The Heat Sources and Sinks of the 1986–87 El Niño

DE-ZHENG SUN

Climate Diagnostics Center, NOAA/CIRES, Boulder, Colorado

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ABSTRACT

The heat balance of the coupled tropical ocean–atmosphere system during the Earth Radiation Budget Experiment (ERBE) period (1985–89) is analyzed in an attempt to better understand the heat sources and sinks of the 1986–87 El Niño. The analysis involves the use of radiation data from ERBE, circulation statistics from National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis, and the assimilated data for the Pacific ocean.

Accumulation of heat in the equatorial upper ocean is found prior to the onset of the 1986–87 El Niño. The accumulated heat in the equatorial upper ocean comes from the surface heating, which exceeds the poleward transport of heat in the upper ocean. The accumulated heat in the upper ocean resurfaces in the eastern Pacific and the 1986–87 El Niño warming develops. The warming results in a substantial increase in the equator-to-pole heat transport in the equatorial ocean. The ocean warming is also accompanied by a significant increase in the poleward transport of energy in the atmosphere and a significant reduction in the surface heat flux into the equatorial ocean, though these changes are smaller than the increases in the poleward heat transport in the ocean. Because of the feedbacks from water vapor and clouds, the variations in the net radiative energy flux at the top of the atmosphere are small and the surface heat flux into the equatorial ocean is mainly modulated by the poleward transport of energy in the atmosphere, which is in turn modulated by the intensity of the cold tongue. The anomalous poleward ocean heat transport does not stop right at the time when the surface warming is terminated, and this ‘‘overshooting’’ pushes the equatorial ocean to a cold state—the 1988–89 La Niña—during which the poleward transport in the atmosphere and ocean is reduced and heat starts to accumulate in the upper ocean again. The coupled system is then in a situation similar to 1985 and is preparing for the onset of another El Niño.

The results suggest that ENSO system behaves like a heat pump: the equatorial ocean absorbs heat during the cold phase and pushes the heat to the subtropical ocean during the warm phase. This picture for El Niño implies that the surface heat flux into the equatorial ocean may be a driving force of El Niño. The relationship between this picture for El Niño and the delayed oscillator hypothesis is explored. An explanation for the absence of El Niño in the tropical Atlantic ocean is offered by noting that the zonal width of the basin limits the amount of heat that can be accumulated in the upper ocean. The implication of the present findings for the response of El Niño to global warming is discussed.

1. Introduction

The question of whether El Niño will become more energetic in response to an increase in the greenhouse effect is of high societal concern. Addressing this question requires a clear understanding of what constitutes the thermal forcing of El Niño. Such an understanding is still lacking (Neelin et al. 1998). The situation, however, is improving. The study of Sun and Liu (1996) and that of Clement et al. (1996) have linked the zonal SST contrast in the equatorial region to the intensity of the surface heat flux into the equatorial ocean. Using coupled models, they found that because of the dynamical coupling between the atmosphere and ocean, the zonal SST contrast increases with increases in the surface heat flux into the ocean. Extending this theoretical result and that of Jin (1996), Sun (1997, 1998) linked the magnitude of El Niño to the intensity of surface heat flux into the equatorial ocean, which in his model is proportional to the zonal SST contrast in the equatorial region [which is in turn proportional to the difference between the tropical maximum SST (T_w) and the characteristic temperature of the equatorial undercurrent (T_c)]. The simple coupled model of Sun (1997) encapsulates the delayed oscillator physics but calculates the total SST. The model predicts that ENSO-like oscillations only occur when the zonal SST contrast or the surface heat flux exceeds a critical value and that the amplitude of the oscillation increases with an increasing surface heat flux into the equatorial ocean. This theoretical result suggests that El Niño is a thermally forced oscillation whose magnitude is proportional to the sur-

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Corresponding author address: Dr. De-Zheng Sun, NOAA–CIRES Climate Diagnostics Center R/CDCI, 325 Broadway, Boulder, CO 80303.
E-mail: ds@cdc.noaa.gov

face heat flux into the equatorial ocean. The relevance of this proposition to the observed system, however, has not been examined. One elementary way to discern the thermal forcing of El Niño from observations is to examine where El Niño derives its heat and where El Niño eventually deposits or loses the heat.

Wyrtki (1985) first noted that El Niño depletes the heat accumulated in the equatorial upper ocean and thereby theorized that El Niño represents a mechanism whereby the accumulated heat in the equatorial upper ocean is purged to higher latitudes. Subsequent studies generally support Wyrtki's hypothesis (McPhaden et al. 1998). Using a numerical model, Zebiak and Cane (1987) demonstrated that whether there is El Niño in the model depends critically on whether the zonal mean heat content of the equatorial upper ocean was allowed to vary. In an ocean model simulation, Springer et al. (1990) found a buildup of heat content in the equatorial upper ocean prior to the onset of the 1982–83 El Niño. The importance of accumulation of heat in driving El Niño is further elucidated by Jin (1996) and Sun (1997) using nearly analytical models. The support for Wyrtki's theory, however, is not unanimous. Using Geosat data, Miller and Cheney (1990) did not find an increasing heat content in the equatorial region prior to the 1986–87 El Niño, raising the question of whether the 1986–87 El Niño falls outside the prescription of Wyrtki's theory. Using the assimilated data for the tropical Pacific ocean (Ji et al. 1994), we will be able to calculate directly the heat content of the upper ocean with precision and show that the heat content was increasing prior to the onset of the 1986–87 El Niño.

Though the importance of the accumulation of heat in the equatorial ocean has been suggested for at least some El Niños, the factors that are responsible for the accumulation of heat in the equatorial upper ocean have not been fully examined using available observations. Is the accumulation of heat in the equatorial ocean prior to the onset of El Niño primarily due to the cumulative effect of surface heating or a consequence of the advection of heat within the ocean from the off-equatorial region? What is the role of the atmospheric transport and the radiative effects of water vapor and clouds in this process? What determines the surface heat flux into the equatorial region and what controls the poleward heat transport in the atmosphere and ocean? How does the thermal structure of the equatorial upper ocean respond to the accumulation of heat? This article attempts to address these questions quantitatively by utilizing the best datasets available for the atmosphere and ocean. We are particularly motivated to clarify and complement the results on the heat sources of El Niño from some previous studies. It has been shown before that the interannual anomaly in the surface heat flux is small compared with the interannual anomaly in the heat content of the upper ocean (Barnett et al. 1991; Brady 1994). In fact, the interannual anomaly of surface heat flux has been found to have a negative correlation with the interannual anomalies of SST (Barnett et al. 1991; Sun and Trenberth 1998). Does this mean that the surface heat flux actually damps El Niño? By examining the evolution of the total energy flux field over an ENSO cycle, we will show that the heat that leads to the surface ocean warming in the first place is provided by the surface heat flux.

The need to examine where El Niño derives its heat is further highlighted by the study of Sun and Trenberth (1998). In an attempt to assess the relative importance of dynamical and radiative feedbacks in regulating El Niño warming, they quantified the increases in the transport of poleward energy in the atmosphere and ocean during the 1986–87 El Niño relative to changes in the cloud reflection of solar radiation for the equatorial region (5°S–5°N). The results show that the enhanced cloud reflection is actually the smallest negative feedback. The corresponding enhancements in the poleward energy transport in the atmosphere and ocean are the dominant negative feedbacks. The large increases in the poleward transport of energy in the equatorial atmosphere and ocean during the surface warming of El Niño raise the question of where the energy removed during El Niño warming comes from in the first place.

We will show that El Niño derives its heat from the surface heating and more generally that the equatorial ocean with the presence of ENSO behaves like a heat pump: it absorbs heat through its surface during the cold phase and pushes the heat out to the subtropical ocean in the warm phase. We will discuss how this ''heat pump'' is driven and explore the relationship between this heat pump picture for ENSO and the delayed oscillator hypothesis.

2. The heat sources and sinks of the 1986–87 El Niño

We start with the energy balance of a coupled ocean–atmosphere column (Fig. 1). Using H_c to represent the heat content of the ocean, we have

$$\frac{\partial}{\partial t}H_c = F_s + D_o, \tag{1}$$

where F_s is the surface heat flux into the ocean and D_o is the convergence of heat in the ocean. The surface heat flux is linked to the energy balance of the overlying atmosphere,

$$F_s = N_T + D_a - \frac{\partial}{\partial t}E_a, \tag{2}$$

where E_a is the total energy in the atmosphere (kinetic energy plus moist static energy), D_a is the convergence of moist static energy in the atmosphere, and N_T is the net radiative flux at the top of the atmosphere (Sun and Trenberth 1998; Trenberth and Solomon 1994) (D for ''dynamics,'' which includes the effects from both mean circulation and transients). Here N_T is related to the greenhouse effect by the following equation:

$$N_T = S_c - E + C_s + C_l + G_a + G', \qquad (3)$$

where S_c is the clear-sky solar radiation, E is the surface emission, C_s is the cloud short-wave forcing, C_l is the greenhouse effect of clouds, G_a is the greenhouse effect of water vapor, and G' is the greenhouse effect of CO_2 and other minor greenhouse gases (Ramanathan and Collins 1991).

a. Surface heat flux and the accumulation of heat in the ocean

Figures 2a, 2b, and 2c show respectively the evolution of $\langle(\partial/\partial t)\widetilde{H_c}\rangle$, $\langle\tilde{D}_o\rangle$, and $\langle\tilde{F}_s\rangle$ over the period of the Earth Radiation Budget Experiment (ERBE). The symbol $\langle\ \rangle$ denotes averaging zonally across the basin. The heat content of the upper ocean H_c was obtained using the monthly mean ocean temperature from the tropical Pacific ocean reanalysis prepared by the National Centers for Environmental Prediction (NCEP) using an ocean data assimilation system (Ji et al. 1994, 1995). The ocean temperature from this dataset has been shown to be accurate in representing annual and interannual variability (Smith and Chelliah 1995). The depth of the upper ocean is chosen as 380 m when integrating the heat content for the computation of H_c. At this depth, the variations in the ocean temperature field are already very small (less than 0.1 K). Further increases in the depth result in little change in $(\partial/\partial t)H_c$. The expression $(\partial/\partial t)H_c$ was obtained from H_c through the use of a central difference scheme; F_s was obtained from Eq. (2). Further, N_T is from the ERBE data (Barkstrom 1989) and D_a is from the NCEP–National Center for Atmospheric Research (NCAR) reanalysis, which makes use of the global observations of temperature, humidity, and winds (Trenberth and Guillemot 1998). With $(\partial/\partial t)H_c$ and F_s, D_o was obtained from Eq. (1). To focus on the slow-varying component of the system, the seasonal variations have been pulled out from all three terms. The seasonal variations here refer to the variations with the annual frequency (i.e., the variations with the period of 12 months). We pull out the seasonal variations by first removing the climatology from the time series and then adding back the long-term annual mean value to the time series. This is equivalent to applying a bandpass filter to Eqs. (1) and (2). An advantage of such a procedure over the use of a bandpass filter is that the total annual mean value for each year is preserved. To retain the total value is important in this exercise because we want to know whether heat is actually converged to the equatorial ocean from the off-equatorial region. The other advantage of this procedure is that it does not result in a reduction in the length of the data. This is also important for the present analysis because the ERBE data only cover a very limited period. The symbol ~ is used to indicate that the quantity has been processed through such a procedure. To indicate the timing of the onset and termination of the 1986–87 El Niño for this period, the corresponding interannual SST anomaly is also presented (Fig. 2d). Over the equatorial region (5°S–5°N), the heat content increases prior to the onset of the 1986–87 El Niño, starts to decrease after the onset of El Niño, and increases again when the tropical Pacific is headed into a strong La Niña condition.

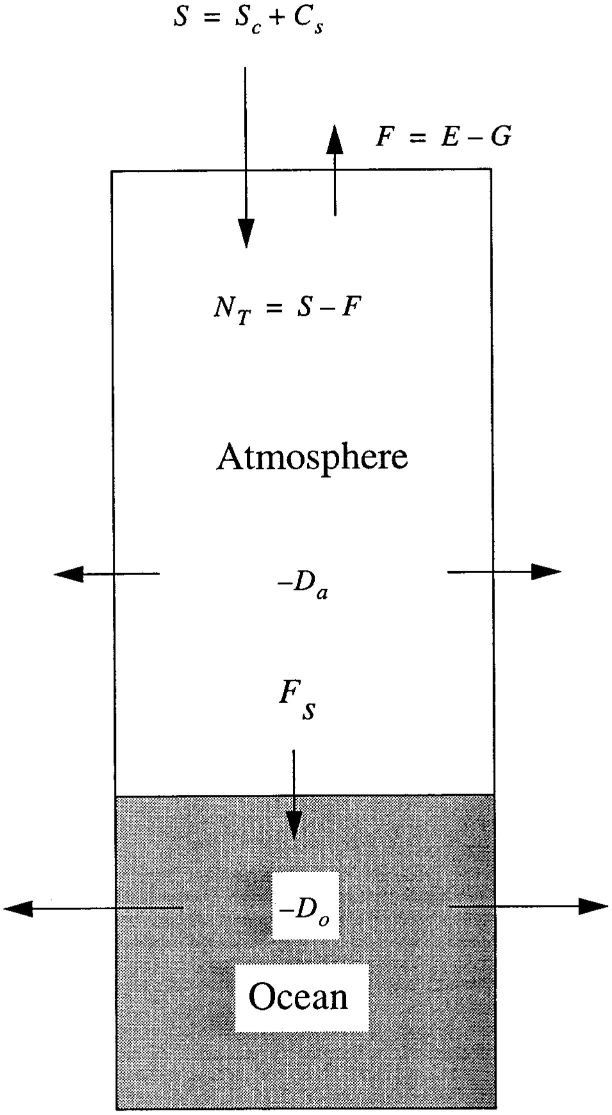
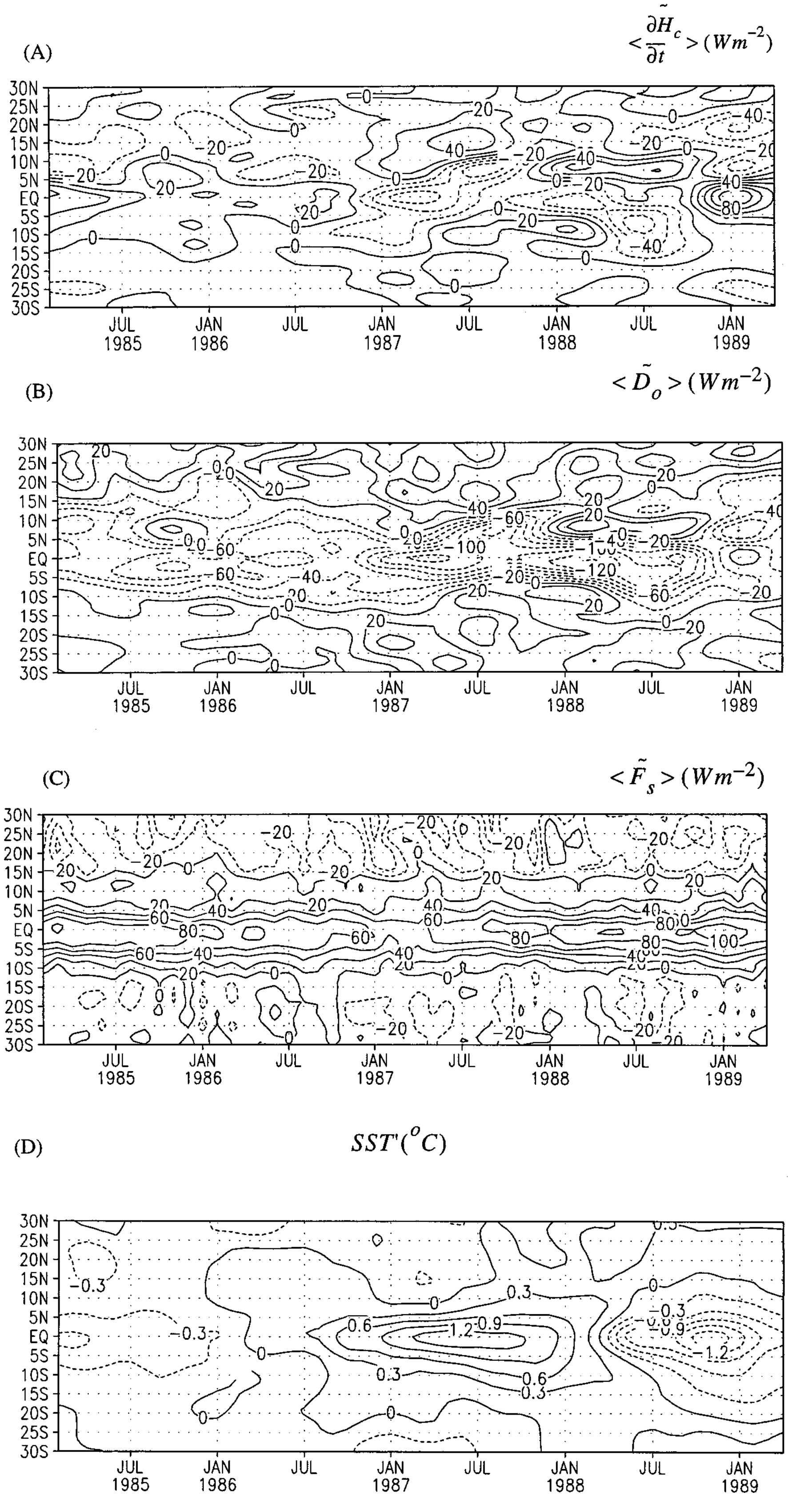


FIG. 1. Schematic of a one-dimensional energy balance model for a coupled ocean–atmosphere column. S and F are, respectively, the net downward solar radiation and the net outgoing longwave radiation at the top of the atmosphere, G is the greenhouse effect, E is the surface emission, $N_T = S - F$, F_s is the net surface heat flux into the ocean. Further, D_a is the convergence of moist static energy in the atmosphere, and D_o is convergence of heat in the ocean (D for ''dynamics,'' which includes the effects from both mean circulation and transients).

The accumulation of heat in the equatorial ocean is due to the cumulative effect of the surface heat flux. In the equatorial region $\langle\tilde{D}_o\rangle$ varies substantially over the period of ERBE, but it remains negative through the



(A) $<\frac{\partial \tilde{H}_c}{\partial t}> (Wm^{-2})$

(B) $<\tilde{D}_o> (Wm^{-2})$

(C) $<\tilde{F}_s> (Wm^{-2})$

(D) $SST'(^oC)$

entire period. Thus by Eq. (1) the ocean dynamics opposes the accumulation of heat in the equatorial ocean throughout an ENSO cycle. Note also that the intensity of surface heat flux does not have to increase with time to result in increases in the heat content of the upper ocean as long as it exceeds the opposing effect from the ocean transport [see Eq. (1)]. Mechanisms that control the poleward transport and the surface heat flux will be discussed after the relationship between the accumulation of heat in the equatorial ocean and El Niño is explored.

b. Consequence of accumulation of heat in the ocean

The distribution of D_o for the year of 1985 (the year prior to the 1986–87 El Niño) is shown in Fig. 3a. The maximum divergence occurs in the eastern Pacific. Figure 3b shows the corresponding divergent component of ocean transport $\mathbf{F}_o$ obtained by solving a Laplace equation with appropriate boundary conditions (see figure captions for more details). Poleward heat transport takes place across the equatorial Pacific. The smaller divergence of heat in the western Pacific is due to the transport of heat from the eastern Pacific. The westward transport of heat in the equatorial Pacific is clearly significant. The distribution of the transport is consistent with the classical picture of the equatorial wind-driven circulation (Philander 1990): warm surface water moves westward and poleward, and cold thermocline water moves eastward and equatorward, resulting in a net poleward heat transport. The poleward heat transport, however, is not sufficiently large during this period to balance the surface heat flux into the equatorial ocean (Fig. 3c). Contrasting Fig. 3c with Fig. 3a reveals that the surface heat flux exceeds the ocean transport at almost all longitudes of the equatorial Pacific. Therefore, accumulation of heat in the equatorial upper ocean takes place across the equatorial Pacific.

The surplus of heat implies that the thermal condition is inherently unstable and warming is bound to develop. Pushing heat downward by increasing the temperature of the subsurface water at a greater depth in the western Pacific (i.e., deepening the thermocline) only delays the surface warming because the warmer subsurface water will eventually surface up in the eastern equatorial Pacific through the equatorial undercurrent and the equatorial upwelling. Data indeed show that the surface warming is preceded by basinwide warming in the thermocline water. Figure 4 shows that the entire equatorial undercurrent during early 1986 is considerably warmer than a year before. Significant surface warming develops in late summer as the subsurface water emerges in the eastern Pacific and triggers the positive feedback of ocean–atmosphere interaction [i.e., the Bjerknes hypothesis (Bjerknes 1966)]. The positive feedback loop allows the surface warming to develop rapidly (Battisti 1988). The rapid mutual adjustments among SST gradients, surface winds, and the wind-driven currents result in a rapid zonal redistribution of warm water accumulated in the equatorial upper ocean (Fig. 5a). This adjustment also results in loss of heat to the higher latitudes. The poleward heat transport is enhanced throughout the equatorial ocean during the 1986–87 El Niño (Fig. 5b), which depletes the accumulated heat in the equatorial ocean. While instability and equatorial waves are important for the rapid development of the warming, the surface heat flux is equally important by first providing the heat that the warming necessarily requires.

By just examining the interannual anomaly, one would have a very different impression of the importance of the surface heat flux in driving El Niño (Fig. 6). We might infer from Fig. 6a that surface heat flux plays no role in driving El Niño because the variations of the surface heat flux are negatively correlated with the SST variations. One may conclude from Fig. 6b that ocean dynamics moves heat from the off-equatorial region to the equatorial region prior to the onset or after the termination of El Niño and therefore the accumulation of heat in the equatorial upper ocean is due to advection of heat from the off-equatorial region. Although there is nothing wrong mathematically with dissecting the total field into the interannual anomaly and the time mean, one should not overlook the fact that the interannual anomaly cannot exist physically independent of the time mean. The constraint of heat balance on El Niño warming does not disappear after such a separation. The important role of surface heat flux in driving El Niño will emerge if one can thoroughly address the mutual dependence of the time mean and the interannual anomaly, though this may prove to be a less direct way.

c. Factors controlling the surface heat flux into the equatorial ocean

Figure 7 shows the time evolution of $\langle \tilde{N}_T \rangle$, $\langle \tilde{D}_a \rangle$, and $\langle (\partial/\partial t)\tilde{E}_a \rangle$. Expression $(\partial/\partial t)\tilde{E}_a$ is negligible compared with $\tilde{N}_T$ and $\tilde{D}_a$. There are little variations in N_T during the ERBE period. The lack of any significant variation in N_T despite significant changes in SST is because the variations of G_a cancel the variations of E while the variations of C_s are canceled by the variations in C_l [recall Eq. (3)] (Sun and Trenberth 1998; Ramanathan and Collins 1991). The variation in F_s is thus mainly modulated by the energy transport in the atmosphere

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FIG. 2. (a) $\langle (\partial/\partial t)\widetilde{H}_c \rangle$ over the period of ERBE; (b) $\langle \tilde{D}_o \rangle$ over the period of ERBE; (c) $\langle \tilde{F}_s \rangle$ over the period of ERBE; (d) interannual anomalies of zonal mean SST. $\langle\ \rangle$ denotes zonal averaging. ∼ indicates that the seasonal variations have been removed.

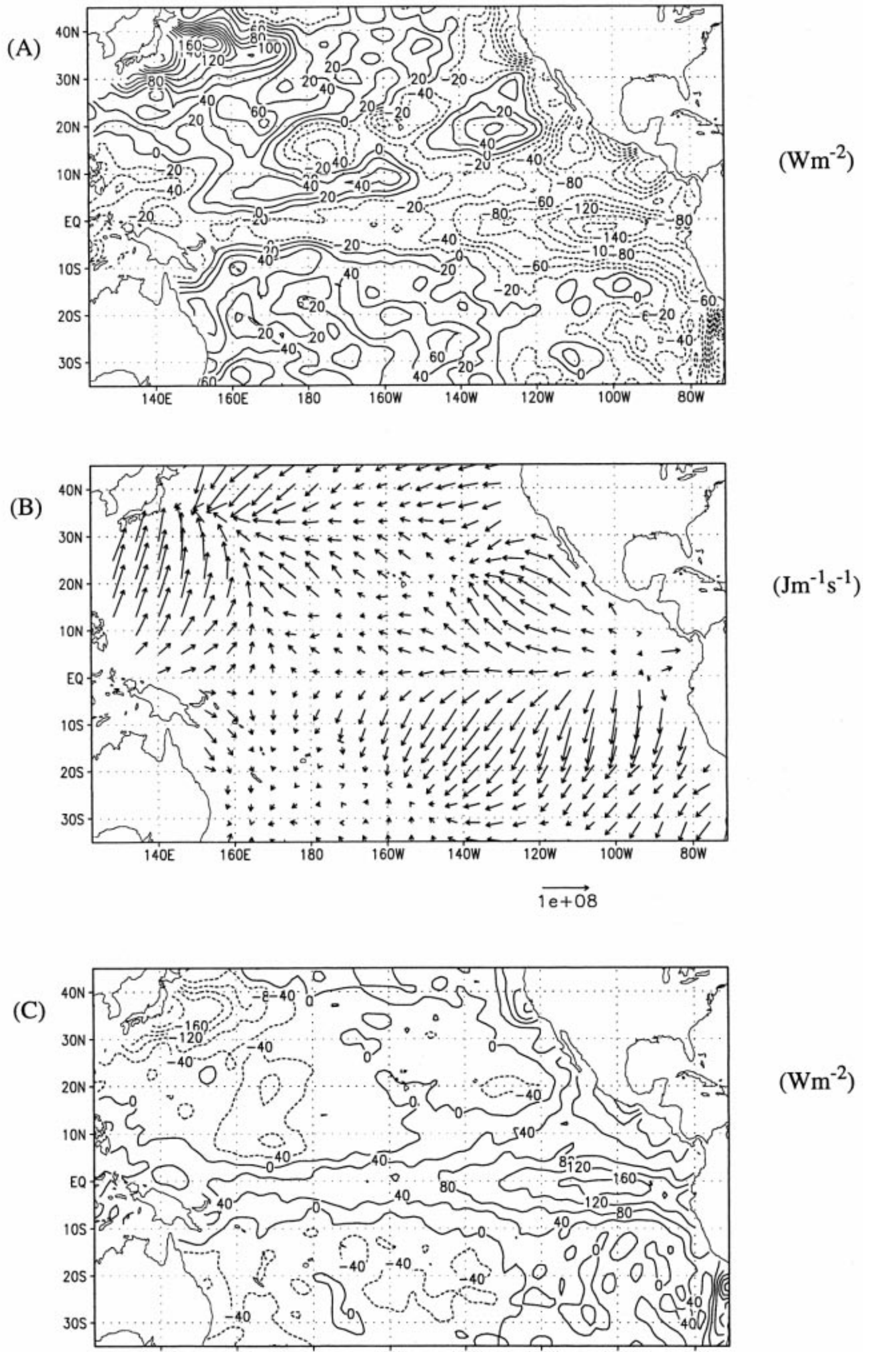

FIG. 3. (a) Distribution of D_o for the year 1985. (b) The corresponding divergent component of the ocean transport $\mathbf{F}_o$ in the Pacific Ocean. The units of $\mathbf{F}_o$ are J m^{-1} s^{-1}. The transport is obtained by solving the Laplace equation $\nabla^2\psi = D_o$ with appropriate boundary conditions. $\mathbf{F}_o = \boldsymbol{\nabla}\psi$. For the lateral boundary condition, realistic topography is used. The meridional domain for the ocean reanalysis data is from 30°S to 45°N. The heat transport outside of the reanalysis model domain is fixed to the climatology over the 1985–89 period, which was first obtained by solving the equation $\nabla^2\psi = F_s$ over a global domain. (c) Distribution of F_s for the year 1985.

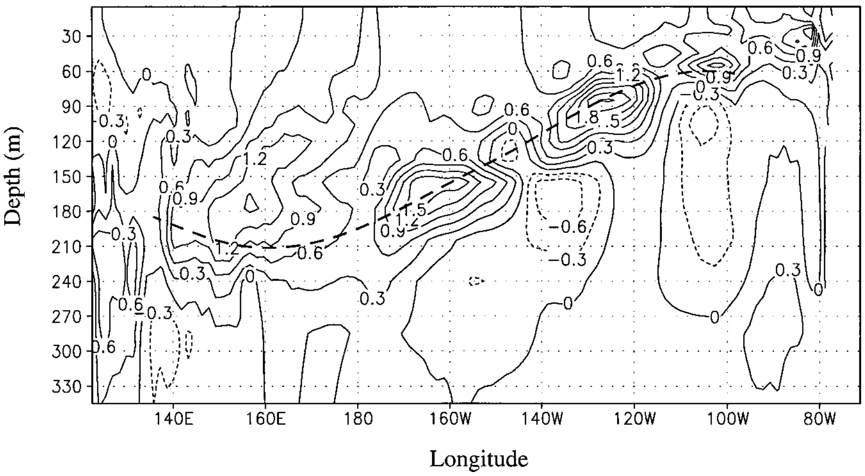

FIG. 4. Temperature difference in the equatorial upper ocean (5°S–5°N) between early 1986 (Jan–Jun 1986) and the same period a year before (Jan–Jun 1985). The thicker dashed line indicates the depth of the corresponding maximum equatorial zonal velocity at each longitude for early 1986 and thus the position of the undercurrent during that period.

[recall Eq. (2)]. In the equatorial region (5°S–5°N), and during the year of 1985 and immediately after the termination of the 1986–87 El Niño, the atmospheric dynamics converges energy into the equatorial region. This is because during a La Niña year, the equatorial cold tongue is sufficiently cold. As a consequence, the convergence of energy over the cold-tongue region outweighs the divergence of energy over the warm-pool region (Fig. 8a). With the onset of El Niño, the intensity of the equatorial cold tongue is reduced and the divergence of energy prevails over the bulk of the equatorial Pacific (Fig. 8b) and, consequently, the surface heat flux is reduced. (The difference between Figs. 8b and 8a is typical of the difference between the El Niño and the pre–El Niño conditions).

These results suggest a positive correlation between the zonal SST contrast and the surface heat flux into the ocean, which is opposite to the suggestion of Hartmann and Michelsen (1993). Based on a highly simplified model in which the free tropospheric specific humidity is set to zero and the boundary layer relative humidity is bounded by an 86% threshold, they suggested that an increase in the zonal SST contrast will increase the surface evaporation. The difference in the surface evaporation between 1987 and 1985 from NCEP–NCAR reanalysis is given in Fig. 9. The zonal SST contrast in the equatorial Pacific in 1985 is stronger than in 1987, but surface evaporation in the equatorial Pacific is weaker. This is because although the zonal surface wind is stronger in 1985 in the central Pacific (Fig. 10a), the surface humidity deficit (the difference between the saturation humidity with respect to SST and the surface air humidity) is also smaller because the SST is colder (Fig. 10b). The NCEP–NCAR data indicate that the latter effect dominates in the central Pacific. Near the east coast, the surface wind is actually weaker in 1985 and the surface humidity deficit is smaller, both of which lead to reduction in the surface evaporation there. The weaker surface evaporation in the equatorial region in 1985 is consistent with the finding that the surface heat flux into the ocean is enhanced as the equatorial cold tongue becomes colder. Note that the changes in the surface evaporation only account for part of the difference in the net surface heat flux into the equatorial ocean between 1987 and 1985. It has been noted that 1985 has less cloud reflection of solar radiation (Ramanathan and Collins 1991; Sun and Trenberth 1998), which also contributes significantly to the strong surface heat flux into the ocean during this cold period.

d. The heat sinks of the 1986–87 El Niño

To isolate the main heat sink of the 1986–87 El Niño, we contrast the difference in N_T, D_a, F_s, D_o, and $(\partial/\partial t)H_c$ between 1987 and 1985 (Fig. 11). There is a noticeable reduction in N_T in a broad region in the northern subtropical region (Fig. 11b). The reduction in N_T in the subtropics during El Niño has been noted before by Chou (1994) based on more limited data. The reduction in N_T, however, is smaller than the anomalous energy removed by atmospheric dynamics from the deep Tropics or the corresponding changes in the surface heat flux into the ocean (Figs. 11c,d). The reduction in N_T is even smaller than the heat removed from the deep Tropics to the subtropics by ocean dynamics (Fig. 11e). Thus, despite its ‘‘fury,’’ El Niño does not result in a significant loss of heat to space. The heat removed from the deep Tropics is mainly stored in the subtropical ocean (Fig. 11f) with the northern subtropical Pacific gaining more heat from El Niño than its southern counterpart.

The mechanisms that control the polewad heat transport in the equatorial ocean have been studied by Brady

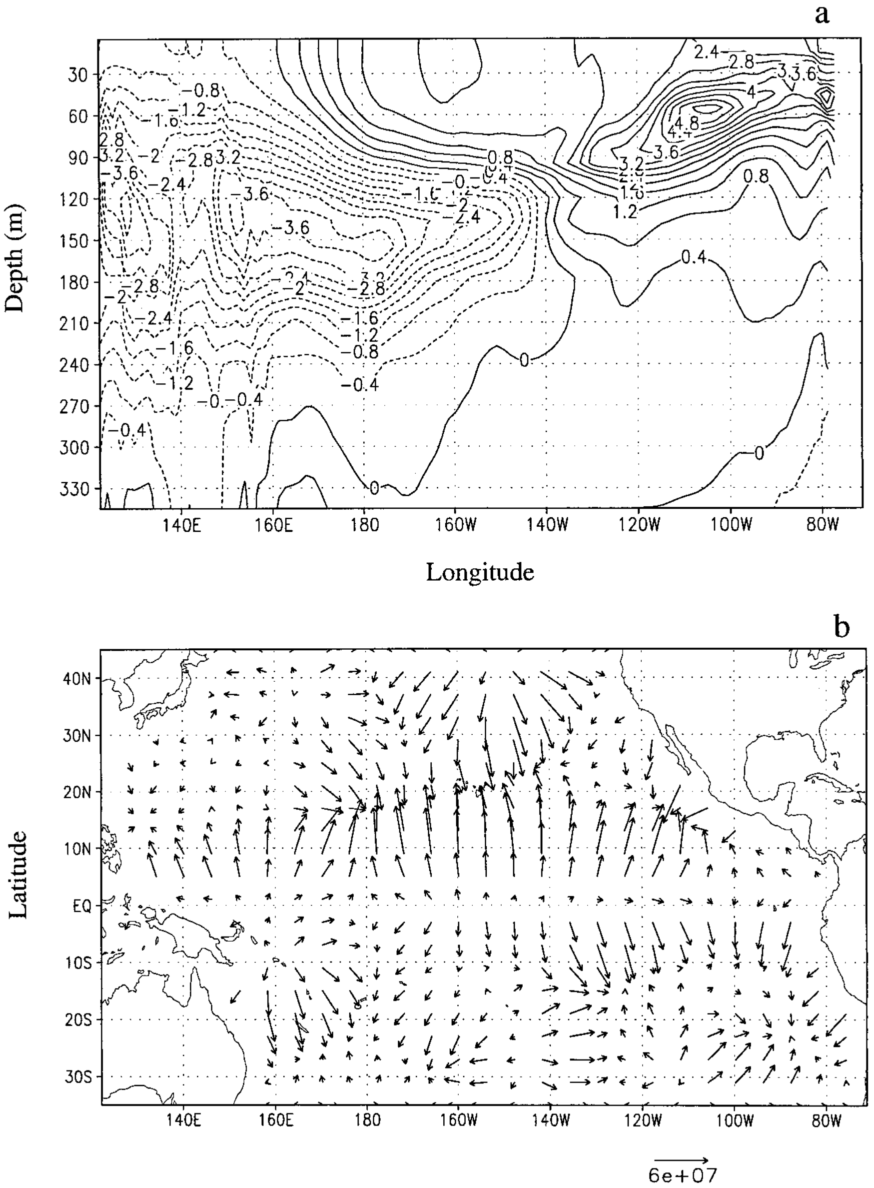

FIG. 5. (a) Temperature difference in the equatorial upper ocean between 1985 and 1987. (b) Difference in $\mathbf{F}_o$ between 1985 and 1987 (1987 minus 1985). Because the ERBE data start at Feb 1985, the data for Jan of the subsequent year 1986 were used in calculating the annual mean of 1985.

(1994) using a numerical model for the tropical Pacific Ocean. After decomposing the total flow into a zonal mean meridional overturning, a horizontal cell, and transient eddies (or instability waves), she found that the increase in the poleward heat transport during El Niño warming is largely due to a reduction in the equatorward heat transport by the horizontal cell and an increase in the poleward heat transport by the meridional overturning. The reduction in the equatorward transport by the horizontal cell is further related to the decreased zonal temperature contrast in the upper ocean between the eastern Pacific and the western Pacific during the warming. (The horizontal cell enters the equatorial region from the western Pacific, flows eastward as the undercurrent, and exits the equatorial region in the eastern Pacific). The differences in the equatorial upper-ocean temperature between 1987 and 1985 indeed show a substantial reduction in the zonal temperature contrast throughout the upper ocean, apparently as a consequence of a smaller zonal slope of the thermocline, which is in turn a consequence of the reduced zonal SST contrast (Fig. 5a). The increase in the transport by the meridional overturning is related to increases in the temperature contrast between surface water and the sub-

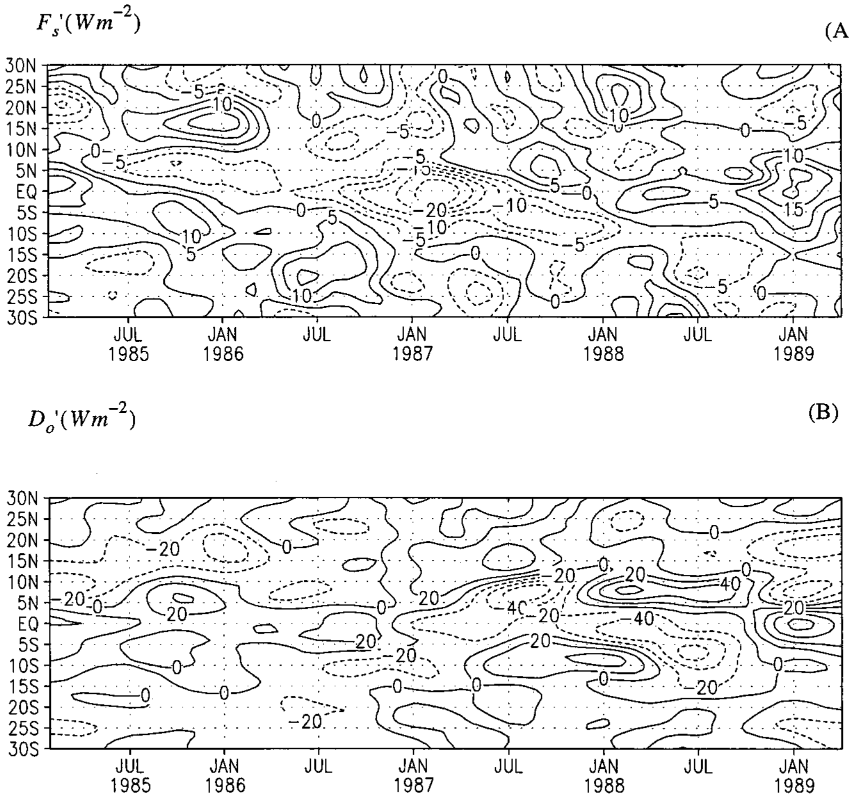

FIG. 6. (a) Interannual anomalies of $\langle F_s \rangle$ over the period of ERBE; (b) $\langle D_o \rangle$ over the period of ERBE.

surface water. Figure 12b shows that the surface water during 1987 is warmer than in 1985 while the subsurface water is colder. Note further that the major contribution to the cooling in the zonally averaged subsurface temperature in Fig. 12b comes from the cooling in the subsurface temperature in the western Pacific, which is related to the changes in the slope of the thermocline and therefore to the zonal SST contrast (Fig. 5a). Therefore, the zonal SST contrast appears to play a key role in determining the poleward heat transport in the equatorial upper ocean.

Following the large increases in the poleward heat transport (Fig. 11e) and significant reduction in the surface heat flux into the ocean (Fig. 11d), the El Niño warming was terminated at the beginning of 1988 (Fig. 2d). The negative trend in the heat content, however, did not stop at the time when the SST had resumed normal (Figs. 2a and 2d), apparently as a consequence of an ‘‘overshooting’’ in the poleward ocean heat transport; the anomalous poleward ocean heat transport incurred during El Niño warming did not cease right at the time when the SST had resumed normal (Fig. 6b). This overshooting in the ocean transport pushed the ocean into a cold state (Fig. 2d). The heat in the equatorial upper ocean started to accumulate again (Fig. 2a), preparing for the onset of another El Niño.

3. A heat pump or a delayed oscillator?

The heat transport in the coupled tropical ocean–atmosphere system over the ERBE period may be summarized as follows: 1) prior to the onset of El Niño, surface heat fluxes pump heat into the equatorial ocean; 2) the heat stored in the subsurface ocean resurfaces in the eastern equatorial Pacific and El Niño develops, which exports excessive heat from the equatorial region; 3) the system overshoots and goes into a La Niña; and 4) the La Niña condition is associated with weaker heat transport in the atmosphere and ocean, which allows heat to accumulate in the equatorial ocean and start the cycle over. Thus, the ENSO system behaves like a heat pump: the ocean absorbs heat through its surface during the cold phase and pushes the heat to the higher latitudes during the warm phase.

This heat pump picture suggests that El Niño derives its heat from the surface heat flux into the equatorial ocean. This view complements the classic description of the heat sources of El Niño from anomaly models that focused on the heat budget of the mixed layer of the eastern Pacific (Battisti 1988; Suarez and Schopf 1988; Zebiak and Cane 1987). In the description of these anomaly models, the surface eastern Pacific is normally cold because of upwelling of cold water from below.

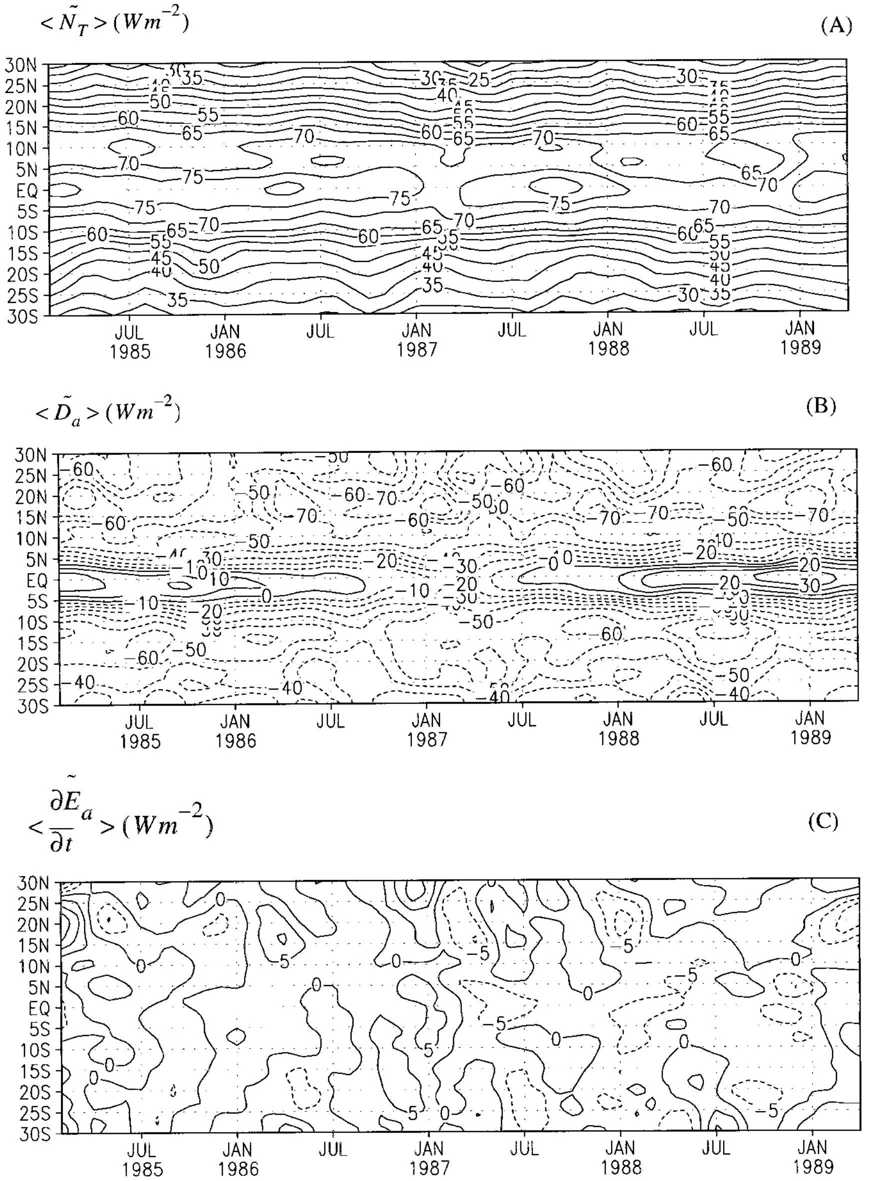

FIG. 7. (a) $\langle \tilde{N}_T \rangle$ over the period of ERBE; (b) $\langle \tilde{D}_a \rangle$ over the period of ERBE; (c) $\langle (\partial/\partial t)\tilde{E}_a \rangle$ over the period of ERBE.

El Niño occurs when trade winds slacken and the cold water flux is reduced. The corresponding Lagrangian view is that the surface is warmer because the water entering the surface mixed layer from below is warmer. In anomaly models of El Niño, the temperature of the upwelling water is parameterized empirically in terms of the thermocline displacements. Therefore, in these models, the deepening of the thermocline appears to be the cause of the increase in the temperature of the upwelling water. An extended and more accurate description is that a deepening of the thermocline requires an increase in the temperature of the subsurface water. The heat that is needed to increase the temperature of the subsurface water and deepen the thermocline comes from the accumulated heat in the equatorial upper ocean. The accumulated heat in the equatorial upper ocean comes from the surface heating.

The heat pump picture attributes the termination of El Niño to the accompanying increase in the poleward transport of energy in the ocean and in the atmosphere, which depletes the fuel for the warming: the accumulated heat in the equatorial upper ocean. We have suggested that the enhanced poleward heat transport in the ocean is due to a warmer poleward flowing flow and a colder equatorward flow feeding the undercurrent. The increases in the poleward transport in the atmosphere is for a similar reason. Figure 12a shows that the air in the ascending and outgoing branch of the Hadley cir-

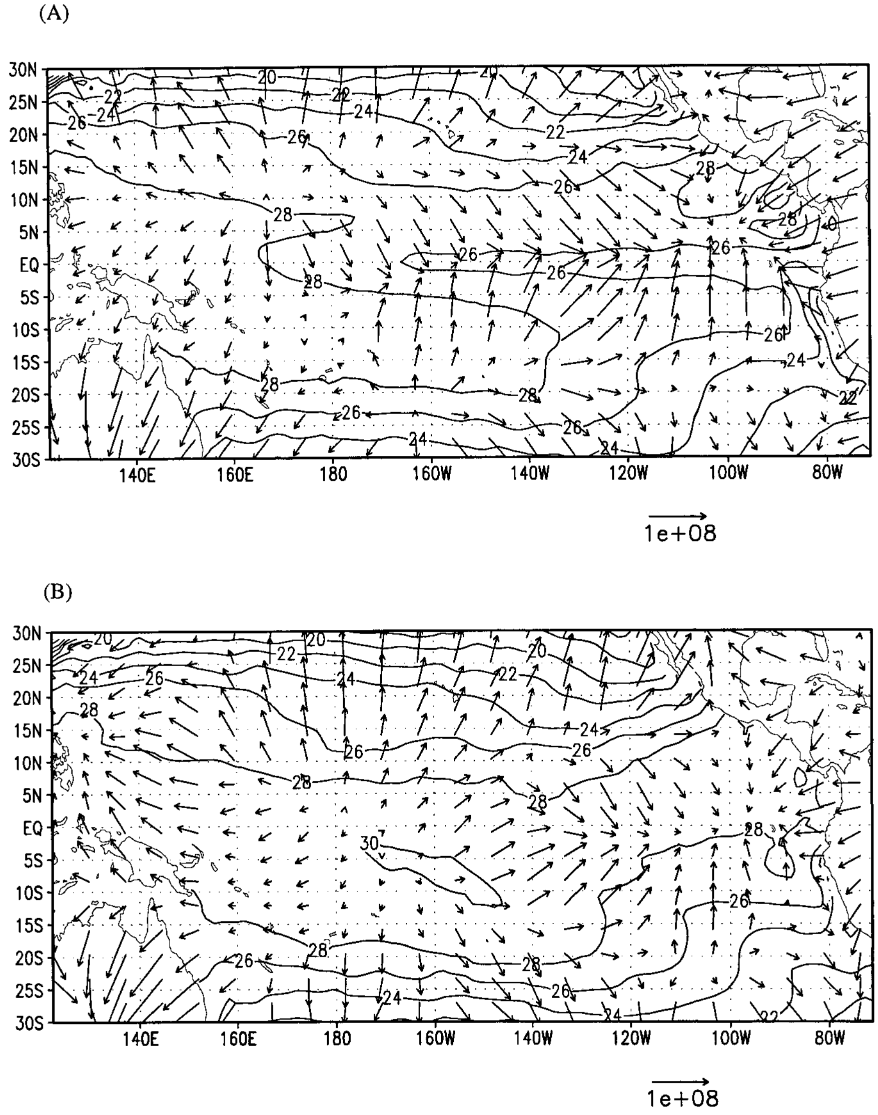

Fig. 8. The divergent component of atmospheric transport of moist static energy ($\mathbf{F}_a$) for (a) Apr 1985 and (b) Apr 1987. SSTs are also plotted to show the dependence of the transport on the SST distribution $\mathbf{F}_a$ was obtained by solving the Laplace equation $\nabla^2\psi = D_a$ on a global domain. $\mathbf{F}_a = \nabla\psi$. The units of $\mathbf{F}_a$ are J m^{-1} s^{-1} while SSTs are in °C.

culation has higher energy in 1987 than in 1985. In addition, there is evidence that with meridional overturning, the Hadley circulation was enhanced during the El Niño warming (Oort and Yienger 1996). Thus the explanation for the termination of El Niño in the heat pump picture differs from the delayed oscillator hypothesis. In the delayed oscillator theory, western boundary reflection and the resulting cooling Kelvin waves are essential for terminating the warm events (Battisti 1988). According to the recent review of McPhaden et al. (1998), not all warm events are terminated by western boundary reflections. Thus, Kelvin waves emanating from the western boundary are likely one of many processes that are responsible for the enhanced poleward heat transport in the ocean.

The heat pump picture for ENSO implies that the surface heat flux and the required poleward heat transport may play a fundamental role in determining the magnitude of El Niño. Such a role is not sufficiently delineated in the delayed oscillator hypothesis, which focuses on the importance of coupled dynamics (Battisti 1988; Suarez and Schopf 1988). This does not mean that coupled dynamics emphasized in the delayed oscillator theory is not important in the heat pump picture. The working of the heat pump relies on coupled dynamics. Three mechanisms have to be in place for the operation of the heat pump. The first mechanism allows the heat absorbed at the ocean surface to be pushed down and stored in the subsurface ocean. The second mechanism allows the stored heat in the subsurface

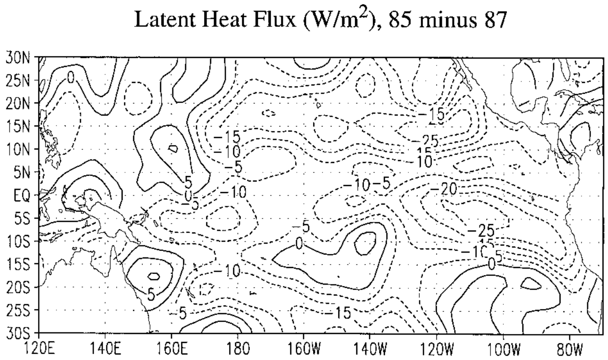
Latent Heat Flux (W/m^2), 85 minus 87

FIG. 9. Differences in the latent heat flux from the ocean's surface between 1985 and 1987 (1985–87).

ocean to be channeled into the surface mixed layer so that a surface warming can develop. The third mechanism ensures that the surface warming will result in a substantial increase in the poleward transport of energy in the atmosphere and ocean so that the accumulated heat in the equatorial ocean can be drained and the cycle can be started over. All three mechanisms rely on coupled dynamics.

The first mechanism is provided by the ability of the coupled system to develop a strong tilt of the thermocline so that a large amount of warm water can be stored in the downwind side of the basin. At the equator and for a zonally bounded basin, the zonal tilt of the thermocline is proportional to the zonal surface wind stress (which is in turn proportional to the zonal SST contrast). A significant zonal tilt exists for all three equatorial oceans (Fig. 13b). However, for the same slope of thermocline, the greater the zonal width of the basin, the greater the depth the warm water can penetrate to in the downwind side of the basin. Figure 13b shows that the tropical Pacific Ocean has a much deeper and zonally extended warm pool than the tropical Atlantic Ocean, whose zonal width is only one-third that of the tropical Pacific Ocean. The tropical Indian Ocean also has a shallower warm pool compared to the tropical Pacific Ocean. Thus the tropical Pacific Ocean is more prone to develop El Niño than the tropical Atlantic and Indian Oceans. The second mechanism is apparently provided by the undercurrent and equatorial upwelling that connect the subsurface water of the downwind side to the surface water of the upwind side. Both the tropical Pacific and Atlantic have an eastward flowing undercurrent (Philander 1990). However, the larger the zonal width of the basin, the longer it takes for the warm water accumulated in the downwind side of the ocean to surface in the upwind side. This is because with a larger zonal width, the warm water can be stored to a greater depth in the downwind side basin. Moreover, it takes more time for the warm water to traverse the basin following the undercurrent if the zonal width of the basin is larger, but the speed of the undercurrent is not proportionally stronger. Consequently, for a basin with a size much smaller than the tropical Pacific, there may be insufficient time for accumulating the critical amount of heat that is necessarily needed to overcome dissipation and develop observable surface warming. The equatorial currents in the Indian Ocean change direction seasonally (Philander 1990), which is an additional disadvantage to support El Niño–like warming. From the heat pump perspective, the disadvantage due to a much smaller zonal width can be compensated by a much stronger surface heat flux. The surface heat fluxes over the three tropical oceans are shown in Fig. 13a. The largest surface heat flux into the equatorial ocean is actually found over the Pacific. This may explain the absence of El Niño–like phenomena in the tropical Atlantic and Indian Oceans in the present climate. This explanation differs from but does not contradict that offered by the delayed oscillator hypothesis. According to the delayed oscillator hypothesis, the reason for the absence of El Niño–like phenomena in the tropical Atlantic and Indian Oceans is that a surface warming in the eastern side of the ocean would not have sufficient time to develop before the cooling Kelvin wave emanating from the western boundary kills the warming. How fast the surface warming can grow, however, is unlikely to be independent of the amount of heat accumulated in the upper ocean.

As we have already discussed, surface warming increases the transport of energy poleward that depletes the fuel for the warming: the accumulated heat in the upper ocean. Thus, El Niño warming is self-destructive. We have also noted that the poleward transport continued to be higher than that is required to balance the surface heating at the time when the SST has resumed normal and this overshooting is apparently responsible for pushing the ocean to a La Niña state. Note that poleward ocean transport depends not only on SST, but also on the subsurface current speed and temperature. When the development of the surface warming is fast, the subsurface flow is not in pace with the surface Ekman flow and therefore not in pace with the SST. Consequently, the poleward transport of heat is not in pace with the surface heat flux (which happens to be in phase with SST), resulting in an overshooting. We have shown that El Niño derives its heat from the heat stored in the upper ocean. To ensure that the surface warming develops rapidly (relative to the adjustment of the subsurface dynamics), a sufficient amount of heat may have to be stored in the upper ocean, which in turn requires a sufficiently strong zonal tilt of the thermocline. Noting further that the slope of the thermocline is proportional to the zonal SST contrast and therefore to the surface heat flux, the role of the surface heat flux in the overshooting is then apparent. The importance of the surface heating for the oscillation may be seen from another angle. The failure of the coupled ocean–atmosphere to find the perfect equilibrium state in which the surface heat flux is always exactly balanced by the poleward

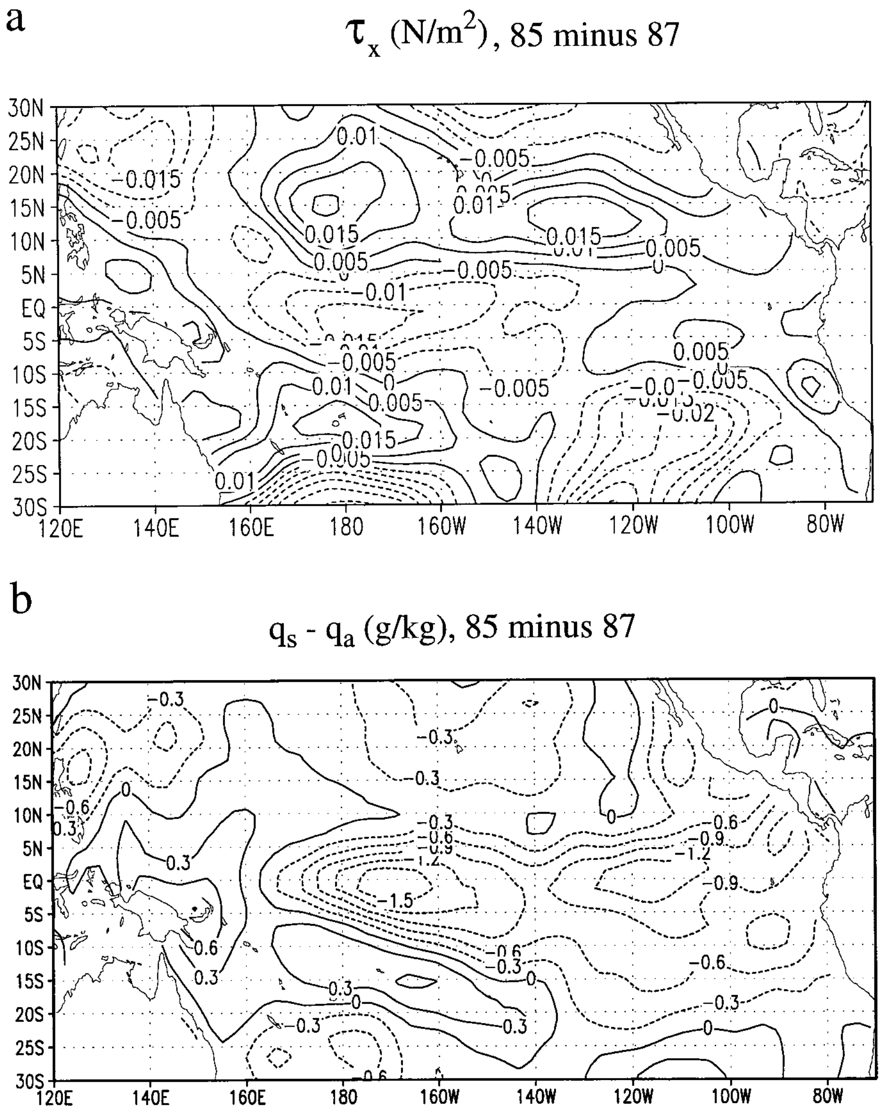

Fig. 10. Differences in (a) the zonal wind stress and (b) the surface humidity deficit ($q_s - q_a$) between 1985 and 1987 (1985–87). Here q_s is the saturation specific humidity with respect to SST; q_a is the specific humidity of surface air.

ocean heat transport implies that such a perfect equilibrium is unstable. The delayed oscillator hypothesis attributed the existence of El Niño to the instability of the time mean state of the coupled ocean–atmosphere (Battisti 1988). Of particular importance for the instability appears to be the positive feedback loop of the Bjerknes hypothesis (1966). Using an analytical model that encapsulates the delayed oscillator physics but calculates the total SST, Sun (1997) showed that the positive feedback loop of the Bjerknes hypothesis is just a necessary condition for the instability. For the instability to occur, the zonal SST contrast and therefore the surface heat flux has to exceed a critical value. Since an observed time mean state was used in the anomaly models for El Niño from which the delayed oscillator theory was derived, the requirement for a sufficiently strong surface heat flux for instability is implicit in the delayed oscillator theory. It thus appears that ENSO is the mode that the ocean has chosen to handle a strong surface heat flux into the equatorial ocean.

4. Summary and further discussion

Using the best data available, we have documented the heat cycle of the 1986–87 El Niño. The results suggest that the ENSO system may be described as a heat pump: it sucks heat into the equatorial upper ocean through the cold phase and pushes the heat to the sub-

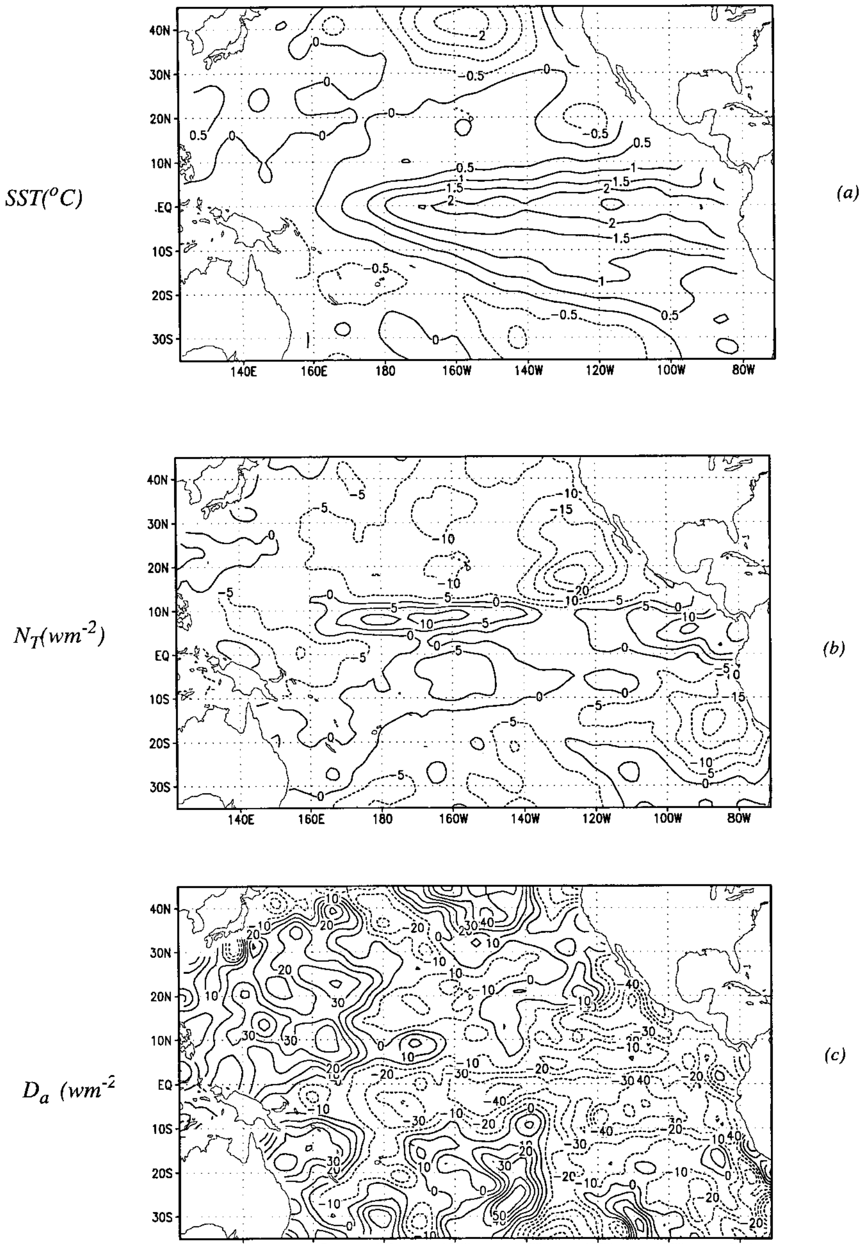

FIG. 11. Annual mean differences in (a) SST, (b) N_T, (c) D_a, (d) F_s, (e) D_o, and (f) $(\partial/\partial t)(H_c$ between 1987 and 1985 (1987–1985). Because the ERBE data start at Feb 1985, the data for Jan of the subsequent year 1986 were used in calculating the annual mean of 1985.

tropical ocean during the warm phase. The surface warming derives its heat from the heat sucked into the equatorial upper ocean during the cold phase and is responsible for the large poleward heat transport during the warm phase. Thus, El Niño represents a basic process by which the Pacific ocean transports heat from the equatorial region to higher latitudes. This suggests that a climate with more heat injected into the equatorial ocean (or, equivalently, more demand of equator-to-pole heat transport in the ocean) may have more energetic El Niño.[1]

Though often assumed, an increase in the greenhouse effect is not always equivalent to an increase in the

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[1] By a more energetic El Niño, we mean more frequent occurrence of El Niño and/or an El Niño with a larger amplitude.

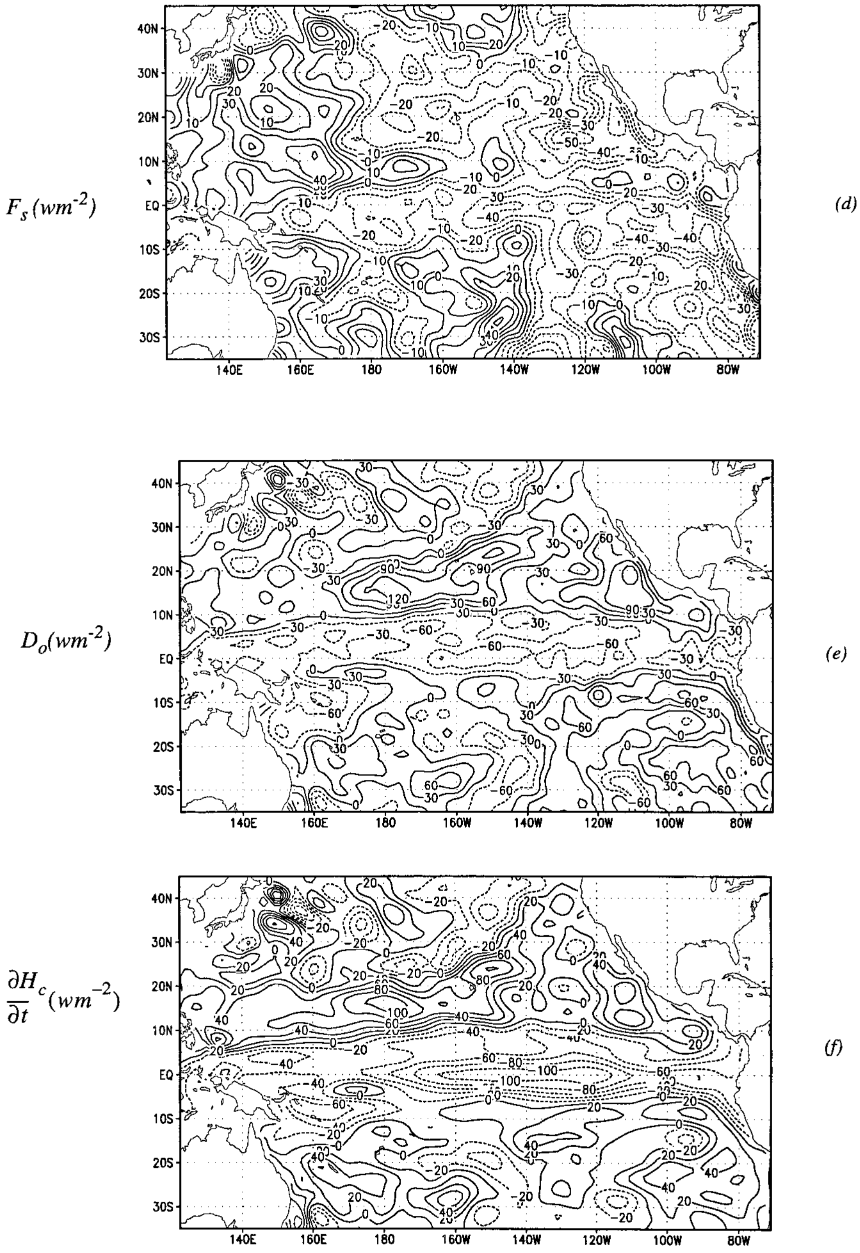

FIG. 11. (*Continued*)

surface heat flux into the ocean. The energy balance of the equatorial atmosphere over the ERBE period sheds more light on the relationship between the surface heat flux and the radiative flux at the top of the atmosphere (or the greenhouse effect). The effect of an increase in the greenhouse effect on the surface heating upon the ocean depends critically on the feedback from the poleward transport of energy (D_a) in the equatorial atmosphere, which is sensitive to the SST contrast between the equatorial cold tongue and the surrounding region (i.e, the warm pool and the off-equatorial region). Recall that the change in this contrast between April 1985 and April 1987 is about 2 K while the corresponding change in $\langle D_a \rangle$ in the equatorial belt (5°S–5°N) is about -34 W m^{-2} (Figs. 7 and 8). [Variables E, G_a, C_s, C_l also depend on SST, but their net feedback is very small in the equatorial region because of the cancellation effect (Sun and Trenberth 1998).] Note further that the increase in N_T from an instantaneous doubling of CO$_2$ is only about 4 W m^{-2}.

It has been suggested that before the thermocline water changes its temperature significantly in response to surface warming in higher latitudes, the SST contrast between the SST of the equatorial cold tongue and its

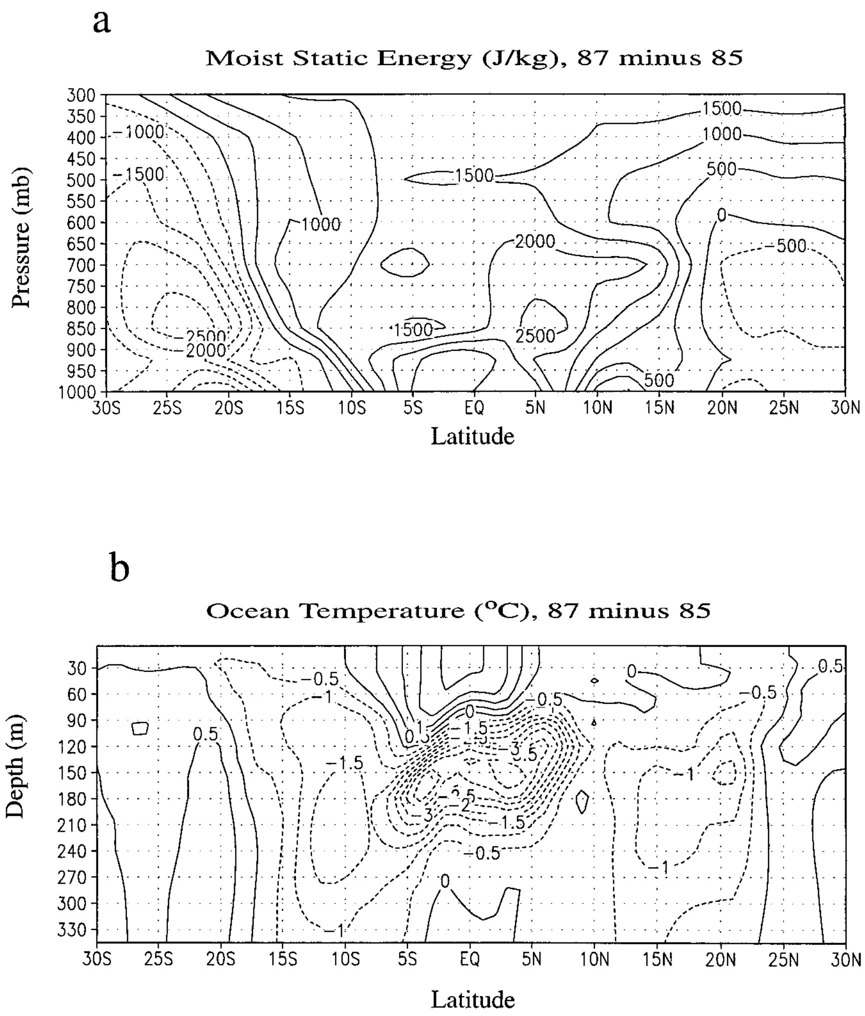

FIG. 12. (a) Difference in the zonal mean moist static energy in the tropical atmosphere between 1987 and 1985 (1987 minus 1985). Humidity data are not available above 300 mb. (b) Difference in the upper-ocean temperature of the tropical Pacific between 1987 and 1985 (1987–1985).

surrounding region may increase as a consequence of an increase in the surface heat flux because of the nonlinear feedback from the equatorial upwelling (Sun 1997; Sun and Liu 1996; Clement et al. 1996). If this result is correct, the energy transport in the atmosphere will act as a positive feedback that amplifies the initial effect of an increase in the greenhouse effect upon the surface flux into the ocean. These considerations compound the concern that the unusual behavior of the tropical SST in the 1990s may be partly due to global warming (Trenberth and Hoar 1996), particularly in view of the finding that the SST contrast between the equatorial cold tongue and its surrounding regions has a positive trend over this century (Cane et al. 1997).

On the other hand, if global warming eventually reduces the SST contrast between the equatorial cold tongue and its surrounding region (Knutson et al. 1997), there is the possibility that global warming may eventually reduce the surface heat flux into the equatorial ocean and result in a less energetic El Niño. Knutson et al. (1997) indeed found a weaker El Niño in their 2000-yr-long global warming experiments. The recent geoarcheological finding that El Niño may not have been present prior to about 5000 yr ago (when the global and regional climate were warmer than today) corroborates this scenario (Sandweiss et al. 1996; Rodbell et al. 1998). Our inference on a possible connection between the zonal SST contrast and the magnitude of El Niño warming may not necessarily contradict the study of Timmerman et al. (1999) because it is not clear whether the cloud and water vapor feedbacks in their model behave as the observed do. If the short-wave forcing of the clouds does not cancel the long-wave forcing of clouds, and the greenhouse effect of water vapor does not cancel the surface emission in their model, then surface heat flux into the equatorial ocean would have a different relationship with the zonal SST contrast.

Thus to the extent an enhanced greenhouse effect

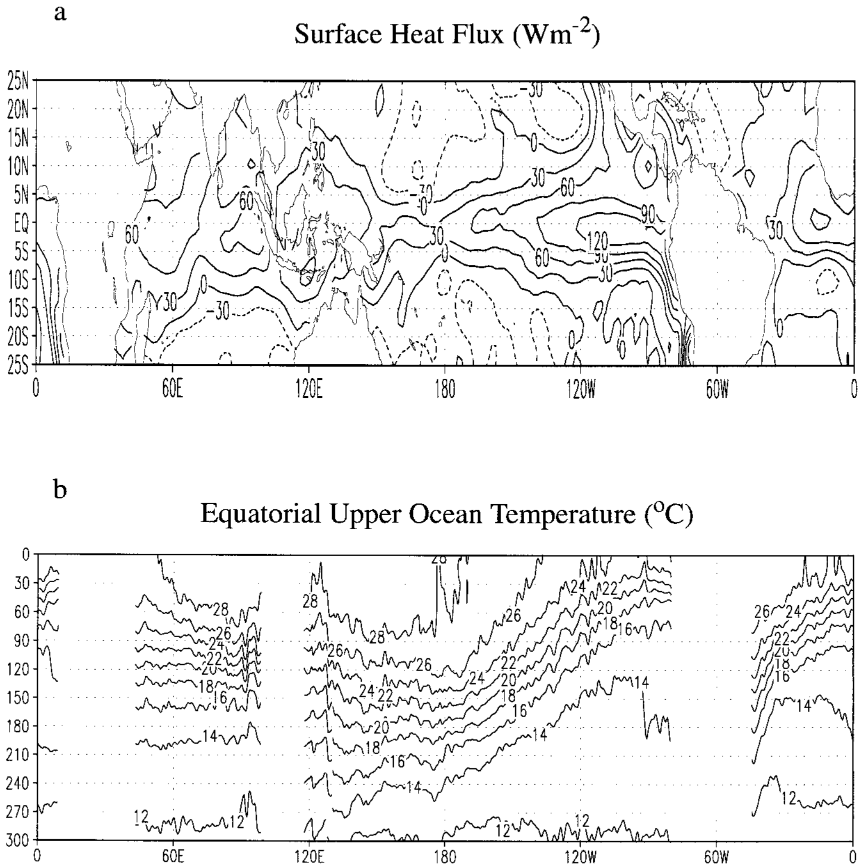

FIG. 13. (a) Long-term annual mean surface heat flux into the tropical oceans. Data used here were obtained from Eq. (2) with N_T from the ERBE data (Barkstrom 1990) and D_a from the NCEP–NCAR reanalysis, which makes use of the global observations of temperature, humidity, and winds (Trenberth and Guillemot 1998). (b) Climatological annual mean temperature distribution in the equatorial upper oceans. The temperature data for this plot are from the Levitus *World Ocean Atlas.*

alters significantly the surface heat flux into the equatorial ocean, global warming will project its effect on El Niño. Moreover, the equilibrium response of El Niño to global warming may be opposite to the initial response. A more detailed prediction can only be derived from modeling studies. The present observational results suggest a basic mechanism by which the greenhouse effect affects El Niño and highlight the fact that the partitioning of the poleward transport of energy in the Tropics between the atmosphere and ocean may be a central issue in the study of the response of El Niño to global warming.

Finally, we would like to emphasize that the inference that ENSO acts as a heat pump of the Tropics is based on the heat balance of the ERBE period. To generalize this inference, one needs to examine the heat cycle of other El Niños. In particular, one would like to see whether bigger El Niños like 1982–83 and 1997–98 are accompanied by larger poleward heat transport. In addition, the temporal relationship of the poleward ocean heat transport with the zonal SST contrast and the surface heating (or, by extension, the relationship of the poleward ocean heat transport with the meridional SST contrast and the meridional differential heating) needs to be better delineated.

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