NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

THE ROLE OF SALINITY IN EQUATORIAL MIXED LAYERS

by

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June 1998

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE June 1998

3. REPORT TYPE AND DATES COVERED Master's Thesis

4. TITLE AND SUBTITLE THE ROLE OF SALINITY IN EQUATORIAL MIXED LAYERS, UNCLASSIFIED

5. FUNDING NUMBERS

6. AUTHOR(S) Pegeen O'Neil Stougard

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(maximum 200 words)*

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14. SUBJECT TERMS
Oceanic Mixed Layer, Salinity, Ocean Models

15. NUMBER OF PAGES 67

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified

20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

THE ROLE OF SALINITY IN EQUATORIAL MIXED LAYERS

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Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY AND PHYSICAL OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
June 1998

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ACKNOWLEDGMENT

The computational costs of this thesis were supported by NOAA and NSF Physical Oceanography under Award Number 9413292.

I. INTRODUCTION

The purpose of this study is to understand the role of surface salinity flux in changing heat exchange between the ocean and the atmosphere by means of its effect on mixed layer dynamics. This study will be accomplished by a series of thirty-day mixed layer experiments using the one-dimensional Naval Postgraduate School (NPS) mixed layer model, which will be discussed in full later. The hypothesis being tested is that without significant changes in the surface heat flux, precipitation can by itself vertically redistribute the ocean's heat content by salinity's effect upon stability.

The primary area of focus is the western equatorial Pacific's warm pool, which was the focus of Tropical Ocean Global Atmosphere (TOGA) Coupled Ocean-Atmosphere Response Experiment (COARE). This study is part of the TOGA COARE research program that was funded by the National Science Foundation (NSF) and the National Oceanic and Atmospheric Administration (NOAA).

A. TOGA COARE

TOGA was a ten year project (1985-1994) whose major objective was to develop an ocean observing system to support studies of large scale ocean-atmosphere interactions on seasonal to interannual time scales. This ocean observing system was completed in December 1994 and is known as the Tropical Atmospheric Ocean (TAO) array (Figure 1).

The array, which spans the equatorial Pacific, consists of nearly seventy moored buoys capable of measuring oceanographic and surface meteorological data. (McPhaden, 1995)

This thesis will focus on two of the four main goals of COARE. These goals are to describe and understand (1) the main processes for coupling the western Pacific Ocean's warm pool and atmosphere and (2) the ocean's response to buoyancy and wind-stress forcing in the same area. Achieving these goals are important for understanding the western equatorial Pacific since it is the location of some of the warmest sea surface temperatures in the open ocean, and it has the largest annual precipitation and latent heat release (Webster and Lukas, 1992).

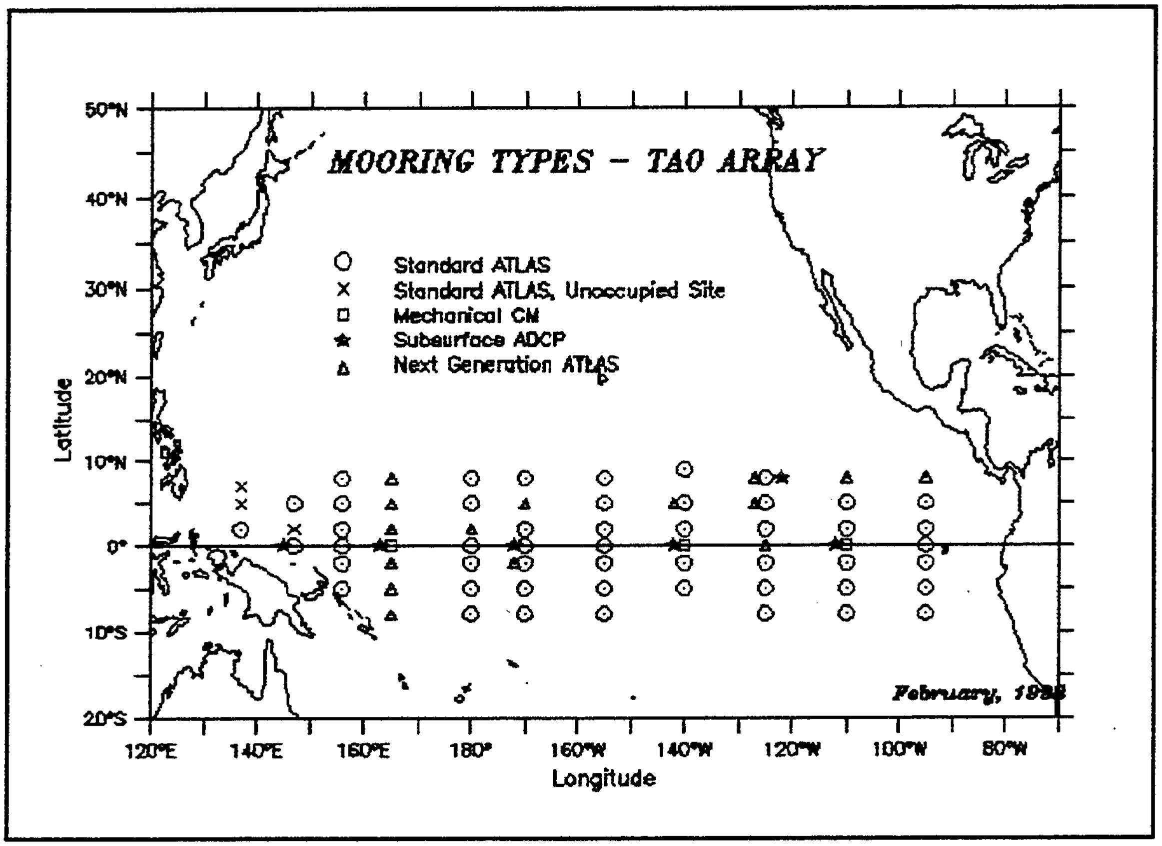

Figure 1. TAO Array. (http://www.pmel.noaa.gov/toga-tao/gif/mooring.gif)

B. LITERATURE REVIEW

How does salinity affect the mixed layer? Miller (1976) was the first to include salinity in a mixed layer model. He used the Kraus and Turner (1967) model which had been modified by Denman (1973) to include dissipation. Miller added the conservation of salt to the equations to examine salinity's effects on the mixed layer. His results showed that a homogeneous saline layer significantly affects the depth and temperature of the mixed layer. The increased difference between the mixed layer's temperature and salinity and the underlying temperature and salinity cause an increased density gradient. This increased density gradient leads to a change in heating and cooling characteristics because it slows the deepening of the mixed layer. Including salinity also tends to reduce the cooling of the mixed layer because of entrainment across the mixed layer boundary. With a salinity difference at the lower boundary and a significant net cooling at the air-sea interface, it is possible to have a mixed layer that is cooler than the layer below. It will not be unstable and overturn as it would if only temperature were contributing to the buoyancy. Depending on which dominates, surface flux or entrainment flux, adding salinity can cause an increase or decrease in the cooling of the mixed layer. (Miller, 1976)

Why has salinity been overlooked in equatorial Pacific ocean modeling even after its effects on the ocean in general were shown? There are two main reasons. Firstly, due to poor data coverage in the Pacific, evaporation and precipitation over the tropical ocean are not known with any degree of accuracy. Secondly, because the thermal expansion coefficient reaches its maximum value at the equator, temperature was thought to have the dominant effect on the dynamics. Salinity does not have a direct effect on the atmosphere and was assumed to have a negligible effect on tropical dynamics (Cooper, 1988).

Cooper (1988) showed that complete density data, comprised of both temperature and salinity information, caused the basic tropical ocean circulation model to produce accurate results during a sixty day simulation. Using just one of the density parameters, either temperature or salinity, gave poorer results than if no density data had been available. The differences due to the individual temperature and salinity gradients are larger than the combined density gradient because of the relationship between temperature and salinity in the equation of state. Cooper also showed that the modeled temperature and surface velocity errors increase when salinity gradients are not included. Temperature differs by a maximum amount of 2°C and the surface velocities differ by up to 40 cm/s without salinity in the circulation models.

In the past, mixed layer and thermocline depths have been determined from data by using a temperature gradient criterion or a net temperature decrease from the surface temperature. Levitus (1982) used this temperature gradient method to define the mixed layer depth. Knowing the importance of density differences, he also employed a change of density criterion. This density criterion was used because of the stabilizing effect of salinity in the upper ocean. Lukas and Lindstrom (1991) used the Levitus method in their study of the western equatorial Pacific Ocean mixed layer.

Lukas and Lindstrom (1991), using CTD measurements from two cruises, found an average mixed layer depth of 29 m. In earlier studies, the western equatorial Pacific Ocean mixed layer was calculated to be about 100 m, three times deeper. The earlier calculations were so different because they were only using temperature gradients as a criterion and the effects of salinity were not included in their calculations. Using a histogram of the differences in the thickness of the isohaline layer and the isothermal layer, Lukas and Lindstrom found that more than fifty percent of the vertical profiles had shallower isohaline layers. This finding suggests that precipitation effects were important in determining the mixed layer depth. Precipitation formed a stable, less dense layer of surface water referred to as a "barrier layer." This barrier layer plays a major role in inhibiting entrainment. They also found that the shallower observed mixed layer depth appears to result from a strong positive buoyancy forcing associated with heavy precipitation combined with intermittent wind forcing in the equatorial Pacific Ocean.

Miller (1976) also examined precipitation events and their effects on the mixed layer in his initial salinity study. He found that the depth of the new mixed layer caused by precipitation depends greatly on the amount of wind stirring during the event. Higher winds produce a deeper mixed layer than lower wind speeds when they happened during a precipitation event. The resultant mixed layer depth depends on the duration of the precipitation and the wind events. Finally Miller found that when heavy precipitation occurs over the tropical ocean, a stable mixed layer is developed at the ocean's surface. In addition, Flament and Sawyer (1995) noted that the contribution of a 1 cm/day precipitation rate to the density structure is equivalent to a heat flux of 40 W/m^2.

II. NPS 1-D MODEL

A. MODEL OVERVIEW

The NPS one-dimensional mixed layer model is a revised version of the Garwood (1977) model. Garwood's entrainment model considers both turbulent erosion and dynamic instability. The version here used has been modified to include salinity. Equation (1) is the basic definition for the rate of change of the mixed layer depth (h), and its solution is fundamental in the model.

$$\frac{\partial h}{\partial t} = w_e - \overline{W}_{z=-h} , \tag{1}$$

where $\overline{W}_{z=-h}$ is upwelling/downwelling. Assuming no mean vertical motion, $\overline{W}$=0, the equation becomes:

$$\frac{\partial h}{\partial t} = w_e , \tag{2}$$

where w_e is entrainment velocity. The entrainment velocity is always greater than or equal to zero because the water column cannot be unmixed. Defining total turbulent kinetic energy (TKE),

$$\overline{E} = \overline{u'^2} + \overline{v'^2} + \overline{w'^2} \tag{3}$$

the vertically-integrated total TKE equation is:

$$\frac{\partial}{\partial t}(h\overline{E}) = 2m_3 u_*^3 + (\overline{u}^2+\overline{v}^2)w_e - gh\Delta b w_e - gh\overline{b'w'}|_0 - D \tag{4}$$

The terms from left to right are the storage or time rate of change of net TKE, wind stress shear production, entrainment shear production, entrainment buoyancy damping, surface buoyancy damping or production, and viscous dissipation. The dimensionless wind-stirring constant m_3 is estimated to be 6. The friction velocity, u_* is equal to $\sqrt{\tau/\rho}$, where wind stress, τ, equals $\rho_a C_D |u_{10}|^2$ *and* ρ_a, C_D, *and* u_{10} are the density of air, the drag coefficient, and the wind at 10 m above the ocean surface, respectively. The variables u and v are wind driven currents and are assumed to be equal to zero below the mixed layer. Gravity is represented by the constant g. Net dissipation is defined as

$D = 2m_1\overline{E}^{3/2}$, *where* $m_1=1$.

Changes in salinity cause density differences that in turn change the buoyancy flux. Buoyancy is negatively correlated with density (ρ), $b=g(\rho_\circ - \rho)/\rho_\circ$ where $\rho_\circ$ is a constant representative density. Thus, a more buoyant particle has less weight. Temperature and salinity are positively correlated so that warmer water tends to be saltier. Usually, salinity reduces the density gradients because it counteracts the thermal effects on density. This is easily seen in the equation of state, $\rho=\rho_0[1-\alpha(T-T_0)+\beta(S-S_0)]$. In the equation $\rho_\circ$ is the density of sea water at a temperature $T_\circ$ and salinity $S_\circ$. The thermal expansion coefficient is α, and β is the salinity expansion coefficient. The values of $T_\circ$ and $S_\circ$ are representative values of temperature and salinity for the case being studied. The thermal expansion coefficient is a function of latitude. In the midlatitudes, α is approximately 0.2 and increases to 0.3 near the equator. Therefore, in a tropical ocean one psu salinity change causes a density change equivalent to that caused by a 2.5°C temperature change.

Dividing the NPS model's buoyancy (b) term into its mixed layer temperature (T) and salinity (S) constituents gives the buoyancy jump at the lower boundary of the mixed layer,

$$\Delta b = (\alpha g \Delta T - \beta g \Delta S)\ ,\ \alpha g \cong 0.3\,cm/s/C\ \ and\ \ \beta g = 0.75\,cm/s/psu \tag{5}$$

where

$$\Delta \overline{T} = \overline{T} - \overline{T}_{z=-h-\delta}\quad and\quad \Delta \overline{S} = \overline{S} - \overline{S}_{z=-h-\delta}. \tag{6}$$

The surface buoyancy flux is

$$\overline{b'w'}(0) = \alpha g \overline{T'w'_0} - \beta g \overline{S'w'_0} \tag{7}$$

where

$$\overline{T'w'_0} = -\frac{Q_{net}}{\rho C_p}\ ,\ \ \overline{S'w'_0} = (Pr - Ev)\overline{S}\quad and\quad Q_{net} = Q_B + Q_H + Q_E - Q_S \tag{8}$$

Q_{net} is net radiation, ρ is ocean density (approximated as 1.028 g/cm^3), C_p is specific heat, Pr is precipitation rate, Ev is evaporation rate, Q_B is back radiation, Q_H is sensible heat flux, Q_E is latent heat flux, and Q_S is downward solar radiation.

Solving for w_e using the quasi-steady state mode, where the total TKE changes with time but the storage terms are negligible,

$$\frac{\partial}{\partial t}(h\overline{E}) \cong 0. \tag{9}$$

Replacing buoyancy with temperature and salinity by substituting Equations 5 through 8 into Equation 4, the result is:

$$\Lambda w_e = \frac{2m_3 u_*^3 - gh\left[\alpha \frac{Q_0}{\rho c_p} - \beta(Pr - Ev)S\right] - D}{gh(\alpha \Delta \overline{T} - \beta \Delta \overline{S}) - (\overline{u}^2 + \overline{v}^2)}\ ,\quad \begin{array}{l} \Lambda = 1\ \ when\ \ \frac{\partial h}{\partial t} > 0 \\ \Lambda = 0\ \ when\ \ \frac{\partial h}{\partial t} < 0 \end{array} \tag{10}$$

The primary difference between Equation 10 and the equation Miller (1976) used is the explicit inclusion of dissipation, D. The modified Denman (1973) equations, which originated from Kraus and Turner (1967), accounted for dissipation by incorporating its effects into the constant used in the wind stress production portion of the equation. This incorporation reduced the wind effects, i.e., $2m_3u_*^3 - D \equiv mu_*^3$ in Miller. This approximation is good only if D is always directly proportional to u_*^3. If D depends upon buoyancy flux, then Miller's parameterization may have significant error.

The NPS mixed layer model is initialized with a temperature and salinity profile chosen by the user. The model can have either a constant surface forcing, or the forcing may change at each time step of one hour via a data file.

B. DATA SOURCES

TOGA COARE's Intensive Observing Period (IOP) was the primary source of data for this study. The area of focus for the TOGA COARE IOP was the western warm pool of the Pacific Ocean, located in the region contained by 10°N, 10°S, 140°E, and the international dateline. The IOP took place from November 1992 to February 1993. The center of the IOP's data collection efforts was the Intensive Flux Array (IFA) located at 2°S and 156°E. (Webster and Lukas, 1992)

A temperature profile from 1.75°S and 156°E on 5 December 1992 was obtained from the TAO Array data and was used to initialize and compare results from the NPS one-dimensional model. Since there was no corresponding salinity profile to accompany the temperature profile from this source, another data source had to be used for the salinity profile. An annual average salinity profile located at 1.5°S and 156°E from Levitus (1982) Climatology data was used to initialize the model. The temperature and salinity profiles were linearly interpolated from the surface to 200 m depth to a standard spacing of one meter. Linear interpolation was used to replace any bad data points found during the period of study.

Forcing data were acquired from the Woods Hole Oceanographic Institution (WHOI) surface (IMET) mooring, which was part of the IFA deployed during the TOGA COARE IOP. The IMET buoy was located at 1.75°S and 156°E and measured net shortwave radiation, latent heat flux, sensible heat flux, net longwave radiation, wind stress, rainfall rate, and the sea surface temperature. The measured data from the IMET buoy was averaged to an hourly format.

III. SALINITY EFFECTS ON NPS MODEL

Using the NPS 1-D mixed layer model, various forcing combinations, listed in Table 1, will be tested. The first two sections of this chapter comprise a sensitivity study of basic salinity effects and the effects of precipitation. These forcing combinations are not normally isolated in nature. The various forcing parameters have been chosen so their individual and combined effects on the mixed layer can be systematically examined. The first section isolates the effects of a salinity gradient with negligible winds in cases 1 and 2 and with moderately strong winds in cases 3 and 4. With just salinity gradients affecting Equation 10, a reduction of mixed layer temperatures should be evident. The second section focuses on precipitation effects under various conditions, including timing of the precipitation, changes in the precipitation rate, and light vs moderately strong winds. With the inclusion of excess precipitation, Pr-Ev>0, the entrainment rate should be reduced due to wind stress and Q_0 alone. Precipitation will have a short term effect on the mixed layer through the surface buoyancy term in Equation 10. It also has a long term effect on the entrainment rate via the entrainment buoyancy term. This long term effect is due to the precipitation induced change in the salinity gradient, which results in increased stratification in the upper ocean. Wind mixing will have an increased effect when salinity is added because of the reduction of the surface buoyancy flux term. But with the inclusion of salinity, by either a positive salinity gradient or changes caused by excess precipitation, the wind mixing effect will be reduced because of the influence of the increased salinity gradient at the entrainment zone. The last section will show the different

Case (Figure)	Forcing	Initial Salinity	τ dynes/cm^2	Precip rate cm/day	Precip time (start time)
1 (3)	Diurnal	Constant	0.01	0	N/A
2 (4)	Diurnal	Climatology	0.01	0	N/A
3 (5)	Diurnal	Constant	1	0	N/A
4 (6)	Diurnal	Climatology	1	0	N/A
5 (7)	Diurnal	Climatology	1	4.5	Constant
6 (8)	Diurnal	Climatology	1	4.5	4 hr (1200L)
7 (9)	Diurnal	Climatology	1	4.5	4 hr (0000L)
8 (10)	Diurnal	Climatology	1	4.5	4 hr (0600L)
9 (11)	Diurnal	Climatology	1	4.5	4 hr (1800L)
10 (12)	Diurnal	Climatology	1	4.5	15 hr (1200L)
11 (13)	Diurnal	Climatology	0.5	4.5	15 hr (1200L)
12 (14)	Diurnal	Climatology	0.5	4.5	4 hr (1200L)
13 (15)	COARE	Climatology	COARE	COARE	COARE
14 (19)	COARE	Climatology	COARE	0	N/A
15 (21)	COARE	Climatology	Average COARE	Average COARE	Constant
16 (22)	Average COARE	Climatology	Average COARE	Average COARE	Constant

Table 1. Forcing used for NPS one-dimensional model.

aspects of in situ forcing and their effects on the mixed layer. This section includes comparing precipitation vs no precipitation and instantaneous vs averaged forcing.

A. BASIC SALINITY EFFECTS

The model is initialized with a temperature profile from 1.75°S and 156°E on 5 December via a bathythermograph (BT) and either a constant salinity profile to simulate no salinity in the model or a Levitus climatology salinity profile from 1.5°S and 156°E (Figure 2).

1. Constant Salinity (Case 1) vs. Climatology Salinity Profile (Case 2)

Using no precipitation and a minimal wind of $\tau = 0.01$ dynes/cm², the precipitation/evaporation portion of Equation 10 becomes zero and the equation becomes:

$$\Lambda w_e = \frac{2m_3 u_*^3 - gh\left(\alpha \frac{Q_0}{\rho C_p}\right) - D}{h(\alpha g \Delta \overline{T} - \beta g \Delta \overline{S})} \tag{11}$$

As u_* becomes very small, the numerator of Equation 11 becomes negative. This would indicate a negative entrainment velocity, which is not possible. Therefore, one must assume no entrainment velocity by definition, see Equation 10. Setting $\Lambda=0$, the left-hand side of Equation 11 equals zero. Solving for h, the governing equation becomes:

$$h = \frac{2m_3 u_*^3 - D}{g\alpha \frac{Q_0}{\rho C_p}} \tag{12}$$

This diagnostic equation for the mixed layer depth, h, is governed by dissipation and surface buoyancy damping/production when wind and precipitation and evaporation are

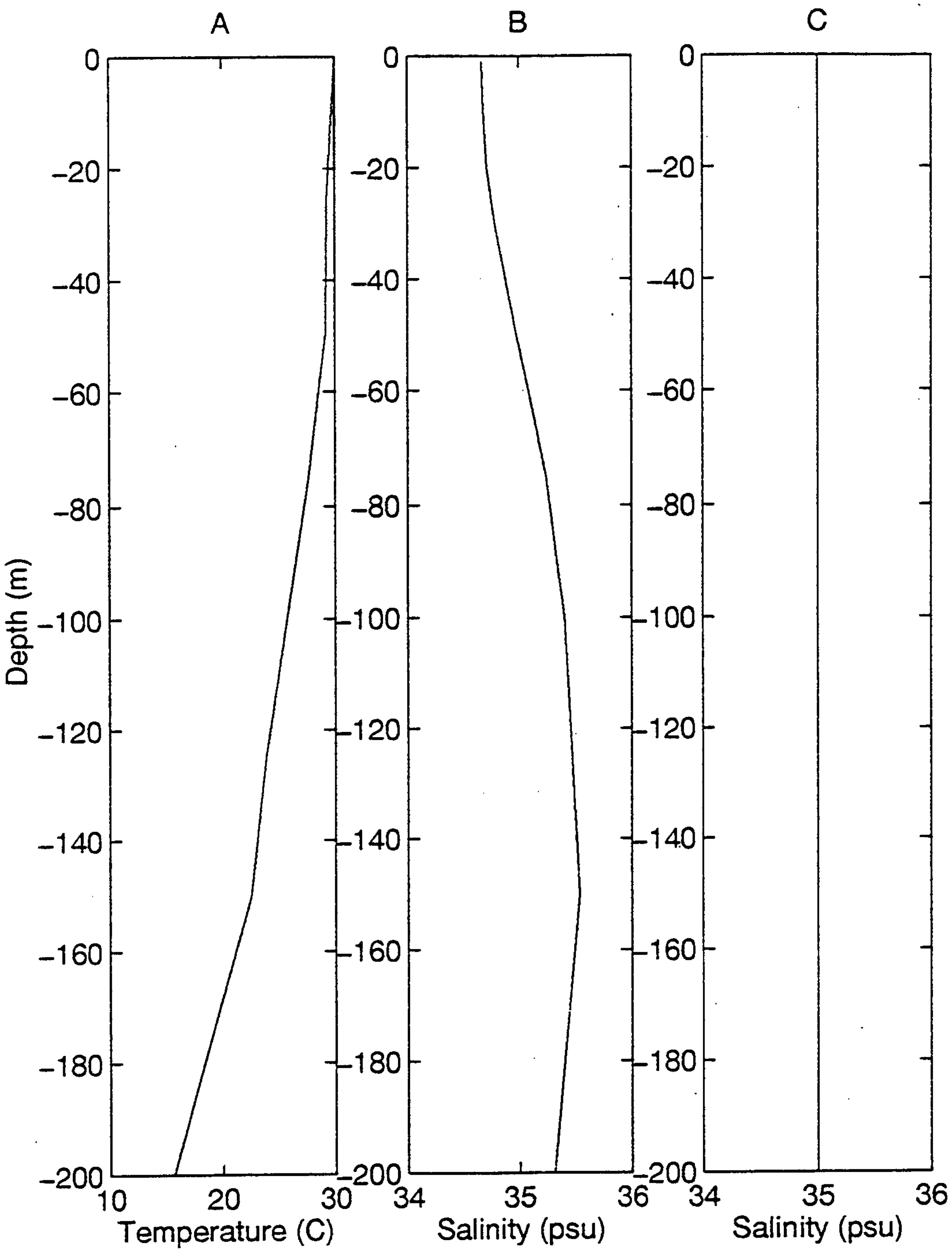

Figure 2. A) December 5, 1992 BT temperature profile from 1.75°S and 156°E. B) Climatology Salinity Profile from 1.5°S and 156°E. C) Constant 35 psu salinity profile.

assumed negligible.

The mixed layer temperatures are identical in both the constant (Figure 3) and climatology salinity (Figure 4) cases. The mixed layer temperature oscillates with the diurnal heating/cooling cycle, with an increased temperature occurring right after the noontime maximum heating rate and decreasing temperature trend during the duration of the 30 day period. For the climatology case, the mixed layer salinity increases throughout the 30 day period. This increase is caused by the entrainment of the higher salinity water into the mixed layer from below. As the description implies, the constant salinity profile remains constant, and only evaporation or precipitation could change S. Both cases have a very strong diurnal pattern in their mixed layer depths, with the layer shallowing at maximum heating times. The mixed layer deepens faster with the constant salinity profile. The change in the deepening rate can be accounted for by looking at the changes in salinity over time and Equation 11. With constant salinity, the salinity jump (ΔS) is always zero. With the climatology, ΔS is positive throughout. Therefore, the constant salinity case does not affect the rate of deepening and the positive salinity jump in the climatology case decreases the rate of deepening because the mixing has to work against the climatological stratification of the water column.

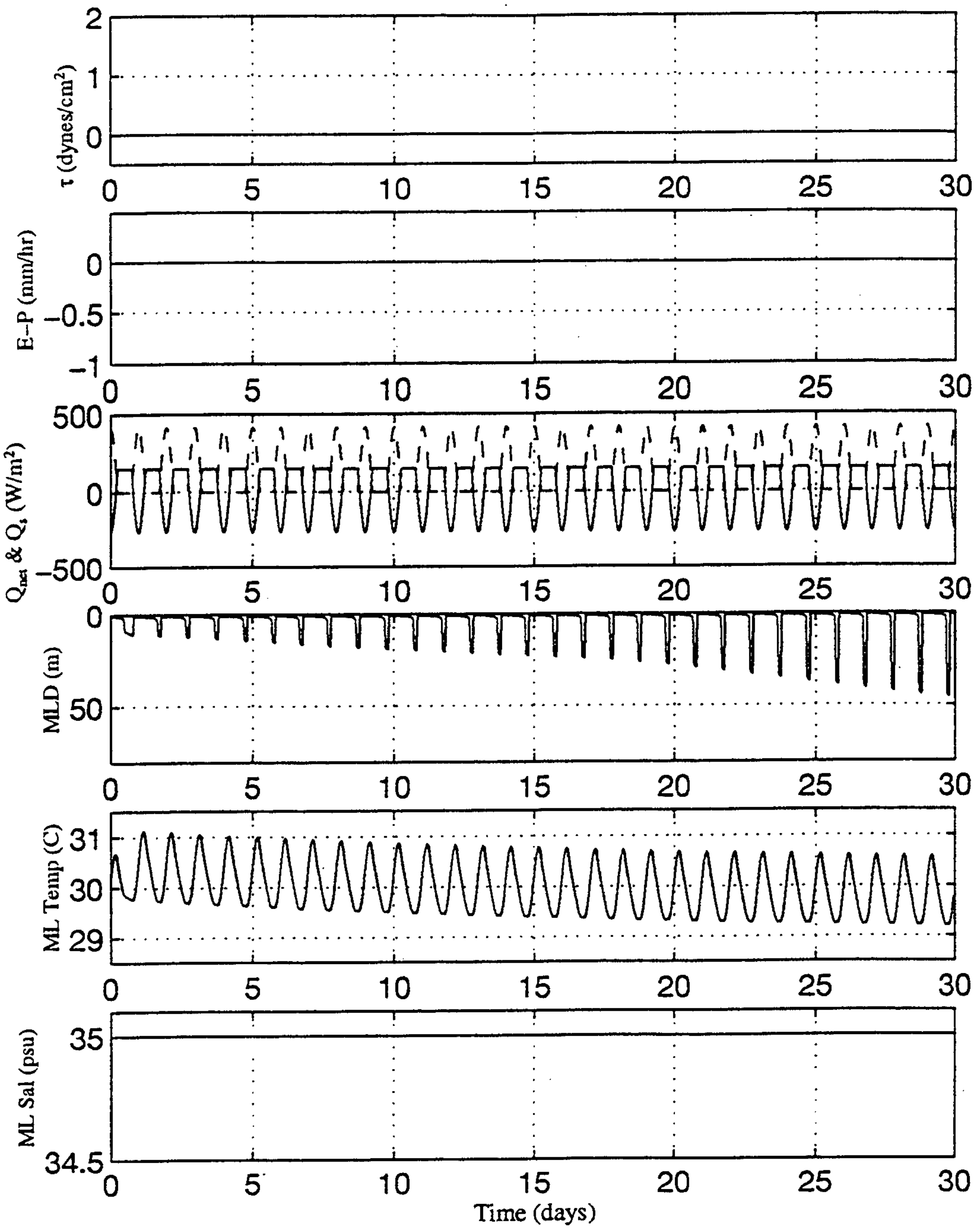

Figure 3. Case 1 - NPS model run using constant salinity and nominal wind stress. (τ is wind stress in dynes/cm^2, E-P is evaporation minus precipitation in mm/hr, Q_{net} & Q_s are net radiation and incoming solar radiation, respectively, in W/m^2, MLD is the mixed layer depth in meters, ML Temp is the mixed layer temperature in degrees Celsius, and ML Sal is the mixed layer salinity in psu).

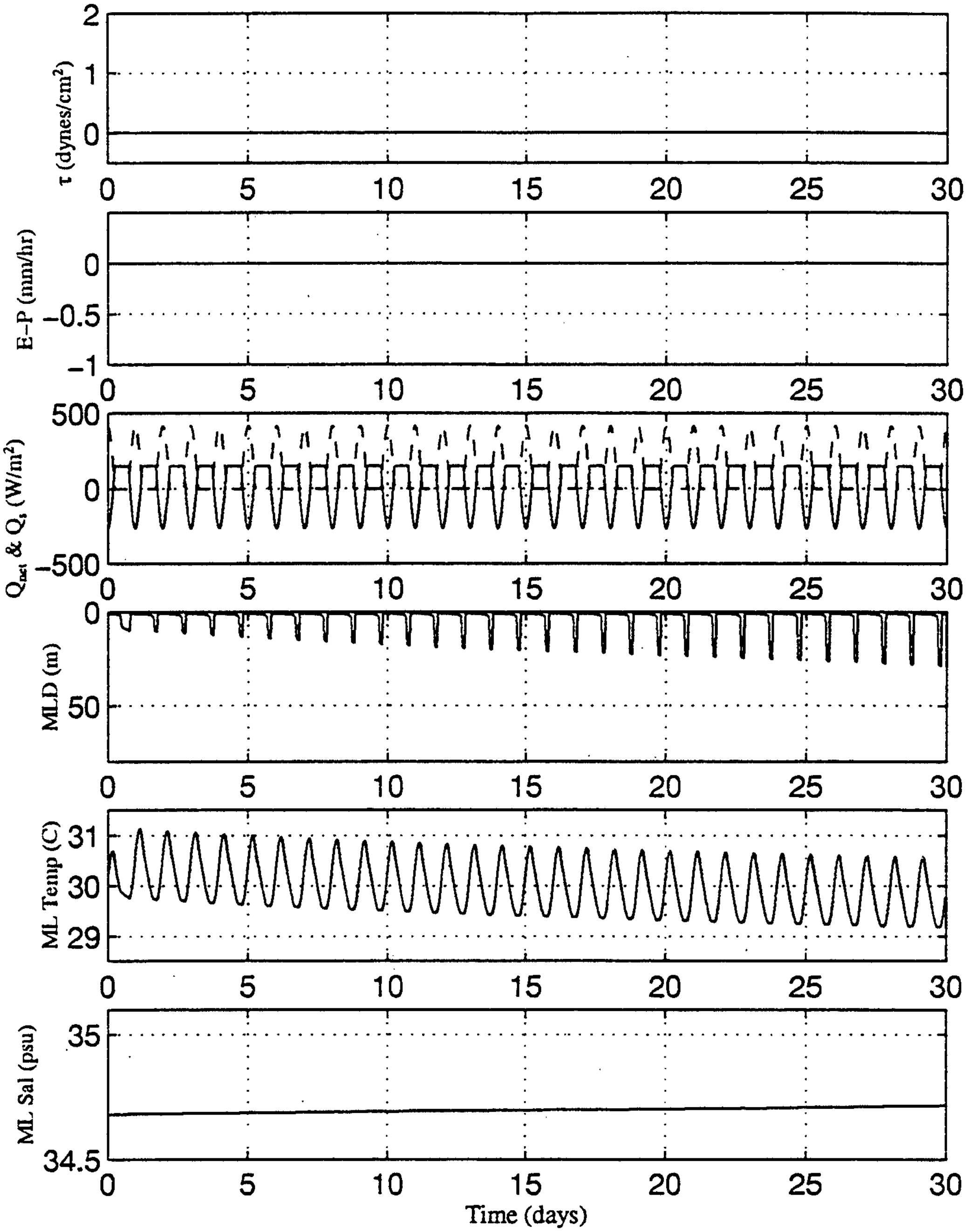

Figure 4. Case 2 - NPS model run using climatology salinity and nominal wind stress. (Same labeling convention as Figure 3).

2. Wind Effects (Cases 3 and 4)

By including the wind effect and still neglecting precipitation/evaporation effects, Equation 10 becomes:

$$w_e = \frac{2m_3 u_*^{\,3} - gh(\alpha \frac{Q_0}{\rho C_p}) - D}{h(\alpha g \Delta \overline{T} - \beta g \Delta \overline{S}) - (\overline{u}^2 + \overline{v}^2)} \qquad \textbf{(13)}$$

With an increase in wind, the wind stress shear production should increase and the entrainment shear production should also increase - both causing an increase in the entrainment velocity.

The overall mixed layer temperatures for cases 3, constant salinity, (Figure 5) and 4, climatology salinity, (Figure 6) decrease at a slightly faster rate over the 30 day period than in cases 1 and 2 because of the additional energy provided by the wind for mixing. The mixed layer temperatures for the case 3 and case 4 salinity cases are similar, but in case 4, the overall temperature cools at a slightly slower rate. The diurnal pattern is damped by the added wind so there is a smaller increase in temperature after the maximum diurnal heating. The climatology salinity increases at a faster rate over the 30 day period with the addition of winds. This is because with greater mixing high salinity waters are mixed into the mixed layer from below. In both cases, the diurnal cycle effect on the mixed layer depth is damped and overall deepening rate increases. This can also be seen from Equation 12. With wind stress added into the equation the heating cycle is not the only parameter controlling the numerator. The equation also helps explain the difference between cases 3 and 4's overall mixed layer temperature trend. With the increased salinity

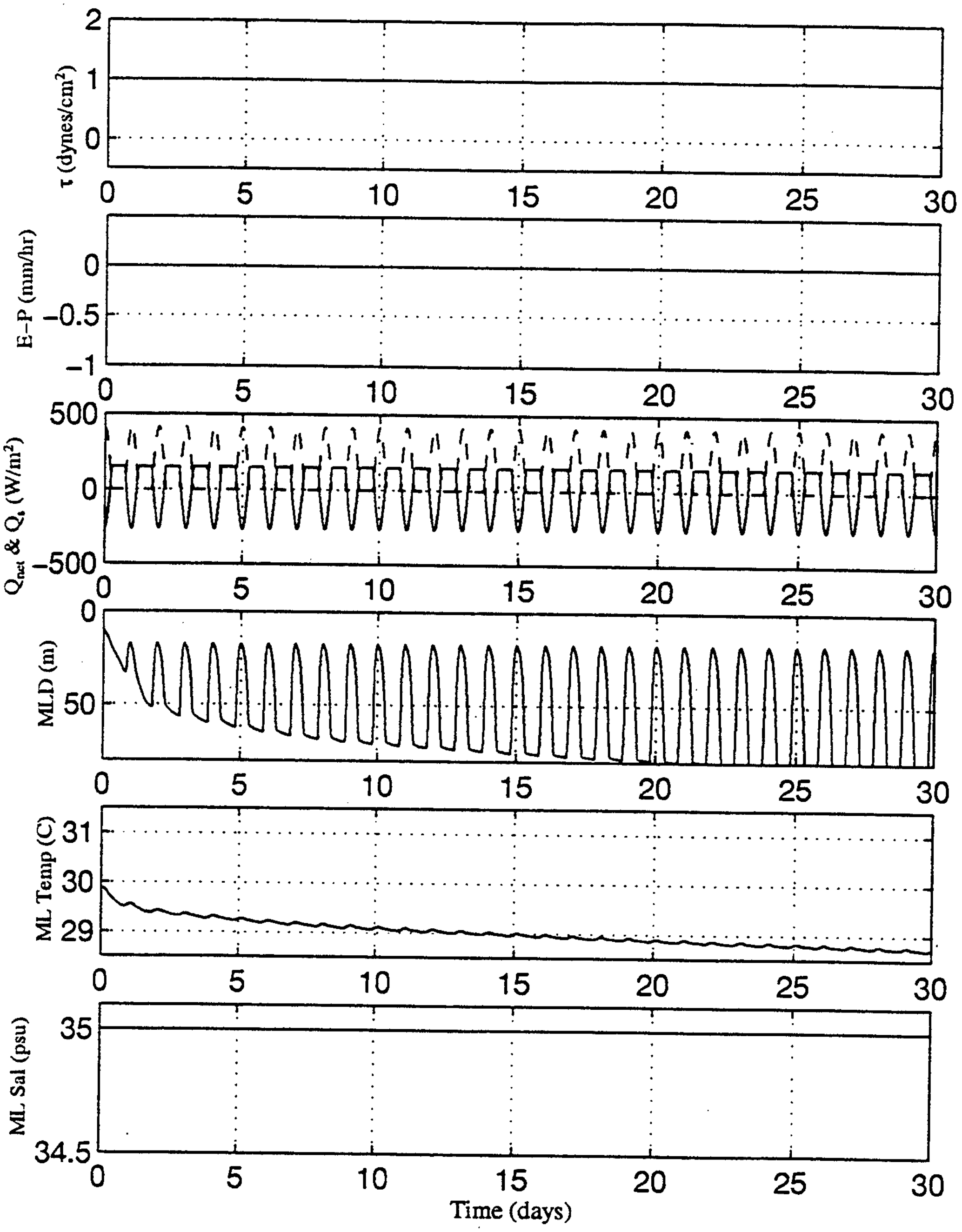

Figure 5. Case 3 - NPS model run using constant salinity and 1 dyne/cm² wind stress. (Same labeling convention as Figure 3).

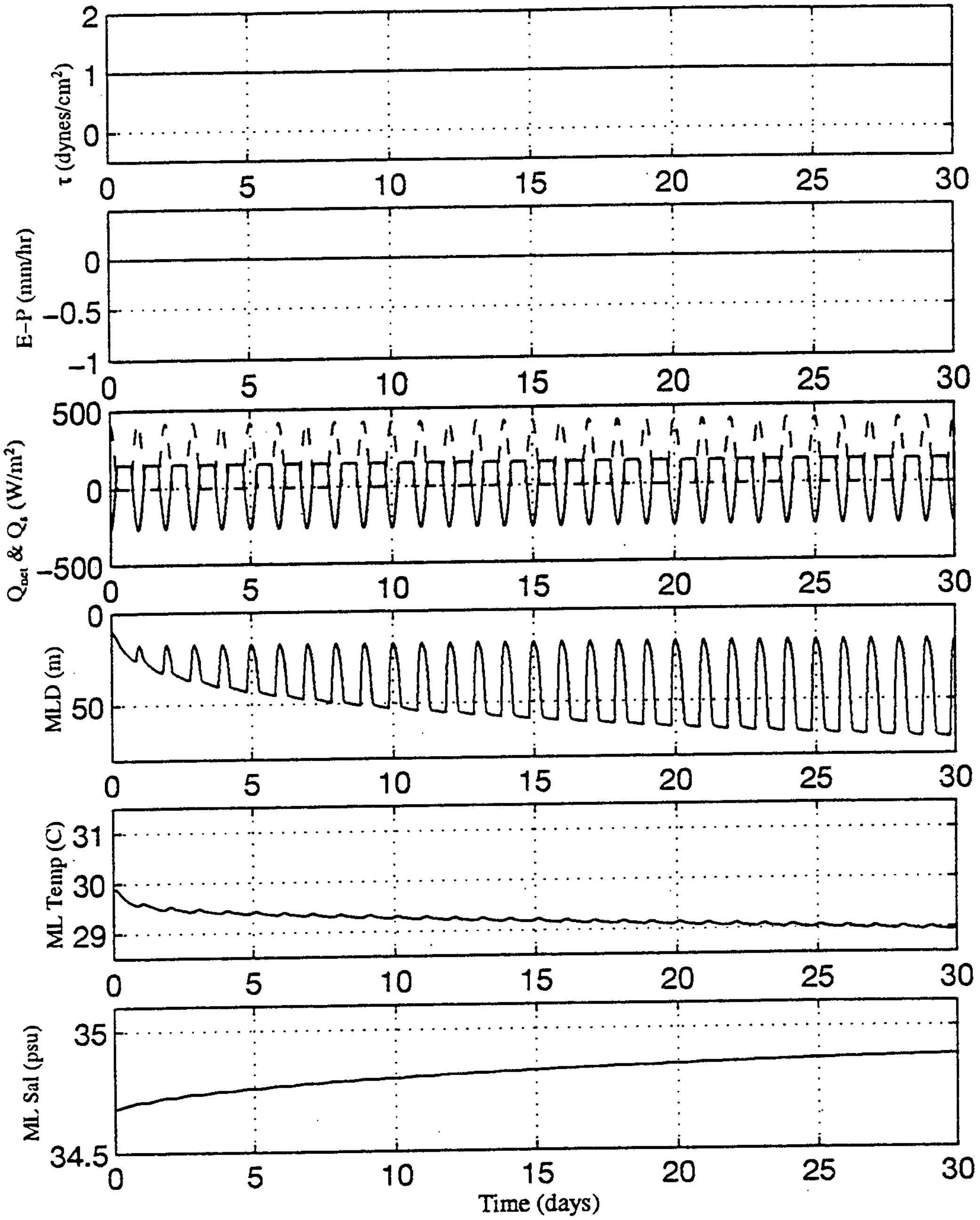

Figure 6. Case 4 - NPS model run using climatology salinity and 1 dyne/cm² wind stress. (Same labeling convention as Figure 3).

jump in case 4 the temperature jump does not have to be as large to get the same deepening rate.

B. PRECIPITATION EFFECTS

The addition of precipitation causes less dense fresher water in the mixed layer over a more dense saltier ocean which has a stabilizing effect. In all precipitation simulations, the climatology salinity profile is used and the precipitation rate is maintained at 4.5 cm/day.

1. Steady Precipitation (Case 5)

When a steady precipitation of 4.5 cm/day is added, large differences occur in the mixed layer depth and salinity (Figure 7) when compared to case 4 with no precipitation. The mixed layer temperature is unchanged with the addition of precipitation. The addition of precipitation adds fresh water to the ocean surface which decreases the mixed layer salinity and has a stabilizing effect. This stabilizing effect greatly slows the overall deepening of the mixed layer while increasing the diurnal difference between the daily shallowing and deepening. In Equation 10, the salinity jump becomes negative as fresh water is added to the mixed layer and the salinity flux term increases causing the buoyancy jump to increase and the buoyancy flux term to decrease leading to a reduction of the mixed layer deepening rate.

2. Diurnal Radiative Forcing

In this section, the phase of the precipitation input relative to the diurnal heating cycle is varied and the length of the precipitation event is set equal to four hours each day.

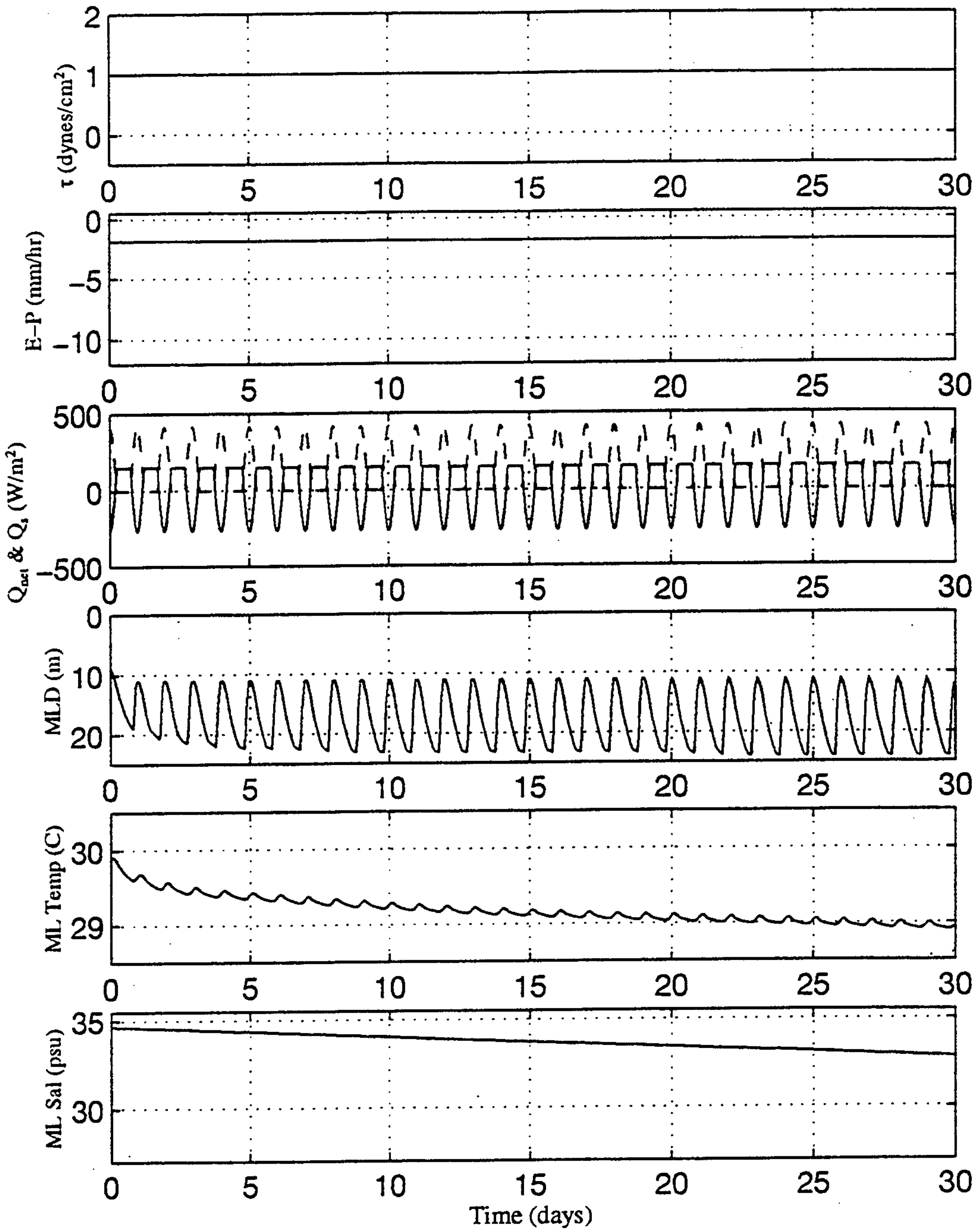

Figure 7. Case 5 - NPS model run using constant precipitation of 4.5 cm/day 1 dyne/cm² wind stress. (Same labeling convention as Figure 3).

a. Four Hour Period of Precipitation Starting at Local Noon (Maximum Heating) (Case 6)

In this experiment (case 6) the same amount of fresh water is added as in the previous experiment (case 5) but it is added over a four hour period beginning at local noon, the time of maximum heating. The mixed layer temperature has a very damped diurnal cycle and an overall cooling of approximately 1 °C over the 30 day period (Figure 8). During the four hour rain event the surface salinity has a sharp decrease. During the rest of the heating cycle the salinity increases smoothly due to entrainment. The mixed layer becomes fresher by approximately 3 psu over the 30 day period. At the beginning of the rain event, the mixed layer shoals to 4 m and remains there until the rain event is complete. When the rain event is complete, the mixed layer deepens at a constant rate until the next rain event. The maximum depth at the start of the period is 13.5 m and increases very slowly over the 30 day period to 14.5 m.

b. Four Hour Period of Precipitation Starting at Local Midnight (No Heating) (Case 7)

The mixed layer temperature (Figure 9) has a similar diurnal pattern as the noon rain case. The mixed layer salinity follows a similar pattern as the noon rain with the twenty-four hour cycle, but it starts at midnight instead of noon, in phase with the rain event. The overall mixed layer salinity decreases the same amount over the 30 days. The mixed layer shoals to 6 m and holds there during the rain event following closely to the local noon pattern. The exception to the noon pattern is that the maximum depth of the mixed layer remains near 15.2 m over the 30 day period.

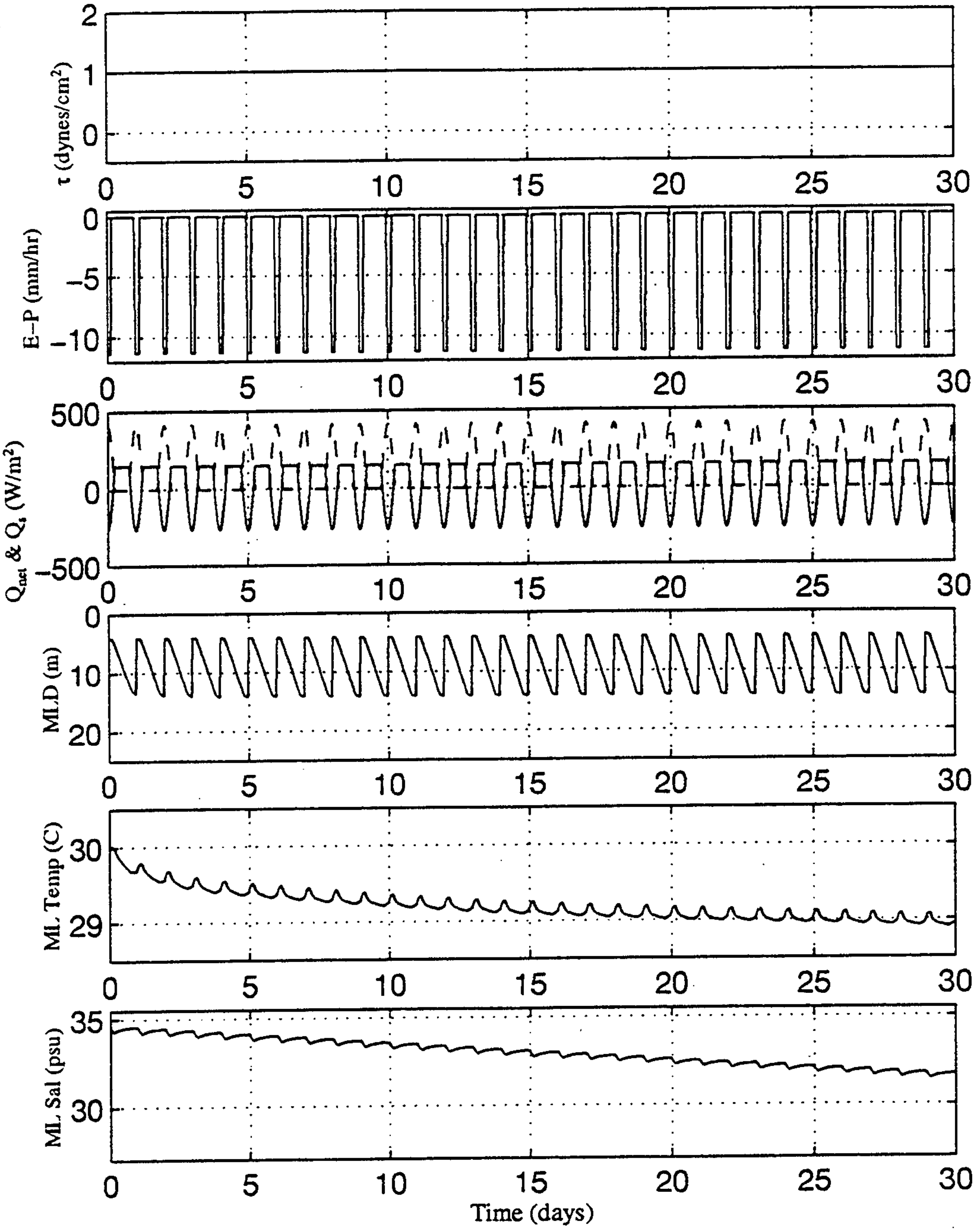

Figure 8. Case 6 - NPS model run using daily 4 hour precipitation of 4.5 cm/day starting at 1200L and 1 dyne/cm² wind stress. (Same labeling convention as Figure 3).

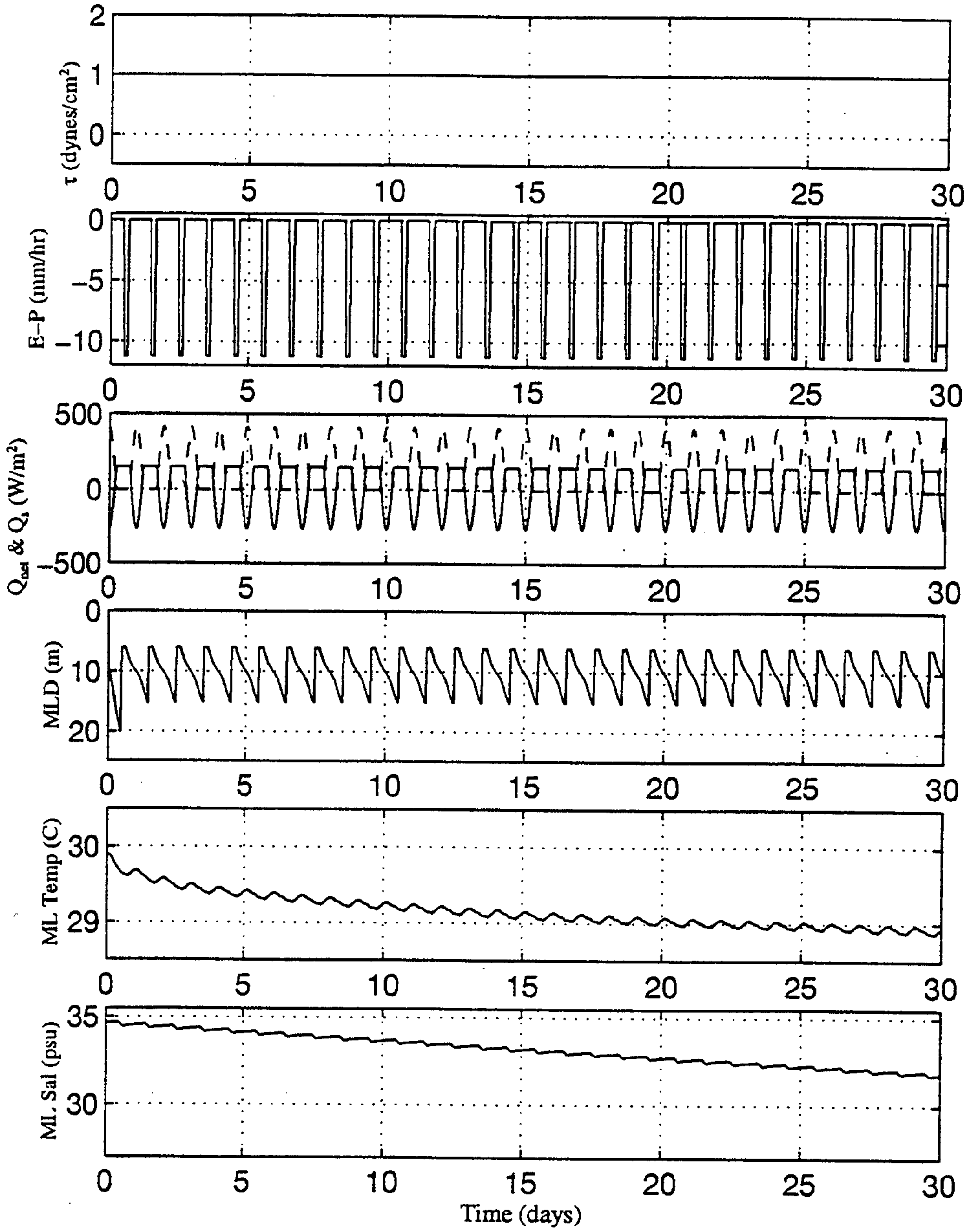

Figure 9. Case 7 - NPS model run using daily 4 hour precipitation of 4.5 cm/day starting at 0000L and 1 dyne/cm² wind stress. (Same labeling convention as Figure 3).

c. *Four Hour Period of Precipitation Starting at 0600 Local (Morning Rain) (Case 8)*

In Figure 10, the mixed layer temperature still follows the same diurnal cycle as the previous cases. The mixed layer salinity follows the same pattern with a shift in phase. The mixed layer shoals to 6 m at the start of the precipitation. When the daytime heating starts, it shoals further to 5 m for the rest of the rain event. The maximum mixed layer depth reached before the next rain event was 16 m.

d. *Four Hour Period of Precipitation Starting at 1800 Local (Evening Rain) (Case 9)*

In Figure 11, the mixed layer temperature is similar to the other cases. The mixed layer salinity has the same pattern as the other four hour rain events with a phase shift so the salinity decrease occurs during the 1800L rain event. The mixed layer depth is the same as the midnight rain event.

By only varying the phase of the precipitation relative to the diurnal heating, no major changes in the mixed layer were seen. Adding the rain at the beginning of the daily heating cycle makes a slight difference in the temperature, while starting the rain event right after the maximum heating occurred causes the overall change in depth to increase with time. More significant changes due to timing may have been seen if the diurnal heating were reduced because of significant cloud cover during the precipitation.

3. Heavy vs. Light Precipitation (Cases 6 vs 10)

a. *Fifteen Hour Period of Precipitation at Local Noon (Case 10)*

In case 10 (Figure 12), the mixed layer temperature shows the same diurnal cycle with a similar 30 day change in temperature as the four hour heavy rain cycle (case

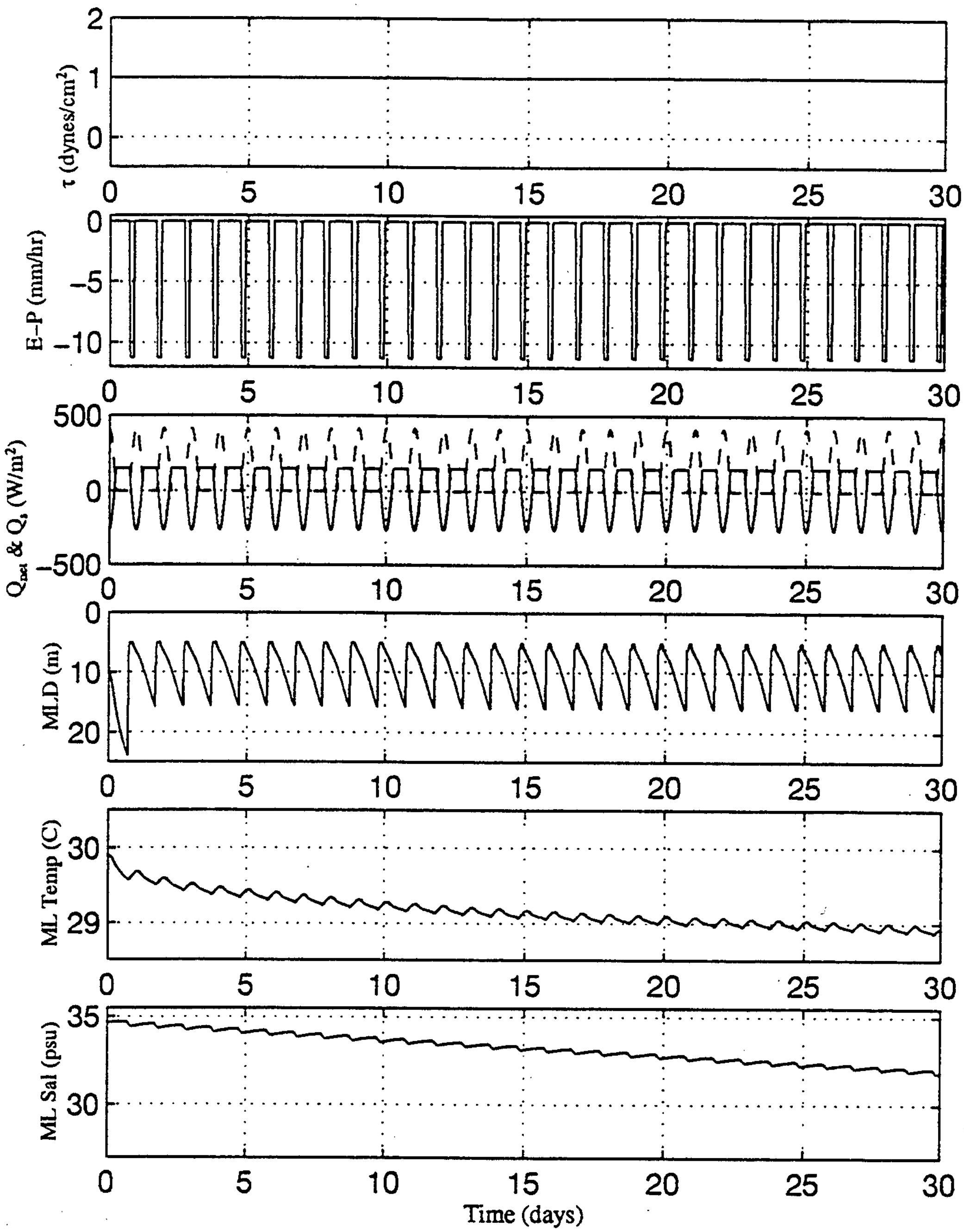

Figure 10. Case 8 - NPS model run using daily 4 hour precipitation of 4.5 cm/day starting at 0600L and 1 dyne/cm² wind stress. (Same labeling convention as Figure 3).

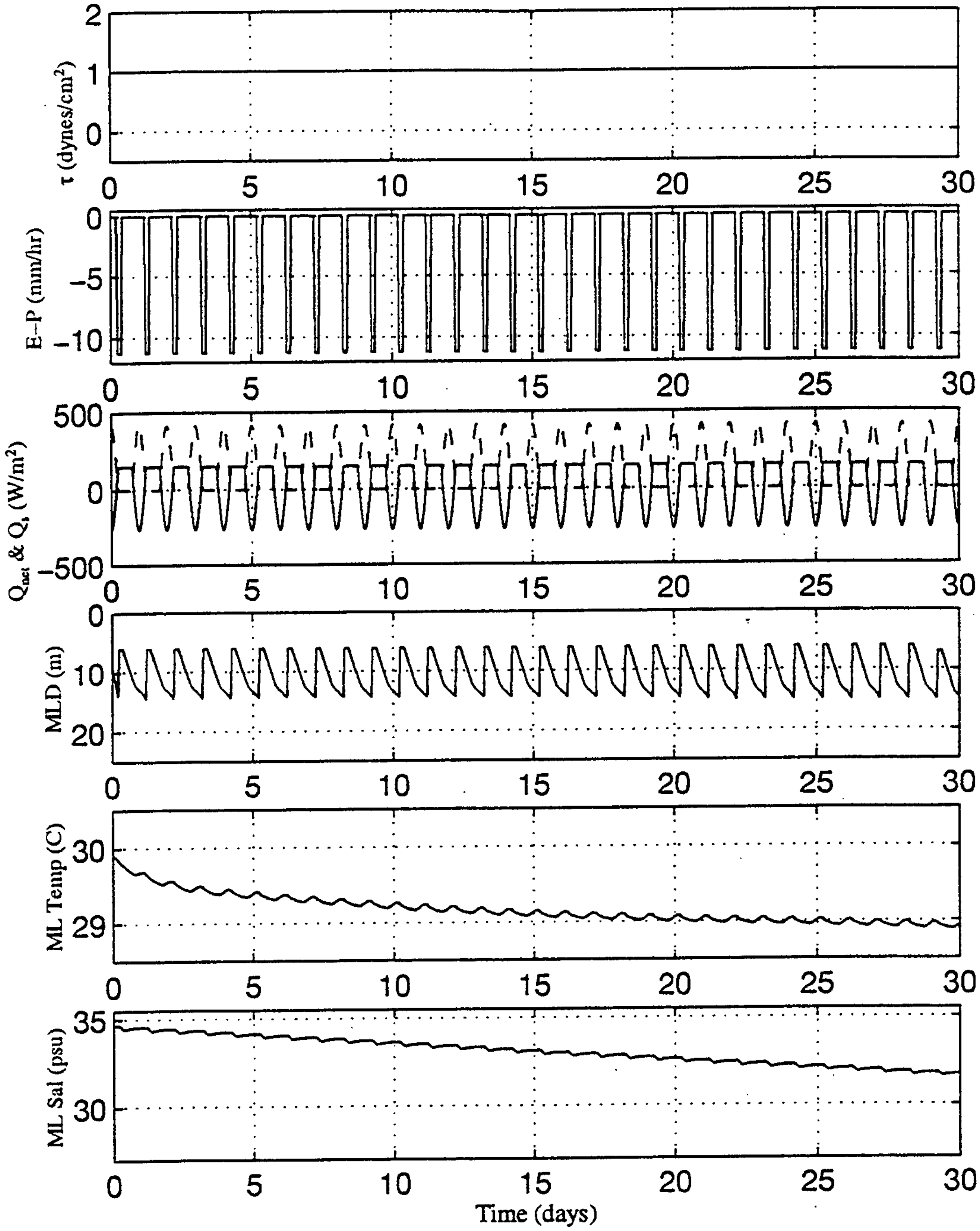

Figure 11. Case 9 - NPS model run using daily 4 hour precipitation of 4.5 cm/day starting at 1800L and 1 dyne/cm² wind stress. (Same labeling convention as Figure 3).

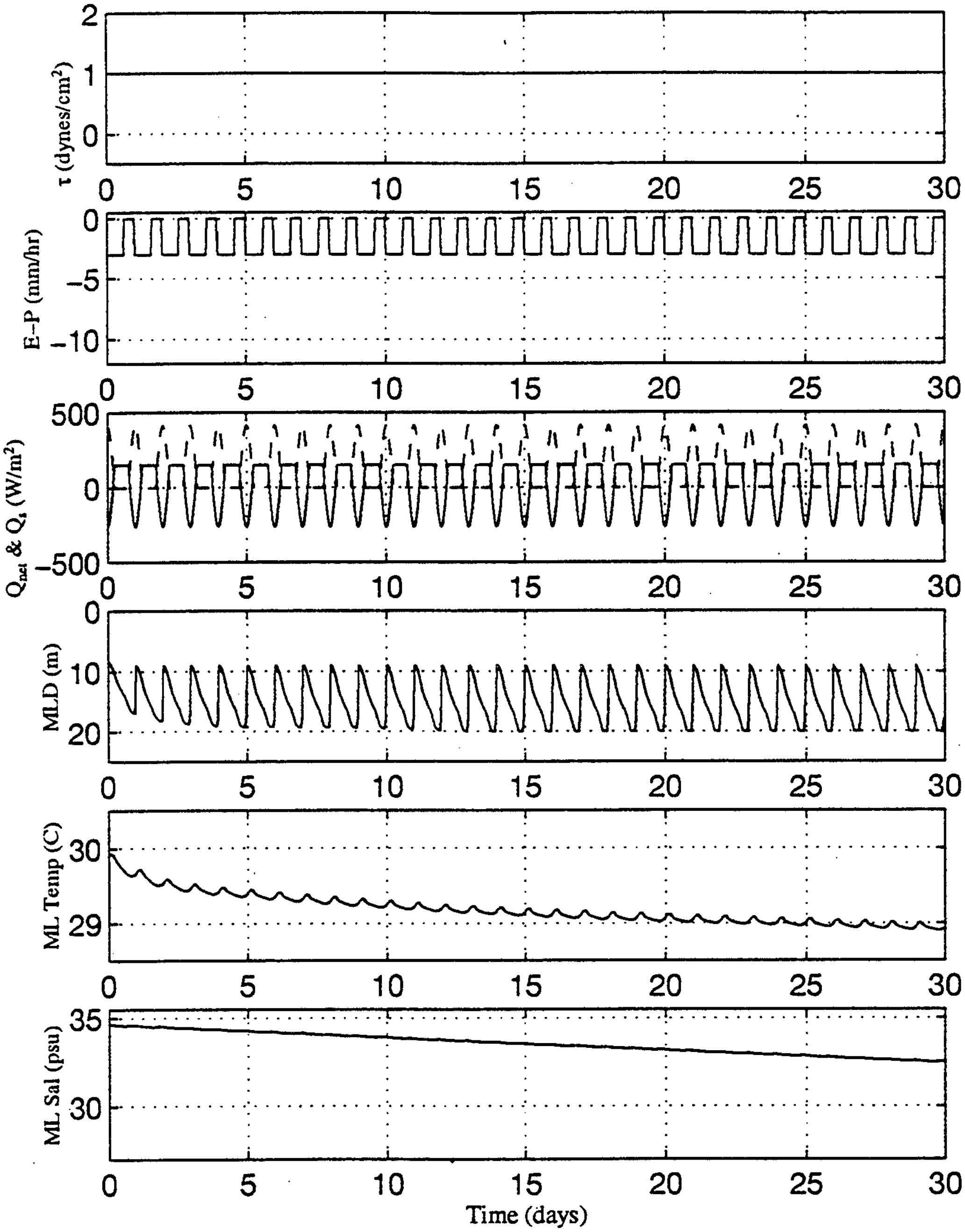

Figure 12. Case 10 - NPS model run using daily 15 hour precipitation of 4.5 cm/day starting at 1200L and 1 dyne/cm² wind stress. (Same labeling convention as Figure 3).

6). The salinity decrease is not as sharp for each rain event because the same total amount of rain falls over a longer period. Over the 30 days, the salinity shows a decreasing trend but not as strong as the heavy rain (2 psu vice 3 psu). The lighter rain results in a deeper mixed layer. This accounts for the smaller salinity change for the 30 day period because there is more mixing from below the layer. With the lighter precipitation, the mixed layer shoals to 9 m at the start of each new rain event but does not remain there throughout the rain event like the heavy rain. After the precipitation starts, the mixed layer deepens again. And there is an overall deepening during the 30 day period of about 2 m.

Heavy vs. light precipitation does make a difference in predicting the mixed layer. The lighter, longer rain period slows down the total salinity decrease by allowing for more entrainment of saltier water from below the layer. This allows for greater deepening of the mixed layer over time.

4. Wind Effects

In these simulations, comparisons between a τ value of 1.0 dynes/cm^2 (cases 6 and 10) and a τ value 0.5 dynes/cm^2 (case 11 and 12) are made. Reducing τ by half effectively reduces the rate of deepening by a third. In Equation 10, the wind effects can be seen in the shear production terms, wind stress and entrainment shear production.

a. Light Precipitation (Case 10 vs Case 11)

The mixed layer temperature of case 11 (Figure 13) has a weak diurnal pattern like case 10 (Figure 12) but cools with time at a greater rate (1 °C vs 0.7 °C in 30 days). The mixed layer salinity of case 11 follows the same trend as temperature with a

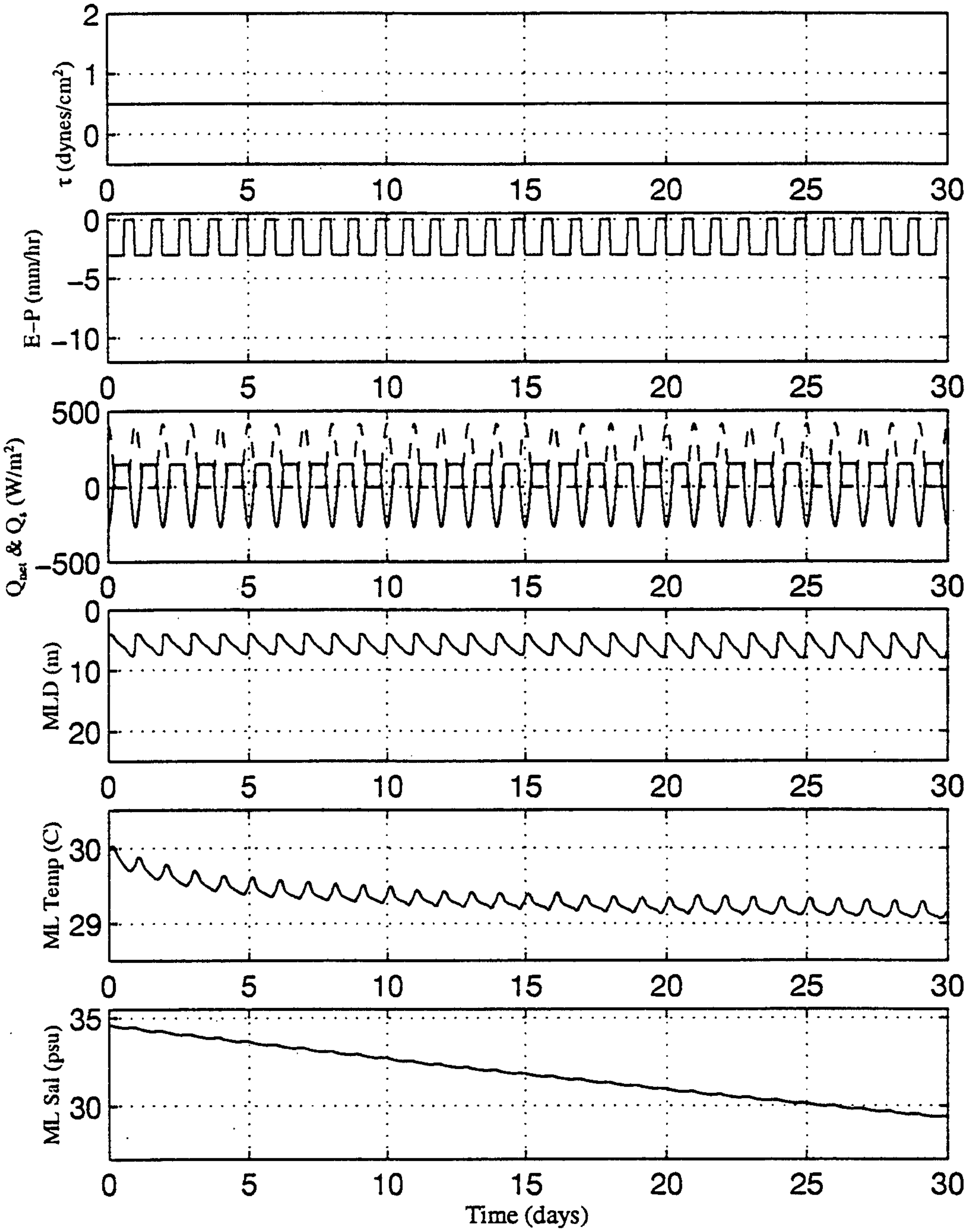

Figure 13. Case 11 - NPS model run using daily 15 hour precipitation of 4.5 cm/day starting at 1200L and 0.5 dyne/cm² wind stress. (Same labeling convention as Figure 3).

similar pattern but a much faster decrease over time when compared to case 10 (2.1 psu vs. 5.0 psu in 30 days). With $\tau = 0.5$ dynes/cm^2 the mixed layer depth deepens at approximately the same rate but shoals to 4 m instead of 9 m and has a diurnal oscillation of 3 to 4 m instead of 10 to 11 m. This accounts for the large change in temperature and salinity as this layer becomes fresher and cooler.

b. Heavy Precipitation (Case 6 vs Case 12)

The mixed layer of case 12 (Figure 14) has a smaller diurnal depth oscillation than the increased wind case 6 (Figure 8), 4 m vs 10 m daily. This is because less energy is available for deepening the mixed layer with reduced wind forcing. With the reduced energy for mixing, the entrainment of waters from the layer directly below the mixed layer is reduced. This leads to the mixed layer salinity decreasing at a much greater rate, 7 psu vs 2 psu in 30 days. Also, the mixed layer temperature cools at a slightly slower rate (0.9°C vs 1°C in 30 days) with the reduced wind.

Wind must be taken into account, especially for light precipitation cases. For lighter, longer rain periods if there is no significant wind effect when the upper layer of the ocean is capped off by the precipitation then a very shallow, fresh, cool mixed layer is created. Miller's (1976) study found the same result when comparing different rain intensities at different wind speeds.

C. COARE FORCING

All cases in this section use real wind, precipitation, and radiation forcing retrieved from the WHOI IMET buoy at 1° 45' S and 156°E during the TOGA COARE IOP. The thirty day period used is 5 December 1992 to 4 January 1993. The NPS model is

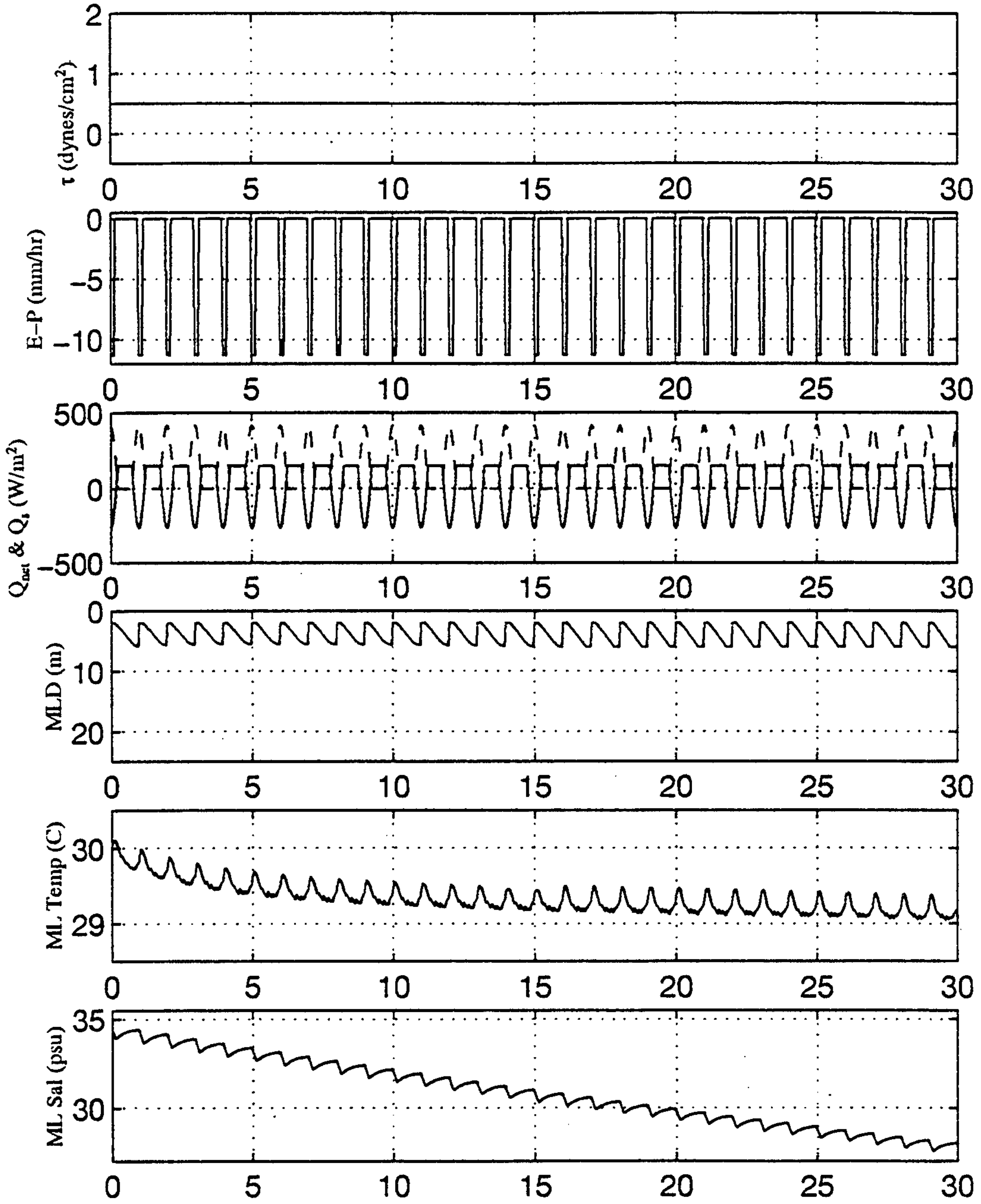

Figure 14. Case 12 - NPS model run using daily 4 hour precipitation of 4.5 cm/day starting at 1200L and 0.5 dyne/cm² wind stress. (Same labeling convention as Figure 3).

initialized with the BT temperature profile from 5 December 1992 as in the idealized experiments and with the climatological salinity profile from the Levitus data at this location.

1. Full Forcing (Case 13)

For the first five days of the COARE case (Figure 15), there is light wind and precipitation with a diurnal heating pattern. The result of this forcing was a shallow diurnal cycle of 1 to 5 m for the mixed layer depth. The mixed layer temperature increased approximately 2.5 °C while the mixed layer salinity decreased slightly. This is similar to what was observed in the light precipitation and light wind forcing cases earlier. On days 5 and 6, there is a large decrease in the mixed layer salinity, an increase in the mixed layer temperature, and the diurnal cycle is not readily seen in the mixed layer depth. This is explained by starting with a very shallow mixed layer and adding nominal wind and light precipitation, which causes the mixed layer to become insulated from the layer below.

Increased winds and heavier precipitation events occur from days 7 to 12. The diurnal heating pattern is reduced by the clouds associated with the precipitation events, especially on days 9 and 10. With this forcing the mixed layer deepens 5 m, cools 3 °C, and freshens nearly 0.5 psu.

There appears to be a storm from days 15 to 17 with very high winds, large precipitation rates, and reduced diurnal forcing due to clouds. During this storm, the mixed layer temperature decreases slightly (~0.5 °C) and the mixed layer deepens 5 m in 2 days, but the mixed layer salinity remains relatively unchanged. During this event there is entrainment of water from the lower layer of the ocean so cooler, saltier water is being

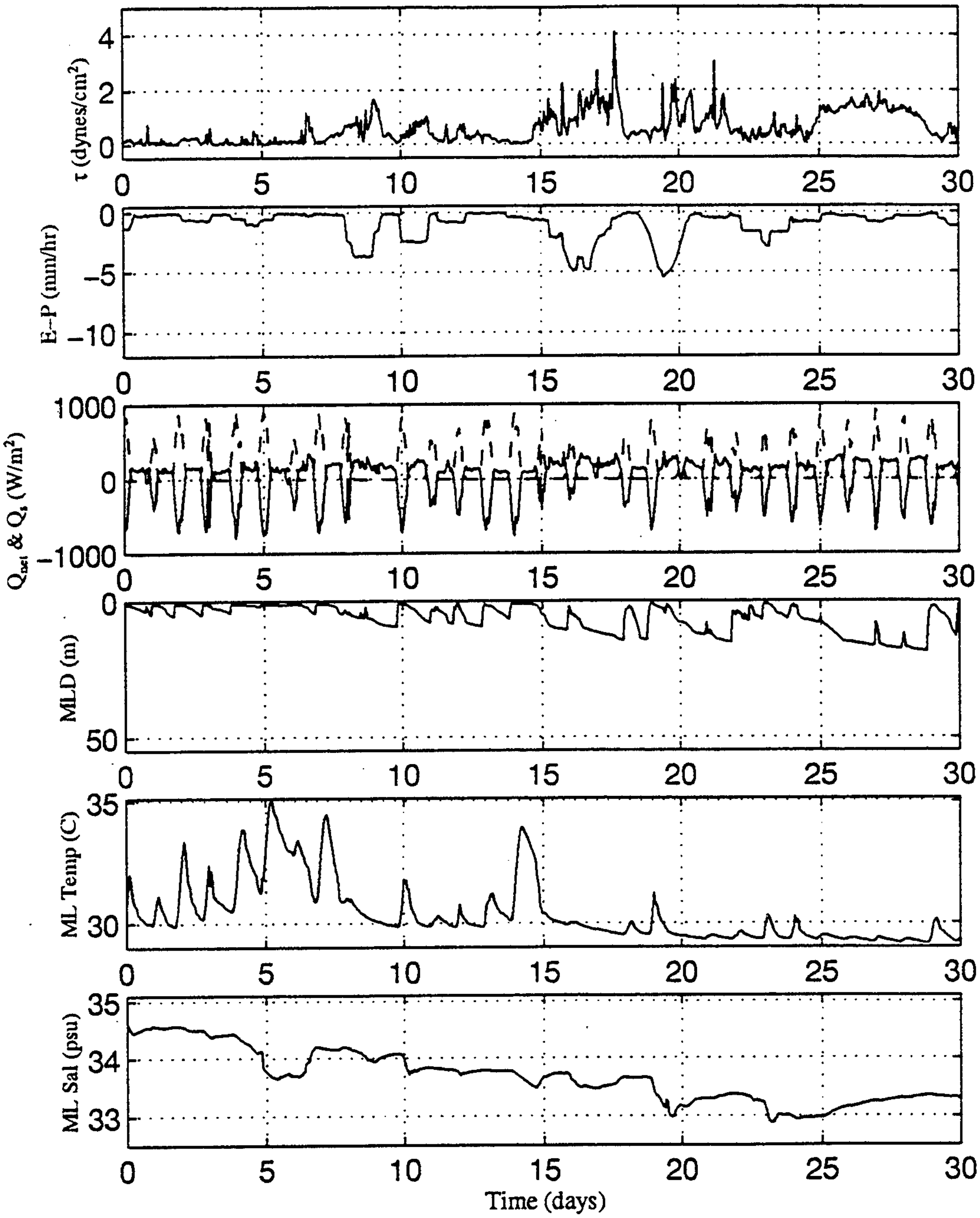

Figure 15. Case 13 - NPS model run using full COARE forcing. (Same labeling convention as Figure 3).

mixed into the layer. With the reduced heating, and the larger mass of water in the mixed layer, the effects of fresh water are mitigated. This is why the mixed layer salinity does not change.

From days 25 to 29, there is light precipitation and a strong diurnal heating pattern, but wind mixing dominates. On day 29, the mixed layer deepens to its greatest depth, 19 m, during the 30 days, while the mixed layer temperature cools slightly and the mixed layer salinity increases due to entrainment of the underlying water.

To check the accuracy of the NPS 1-D model, the daily model temperature profiles were compared with the IMET buoy temperature profiles. Looking at the upper 200 m, (Figure 16), the difference in the lower layers is ±1 °C. Because the model focuses on the mixed layer dynamics, there is little to no effect on the lower 150 m. Concentrating on the mixed layer environment, surface to 50 meters (Figure 17), one sees that the main difference is in the upper 3 m of the ocean. The model appears reasonably accurate, ±1 °C, for the majority of its domain (Figure 18). It does tend to overheat the mixed layer by 2 to 3 °C when the mixed layer is very shallow and the wind and precipitation are light. This may seem like a large error when looking at temperature only. But when considering the overall heat content in the upper 3 m, the error is small.

2. Partial Forcing - No Precipitation (Case 14)

To provide an overall understanding as to how precipitation affects the mixed layer, case 14 was run using the in situ forcing from the IMET buoy except for the precipitation (Figure 19). The most obvious difference without the precipitation is the change in mixed layer salinity value, which was to be expected. If there is no

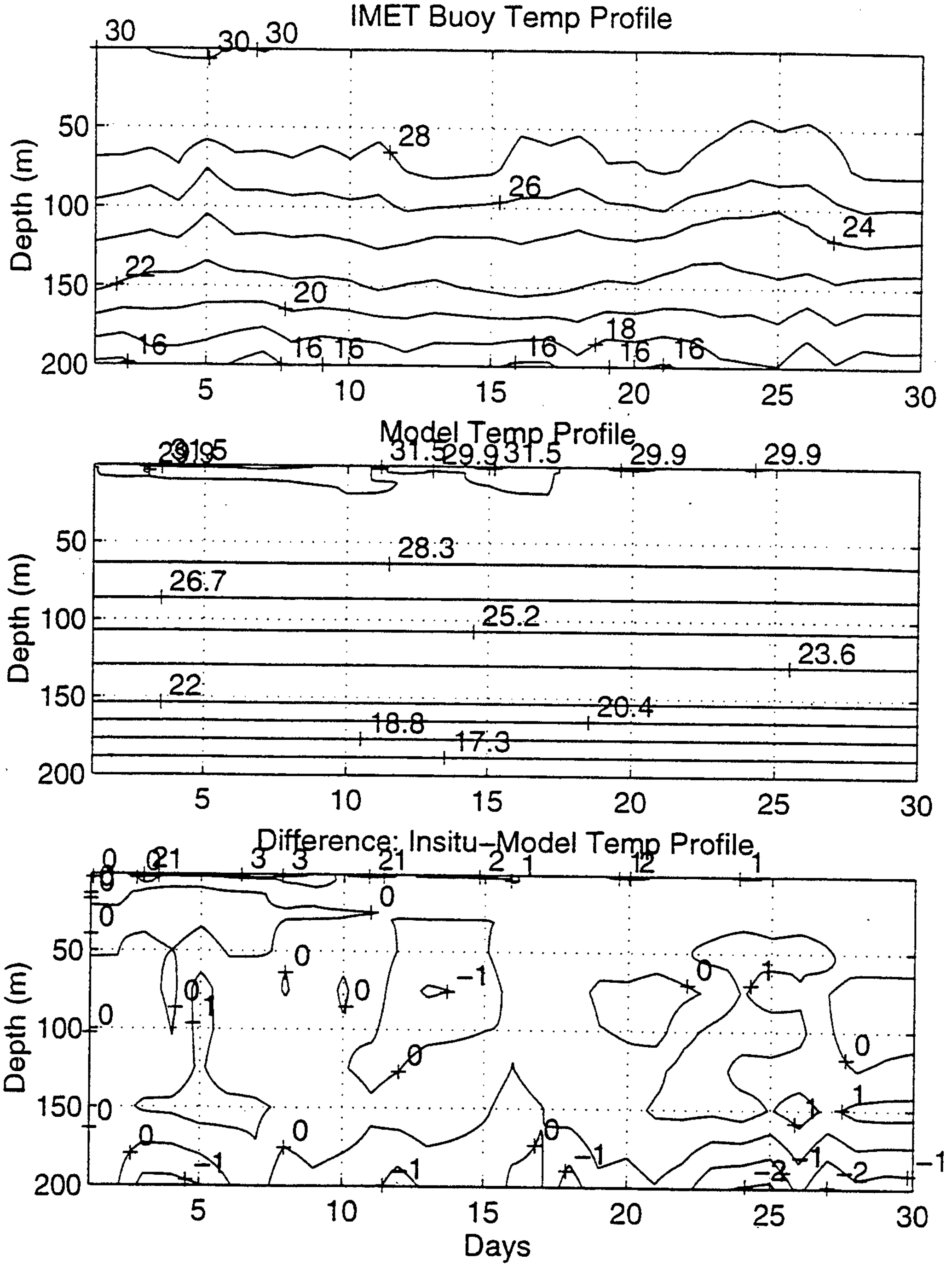

Figure 16. Comparison of IMET buoy and NPS model temperature profiles from 0 to 200 m depth. Contours are temperature in degrees Celsius.

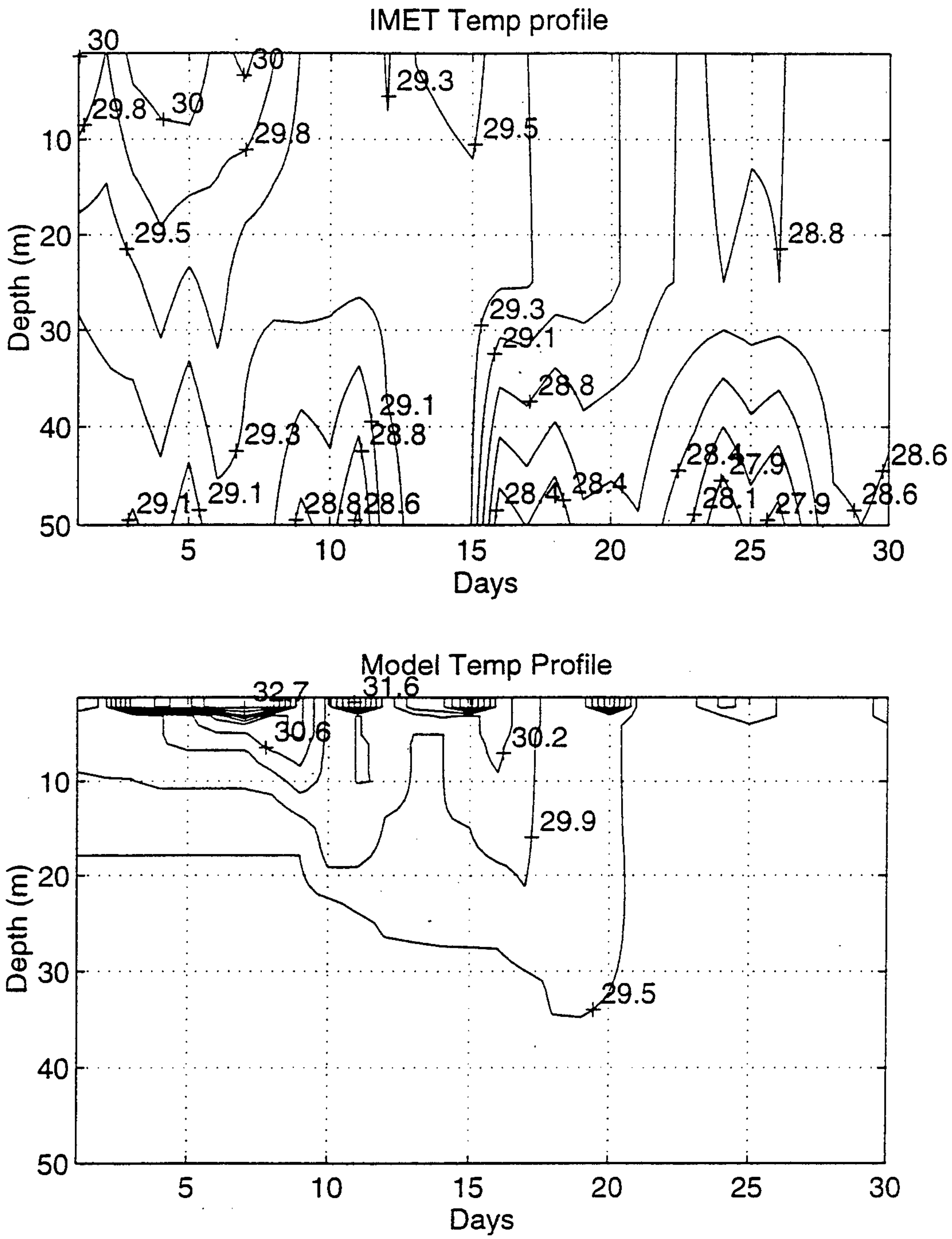

Figure 17. IMET buoy and NPS model temperature profiles from 0 to 50 m depth. Contours are temperature in degrees Celsius.

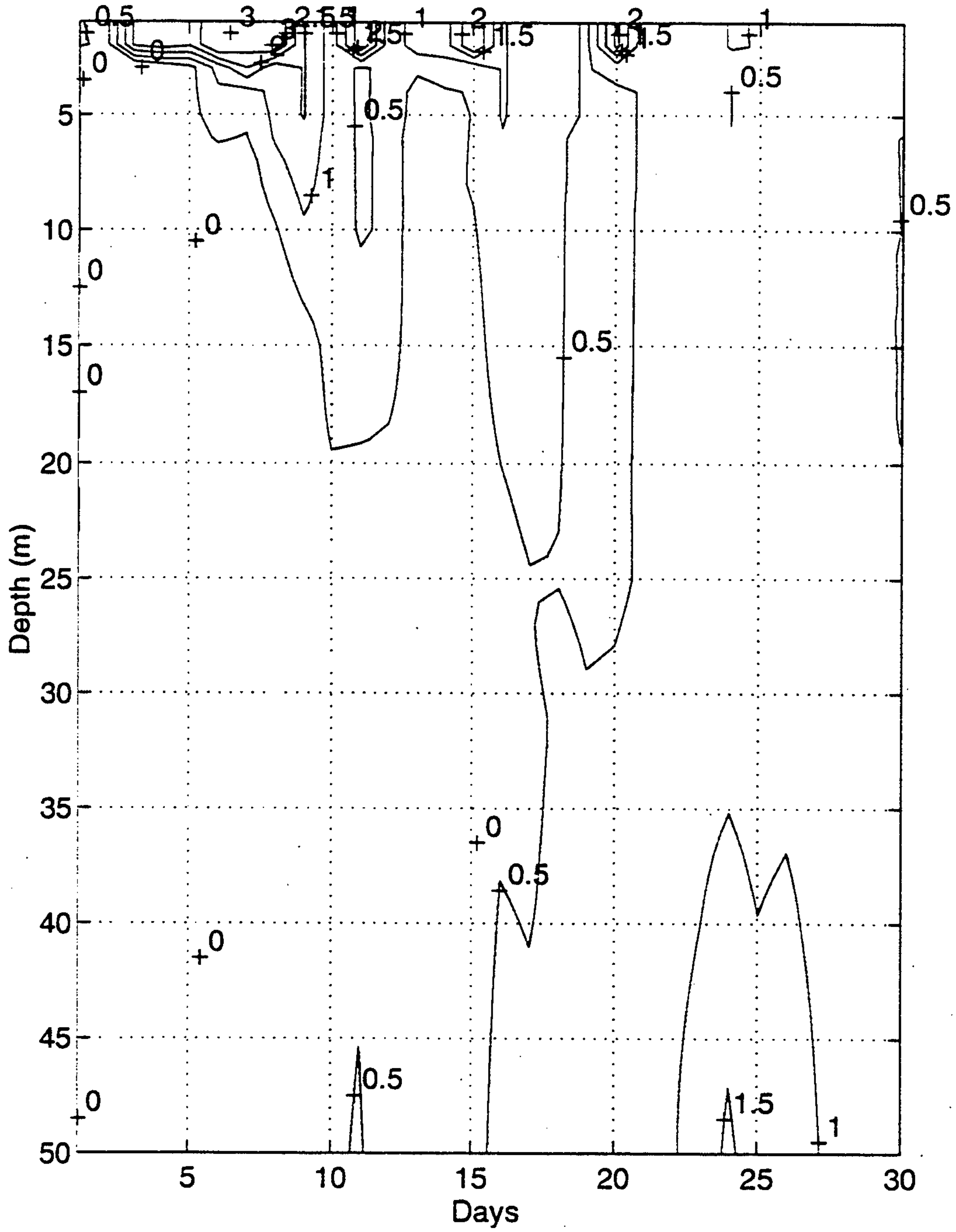

Figure 18. Difference between IMET buoy and NPS model temperature profiles from 0 to 50 m depth. Contours are temperature in degrees Celsius.

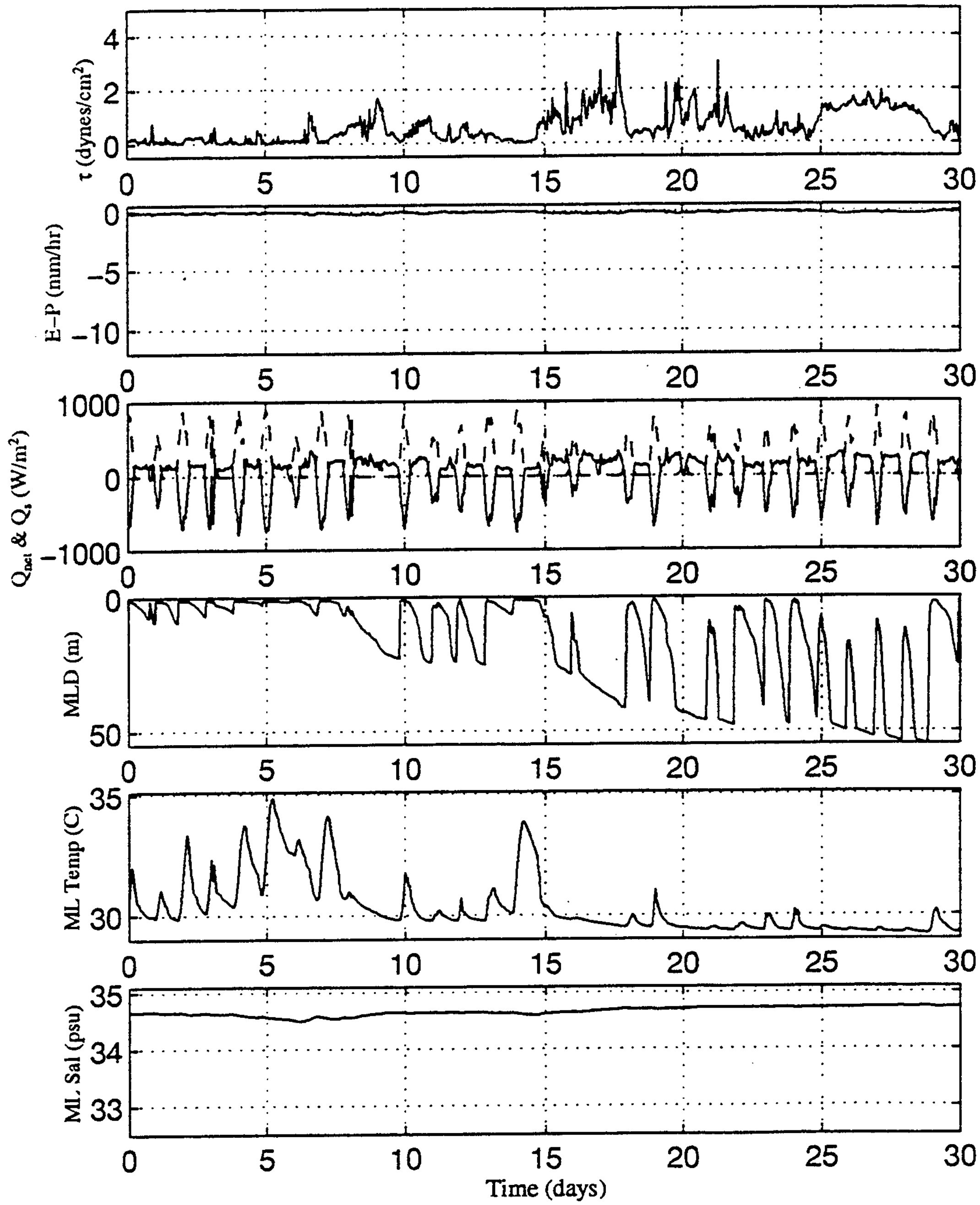

Figure 19. Case 14 - NPS model run using COARE forcing with no precipitation. (Same labeling convention as Figure 3).

addition of fresh water from an outside source, the mixed layer salinity will have small changes because the tropical Pacific's salinity differences are small throughout the region. The other difference of note is the increased depth the mixed layer reaches without precipitation. Including precipitation in case 13, the maximum depth reached by the mixed layer in the 30 day period was 18 m. Without precipitation, the mixed layer depth is more than double that amount as it extends deeper than 50 m. To examine the more subtle changes, the case 14 profile has been subtracted from the case 13 profile (Figure 20). Besides the mixed layer salinity and layer depth, there is also a very small mixed layer temperature difference during the period. The largest temperature difference (0.5 °C) occurs between days 4 and 8. This occurs at the time of a very shallow mixed layer with light wind and precipitation in the full forcing case which, as mentioned earlier, caps off the upper layer and allows for increased heating of the layer.

3. Averaged Forcing

The averaged forcing was obtained by taking the mean of each of the COARE thirty day hourly forcing inputs: wind stress, precipitation, downward solar radiation, back radiation, sensible heat flux, and latent heat flux. This was done to see how the fluctuations of the forcing affected the 30 day output.

a. Averaged Wind and Precipitation Forcing Only (Case 15)

Including the fluctuations in the radiation terms so that a diurnal heating cycle would still be in place, the NPS model was run with averaged hourly wind stress and precipitation values (Figure 21). With the averaged wind stress and precipitation forcing

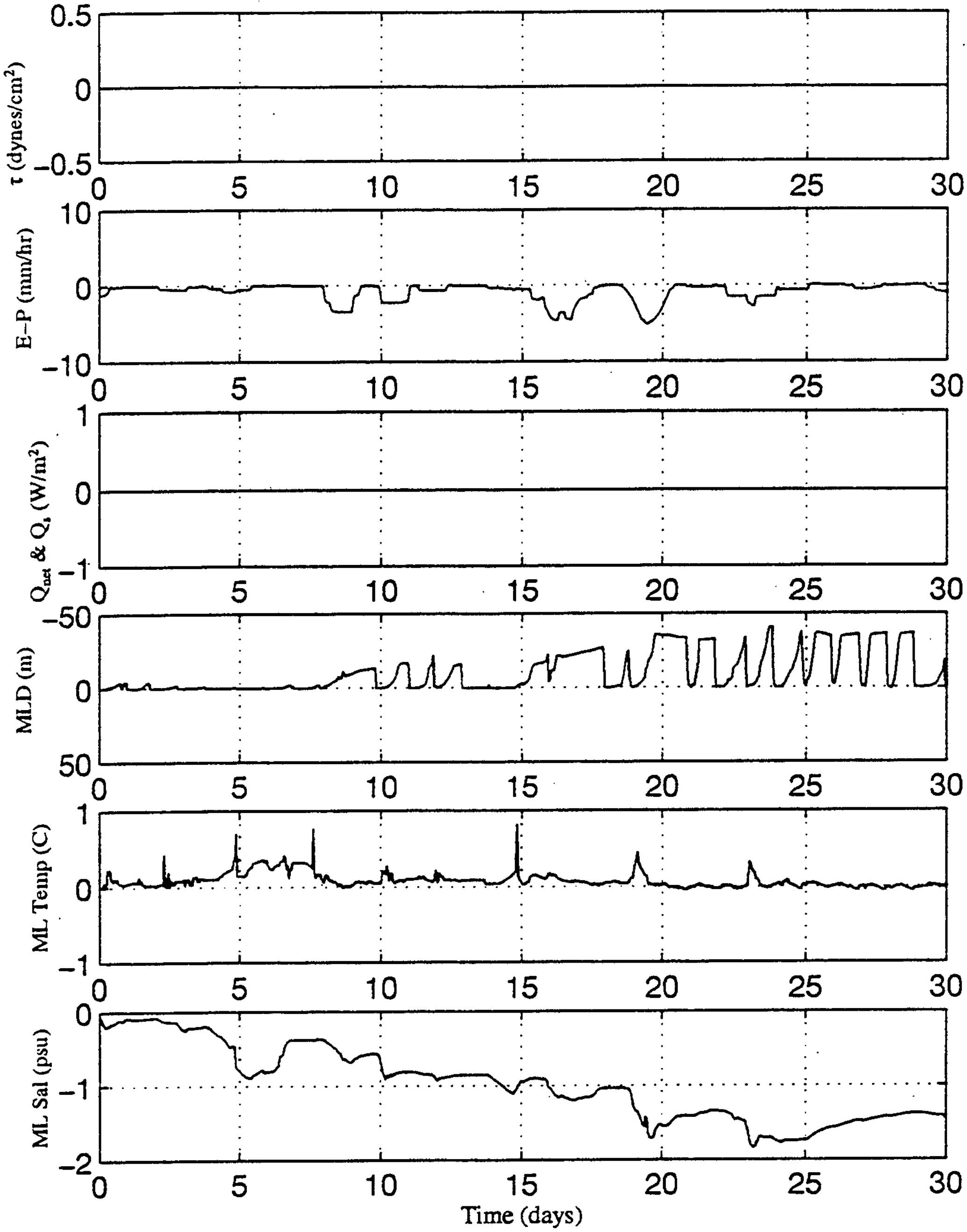

Figure 20. Difference between full COARE forcing (Case 13) and COARE forcing with no precipitation (Case 14). (Same labeling convention as Figure 3).

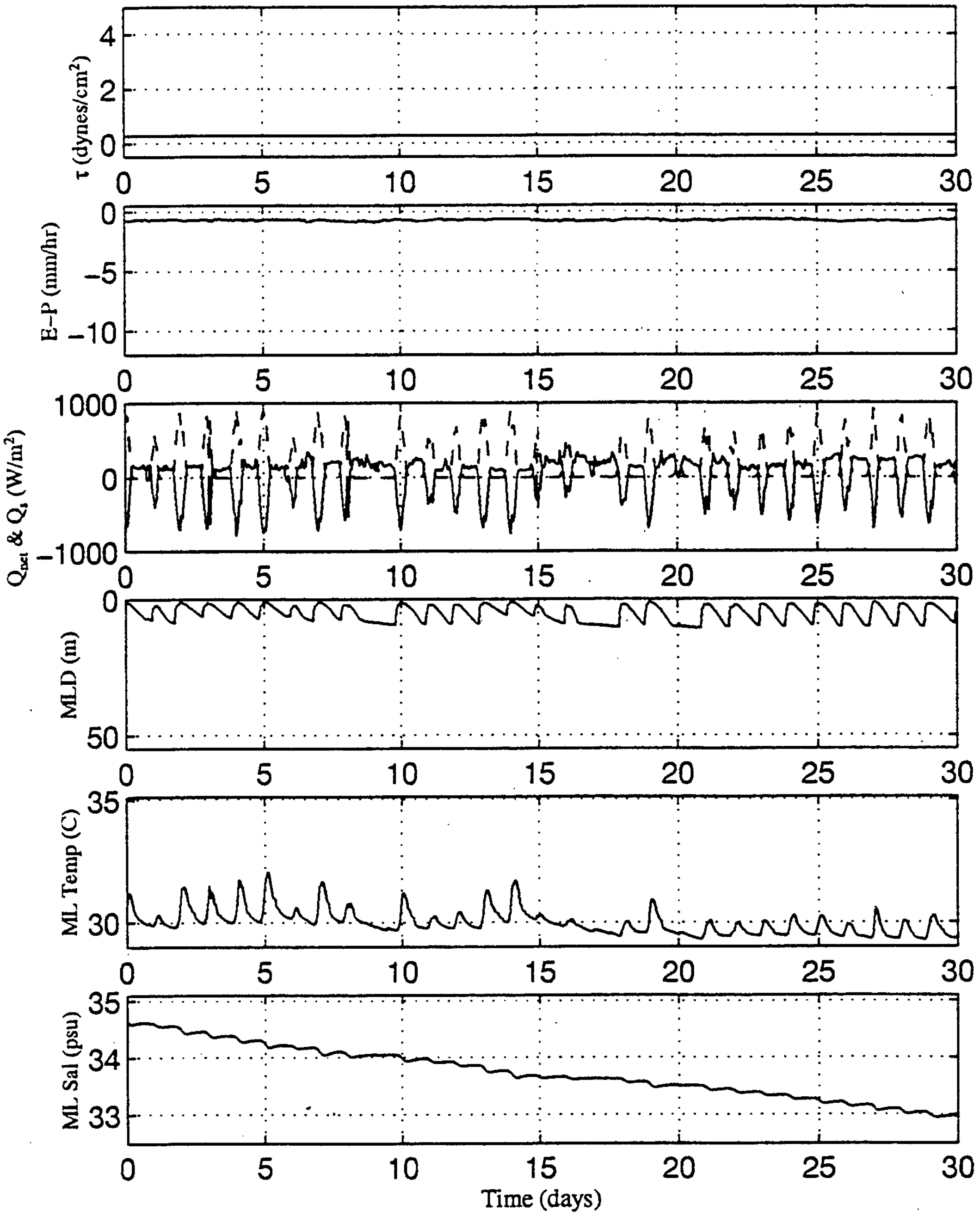

Figure 21. Case 15 - NPS model run using COARE forcing with average wind stress and precipitation values. (Same labeling convention as Figure 3).

the mixed layer stayed between 1 m and 10 m depth. The mixed layer temperature finished reasonably close to the real forcing case after 30 days, with both reaching approximately 29 °C, but case 15 only had a maximum temperature of 32 °C while case 13 had a maximum mixed layer temperature of 35 °C. The mixed layer salinity decreased from 34.5 psu to 33 psu over the 30 day period. Thus, the instantaneous forcing is 0.4 psu saltier than the averaged precipitation and wind stress forcing.

b. Averaged Radiation, Wind, and Precipitation Forcing (Case 16)

Using only the averaged COARE forcing (Figure 22), the same trends appear as with the partial averaged forcing case. The mixed layer temperature after 30 days is 29.8 °C, which is less like the real forcing mixed layer temperature than the partial forcing case. With case 16, the mixed layer salinity is 32.7 psu while the real COARE forcing of case 13 gave a mixed layer salinity of 33.3 psu at the end of the period.

The primary finding from this series of experiments is that the variation of the forcing is important. To use the average heat, wind, and/or precipitation for a forcing period will not allow modeling of the mixed layer with reasonable accuracy. The temporal variation of the forcing is important.

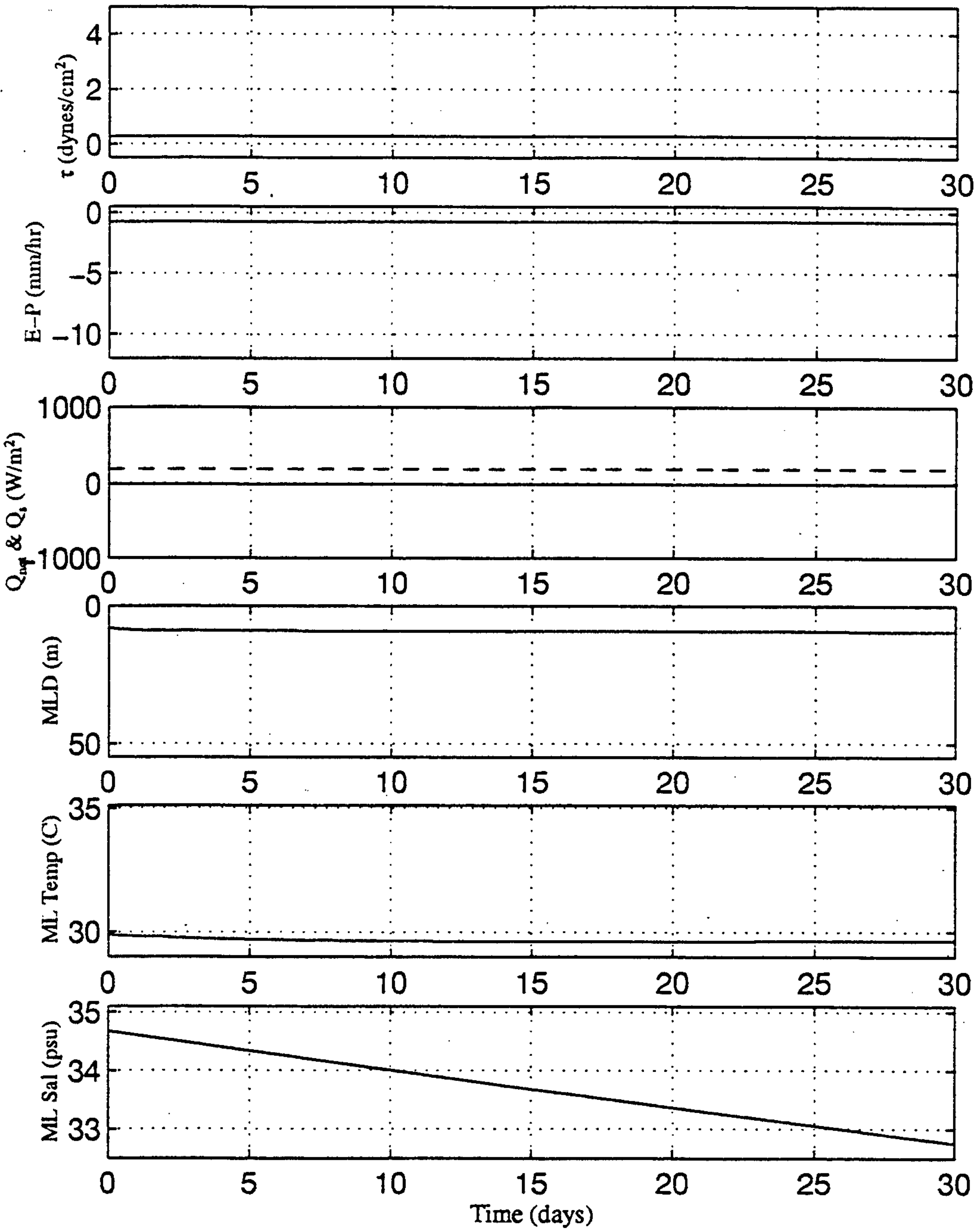

Figure 22. Case 16 - NPS model run using averaged COARE forcing. (Same labeling convention as Figure 3).

IV. A BRIEF LOOK AT LARGE-EDDY SIMULATION, DISCUSSION AND RECOMMENDATIONS

Several conclusions can be drawn from this study of the effects of salinity in equatorial mixed layers. Results from the NPS one-dimensional mixed layer model, forced with both idealized and in situ data, demonstrate that salinity can play a significant role in potentially changing the surface heat flux, with its effect on the mixed layer depth and mixed layer temperature. Precipitation stabilizes the mixed layer by creating a barrier layer, which slows down entrainment. Another important conclusion is that the fluctuations of the surface forcing play a significant role in the formation of the mixed layer. This is most apparent in the comparison between the average COARE forcing and the full COARE forcing. This also explains the difference between the four hour and fifteen hour rain events. Rain rate is an important consideration especially when varying wind mixing is involved.

The NPS 1-D mixed layer model did a good job modeling the western equatorial mixed layer in only one dimension, but the mixed layer is governed by turbulence which is fundamentally a three dimensional phenomenon. Currently, there is a study in progress which is uses a Large Eddy Simulation (LES) model to evaluate the effects of precipitation on the three dimensional turbulence in the western equatorial Pacific Ocean. In Figure 23, the turbulence cells, known as Langmuir cells, are visible as pressure fluctuations from a LES model experiment at 2 °N latitude, which has the same Coriolis value as the location used for the NPS 1-D mixed layer model in this paper. The depth of the vertical slice is 200 m to coincide with the 1-D model's domain and the turbulence can

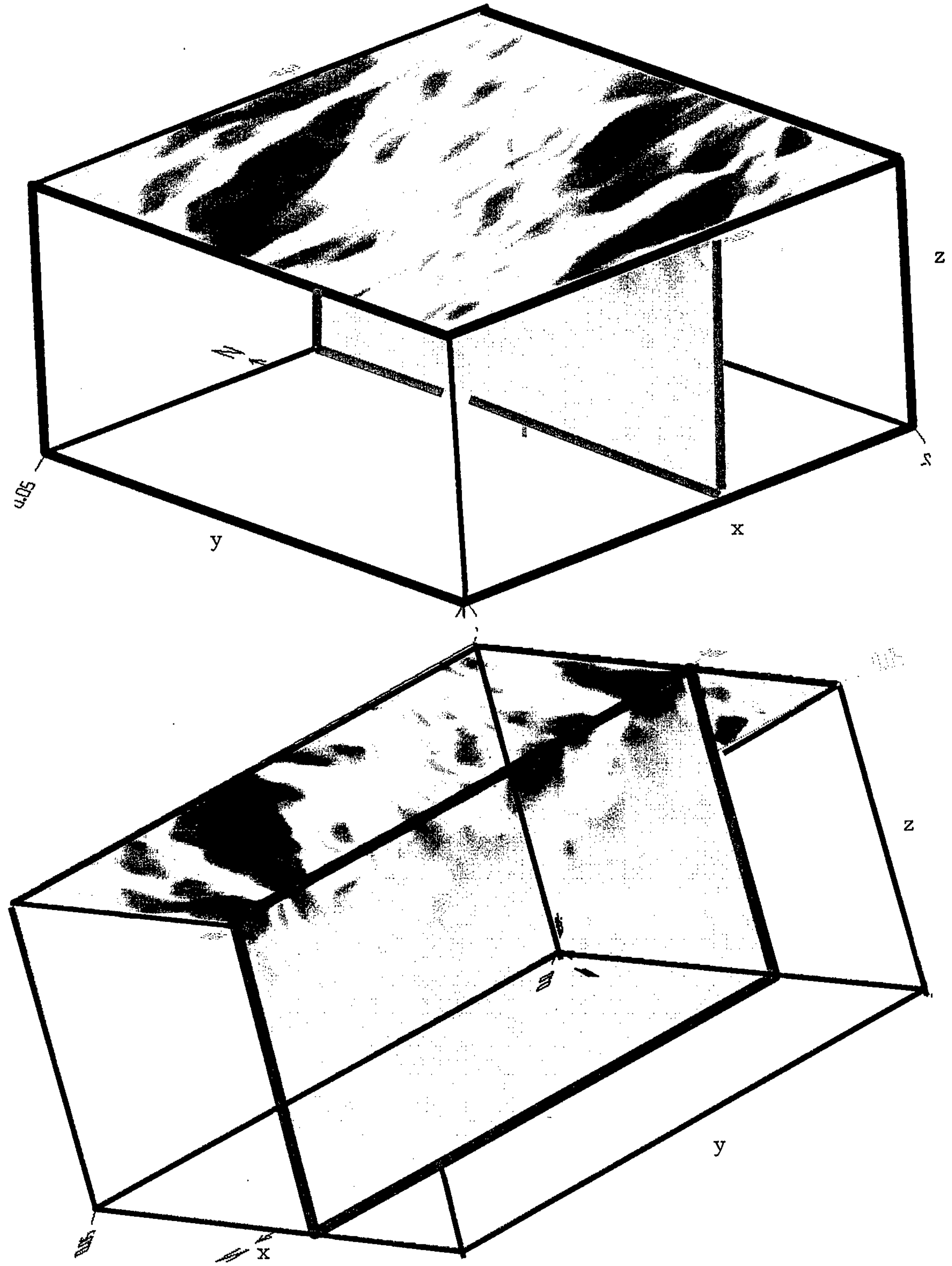

Figure 23. LES simulation at 2°N. The model domain is 640 m x 640 m x 200 m. The grid resolution was 5 m in each direction.

be seen reaching nearly to 100 m. Analysis of the LES model output enables statistical characterization of the three dimensional turbulence and the buoyancy flux. This study, and use of an embedded mixed-layer ocean general circulation model, modified to include salinity, will provide an even better overall understanding of salinity/precipitation effects in this region.

Finally, since the western equatorial Pacific Ocean is referred to as the “warm pool” and is believed to play a significant role in the global climate, future studies in this area should include the use of a coupled atmosphere-ocean model to study the effects of salinity on the feedback cycles. This should provide better understanding of the western equatorial Pacific’s warm pool and its role in the earth’s climate.

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