixed layer depth is similar to that shown in Figs. 6 and 7, the combination of all observations into a monthly analysis may be somewhat ambiguous. In some cases the transient shallow mixing depths will be observed and reported, whereas only the deeper thermocline will be detected in other XBT's. There is less ambiguity in the temperature profiles due to these diurnal features, because the temperature increases near the surface will be small unless the afternoon effect is confined to a very shallow layer. To eliminate these effects in the model predictions, we calculate the monthly mean thermal structure based on profiles at the time of largest mixed layer depth during each day.

One of the best predictions was at 38°N, 165°W, as shown in Fig. 8. The initial (September) temperature profile is rather unusual in that it has a mixed layer depth that is less than 10 m. Thus there is cold water quite near the surface which will be uncovered by the mixing, as suggested by Namias (1978). The predicted October profile illustrates the large temperature decreases of about 6°C near the surface. The associated temperature rises noted in the 45-75 m layer are consistent with a vertical mixing process. Further deepening and cooling of the upper layer is predicted from October to November, and at a lesser rate into December. These changes are consistent with the number and

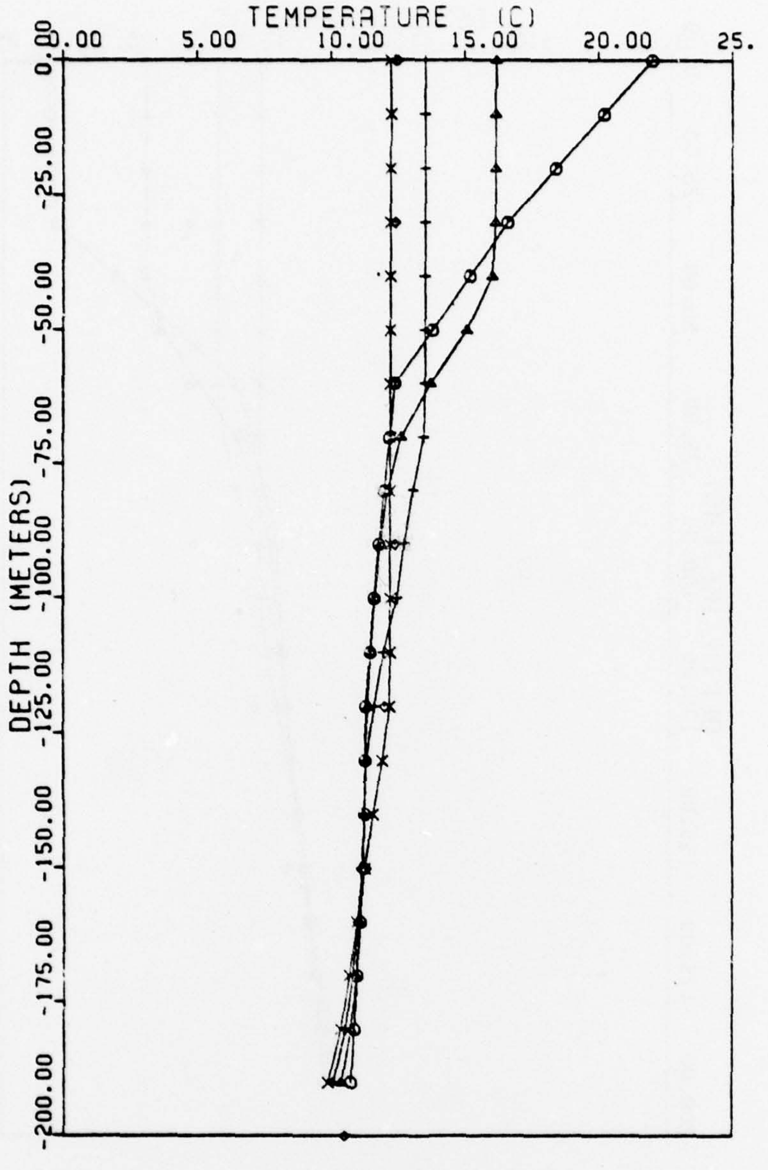

Fig. 8 Initial (circles) temperatures profiles at 38°N, 165°W from September 1976 TRANSPAC analysis and mean predicted values at 10m intervals for months of October (triangle), November (horizontal dash) and December 1976 (cross). Verification data from December 1976 TRANSPAC analysis are given at 0, 30, 60, 90, 120, 150 and 200 m (diamond).

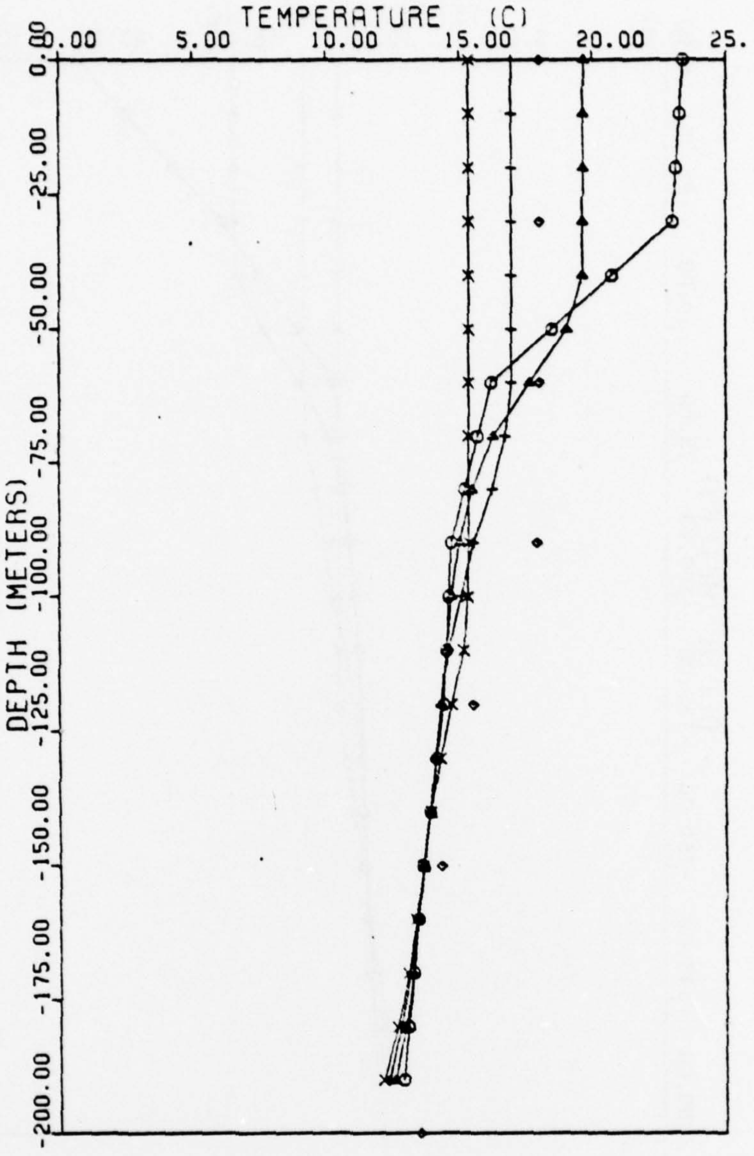

Fig. 9 Similar to Fig. 8 except at 32°N, 175°W.

strength of the wind mixing events indicated in the atmospheric forcing (Fig. 2). The predicted December temperature profile is isothermal to about 125 m with only a small temperature decrease to 200 m. Analyses of the TRANSPAC data during December at the surface and at 30, 60, 90, 120, 150 and 200 m are in close agreement with the prediction. It would thus appear that at this location the surface mixing processes are capable of explaining the thermal structure evolution.

At other locations, particularly in the southern and western ends of the cross in Fig. 1, the predicted temperature profiles were consistently colder than the analyzed profiles. A typical example from 32°N, 175°W is given in Fig. 9. In this case the initial September profile had a mixed layer depth of about 40 m. Again the largest temperature decreases were calculated during September to October, with smallest changes between November and December. Note that the predicted December profile is colder than the analyzed December values by more than 2°C down to 100 m, and by about 1°C between 100 m and 200 m. This could be an indication that a deep, warm eddy has moved into the region or that Ekman downpumping has occurred. Such advective processes are not included in the one-dimensional model. Other explanations may be possible. There may not have been adequate XBT's in this latitude belt, if the ship tracks were predominately farther north during December. The objective analysis scheme may then have resulted in a warm bias along the southern and western boundaries of the domain (Warren White is examining this question and re-analyzing the data.). It has also been noted that a positive temperature bias can result if the instrument does not release properly. If an adequate number of independent observations were available, it seems unlikely that a few defective instruments could account for the observed bias over such a large area.

The systematically lower mixed layer temperature predictions south of 38°N are displayed in Fig. 10. It can be seen that the bias already existed in the October prediction. North of 38°N the agreement in the October prediction and analysis was quite good. Reasonable agreement between prediction and analysis continues between 38°N and 42°N during November and December. During this period the shipping lanes are displaced southward and the analysis is not available north of 44°N. The model indicates a steady lowering of the temperature to about 5°C in the northern latitudes during December. It should be noted that salinity data were not available during this period, and thus salinity effects were not included in the model predictions.

The corresponding mixed layer depth predictions along 175°W are shown in Fig. 11. The major feature is the larger seasonal deepening in the northern latitudes in response to the strong forcing. Agreement between the model predicted and analyzed layer depths for October is within 10 m over most of the domain. The differences are larger for November with the model depths larger than the analyzed values by 20 m. As indicated above, there were no analyzed values north of 44°N during December. In addition, the values at 38°N and 40°N were clearly inconsistent with the remainder of the values, and thus were not plotted. Given the uncertainty in the analyzed values(especially near southern and northern boundaries) and in the model predictions, it is perhaps best to look only at the overall evolution. Clearly more comparisons are necessary before a judgment can be made regarding the suitability of the model predictions.

Comparisons of model-predicted and analyzed mixed layer temperature along 38°N are shown in Fig. 12. It should be noted that the analysis is for each 5° longitude, so that more detail is shown in the analyzed values. The overall trend is for larger temperature decreases in the central Pacific and

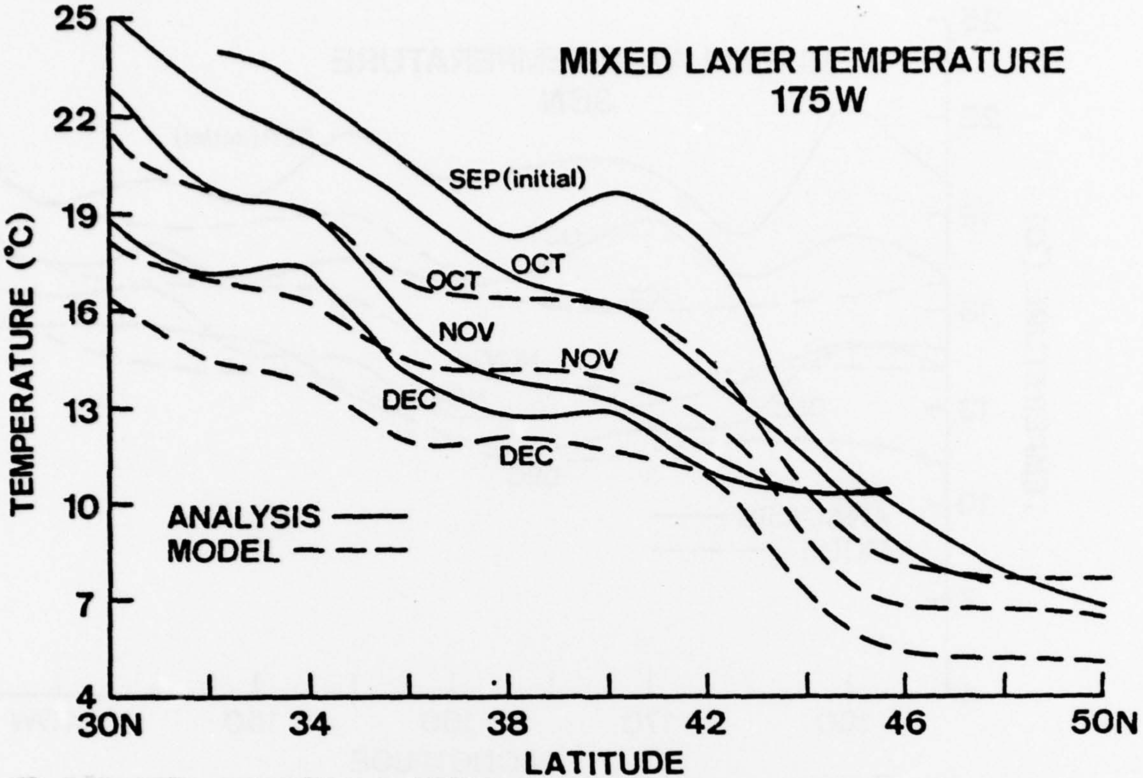

Fig. 10 Mixed layer temperature (^{o}C) along 175^{o}W from TRANSPAC analyses (solid) during September, October, November and December 1976 and model predictions (dashed) during October, November and December.

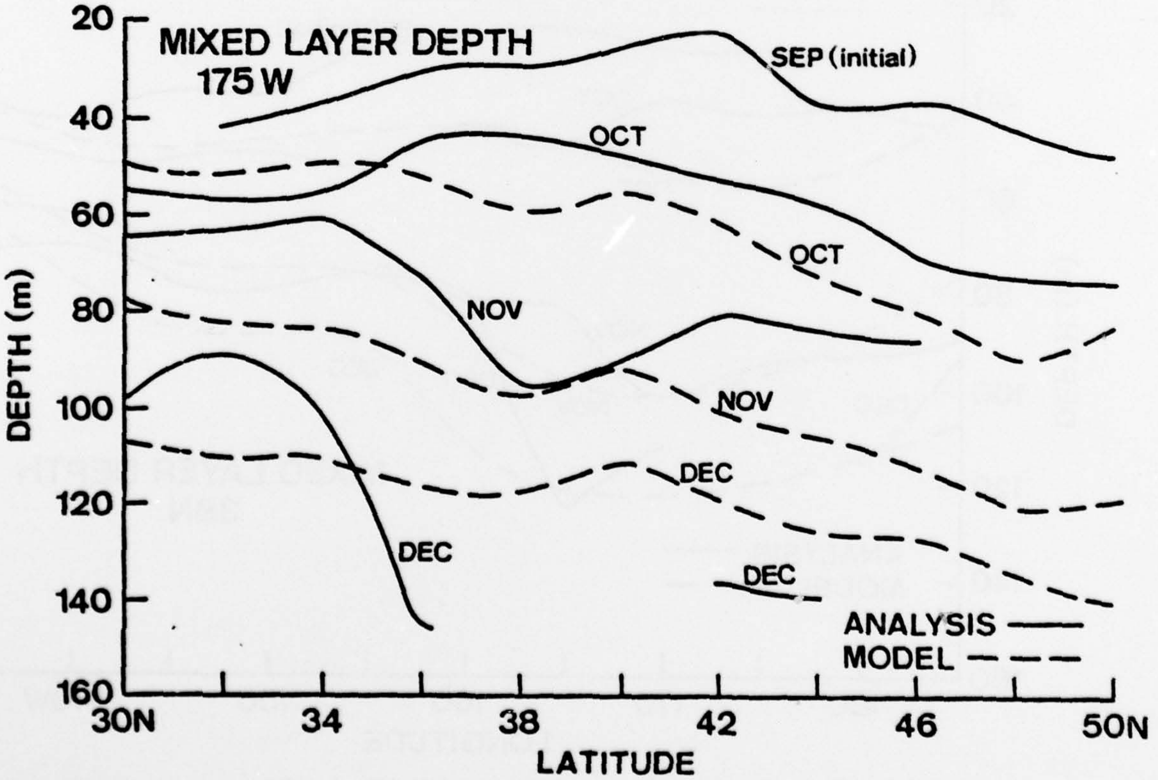

Fig. 11 Similar to Fig. 10 except for mixed layer depth.

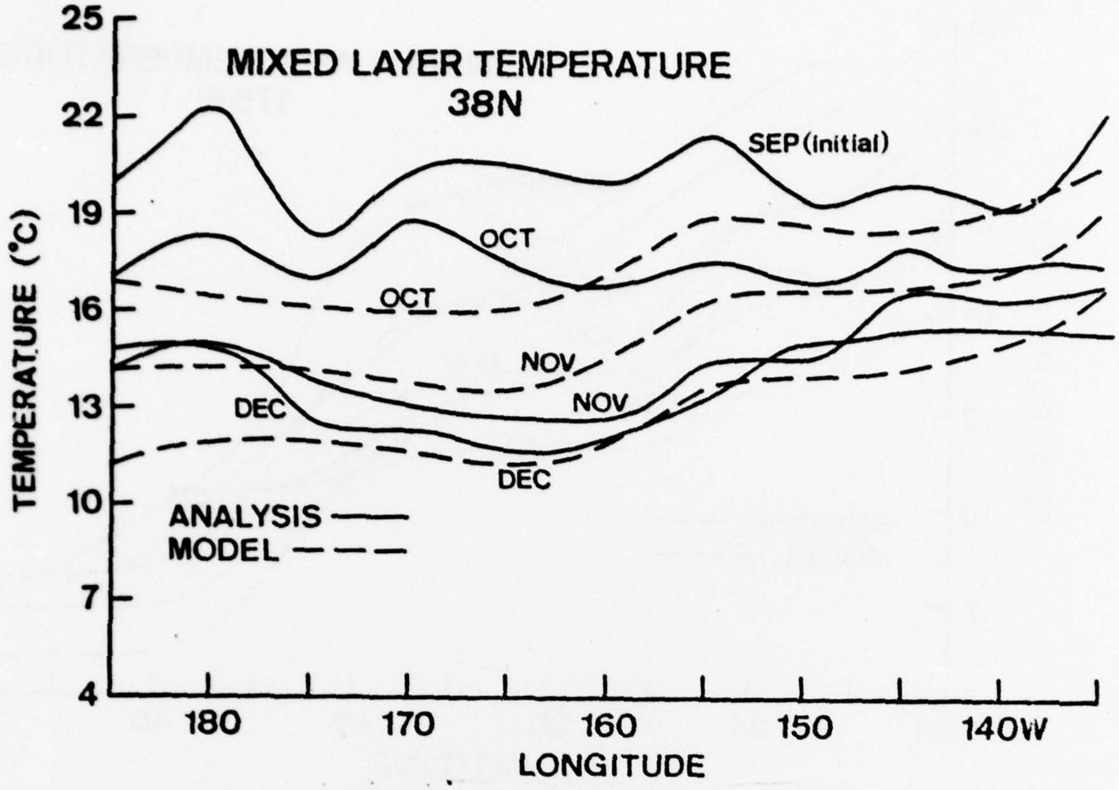

Fig. 12 Similar to Fig. 10 except along 38°N.

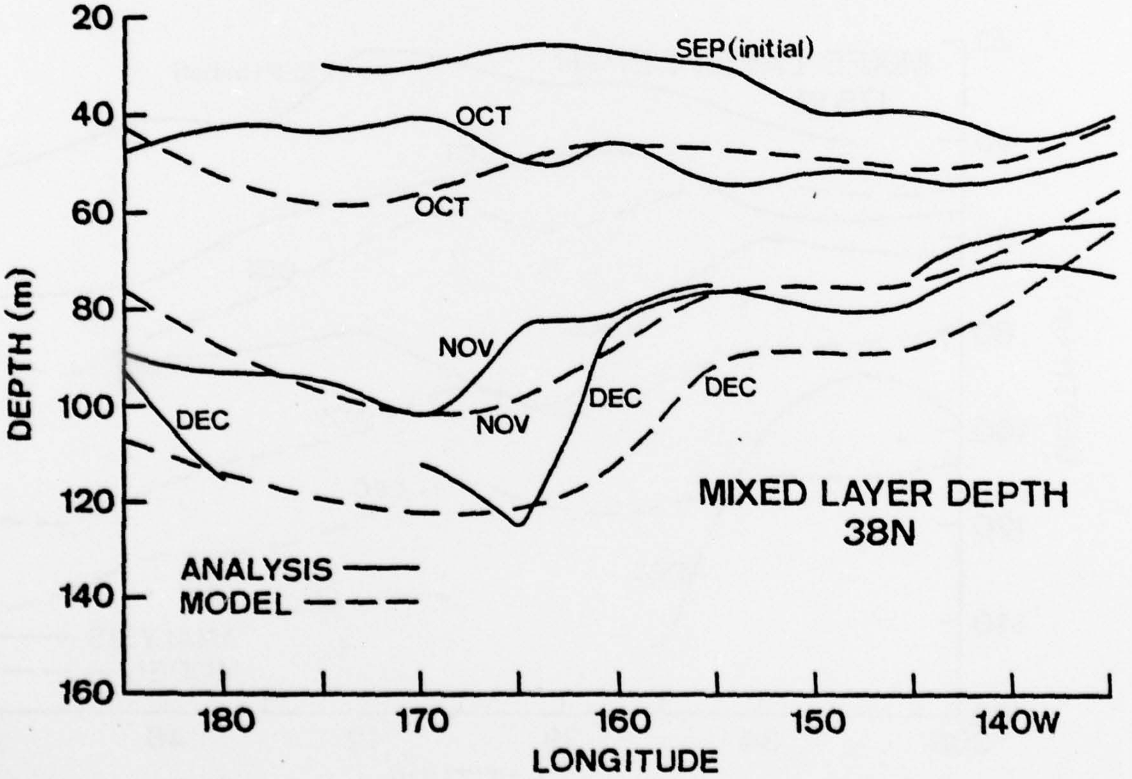

Fig. 13 Similar to Fig. 12 except for mixed layer depth.

smaller temperature decreases in the eastern Pacific. During October and November the model predictions are warmer than the analyzed values in the eastern part of the domain and colder in the west. In December the prediction and analysis are very close, except at the boundaries. This agreement might be considered somewhat fortuitous, although it may suggest that the heat budget was nearly one-dimensional in this region of the central Pacific over the three-month period.

Finally, the corresponding mixed layer depth predictions along 38°N are given in Fig. 13. Recall that there are twice as many points in the analysis traces, so that some of the smaller features may not be compared. The striking feature in this graph is the large increase in layer depth in the central Pacific compared to the eastern Pacific. If mixing is the primary process involved, this trend is consistent with the temperature changes in the two regions, as shown in Fig. 12. Excellent agreement between the predicted and analyzed layer depths is shown in most locations during the entire period. Some exceptions are in the region of 175°W in October and 155°W in December, as well as near both boundaries in November and December. Good agreement in the mixed layer depth and temperature (Fig. 12) along 38°N suggests that the vertical mixing processes were dominant in the thermal structure evolution during this period.

4. Conclusions

The results reported here must be regarded as preliminary, because only a limited number of latitudinal/longitudinal points and a relatively short period have been considered. The following tentative conclusions will be re-examined as testing continues.

(1) It appears that the atmospheric wind and heat budget field derived from the Fleet Numerical Weather Central atmospheric model provide realistic synoptic time scale forcing parameters for ocean prediction. Earlier tests

by Johnson (1977) and Paulus (1978) had indicated that the FNWC forcing could be used at the ocean weather ship locations. In the present case the forcing has been tested over a much wider domain away from fixed station locations. The capability (Gallacher, 1979) to reconstruct hourly values of the solar flux from instantaneous values is important for representing properly the vertical mixing processes. Since March, 1978, the instantaneous solar flux has been archived at 6-h intervals rather than 12-h, which should improve this field. Many comparisons of the cumulative forcing over various seasons and domains will be necessary to demonstrate more conclusively that there is not a systematic bias in these fields in regions without regular observations to update the solution.

(2) The one-dimensional ocean model of Garwood (1977) appears to represent correctly the vertical mixing processes on the monthly time scales tested here. One of the purposes of these preliminary tests has been to see if systematic tendencies would result from the model disposable parameters that were tuned for ocean weather ship conditions. No further tuning has been done. The predicted longitudinal variations along 38°N appear to be quite good except near the western end of the domain. It is not clear to what extent the energetic eddies in this region can account for the differences between the model predictions and the TRANSPAC analyses. Systematic differences were found along the meridional cross-section. Thus far, it is difficult to separate uncertainties in the analysis near the boundary from processes omitted in the mixing model.

What do these experiments suggest regarding the development of an ocean prediction model? First, it should be emphasized that we have initialized and verified the model on monthly time periods. The preliminary results must be viewed as encouraging. Although it has not been documented here, the model improves on a climatology forecast, because of the anomalous conditions during the fall of 1976. More tests and verifications are required under less intense forcing conditions. Other fall deepening periods should be examined. Likewise we will test the temperature anomaly generation mechanism of Elsberry and Garwood (1978) using initial conditions and atmospheric forcing during the late winter and spring. Second, the initialization problem will be more severe if daily predictions are to be attempted. White and Bernstein (1979) designed the objective analysis scheme for monthly time scales and large space scales that are consistent with data density provided by the TRANSPAC ship-of-opportunity program. It has not been established that adequate data are available to provide initial conditions on smaller time and space scales. Third, the horizontal resolution of the atmospheric forcing may not be adequate if daily predictions of smaller scale ocean phenomena are to be attempted. Perhaps the only way to answer these questions is to acquire ocean data and atmospheric forcing on an array of the desired space scale and then attempt deterministic predictions.

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