Diurnal Restratification Events in the Southeast Pacific Trade Wind Regime

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ABSTRACT

This paper describes the occurrence of diurnal restratification events found in the southeast trade wind regime off northern Chile. This is a region where persistent marine stratus clouds are found and where there is a less than complete understanding of the dynamics that govern the maintenance of the sea surface temperature. A surface mooring deployed in the region provides surface meteorological, air–sea flux, and upper-ocean temperature, salinity, and velocity data. In the presence of steady southeast trade winds and strong evaporation, a warm, salty surface mixed layer is found in the upper ocean. During the year, these trade winds, at times, drop dramatically and surface heating leads to the formation of shallow, warm diurnal mixed layers over one to several days. At the end of such a low wind period, mean sea surface temperature is warmer. Though magnitudes of the individual diurnal warming events are consistent with local forcing, as judged by running a one-dimensional model, the net warming at the end of a low wind event is more difficult to predict. This is found to stem from differences between the observed and predicted near-inertial shear and the depths over which the warmed water is distributed. As a result, the evolution of SST has a dependency on these diurnal restratification events and on near-surface processes that govern the depth over which the heat gained during such events is distributed.

1. Introduction

Sea surface temperature (SST) plays an important role in air–sea exchanges and provides the surface boundary condition for the atmosphere. In recent years there has been interest in the coupling of the ocean and atmosphere in the region of persistent marine stratus clouds in the trade wind regime east of northern Chile (Mechoso et al. 2013). The subtropical southeastern Pacific (SEP) region is characterized by relatively cool SST compared to the other tropical regions, and links between the cool SST and the stratus cloud cover have been investigated (Xu et al. 2005; Eastman et al. 2011). Challenges to realistic prediction of both cloud amount and type and of the SST in the region have motivated research studies focused on this region over the last decade. Model SSTs are typically biased high in the region, and a lack of realism in the models’ representation of oceanic processes has been suggested as a cause (Zheng et al. 2011). As a step toward improved understanding of the coupled ocean–atmosphere dynamics of the region and of the deficiencies in the models, a number of studies have made efforts to identify the different processes that govern the evolution of SST in the region (Colbo and Weller 2007; Shinoda and Lin 2009; Holte et al. 2013). We seek here to add further to the understanding of the ocean surface layer and the evolution of SST in this region.

Our perspective here is to focus on the occurrence and life cycle of diurnal restratification events in the region using data from a surface mooring deployed there. The mooring provides observations of surface meteorology; air–sea exchanges of heat, freshwater, and momentum; and upper-ocean salinity, temperature, and velocity. Because of the nonlinearities in the dynamics of the ocean surface mixed layer that result in rectification of the diurnal response (Ham et al. 2010) and the role of diurnal variability in setting the mean SST (Bernie et al. 2005), an awareness of the high-frequency covariability of the atmosphere and ocean is a necessary part of

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understanding the dynamics that govern the seasonal and longer-term evolution of SST. To an extent, we also seek to document the diurnal restratification events in the region because we had not anticipated finding such events under the marine stratus clouds in the presence of steady trade wind forcing and thus had not considered the possibility of diurnal restratification having a role in setting SST in this region.

However, we do find episodes during the year when the speed of the trade winds drops dramatically and when the heat flux is sufficient to generate diurnal restratification. These periods of diurnal restratification end when the trade winds accelerate back toward their typical strength and the shallow, diurnal layer is mixed downward. During a number of these periods, at the end of the sequence of diurnal warming events, the mean SST is warmer. Over the years, the warming of SST during the spring at the mooring is characterized by a number of such upward steps following periods of diurnal restratification. We investigate whether or not the occurrence and magnitudes of the individual diurnal warming events are successfully replicated by a one-dimensional upper-ocean model (Price et al. 1986) initialized with data from the mooring and forced by the observed air–sea fluxes. At the same time, we examine if the model, when run for a number of days over a sequence of diurnal events, yields the net warming observed at the end of these periods.

We use data collected from October 2006 to October 2007 on a mooring called the Stratus Ocean Reference Station located at 20°S, 85°W, about 800 nm west of the coast of northern Chile. In the following, we investigate the life cycle of the restratification events. They are initiated when synoptic weather patterns disrupt the high pressure cell typically found in the eastern South Pacific. The diurnal restratification events end when the South Pacific high is reestablished and the trade winds over the region return to their mean value of close to 7 m s\(^{-1}\). The onset of renewed trade winds is a change in magnitude but not direction of the wind stress. The tendency to restratify is opposed by mixing processes, so we look at the upper-ocean velocity as well as temperature, salinity, and density fields. We find energetic near-inertial oscillations near the surface, and when we contrast observed diurnal restratification events with the model results, we also contrast observed and modeled near-inertial oscillations that contribute to the vertical shear and mixing.

We first provide a summary of the source of the data we use (section 2). Then an overview of the year-long records of the surface meteorology and air–sea fluxes of momentum, heat, and freshwater and of the upper-ocean temperature, salinity, and velocity is provided (section 3). We then focus on the diurnal warming events observed during this year of data. In doing so, we look at the regional surface meteorological context for the low wind events and also at the variability in the diurnal warming response observed during such low wind events and how often during the year such events occurred (section 4). The variation in the response was found to depend not only on the coincidence of low wind stress and net heating but also on whether or not near-surface, near-inertial shear was generated in association with the sagging or acceleration of the surface wind. Section 5 looks at the three different periods in more detail, the life cycle of these diurnal warming events, and, in particular, how both the observed individual restratification events and the net warming after a low wind period compare to the response predicted using the Price et al. (1986) model. Discussion and conclusions follow in section 6.

2. Data

To understand the long-term interaction and coupling of the atmospheric and oceanic boundary layers in the stratus cloud-covered SEP region, the lead author and the Upper Ocean Processes Group of the Woods Hole Oceanographic Institution (WHOI) have been maintaining a mooring near 20°S, 85°W since October 2000. The fully instrumented surface buoy of the mooring measures redundant time series of surface meteorology with a 1-min sampling rate. These are subjected to careful quality control processes and used to produce accurate, hourly time series of the surface fluxes of heat, freshwater, and momentum (Colbo and Weller 2009). The meteorological sensors are calibrated both before and after deployment. In addition, two field intercomparisons of sensors are carried out. First, during the cruise to service the mooring, the new surface mooring is deployed several days prior to the recovery of the surface mooring that has been in the water for a year; this supports analysis of the performance of the sensors that have been in service for a year with the fresh set of moored sensors. Second, during that period of overlapping mooring deployments, the ship is stationed for a day or more just downwind of each mooring, bow into the wind, and the ship’s set of calibrated meteorological sensors provide the basis for another intercomparison and check on the quality of the moored meteorological data. Colbo and Weller (2009) concluded that averaged net heat flux has an accuracy of 8 W m\(^{-2}\) and the averaged magnitude of the wind stress has an accuracy of 0.007 N m\(^{-2}\).

The mooring line beneath the buoy carries velocity, temperature, and salinity sensors concentrated in the upper ocean to support the investigation of the processes that control SST and the evolution of the surface mixed layer (Colbo and Weller 2007). For one deployment in particular, we increased the instrumentation. The Stratus
7 deployment, which ran between October 2006 and October 2007, had additional oceanographic instrumentation in the upper ocean in order to sample with higher vertical resolution; we therefore have used the data from Stratus 7 for this study. Temperature and salinity were recorded at least every 5 min to a depth of 450 m. Temperature sampling had a finer vertical resolution than the salinity measurements during this period and was available at depths of 0.055, 0.125, 1, 2, 3.7, 7, 16, 25, 30, 35, 37.5, 40, 45, 55, 62.5, 70, 77.5, 85, 92.5, 96.3, 100, 115, 130, 145, 160, 175, 182.5, 190, 220, 235, 250, 290, 310, 350, 400, 450, and 852 m. The salinity time series came from depths of 1, 3.7, 7, 16, 30, 37.5, 40, 62.5, 85, 96.3, 130, 160, 190, 220, 250, and 310 m. The velocity time series came from Aanderaa current meters at 10, 20, and 33 m, which sampled at 30-min intervals, and from vector measuring current meters (VMCMs) with 1-min sampling at 45-, 55-, 145-, 183-, 235, 290-, and 852-m depths. An RDI acoustic Doppler current profiler (ADCP) was deployed at 135 m, looking upward, with 10-m bin spacing, though the velocity time series recorded by the ADCP in the upper 60 m were noisy and had gaps.

The oceanographic temperature and conductivity sensors were calibrated before and after the deployment, and the temperature and salinity time series were quality controlled to correct for sensor drift, clock drift, and consistency. The velocity time series were also quality controlled. VMCM time series were truncated when either propeller sensor showed evidence of slowing down or stopping; both biofouling and entanglement by fishing line were evident on some VMCMs upon recovery. Basic merged temperature and salinity datasets were created at 5-min and 1-h sampling rates. Merged velocity datasets were created also at 5-min and 1-h sampling rates; in this case the Aanderaa and RDI time series were interpolated to 5-min sampling.

The basic time series for the Stratus 7 ran from 16 October 2006 to 29 October 2007. In this discussion statistics computed for 1 yr or an annual period are computed from 16 October 2006 to 16 October 2007. In this discussion austral summer or summer will be taken as December, January, and February. Austral fall or fall will span March, April, and May. Austral winter or winter will span June, July, and August. Austral spring or spring will span September, October, and November.

3. The meteorological, air–sea flux, and oceanic setting

a. Surface meteorology and air–sea fluxes

To set the context, we begin with a brief overview of the surface meteorology at the Stratus mooring during the 2006/07 deployment; the Stratus 7 surface meteorology is shown in Fig. 1, and 1 yr means are shown in Table 1. The site is located in the southeast trade winds and exhibits exceptionally steady winds, oriented toward 306° in the annual mean. The steadiness (the ratio of the vector average to the scalar average wind speed) of the 1-day-averaged wind data was 0.98. The wind speed had an annual mean of 6.7 m s⁻¹ and an annual cycle with stronger winds in the austral fall, winter, and spring. Although steady, the trade winds did, on several occasions during the year, drop to close to zero. There was an annual cycle in barometric pressure with an amplitude of about 6 mb with a minimum in February and a maximum in August; the annual mean was 1018.2 mb. In the austral fall and winter, the center of the South Pacific high pressure cell both had a higher central pressure and was located farther toward the northeast, increasing the surface pressure gradient supporting the trade winds.

Air temperature and sea surface temperature both had annual cycles, with amplitudes of 7.1°C in air temperature and of 6.3°C in sea surface temperature. The minimum in air temperature (15.3°C) occurs in early September, and the maximum (22.5°C) occurs mid-February. The cycle in sea surface temperature is shifted later, with a minimum in the sea surface temperature occurring in mid-October (17.0°C) and maxima occurring at the end of February (23.1°C). The shift in the timing, shape, and magnitude of the air and sea surface temperatures leads to an annual cycle in the air–sea temperature difference. The temperature difference is smallest in late December (−0.3°C) and largest in mid-July (−1.5°C). Relative humidity (RH) did not show an annual cycle. There was considerable variability about the annual mean of 72.2% RH; this was observed on the time scales of synoptic weather events, when daily mean relative humidity varied between 62% RH and 89% RH. Significant rain that reached the sea surface was rare. The annual-mean, measured rain rate was 0.015 mm h⁻¹, and the heaviest rain event of the year contributed only 8 mm.

The Stratus site is characterized by marine stratus clouds. These clouds have periods in which they thin on a daily basis. Burleyson et al. (2013) report thinning of the stratus over the region in the late afternoon, local time. The impact of that thinning is seen in the incoming longwave radiation, which during these periods decreases by 60 W m⁻² in the late afternoon and early evening. During the periods of afternoon thinning, the hourly incoming longwave radiation (Fig. 1) drops and then rises as clouds reform; this gives the time series the appearance of toggling between the cloud-covered and clear-sky values. Incoming shortwave radiation shows
the astronomical daily and seasonal cycles but also shows the modulation associated with the periods when the stratus clouds thinned. The 48-h low-pass filtered incoming shortwave and longwave radiation (Fig. 1) show that periods of lower averaged incoming longwaves correspond to periods of higher averaged incoming shortwaves. Note that in all plots, time is given in UTC; local time at the Stratus site is UTC-6.

Hourly time series of surface meteorology were used together with the Coupled Ocean–Atmosphere Response Experiment (COARE) bulk formulae, version 2.6 (Fairall et al. 1996a), to compute time series of wind stress, latent heat flux, and sensible heat flux. The algorithm includes cool skin and warm layer adjustments based on Fairall et al. (1996b). Net shortwave radiation was determined from observed incoming radiation following the COARE algorithm, with the assumption of a constant surface albedo. Net longwave radiation was calculated from observed incoming longwave radiation by estimating the outgoing longwave radiation as \(\epsilon(\sigma T^4 - R_L)\), where the emissivity \(\epsilon = 0.97\), \(\sigma\) was the Stefan–Boltzmann constant, \(T\) was the sea surface skin temperature in K, and \(R_L\) was the observed incoming longwave radiation. As discussed above, Colbo and Weller (2009) examined the accuracy of the meteorological sensors and of the computed air–sea fluxes, including the propagation of measurement error through the bulk formulae and developed estimates for the accuracy of the fluxes.

**TABLE 1.** Stratus 7 mean meteorology, averaged from 16 Oct 2006 to 16 Oct 2007. The heights of the sensors above the sea surface are given in the second column.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Height (m)</th>
<th>1-yr mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>2.68</td>
<td>19.05°C</td>
</tr>
<tr>
<td>Sea temperature</td>
<td>−0.92</td>
<td>20.17°C</td>
</tr>
<tr>
<td>Barometric pressure</td>
<td>2.76</td>
<td>1018.2 mb</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>2.68</td>
<td>72.2%</td>
</tr>
<tr>
<td>Specific humidity</td>
<td>2.68</td>
<td>9.8 g kg(^{-1})</td>
</tr>
<tr>
<td>Incoming shortwave</td>
<td>3.42</td>
<td>205.8 W m(^{-2})</td>
</tr>
<tr>
<td>Incoming longwave</td>
<td>3.42</td>
<td>371.9 W m(^{-2})</td>
</tr>
<tr>
<td>Wind speed</td>
<td>3.16</td>
<td>6.79 m s(^{-1})</td>
</tr>
<tr>
<td>Wind direction (toward)</td>
<td>3.16</td>
<td>305.7°</td>
</tr>
<tr>
<td>Rain rate</td>
<td>3.14</td>
<td>0.015 mm h(^{-1})</td>
</tr>
</tbody>
</table>
The setting at the site from the perspective of the air-sea fluxes is one of a steady, moderate trade wind, wind stress forcing associated with a small annual heat gain and considerable evaporation. The flux time series are shown in Fig. 2 and the annual means of the flux components are given in Table 2. The annual-mean net heat flux for Stratus 7 was 16.4 W m$^{-2}$, with oceanic heat gain coming from the net shortwave radiation (annual mean of 194.5 W m$^{-2}$) and oceanic heat loss associated with the latent heat flux (annual mean of −121.6 W m$^{-2}$), the net longwave radiation (annual mean of −45.5 W m$^{-2}$), and the sensible heat loss (annual mean of −11.0 W m$^{-2}$). As little rain accumulated, there was no significant heat loss associated the rain falling at the wet bulb point temperature. The annual latent heat flux was associated with evaporation over the year of 1.5 m of water at the sea surface. The annual-mean wind stress was 0.093 N m$^{-2}$ toward 306°. As noted in the discussion of the wind velocity, the wind stress, though varying little in direction, did have events both higher and lower in magnitude.

The ocean gains heat during the austral spring and summer and loses heat during the fall and winter. To a large extent, this annual cycle reflects the astronomical annual modulation in incoming shortwave radiation. Following Cronin et al. (2006) and Iqbal (1988), the 48-h low-pass filtered, predicted, cloud-free surface shortwave radiation is plotted over the observed 48-h low-pass filtered surface net shortwave. While the predicted
cloud-free time series sets the annual modulation of the upper bound on the observed surface shortwave, it is also apparent, for example, in the October 2006 to February 2007 period, that variability in cloud cover further modulates the surface shortwave radiation.

b. An overview of upper-ocean structure and variability

There is a strong annual cycle in the structure of the upper ocean at the Stratus location (Fig. 3). Figure 3 provides a look at the low-frequency evolution of the structure by including lines showing two low-pass filtered (44-h running mean) estimates of the mixed layer depth (MLD) in the temperature and salinity contour plots. The surface mixed layer deepens from February to September 2007, reaching 170-m depth in the spring. The mixed layer then shoals dramatically in the summer. In January the layer restratifies, and a new, shallow, warm, and salty surface layer forms on top of the older, deeper layer with the mixed layer depths at times 20 m and less. In late summer, the mixed layer starts deepening that continues through fall and winter and into spring. The warmest surface layer temperatures, approaching 23°C, occur in late summer to early fall. The ongoing evaporation keeps the surface layer more saline than the water below, and the most saline surface water is seen in late summer to early fall when the evaporation acts on the thinnest surface layer. Below the mixed layer throughout the year, at 150-250-m depths, is a layer of fresher water, which has been identified as a mode water formed south of the site known as Eastern Pacific Intermediate Water (Schneider et al. 2003).

When averaged over several years, the mean ocean velocities at the Stratus site are small, of order several hundredths of a meter per second. Within the Stratus 7 year, a number of eddies moved over the mooring. Propagation speed was slow and the diameter of the eddies, as seen in altimetry and in subsequent years as surveyed by shipboard sampling (Holte et al. 2013), was roughly 100 km, so that the strongest signal in the Stratus 7 velocity data was the slowly varying signature of the eddies, with speeds of up to 0.5 m s⁻¹.

4. Diurnal warming events during Stratus 7

The feature of the Stratus 7 ocean temperature data that motivated this present study was the occurrence of a number of diurnal warming events. Predominantly during the austral summer, but also during other seasons, rapid increases in SST were seen in the afternoon that were followed by cooling in the evening. Over the Stratus 7 record length, these diurnal warming events are seen even more clearly when SST is high-pass filtered. In Fig. 4, a 24-h running mean of SST has been subtracted from the hourly SST, yielding the second time series down. Vertical dashed lines have been used to bracket several periods of diurnal warming and show how they coincide with periods when the wind decays while coincidentally there is net gain by the ocean. These diurnal warming events raised SST by as much as just over 2.0°C. During the Stratus 7 deployment there were 18 days in which the sea surface temperature rise between midafternoon and early in the local morning exceeded 0.5°C. Indeed, the occurrence of diurnal warming events in Stratus 7 led Prytherch et al. (2013) to include this dataset in a broader analysis of the dynamics and modeling of diurnal warming events in which the other datasets came from strongly heated regions such as the Arabian Sea, the eastern tropical Pacific, and the Red Sea.

Our interest is further enhanced by the coincidence, at times, of the diurnal warming events with net warming and restratification of the surface layer. In early January 2007, as shown in Fig. 5, the low-passed surface ocean mixed layer depth, defined as the depth at which temperature was 0.5°C less than SST, was slightly deeper than 50 m, and the low-passed relict mixed layer depth, defined using a temperature change of 1.0°C, was at about 100 m. In mid-January both shoaled. Evidence of moderate diurnal restratification was seen on 1 to 10 January. Then, a period of stronger, more surface-intensified diurnal warming that began on 13 January that was accompanied by shoaling of both these low-passed mixed layer depths as well as warming of the surface layer.

We provide in this section discussions of two aspects of events like this one in January. First, a more detailed look at the surface meteorology and air–sea flux forcing during such events at the Stratus buoy is provided, including discussion of whether such conditions were seen over a broader area around the site. Second, we provide an overview of the occurrence of diurnal restratification.
events during the year. Figure 4 suggested that the co-
incidence of low wind events and periods of net heating
of the ocean were sufficient to produce a diurnal warm-
ing event. We make a census of diurnal restratification
events during the year and look at the dependency of the
temperature rise each day on the observed forcing.

a. The meteorological setting for diurnal warming
events

To examine the surface meteorology and forcing with
a case study, consider in January 2007 the sequence of
diurnal warming events and accompanying increase in
SST that occurred beginning 15 January and continued
through 27 January. During this period (Fig. 6) there
is both a decrease in the wind stress and an increase in
low-passed (24-h running mean) net heat flux of about
100 W m$^{-2}$. The increase in oceanic heating stems from
a number of sources. This was a period in which skies
cleared more during the daylight hours, allowing more
shortwave radiation to reach the surface; there was
a reduction of latent heat loss under lower winds; and
there were reductions in net longwave loss at night when
low clouds reformed. The strong diurnal warming that
began late on 18 January, for example, saw the wind
stress drop to close to 0.0 coincidentally with a period of
clear skies and strong heating of the ocean surface.
Another strong heating event that began late on
25 January had the same setting, winds dropping to zero
and strong insolation under clear skies. For 3 h late on
14 January, wind speeds dropped below 2.0 m s$^{-1}$. For an

Fig. 3. Contour plots based on hourly temperature (°C) and salinity (psu) data from Stratus 7, covering October
2006 to October 2007. On the (a) temperature and (b) salinity plots, mixed layer depths determined as 0.5°C (cyan) and
1.0°C (white) less than the surface temperature and low-pass filtered with a 44-point running mean are shown. Data
gaps are shown in white.
hour late on 18 January, wind speed fell under 1.0 m s$^{-1}$, embedded in a 2-h interval with wind speed under 2.0 m s$^{-1}$. For a 4-h period late on 25 January, wind speed did not exceed 2.0 m s$^{-1}$.

Characteristically, at the Stratus site, a moderate southeast trade wind is observed at the mooring site; the mean 10-m wind speed at the Stratus 7 buoy was 6.8 m s$^{-1}$. This trade wind is established by the presence of a high pressure located to the southwest of the buoy and the associated spatial gradient (about 16 hPa over 3000 km) in sea level pressure between the center of the high and the northern coast of Chile (Fig. 7). On some occasions, however, this sea level pressure pattern was not present. Instead, for several days, as on 15–27 January 2006, a low pressure cell established itself south of the mooring at about 50°S, and the high pressure cell was displaced farther west than usual (Fig. 8). As a result, a broad region of weak spatial gradients in sea level pressure was found west of Chile, including where the Stratus mooring was deployed, and the winds at the buoy were light, dropping at times to under 2 m s$^{-1}$. At the end of January, the South Pacific high was reestablished to

![Diurnal warming events – Stratus 7](image)

**FIG. 4.** (top to bottom) Hourly time series of SST; hourly high-pass filtered SST, computed as the difference between the SST and a 24-h running mean; the magnitude of the wind stress; and the 24-h running mean of the net heat flux.

![Contour plot of hourly ocean temperature (°C) data from Stratus 7 for 1 to 31 Jan 2007. Contour lines are every 0.05°C. The cyan line is the low-pass filtered time series (44-point running mean) of surface mixed layer depth defined as the depth where temperature is 0.5°C less than SST; the white line is relict mixed layer depth, calculated with the same low-pass filter applied to the time series of the depth where temperature is 1.0°C less than SST.](image)
the southwest of the mooring site, and the trade winds increased in strength. Over the year, it is this transition away from the typical dominance of the South Pacific high and moderate southeasterly trade winds that leads to weak winds at the mooring with associated diurnal restratification. Such restratification events end when the South Pacific high returns and the trade winds increase in strength.

b. The occurrence of diurnal warming events

Based on the time series of the surface meteorological and air–sea flux records together with the diurnal warming events in Fig. 4, there is a general coincidence of diurnal warming events with periods of low wind and positive surface heat flux. There were 18 events in which the diurnal warming, defined as the SST rise between just before sunrise and its maximum in the afternoon, exceeded 1.0°C. There were 126 events in which diurnal warming exceeded 0.25°C. All occurred during low winds.

Extracting the magnitudes of the SST rise \( \Delta T \) from early morning to midafternoon for each day of the Stratus 7 record and plotting those magnitudes against the average wind stress and average net heat flux for the matching days yielded Fig. 9. The tendency for the magnitude of the diurnal warming to increase as both net heat flux increases and the magnitude of the wind stress decreases is evident as the upper limit of the points slopes upward toward the far corner.

Price et al. (1986) had previously developed a one-dimensional model of the upper ocean. Their scaling of the diurnal warming magnitude points to \( \Delta T \approx Q^{3/2} \tau^{-1} \), where \( Q \) is the net heat flux, and \( \tau \), in this case, is the magnitude of the wind stress. A surface with those dependencies when superimposed upon the data in Fig. 9 captures the dependencies on heating and wind stress suggested by the data. In addition, the Price et al. (1986) scaling had some skill in predicting observed \( \Delta T \), and further analysis of the diurnal restratification events was done using the Price et al. (1986) model, hereinafter referred to as PWP.

5. The life cycle of three diurnal warming periods

We chose to examine three diurnal warming periods during summer and fall. The closer examination was motivated not only by the variability in the individual diurnal warming events during periods of low winds and net heating but also with the intent of better understanding the net warming that typically resulted by the end of a period of low winds and diurnal restratification events. In Fig. 6, SST at the beginning of January was close to 20°C, but following the series of diurnal warming events, mean SST reached over 22°C and stayed there as the trade winds picked up again. In Figs. 5 and 6, every day showed a warming response to the insolation. The depth of penetration of the warming and the magnitude of the SST response varied day to day. Figure 5 also shows that as the wind decreased in mid-January, the mixed layer shoaled and warmed. There is the suggestion, that at times, as on 5 to 11 January and on 23 to 25 January, heat penetrated more deeply. The warmed surface layer deepened at the end of January.

We looked at how well PWP did at replicating not only the occurrence of individual restratification events but also the life cycle of the low wind periods and whether PWP could also reproduce the observed associated mean warming and restratification of the upper ocean. The mixing processes that the model represents include convective deepening and two different shear-driven overturning processes: one mixing momentum down from the surface based on shear flow stability and ensuring that the gradient Richardson number is greater than or equal to 0.25 and the second parameterizing mixed layer entrainment based on ensuring mixed layer stability as determined by keeping a bulk Richardson number dependent on the shear across the base of the mixed layer greater than or equal to 0.65. Because of the role that velocity shear plays in the physics represented by the model, we investigate the velocity structure in the upper ocean during the diurnal warming events observed during the Stratus 7 deployment. A related hypothesis is whether the variability in the actual shear introduces some of the observed variability in the diurnal response.

FIG. 6. Hourly time series from 1 to 31 Jan 2007 of (top) SST; (middle) magnitude of the wind stress; (bottom) 24-h running mean of the net heat flux with 24-h low-pass filtered hourly net heat flux (red) and unfiltered hourly net heat flux divided by 5.0 (black). Time is in UTC in all plots.
During the period of the day that the surface heat flux is positive, the buildup of an increasingly stable, warm surface layer is opposed by shear-driven mixing at the base of that layer. Steady, unidirectional wind forcing during the heating leads to a surface-intensified diurnal jet (Price et al. 1986). Impulsive or varying wind forcing leads to near-inertial oscillations in the surface layer (Weller 1982). Wind-forced near-inertial motion is often seen as a response to synoptic weather events where wind direction as well as magnitude varies. At the Stratus mooring site, although the observed wind stress was unidirectional, we filtered the time series from the current meters to look for near-inertial motions. We found, at times, show of strong near-inertial currents.

For the three different diurnal warming events, the energy flux from the wind to the near-inertial currents in the upper ocean is given (Silverthorne and Toole 2009) by

$$\Pi_W = \text{Re}(\tau_I Z_I^*),$$

where \(\tau_I\) and \(Z_I\) are the near-inertial wind stress vector \((\tau = \tau_x + i\tau_y)\) and the near-inertial complex velocity.
\((Z = u + iv)\) at the surface. We use a second-order Butterworth filter with a passband of 0.8\(f\) to 1.2\(f\), where \(f\) is the local inertial frequency, to extract the near-inertial components of winds and currents; the inertial time period for this location is 35 h. We estimate \(\Pi_W\) using observations and the PWP model results for these three events. A positive \(\Pi_W\) suggests a net increase in the mixed layer near-inertial kinetic energy and vice versa.

The PWP model is initialized with vertical profiles of temperature and salinity based on the mooring data at the beginning of each event. Assuming the initial currents are zero, we simulate each of these three events using the model driven by wind stress, freshwater, and surface heat fluxes, with a vertical resolution of 0.5 m and a time step of 1 h, without reinitialization. To incorporate the radiation of near-inertial waves from the transition layer to the interior we use a linear damping term \(r\), where \(1/r = 5\) days. We assume the water type at our mooring site corresponds to clear midocean water (type 1A) (Paulson and Simpson 1977). We did test the sensitivity of the PWP results to the choice of water type, trying other open-ocean water types and running PWP for the month of January 2007. The predicted diurnal warming events happened at the same time and amplitudes were similar, within tenths of a degree, and to similar depths (within meters).

### a. January 2007

The January 2007 event is shown in Figs. 5 and 6. The wind stress magnitude varies between 0 and 0.19 N m\(^{-2}\), and the mixed layer shoals mid-January as the wind weakens and a series of diurnal warming events is observed. The wind stress drops from 6 to 10 January and has a relatively modest diurnal restratification response. The longer period of low winds from 14 to 27 January is accompanied by stronger events, with the strongest diurnal warming events occurring on 18 and 25 January.

Figure 10 presents a view of the January 2007 period that compliments Figs. 5 and 6. Wind-generated near-inertial motion was evident near the surface and at times within the water column. Near the surface, near-inertial motions were excited as the wind decayed on 5 January and again when the wind accelerated on about 24 January. The oscillations in the first event decayed as the trade winds accelerated on 11 and 12 January. In the presence of the near-inertial motions in the surface layer that strengthen after 6 January, the heat from the insolation was seen in Fig. 5 to be mixed rapidly down through the upper 50 m during 9 to 13 January. The strongest diurnal response early in the month, late on 6 January to early on 7 January, is seen as these oscillations are increasing in amplitude and thus perhaps in advance of strong, shear-driven mixing. Mixing over the upper 50 m results in low-amplitude diurnal events and relatively small net warming of SST.

In contrast, the decay of the wind on 13 to 14 January does not have associated, near-inertial oscillations in the surface layer. The decrease in wind speed came at a time of very weak near-inertial motion near the surface, and the heat from the insolation remained near the surface. As a result, the amplitudes of the diurnal SST responses later in the month are larger, and the mixed layer shoals and warms. As the wind speed increases again, with a modest increase on 24 January, the shallowest current meters show stronger near-inertial oscillations that further increases in strength following a lull in the wind late on 25 January. The lull late on 25 January coincides with local noon, and a diurnal rise in SST in excess of 1°C is seen. Following the lull, wind stress increases, near-inertial oscillations are stronger, and the heat from the
Insolation is mixed more deeply as the surface layer deepens.

We run PWP for January 2007, initializing with vertical profiles developed from the mooring data and forced by the observed air–sea fluxes (Fig. 11). The model replicates the occurrence of the individual diurnal warming events and their magnitudes. The time series of the observed and model SSTs in the bottom panel of Fig. 11 show that the model yielded a warmer mean SST at the end of January than the observations. Though the individual diurnal amplitudes from the model and observations, defined as the SST rise from before sunrise to the afternoon maximum, are in close agreement, the SSTs at the end of the events, after sunset each day, are typically warmer in the model. The observations show that the sequence of diurnal warming events from 15 to 22 January is accompanied by a rise in SST of 2°C and a shoaling of the surface mixed layer. In contrast, the model SST warms by over 6°C by the end of the month.

We include in Fig. 11 the bandpassed, near-inertial zonal currents as well. In the data, as noted earlier, there are near-inertial oscillations during the low winds of 5 to 10 January and then again when the wind accelerates at the end of the month. In contrast, the most prominent near-inertial oscillations in the model results begin as the wind decreases on 14 January. These strong near-inertial oscillations are located in the mixed layer during 13–23 January. The wind work is positive during this period. Later, during 23–26 January, the wind extracts energy and damps the near-inertial oscillations in the model. The weak and shallow near-inertial currents are seen at the end of the month just as the wind supplies energy and the observed near-inertial currents strengthen and deepen.

In the observations, as the wind begins to accelerate on 23–24 January, near-inertial oscillations are seen in the surface layer. The near-inertial energy flux is consistent with the variations of near-inertial currents as observed in the shallow current meters. There is near-inertial energy input in early January, before 13 January, then near-zero flux during the diurnal warming events of 15 to 23 January, followed by growth in the energy flux on 23 to 27 January and again 29 January onward. The current meter data show near-inertial motions in the surface layer 6 to 13 January, followed by a period of low near-inertial amplitudes from 15 to 21 January. After 21 January, new, strong, near-inertial motions grow very near the surface at the same time near-inertial motions grow below the base of the surface layer and down through 150 m. After 15 January, with the wind down again and in the absence of strong surface near-inertial motion, the heating is trapped near the surface and the mixed layer shoals. Figure 5 shows instances of warm water penetrating more deeply on 22 to 27 January, and
then warm water moving deeper as the low-passed mixed layer depths deepen after 27 January. These events happen in conjunction with the appearance of stronger near-inertial motion below the mixed layer on 23 to 27 January and with the growth of strong, near-inertial motion in the surface layer after 25 January.

To further contrast the observed warming with that predicted by PWP, we reference the temperature data in each profile to that observed at the beginning of 1 January 2007 and contrast the contour plots for January (Fig. 12). There is warming that is seen at greater depth in the observations during both low wind periods.

b. December 2006

In December 2006, the wind decays, with the magnitude of the stress dropping from close to 0.13 N m$^{-2}$ to close to 0.0 late on 14 December to midday on 16 December (Fig. 13). Moderate diurnal warming events are seen starting 9 December that grow in amplitude as the wind stress decreases. A strong diurnal warming of about 1.5°C occurs late on 15 December, with a smaller response on 16 December. Then as the wind accelerates, the diurnal events diminish in amplitude. The observed mean SST increases about 0.5°C due to the heat gained by the surface layer over this period.

As the wind decelerates from 9 to 15 December, the current meter data show a strengthening of near-inertial oscillations within the roughly 100-m-deep mixed layer. On 15 December, the mixed layer shoals and near-inertial shear develops across the base of the layer beginning on 11 December. The shallow oscillation intensifies as the wind accelerates on 21 to 23 December, when a more complicated vertical structure in the observed near-inertial currents develops. The wind work is negligible in both the data and the model during the first half of this event between 1 and 16 December. As the wind picks up between 17 and 23 December and forces a shallow mixed layer, the increase in observed wind work reaches a maximum of 1 mW m$^{-2}$ on 20 December (Fig. 13). The observed wind work is negative thereafter. On the other hand, the model shows a very different wind work evolution with weak, positive values between 17 and 23 December.
The model again stores more heat near the surface, yielding a surface layer in late December 3°C warmer than observed. The earlier shoaling of the model mixed layer from 10 to 16 December is accompanied by greater warming of the model SST.

c. April 2007

Another event during April 2007 shows a pair of restratification events midmonth (Fig. 14). During this event, MLD and the relict layer are about at a depth of 60 m. Wind stress varying between 0.2 and 0.009 N m$^{-2}$ generates near-inertial motion at the beginning and the end of the time series.

We estimate the MLD from the model results using the same temperature criterion to compute MLD using observations. The model MLD, varying between 0 and 60 m during this event, is modulated by the wind stress and disappears as wind stress becomes minimum on 16 April; this thinning of MLD is associated with a 1°C peak in the diurnal SST (Fig. 14, third panel). The model predicts a warmer mean SST than the observations with a 0.5°C warming from 16 April onward; the mean model SST becomes about 1°C warmer at the end of this event. The bandpassed, near-inertial currents from the model are strong at the beginning and the end of the time series and are in agreement with the observations, but relatively weaker in amplitude. The near-inertial energy from the wind is weak during the first half of the event and exhibits higher positive values as the currents become stronger in the second half of the event between 19 and 25 April. The wind work from the model results is relatively stronger than the observations during the entire event, suggesting a greater increase in model near-inertial kinetic energy compared to the observations.

The divergence between the observed and model SST in this case stems mainly from a warm offset in the model mean SST that persists after the diurnal warming on 15–16 April. The model’s shallow surface layer on 15 April persists longer, with only a short-lived deepening at night, and gains more heat than the observed surface layer.

6. Discussion and conclusions

We find that even in the trade wind regime of the eastern South Pacific, there is evidence of diurnal restratification events. In 2006/07, a year of data collected from a surface mooring provided a record of surface meteorology, air–sea fluxes of heat, freshwater, and momentum and of upper-ocean temperature, salinity, and currents. Though a large high pressure cell was typically found in the eastern side of the South Pacific along with steady trade winds from the southeast that had an annual average of 6.8 m s$^{-1}$, this regime was perturbed on occasion by synoptic weather systems farther south, and a region of low wind speed would persist west of Chile for a day to several days at a time. Thus, the trade winds at the location, though very steady in direction when they were present, did, at times, decelerate and die away, to be followed by acceleration back toward steady trade winds. During these periods of low wind, a range of magnitudes of diurnal warming were observed, ranging up to 2.0°C. Surface analyses from the National Centers for Environmental Prediction (NCEP) model show that these low winds are found over a broad area west of Chile (Fig. 8). Thus, the diurnal warming of SST observed at the mooring is taken to be characteristic of a broader area of the eastern South Pacific. Austral summer and fall in this region is a time of strong evaporative cooling and is prone to convective mixing. The negative buoyancy flux and wind mixing by steady trade winds can generally keep the mixed layer deep. However, during this time, the mixed layer can restratify and become shallow when the negative buoyancy flux is overwhelmed by insolation confined to a very shallow surface layer, which happens only during these low wind periods.

There is a growing awareness of the need to consider the impacts of atmosphere–ocean coupling at the diurnal period in coupled modeling (e.g., Bernie et al. 2005; Danabasoglu et al. 2006; Ham et al. 2010). Rectification of the diurnal variability can alter the lower-frequency evolution of SST. At the mooring site we
found that low wind periods, during which two to several individual diurnal warming events were seen, mean SST at the end of the period was often warmer and shallower. Thus, to an extent, it appeared that spring warming and restratification of the upper ocean was supported by the occurrence of a number of periods of low wind accompanied by series of diurnal restratification events.

While these diurnal restratification events occurred when low wind stress and daytime solar heating were coincident, we pursued a more detailed examination of several events. Of interest were not only the ability to predict the amplitude of the individual diurnal warming events but also looking into what governed the net warming of mean SST after a low wind period. One tool we used in analyzing the ocean response during the low wind periods was the PWP one-dimensional model, initialized for each period with temperature and salinity data from the mooring and forced with the observed air–sea fluxes. We found the model to be very good at predicting the timing and amplitude of the SST rise during individual diurnal warming events. The diurnal amplitude of the SST is obtained simply subtracting hourly SST by a daily running mean SST for the entire time series. Indeed, the diurnal amplitude of the observed and predicted SST yielded time series that were very close when superimposed; the mean and the standard deviation of the difference between the diurnal amplitudes of the model and observations are 0.06°C and 0.12°C for the January event, 0.02°C and 0.09°C for the April event, and 0.04°C and 0.12°C for the December event. However, the model did not do well at predicting the net warming of the surface layer and change in its vertical structure during these low wind periods. Typically, the model overestimated the SST seen at the end of the low wind period.

The heating of the surface layer and the balance between vertical mixing and the stability associated with the buoyancy flux are important components of the dynamics that govern SST. If during the morning and midday periods the penetrating radiation warms the near-surface layer and shear-driven mixing near the surface remains small, then the new warming is
superimposed upon the existing structure. In this case, the model, with the appropriate choice of optical extinction coefficients should do well at replicating that new warming. In this case, the good agreement of the high-filtered observed and the model SSTs is support for this conclusion.

We found, however, that the net effect of the heating over several individual diurnal warming events was not always well replicated by the model. In addition to the energetic spectral peak in the net heat flux associated with solar insolation, the other energetic spectral peak found in the mooring data was that seen in ocean velocity and in the vertical shear. Those peaks were found at near-inertial frequencies, 0.0285 cph for 20°S, corresponding to a period of 35 h. This additional source of high-frequency variability must be taken into account when considering the shear-driven, vertical mixing processes that mix the heat from the insolation downward.

A number of studies have pointed to strong near-inertial currents generated at midlatitude by storms (Weller 1982; D’Asaro 1985). D’Asaro (1985) points to cold fronts and low pressure systems 100 km in size, where the wind stress changes in direction as well as in magnitude, as being effective generators of mixed layer near-inertial motions. Such fronts and well formed, small synoptic weather systems are not characteristics of the region where the Stratus mooring is located. Instead, as described above, there is a steady trade wind regime, embedded in which there a number of periods each year when low winds are to be found at and around the Stratus mooring site. The southeasterly wind dies and then some days later accelerates back toward the more typical state. At the Stratus mooring, it is these low wind events that generate near-inertial oscillations in the surface.

To better understand the life cycle of the low wind periods at the Stratus mooring and how the heat accumulated during the diurnal restratification events is distributed near the surface, we looked at the observed and modeled near-inertial currents. The changes in wind speed, both deceleration and acceleration, were found to be capable of exciting near-inertial oscillations in the surface layer. The variability in the near-inertial response and the presence or absence of near-inertial shear at the base of the surface layer were found to introduce a source of the difference between observed and modeled mean SST evolution.

In the January 2007 (Fig. 12) low wind period, there is a strong contrast between the observed and modeled near-inertial oscillations. From 5 to 11 January, during lower wind stress, we saw in the observations

![Graphs and images from the document]
near-inertial currents spanning a surface layer of close to 50 m and warming (Fig. 13) across and below that layer. In contrast, the surface layer at that time in the model shoaled in the presence of weaker near-inertial currents, also seen in $\Pi_{19}$. The second decay of the wind stress, beginning 15 January generated shallow near-inertial oscillations that decayed away in the model that were not evident in the data, consistent with the differences in $\Pi_{19}$ between data and model. The observations showed near-inertial oscillations with greater vertical shear from 23 to 27 January and shallow near-inertial oscillations in a deepening surface layer beginning 24 January. Warming in the model run is stronger and more surface concentrated and at the end of January model, the SST is over 3°C warmer than observed.

One might propose then that the difference in near-inertial shear and hence in the vertical mixing between the observed ocean and PWP causes the different evolution of mean SST over the course of a low wind period. In the second low wind period, that in December 2006 (Fig. 14), it appears to be the decelerating wind stress over 9 to 15 December followed by the acceleration on 16 to 19 December, which generates near-inertial oscillations in both the observations and in the model, though the wind work for observations is considerably higher. In the model, mixed layer shoaling starts as the wind begins to drop on 8 December and a shallower mixed layer with weaker, less deeply penetrating near-inertial oscillations in the middle of December in the model becomes even warmer relative to the observations.

The April low wind period provides another instance in which the model yields a warmer mean SST. From 7 to 15 April, the observed and model SST track each other. Then following the first of two diurnal warming events, the model SST becomes a bit warmer relative to the observed SST. The model produced a shallower surface layer over these 2 days. Even though the model wind work is higher than observed, the shallow mixed layer traps the heat. At the end of April and into early May, the model again warms relative to the observations. The model mixed layer is shallower and shoals more at the end of this period.

The reliance on a one-dimensional model is not without hazard. For one, the local heat budget at the Stratus mooring likely includes cooling contributions from eddy fluxes (Colbo and Weller 2007) and/or lateral advection (Holte et al. 2013). If these cooling contributions were more persistent than the relatively brief span of the low wind periods, we do not believe they are the source of the divergence between the observed and modelled SST that arises during the low wind periods. However, the expectation that the near-inertial oscillations at the mooring and hence the shear-driven vertical mixing associated with them can be replicated by PWP has more substantial challenges. We have in the past (Weller 1982, 1985) found that the near-inertial currents in the surface layer are modulated by the quasigeostrophic flow field, and the Stratus mooring region is marked by the presence of eddies (Chaigneau et al. 2011; Colas et al. 2012). Thus, the temporal evolution of the near-inertial currents at the mooring may have other dependencies than the local wind forcing, and this additional variability could not be replicated by the model.

The eastern boundary region of the South Pacific has, in a number of model results, been characterized by a warm bias in SST. We find that periods of low wind spanning two to several days have associated series of diurnal warming events and that mean SST after many of these periods is warmer. Our one-dimensional modeling of these low wind periods yielded, a number of times, a mean SST warmer than the observed mean SST. With in situ surface forcing, the one-dimensional model replicates the timing and amplitude of the daily maximum in SST. We believe that warm bias in our one-dimensional model runs results from the heat from the insolation being trapped too near the surface in PWP and that at the mooring, a different temporal and vertical evolution of near-inertial oscillations compared to the model leads to stronger shear-driven vertical mixing. In addition, the model, once it produces near-inertial oscillations, relies on a damping term to remove the energy not lost through interaction with the wind. Thus, should the model have existing near-inertial oscillations over, for example, the upper 50 m, the formation of a new, shallow surface layer in the upper 10 m leaves behind deeper near-inertial oscillations that persist, decaying according to the chosen damping.

Thus, accurately representing in models the impact of low wind periods with a sequence of diurnal warming events on the evolution of the SST and upper ocean may pose a number of challenges. First, the surface forcing fields would need to resolve time scales shorter than a day and to accurately capture the periods of low wind speeds when the trade winds decay. Second, the ocean model would need good vertical resolution. The diurnal layer is shallow, and accurately representing the near-inertial oscillations stemming from the changes in the magnitude of the wind stress is important to quantifying the vertical shear that mixes the heat downward. Third, we find in the Stratus mooring data that the occurrence, amplitude, and vertical structure of the near-inertial oscillations that we observed do not match those predicted by the model. Accurate representation of the interaction of the near-inertial currents with the mesoscale flow field would require a more sophisticated model.

Indeed, the current meter data from Stratus 7 show the occurrence of near-inertial oscillations through the
thermocline as well as in the surface layer. Figures 10, 13, and 14 show near-inertial oscillations below the mixed layer. At times phase propagation suggested downward propagation of near-inertial internal waves from the surface layer. However, at other times, near-inertial motion in the thermocline was observed without evident links to surface forcing events. As noted above, the eddy flow field modulates the amplitude of the near-inertial motions in the water column (Klein 2008). Instabilities in the baroclinic flow might also be the source on near-inertial motions (Lelong et al. 1999). It is possible as well that the formation of the shallow diurnal layer, which isolates the surface flow from the underlying flow field, can itself lead to inertial oscillations of the surface layer, analogous to inertial oscillations seen at night over land in the atmospheric boundary layer when surface heating and strong vertical mixing cease after sunset (Hoxit 1975). Among the remaining challenges then improving understanding of the near-inertial motions and their role in mixing the upper ocean is a significant one.

We will seek to further explore the processes that govern the near-surface structure of the ocean over the diurnal time scale and their contributions to the seasonal evolution of SST and the upper ocean. Improved observing capabilities are needed, and sustained, successful operation of current, temperature, and salinity sensors with vertical resolution of 1 m near the surface in the presence of biofouling and fishing activity remains a challenge. However, we believe better understanding of and more realistic inclusion of these processes in models are necessary to steps to improve understanding of the evolution of the upper ocean and SST.

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