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surface longwave  
radiation during  
ENSO**

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# ENSO surface longwave radiation forcing over the tropical Pacific

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## Abstract

We have studied the spatial and temporal variation of the surface longwave radiation (downwelling and net) over a 21-year period in the tropical and subtropical Pacific Ocean (40 S–40 N, 90 E–75 W). The fluxes were computed using a deterministic model for atmospheric radiation transfer, along with satellite data from the ISCCP-D2 database and reanalysis data from NCEP/NCAR (acronyms explained in main text), for the key atmospheric and surface input parameters. An excellent correlation was found between the downwelling longwave radiation (DLR) anomaly and the Niño-3.4 index time-series, over the Niño-3.4 region located in the central Pacific. A high anti-correlation was also found over the western Pacific (15–0 S, 105–130 E). There is convincing evidence that the time series of the mean downwelling longwave radiation anomaly in the western Pacific precedes that in the Niño-3.4 region by 3–4 months. Thus, the downwelling longwave radiation anomaly is a complementary index to the SST anomaly for the study of ENSO events and can be used to assess whether or not El Niño or La Niña conditions prevail. Over the Niño-3.4 region, the mean DLR anomaly values range from  $+20 \text{ Wm}^{-2}$  during El Niño episodes to  $-20 \text{ Wm}^{-2}$  during La Niña events, while over the western Pacific (15–0 S, 105–130 E) these values range from  $-15 \text{ Wm}^{-2}$  to  $+10 \text{ Wm}^{-2}$ , respectively. The long-term average (1984–2004) distribution of the net surface longwave radiation to the surface over the tropical and subtropical Pacific for the three month period November–December–January shows a net thermal cooling of the ocean surface. When El Niño conditions prevail, the thermal radiative cooling in the central and south-eastern tropical Pacific becomes weaker by  $10 \text{ Wm}^{-2}$  south of the equator in the central Pacific (7–0 S, 160–120 W) for the three-month period of NDJ, because the DLR increase is larger than the increase in surface thermal emission. In contrast, the thermal radiative cooling over Indonesia is enhanced by  $10 \text{ Wm}^{-2}$  during the early (August–September–October) El Niño phase.

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# 1 Introduction

The El Niño Southern Oscillation (ENSO) is a natural cycle that couples the ocean-atmosphere system over the tropical Pacific and operates on a timescale of 2–7 years. Once developed, it causes a shift in the seasonal temperature and precipitation patterns in many different regions of the world, since heating of the tropical atmosphere creates changes in the global atmospheric circulation. Thus, ENSO is a dominant source of inter-annual climate variability around the world. Following the early work of Bjerknes (1966, 1969) who attributed ENSO to coupled Pacific ocean-atmosphere interactions, the dynamics of this pattern of climate variability was extensively studied by many workers (e.g., Philander, 1990; McCreary and Anderson, 1991; Neelin et al., 1998). Normally, the equatorial Pacific Ocean is characterized by warm waters in the west and cold waters in the east. The ENSO warm phase (El Niño) is associated with an unusual warming of the eastern and central equatorial Pacific. La Niña, the ENSO cold phase, is the counterpart to El Niño, often following it. It is characterised by cooler than normal sea surface temperatures across the equatorial eastern Pacific. Thus ENSO is an oscillation between warm and cold events with a peak that typically occurs late in the calendar year (late December–early January). Both El Niño and La Niña events last for about a year, but they can last for as long as 18 months (see the recent review by Wang and Fiedler, 2006). Over the past two decades a large number of studies have appeared, attempting to explain the mechanism of the oscillation between the two phases of the ENSO phenomenon and many models have been proposed (e.g., Suarez and Schopf, 1988; Cane et al., 1990; Jin 1997a, b; Picaut et al., 1997; Wang et al., 1999; Wang, 2001). A recent short review summarizing theories and mechanisms about El Niño variability is given by Dijkstra (2006).

During ENSO, a feedback between atmospheric and ocean properties is observed. Sea surface temperature (SST) anomalies induce wind stress anomaly patterns that in turn produce a positive feedback on the SST. Variation of the above properties cause significant changes in other oceanic and atmospheric variables, e.g., the mean depth

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of the thermocline, the water vapour content of the atmosphere and the relative distributions of low, middle and high clouds. Water vapour and clouds are the main regulators of the radiative heating of the planet since changes in these parameters modulate the variability in the radiation fluxes that regulate the heating or cooling of the Earth's surface and atmosphere. The radiation field in turn, influences SST and atmospheric water vapour. Thus ENSO involves complex climatic processes and feedbacks that make its onset time, duration, strength and spatial structure difficult to predict (see Fedorov et al., 2003, and references therein). International monitoring programmes of the coupled atmosphere-ocean system started in the Pacific around 1985 and led to the TAO/TRITON (Tropical Atmosphere Ocean project/Triangle Trans Ocean Buoy Network) array of moored buoys. The aim of this programme is to provide real-time measurements of winds, sea surface temperature, subsurface temperature, sea level and ocean flow that help in the understanding of the physical processes responsible for ENSO (McPhaden et al., 1998).

The variability and the spatial distribution of the ocean and atmospheric variables are not the same for all ENSO events. Thus a definition of ENSO is necessary for the study of this phenomenon (Trenberth, 1997). The phase and strength of ENSO events are defined by an index. Several different indices have been used in the literature, mostly based on SST, although there is one index, the Southern Oscillation index, which is related to air pressure differences at sea level, between Darwin (Australia) in the west and Tahiti in the east. The SST based indices are obtained from the SST anomalies with respect to average values over some specified region of the ocean (see for example, Trenberth and Stepaniak, 2000; Hanley et al., 2003). There has been also an effort to combine several atmospheric-oceanic variables into a single index like the multivariate ENSO index (Wolter and Timlin, 1998). Averages of 850 mb wind, outgoing longwave radiation (OLR) at the top of the atmosphere as well as precipitation over specific regions (Curtis and Adler, 2000) are also used, although not often, to monitor ENSO.

The Earth's climate system is driven by the radiative energy balance between the so-

lar shortwave radiation (SW) absorbed by the atmosphere and the surface of the Earth and the thermal longwave radiation (LW) emitted by the Earth to space. In this respect, ENSO events are expected to be associated with the spatial and temporal variability of the radiative energy balance over the tropical and subtropical Pacific. The net heat flux into the ocean plays a key role in ENSO evolution and is a significant variable in the models that have been developed to make ENSO predictions (Dijkstra, 2006). The variation of the net heat flux during ENSO events is of paramount importance to the dynamics of the system (Harrison et al., 2002; Chou et al., 2004). The net heat flux into the ocean is a small residual of four terms, the downward shortwave radiation at the surface (DSR), the latent heat loss, the sensible heat transfer and the net longwave radiation to the Earth's surface (NSL). The NSL is the difference between the downward longwave radiation (DLR) at the Earth's surface and the Earth's surface thermal emission. The DLR at the Earth's surface is a very important component of the surface radiation budget with variations arising from increases in greenhouse gases or from changes in other atmospheric properties that occur during ENSO events (Intergovernmental Panel on Climate Change, IPCC, 2001). In this work we shall focus on the behaviour of the DLR and NSL during warm and cold ENSO events over the tropical and subtropical Pacific Ocean. The DLR depends mainly on the vertical distributions of temperature and water vapour in the lower troposphere, as well as on the cloud amounts and cloud radiative properties. We shall show that the DLR is a very useful index for the description of the phase and evolution of ENSO events.

We present DLR and NSL data generated by a deterministic radiation transfer model for the period 1984–2004 for the tropical and subtropical Pacific Ocean and examine their spatial and temporal variability during ENSO events. In addition, we investigate the correlation of DLR and NSL anomalies with the Niño 3.4 index. In Sect. 2 we describe the radiation model and the input data used. In Sect. 3, the surface longwave radiation distribution and its variation during warm and cold ENSO phases are presented. In Sect. 4, the DLR and NSL variation during ENSO evolution is examined. In Sect. 5, the correlation of the Niño 3.4 index and surface radiation parameters are pre-

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sented while in Sect. 6 a more detailed analysis of radiation parameters in the western Pacific is presented. In Sect. 7, we discuss our results and in Sect. 8 we present our conclusions. Table 1 lists the symbol definitions of the radiation parameters that are most often used in this paper.

## 2 Radiation model and data description

We use the FORTH deterministic model (Pavlaklis et al., 2004) for the radiation transfer of terrestrial infrared radiation, to compute the downward longwave radiation at the surface of the Earth (DLR). This model is based on a detailed radiative-convective model developed for climate change studies (Vardavas and Carver, 1984), but modified in order to model the longwave atmospheric radiation fluxes at the Earth's surface and at top of atmosphere (TOA), on a  $2.5^\circ \times 2.5^\circ$  grid for the entire globe.

The model DLR has a temporal resolution of one month, and a vertical resolution (from the surface up to 50 mb) of 5 mb, to ensure that the atmospheric layers are optically thin with respect to the Planck mean longwave opacity. The atmospheric molecules considered are;  $H_2O$ ,  $CO_2$ ,  $CH_4$ ,  $O_3$ , and  $N_2O$ . The sky is divided into clear and cloudy fractions. The cloudy fraction includes three non-overlapping layers of low, mid and high-level clouds. Expressions for the fluxes for clear and cloudy sky can be found in Hatzianastassiou et al. (1999). The model input data include cloud amounts (for low, mid, high-level clouds), cloud absorption optical depth, cloud-top pressure and temperature (for each cloud type), cloud geometrical thickness and vertical temperature and specific humidity profiles. For the total amount of ozone, carbon dioxide, methane, and nitrous oxide in the atmosphere, we used the same values as in Hatzianastassiou and Vardavas (2001).

All of the cloud climatological data for our radiation transfer model were taken from the International Satellite Cloud Climatology Project (ISCCP-D2) data set (Rossow and Schiffer, 1999), which provides monthly means for 72 climatological variables in 2.5-degree equal-angle grid-boxes for the period 1984–2004. The vertical distributions of

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the temperature and water vapour as well as the surface temperature, were taken from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis project (Kistler et al., 2001), corrected for topography as in Hatzianastassiou et al. (2001). These data are also on a 2.5-degree resolution, monthly averaged and cover the same 21-year period as the ISCCP-D2 data.

A full presentation and discussion of the model and DLR distribution can be found in Pavlakis et al. (2004). There, a series of sensitivity tests were performed to investigate how much uncertainty is introduced in the model DLR by uncertainties in the input parameters, such as air temperature, skin temperature, low, middle or high cloud amount as well as the cloud physical thickness, cloud overlap schemes, and the use of daily-mean instead of monthly-mean input data. The model DLR was also validated against BSRN station measurements for the entire globe (Pavlakis et al., 2004; Matsoukas et al., 2005).

### 3 Long-term surface longwave radiation

The geographical distribution of the 21-year average (1984–2004) DLR at the surface, over the tropical and subtropical Pacific Ocean (40 S–40 N, 90 E–75 W), with a spatial resolution of 2.5°(latitude)×2.5°(longitude), is shown in Fig. 1 top panel (a), for the 3-month period November, December and January (NDJ). The three month period NDJ is selected as best representing the mature phase of ENSO evolution (see Sect. 4), when the strongest changes in the DLR are observed.

The five significant El Niño events in our 21-year study period, 1984–2004, were during 1986–1987, 1991–1992, 1994–1995, 1997–1998 and 2002–2003. In the same period, the more significant La Niña events were during 1984–1985, 1988–1989, 1998–1999, 1999–2000, 2000–2001 (Trenberth, 1997; Wang and Fiedler, 2006). We have calculated, for each grid-box, the mean monthly DLR averaged over the 11 neutral years ( $DLR_{NE}$ ), i.e., the years when no significant El Niño or La Niña events occurred for the period NDJ and our results are shown in Fig. 1 top panel (b). Both the long-term

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mean DLR and the  $DLR_{NE}$  for NDJ show similar spatial patterns. As expected, the maxima in DLR, reaching about  $430 \text{ Wm}^{-2}$ , occur over the western Pacific, where the Western Pacific Warm Pool is located. The highest open ocean water temperatures on Earth are observed there. Because of these high temperatures, the atmosphere is supplied with large amounts of water vapour, the most important greenhouse gas, resulting in high DLR values.

We also computed, for each grid-box, the average DLR over the five years<sup>1</sup> when El Niño ( $DLR_{EN}$ ) conditions prevailed (Fig. 1, bottom panel c) and the corresponding average DLR over the five years when La Niña ( $DLR_{LN}$ ) conditions prevailed (Fig. 1, bottom panel d), for the three month period of NDJ. It is evident from these figures that high values of DLR are observed over much more extended areas of the central and eastern Pacific, during the El Niño years compared to the La Niña average.

In Fig. 2, top panel (a) we show the geographical distribution of the 21-year average (1984–2004) net surface longwave radiation (NSL) for NDJ. In the same figure (top panel b), we show the corresponding distribution of the NSL averaged over the 11 neutral years ( $NSL_{NE}$ ), for the three month period NDJ. The NSL is defined as  $NSL = DLR - \varepsilon\sigma T^4$ , where  $\varepsilon\sigma T^4$  is the surface longwave emission,  $\varepsilon$  is the ocean surface emissivity taken to be 0.95 and T is the SST. The NSL and  $NSL_{NE}$  show similar values over the tropical and subtropical Pacific. Clearly, NSL is negative over most of the region. The highest negative values, reaching  $40\text{--}45 \text{ Wm}^{-2}$ , occur in the central and south-eastern Pacific.

In Fig. 2 are shown the average NSL over the five years when El Niño ( $NSL_{EN}$ ) conditions prevailed for NDJ (bottom panel c), and the corresponding average NSL over the five years when La Niña ( $NSL_{LN}$ ) conditions prevailed (bottom panel d). It is clear from these figures that when El Niño conditions prevail, the thermal radiative cooling in the central and south-eastern tropical Pacific becomes weaker.

During ENSO warm (El Niño) or cold (La Niña) phases, the equatorial Pacific warms

<sup>1</sup>An “El Niño year” is defined, for our purposes, as starting in July and ending in June of the next year.

or cools, respectively, by as much as 3°C. This warming or cooling of the Pacific ocean is accompanied by significant changes in DLR and NSL, as shown in Figs. 1 and 2, indicating a significant change in the longwave radiation budget of the region.

In Fig. 3a we show the distribution of the difference  $DLR_{EN}-DLR_{LN}$ , over the tropical and subtropical Pacific. This difference will be referred to as the El Niño DLR anomaly ( $DLR-A_{LN}$ ) with respect to La Niña DLR. In the same figure, the rectangles designate the regions most commonly used to define El Niño indices, based on sea surface temperature, for monitoring and identifying El Niño and La Niña events (Hanley et al. 2003). The Niño-1+2 region, (0–10 S, 80–90 W) is the region that warms first in most El Niños, especially before 1976. For some time, the Niño-3 region (5 S–5 N, 150–90 W) was used for the monitoring of El Niño, but in recent years the Niño-3.4 region (5 S–5 N, 170–120 W), somewhat further to the west of the Niño-3 region is used widely as a region with high SST anomalies and with a proximity with the main deep-convection centers during ENSO events. As can be seen in Fig. 3a the  $DLR-A_{LN}$  obtains the highest values, reaching a maximum of about  $+30 \text{ Wm}^{-2}$ , in a broad swath in the Central Pacific extending to the coast of South America. This region almost coincides with Niño-3.4. In the western Pacific, on the other hand, the sign of the  $DLR-A_{LN}$  is reversed, with the  $DLR_{EN}$  being lower by  $5-10 \text{ Wm}^{-2}$  than  $DLR_{LN}$ .

In Fig. 3b we also show the corresponding El Niño NSL anomaly with respect to La Niña years ( $NSL-A_{LN}$ ). It is evident, the  $NSL-A_{LN}$  values are much lower than the  $DLR-A_{LN}$  values, ranging between about  $-10 \text{ Wm}^{-2}$  and  $+15 \text{ Wm}^{-2}$ . The highest values of  $NSL-A_{LN}$  appear south of Niño-3 and Niño-3.4 regions. Generally, a net thermal radiative heating of the central and eastern Pacific occurs during El Niño with respect to the La Niña years, and a net cooling of the western Pacific, that includes Indonesia and Northern Australia.

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## 4 DLR variation during ENSO evolution

In this Section, we investigate the evolution of ENSO related changes in the distribution and values of DLR over the tropical and subtropical Pacific.

First, we investigate the evolution of each El Niño or La Niña event, in the representative Niño-3.4 region, in order to define the time-span of the early and mature phases of the phenomenon with respect to DLR. We thus calculate the mean monthly DLR in the Niño-3.4 region averaged over the 11 neutral years ( $DLR_{NE}^{[3,4]}$ ), i.e., the years when no significant El Niño or La Niña events occurred. We then defined the parameter  $\Delta(DLR)_{3,4} = DLR_{EN}^{[3,4]} - DLR_{NE}^{[3,4]}$ , which gives the difference between the mean monthly DLR in the Niño-3.4 region ( $DLR_{EN}^{[3,4]}$ ) for each El Niño event and the average neutral year DLR ( $DLR_{NE}^{[3,4]}$ ) for the same month.

In Fig. 4a, we show the time evolution of  $\Delta(DLR)_{3,4}$  for each El Niño event. The same procedure is followed for the La Niña events, and the corresponding plots for the individual La Niñas are shown in Fig. 4b. In order to facilitate the interpretation of these figures and to show clearly the beginning and end of an event, we present 24-month time-series.

It is evident from Fig. 4 that the maximum DLR change during warm (El Niño) or cold (La Niña) ENSO events occurs between November and January, except for the 1986–1987 El Niño, which displays a double peak behaviour (see also Wang and Fiedler, 2006), with a second maximum around August 1987. Usually the highest value of  $\Delta(DLR)_{3,4}$  occurs within the 3-month period from November to January. Consequently, in our subsequent analysis we use the three month period of November, December and January (NDJ) to study the mature phase of El Niño or La Niña events and August, September and October (ASO) for the earlier stages of ENSO development. Thus, in spite of the significant differences in the onset and evolution of individual ENSO events, the NDJ and ASO periods provide a frame of reference for studying in broad terms the evolution of ENSO.

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## 4.1 El Niño events

We now define the difference  $\text{DLR}_{EN} - \text{DLR}_{NE}$ , as the El Niño DLR anomaly with respect to the neutral years (El Niño  $\text{DLR} - A_{NE}$ ). This quantity gives the change in DLR during El Niño years with respect to neutral years. In Fig. 5 we show the El Niño  $\text{DLR} - A_{NE}$  for the three month periods of ASO and NDJ (top panel).

The El Niño  $\text{DLR} - A_{NE}$  during the early stage of El Niño development is around  $+10 \text{ Wm}^{-2}$  in the central Pacific and  $-10 \text{ Wm}^{-2}$  over Indonesia and Northern Australia. During the mature phase of El Niño, the region where significant El Niño  $\text{DLR} - A_{NE}$  is observed extends from the central Pacific to the coast of Peru, while the values of the anomaly reach about  $+20 \text{ Wm}^{-2}$ .

In order to investigate and identify the regions that show significant changes in the DLR during El Niño years with respect to the DLR variability during neutral years, (significant El Niño DLR anomalies,  $\text{DLR} - A_{NE}$ ), we calculated for each grid-box the standard deviation ( $\sigma_{NE}$ ) of the 11  $\text{DLR}_{NE}$  values (corresponding to the 11 neutral years) around their mean, for the two representative 3-month periods of ASO and NDJ. The ratio  $R_{NE}$  of the El Niño  $\text{DLR} - A_{NE}$  to  $\sigma_{NE}$  provides a measure of the statistical significance of the anomaly values. In the middle panel of Fig. 5 we show the geographical distribution of  $R_{NE}$  for the ASO (c) and NDJ (d). Values of  $R_{NE}$  larger than 2 are considered to be statistically significant. During the mature phase of ENSO, the statistical significance of the anomalies is very high over the Niño-3.4 (the highest value of  $R_{NE} \sim 3.5$  is observed in this region) and Niño-1+2 regions (values of  $R_{NE} \sim 1.5$ ) but there is no significant DLR signal in the western Pacific. On the other hand, during the early phase (ASO), the anomalies appear to be significant over a region in the western Pacific, over Indonesia and Western Java (highest value of  $R_{NE} \sim 2.5$ ). The DLR change in this region precedes the appearance of significant anomalies in the Niño-3.4 region. This will be further discussed in Sect. 6.

During different ENSO events, the geographical distribution of the DLR anomalies can vary significantly. We have thus attempted to identify the regions that show sig-

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nificant changes for all of the events studied. For this purpose, we defined the ratio  $R_{EN}$  of the El Niño DLR- $A_{NE}$  anomaly over  $\sigma_{EN}$ , where  $\sigma_{EN}$  is the standard deviation of the 5 DLR $_{EN}$  values (corresponding to the 5 El Niño years) around their mean. High values of  $R_{EN}$  indicate that significant El Niño related DLR anomalies always occur in the particular grid-box during warm ENSO phases. The geographical distribution of  $R_{EN}$  is given in the bottom panel of Fig. 5. According to this figure, there are two areas that always show significant DLR modification during the mature warm phase of ENSO: a sub-region of Niño-3.4, i.e. 5 N–5 S, 160–140 W and a second region in the eastern Pacific between 0–10 S and 105–90 W. In both regions we observe values of  $R_{EN}$  higher than 4. During the early phase (ASO), the region over Indonesia and western Java show significant changes for all events studied.

A similar analysis was conducted for the El Niño NSL anomalies (not shown here). The various parameters are defined in the same way as above but for NSL. The El Niño NSL- $A_{NE}$  during the early stages (ASO period) of El Niño development has a minimum value of about  $-10 \text{ Wm}^{-2}$  over Indonesia and Northern Australia with  $R_{NE} \sim 1.5$ . In contrast, over the central Pacific the signal is not significant. During the mature phase of El Niño (NDJ period), the NSL- $A_{NE}$  is around  $+10 \text{ Wm}^{-2}$  south of the equator in the central Pacific (7–0 S, 160–120 W) with  $R_{NE} \sim 2$ .

## 4.2 La Niña events

A similar analysis was conducted for the DLR anomalies during La Niña events. The various parameters are defined in the same way as in Sect. 4.1, but for the La Niña years. Instead of the suffix EN (El Niño), we use here the suffix LN (La Niña). The resulting geographical distribution of the La Niña DLR anomalies (DLR- $A_{NE}$ ), with respect to neutral years, is shown in the top panel of Fig. 6a for ASO and (b) for NDJ. Large negative values (i.e., lower DLR for the La Niña years) of about  $-20 \text{ Wm}^{-2}$  are observed in the central Pacific, in the region 2.5 S–2.5 N, 180–150 W. In the middle panel of Fig. 6 we present the geographical distribution of  $R_{NE}$  (the ratio of the La Niña DLR- $A_{NE}$  over the standard deviation around the mean of the DLR $_{NE}$ ), which confirms

that the region in the Central Pacific indicated above, displays statistically significant anomalies during the ENSO cold phase for both early phase ASO, and mature phase NDJ with values of  $R_{NE} \sim 2.5$ . In the bottom panel of Fig. 6, we identify the regions that show significant anomalies during all of the La Niña events studied. As can be seen, only part of the previously defined area, shows significant anomalies in all five La Niñas.

## 5 Correlation of Niño-3.4 index and DLR anomaly

The Niño-3.4 index based on sea surface temperature (SST) is used extensively in recent years for identifying El Niño or La Niña events. This index is defined as the three-month smoothed SST departures from normal SST, in the Niño-3.4 region in the equatorial Pacific. For the same region (Niño-3.4), we have calculated the 3-month smoothed anomaly of the mean monthly DLR at the surface with respect to the average monthly DLR for the whole study period 1984–2004. This parameter will be denoted by DLR-A[3.4] and will be called “DLR-A[3.4] index”.

Figure 7a shows the time-series of the DLR-A[3.4] index for the period 1984–2004 (black line). For comparison we have overlaid on the same diagram the time-series of the Niño-3.4 SST index (red line). The agreement between the two time-series is excellent. In both time-series there are clear peaks during El Niño events and minima for the La Niña events. Moreover, the relative strengths of warm and cold ENSO events are very similar. DLR-A[3.4] reaches values as high as  $+20 \text{ Wm}^{-2}$  (during the strong 97–98 El Niño), and as low as  $-20 \text{ Wm}^{-2}$  (during the La Niña of 2000–2001).

Figure 7b shows the corresponding time-series of the 3-month smoothed anomaly (NSL-A[3.4]) of the mean monthly NSL with respect to the average monthly NSL for the whole study period 1984–2004 in the Niño-3.4 region. The NSL-A[3.4] shows lower variability than the DLR-A[3.4] but this is at least partly due to the fact that the region of the most significant NSL changes during the ENSO lies to the south of the Niño-3.4 region (see Fig. 3b).

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Linear regression between DLR-A[3.4] and the Niño-3.4 index yielded a correlation coefficient of  $r=0.91$  and a slope of  $7.7\pm 0.2 \text{ Wm}^{-2}/^{\circ}\text{C}$ , as shown in Fig. 8a. The corresponding plot for NSL-A[3.4] vs the Niño-3.4 index is shown in Fig. 8b. The correlation coefficient is 0.51 and the slope equals  $2.0\pm 0.2 \text{ Wm}^{-2}/^{\circ}\text{C}$ . These values show that during El Niño conditions in the Niño-3.4 region, the DLR increases at a higher rate than the longwave emission from the surface due to the increase in the sea surface temperature. Thus the NSL in the Niño-3.4 region increases during the warm phase of ENSO by roughly  $2 \text{ Wm}^{-2}$  for a 1 degree increase in SST.

In Fig. 9a we show the geographical distribution of the correlation coefficient given by linear regression of the time-series of DLR-A in each  $2.5\times 2.5$  degree grid-box and the Niño-3.4 index time-series. The maximum values of the correlation coefficient are observed, expectedly, in the Niño-3.4 region itself although there are values higher than 0.5 all over the central and eastern Pacific. In the western Pacific there is an anti-correlation between the DLR-A and Niño-3.4 index time-series, although in absolute terms the correlation coefficients are not as high as in the eastern Pacific.

In Fig. 9b, we also show the distribution of the correlation coefficient given by linear regression of the time-series of NSL-A in each  $2.5\times 2.5$  degree grid-box and the Niño-3.4 index time-series. The maximum values of the correlation coefficient here do not exceed 0.7 and they are observed over a smaller region, to the south of the Niño-3.4 region, at (0–10 S, 160–140 W).

### 6 Time lag between western and eastern Pacific DLR anomalies

There is a region in the western Pacific (over Indonesia and Western Java) which displays significant anomalies during the early phase (ASO) of ENSO development. The DLR anomalies in this region seem to precede the appearance of significant anomalies in the Niño-3.4 region. In order to further investigate this, we have produced correlation coefficients for each  $2.5\times 2.5$  pixel, between the time-series of the DLR-A in each pixel and the time-series of the DLR-A[3.4] index, after introducing in the latter a time shift of

−1, −2, . . . , −8 months. We constructed geographical distributions of the correlation coefficients, and compared them against the map with zero time lag (Fig. 9a). In all cases but one, the correlation deteriorated over the entire area. The one exception is shown in the map of the 3-month shift (Fig. 10a). There is a region in the western Pacific, north of Australia, indicated by a rectangle (0–15 S, 105–130 E), where the (anti)correlation improves, and takes its highest absolute value when the time-series of the DLR-A[3.4] index is shifted by −3 months. The maximum value of the correlation coefficient increases in absolute value from 0.42 with no time shift, to 0.57 with a 3-month time shift.

We have, subsequently, calculated the correlation coefficient between the average DLR-A in the western Pacific rectangle shown in Fig. 10a and the DLR-A[3.4] index shifted by 0, −1, . . . , −8 months. In Fig. 10b we have plotted the value of this correlation coefficient (the values are negative, because the two DLR anomalies are anti-correlated) as a function of the time lag introduced (in months). It is again obvious that highest anti-correlation is observed when the DLR-A[3.4] index time-series is shifted by −3 to −4 months. This means that DLR anomalies in the western Pacific rectangle precede the anomalies in the Niño-3.4 region by 3-4 months. The significance of the western Pacific for initializing El Niño has already been noted by Wang (2002) who found that the 850-mb zonal wind anomalies in the western Pacific region with coordinates 5 S–5 N, 120–170 E lead the Niño-3 SST anomalies by 4 months (note the overlap of our west Pacific region with that of Wang, 2002).

In Fig. 11a, we show the mean DLR-A time-series in the western Pacific rectangle (black line). For comparison we have overlaid on the same diagram the DLR-A[3.4] index time-series (red line). It is clear that the DLR-A in the western Pacific shows a deep before the peak of the DLR-A[3.4] index for each El Niño. The minimum value of the DLR-A in the western Pacific is about  $-15 \text{ Wm}^{-2}$  before the intense 1997–1998 El Niño.

In Fig. 11b, we also show the mean NSL-A time-series in our western Pacific rectangle (black line) and the DLR-A[3.4] index time-series (red line). The behaviour of

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the NSL-A time-series in the western Pacific rectangle is very similar to that of DLR-A, although the variability is much lower.

## 7 Effects of total precipitable water and cloud amount variability on DLR during ENSO

5 The air temperature as well as the water vapour content of the atmosphere, especially of the lower atmospheric layer, play the most important role in determining the DLR reaching the Earth's surface, followed in order of significance by the cloud amount of low, middle and high cloud, respectively (Pavlakis et al., 2004).

10 The time-series of the anomaly of the mean monthly DLR in the Niño-3.4 region (DLR-A [3.4] index) with respect to the average monthly DLR for the entire study period 1984–2004, shows an excellent correlation with the Niño-3.4 index. This is due to the fact that the Niño-3.4 index is based on sea surface temperature (SST) which is linked to the water vapour content of the atmosphere. We calculated the anomaly of the mean monthly total column water vapour with respect to the average monthly total column water vapour from the NCEP/NCAR database for the whole study period 1984–2004 in the Niño-3.4 region (Total water–A[3.4]). Linear regression between the Total water–A[3.4] and the Niño-3.4 index yielded a correlation coefficient of 0.84 and a slope of  $0.31 \pm 0.01 \text{ gcm}^{-2}/^{\circ}\text{C}$ , as shown in Fig. 12a.

20 We also calculated the anomaly of the mean monthly low, middle and high-level cloud amount with respect to the corresponding values, for the whole study period 1984–2004 in the Niño-3.4 region. We then created scatter plots between these anomalies and the Niño-3.4 index. We found no correlation between the low cloud amount anomaly and the Niño-3.4 index (correlation coefficient  $r=0.1$ ). Linear regression between the middle and high cloud amount anomalies and the Niño-3.4 index yielded a correlation coefficient of 0.83 and 0.77, respectively. In Fig. 12b we show, as an example, the scatter plot of the middle cloud amount anomaly ( $CA_{\text{mid}}-A[3.4]$ ) versus the Niño-3.4 index. However, in the tropics the middle and high clouds only marginally influ-

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ence the DLR owing to the high moisture in the lower part of the atmosphere (Tian and Ramanathan, 2002). This is verified by inspection of the scatter plot between  $CA_{\text{mid}} - A[3.4]$  and Niño-3.4 index (Fig. 12b). The slope in the scatter plot becomes steeper for values of Niño-3.4 index greater than  $1.5^{\circ}\text{C}$ . The same is true for the scatter plot between high cloud amount anomaly and Niño-3.4 index (not shown here). The steeper slope in these scatter plots is indicative of the onset of deep convection in the region (Ramanathan and Collins, 1991). The onset of deep convection however does not change the rate of increase of the DLR- $A[3.4]$  for SST anomalies greater than  $1.5^{\circ}\text{C}$ . In contrast other radiation variables crucial for the development of an ENSO event such as the downward shortwave radiation (DSR) at the surface or the longwave radiation absorbed by the atmosphere in the Niño-3.4 region are affected by the onset of deep convection.

The time-series of the mean monthly DLR anomaly (DLR-A) in the region north of Australia ( $15\text{ S}-0\text{ S}$ ,  $105\text{ E}-130\text{ E}$ ), exhibits an anti-correlation with the DLR-A  $[3.4]$  time-series and precedes it by 3–4 months. We have found that only the time-series of total water vapour anomaly (Total water-A) leads the DLR-A  $[3.4]$  time-series by 3-4 months in contrast with the time-series of the other parameters that influence the DLR.

## 8 Conclusions

To summarize, our model calculations, which are based on ISCCP-D2 cloud climatologies, and temperature and humidity profile information from NCEP/NCAR reanalysis, show a high variability in the downward longwave radiation (DLR) at the surface of the Earth and the net surface longwave radiation (NSL) over the tropical and subtropical Pacific Ocean during ENSO events. We have found that the enhancement of DLR during warm ENSO phases, compared with neutral years, is not confined to the Niño-3.4 region but extends over a much broader area in the central and eastern Pacific. This enhancement of DLR (DLR- $A_{NE}$ ), for the tree month period NDJ, is more than  $+10\text{ Wm}^{-2}$ , in a broad swath in the central Pacific extending to the coast of South America. A max-

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imum DLR- $A_{NE}$ , of about  $25 \text{ Wm}^{-2}$ , is observed within the Niño-3.4 region.

During the cold phases of ENSO, values of DLR- $A_{NE}$  less than  $-10 \text{ Wm}^{-2}$  are observed in a small sub-region of the Niño-3.4 region (5–5 N, 180–150 W), for both ASO and NDJ periods. Minimum values of DLR- $A_{NE}$ , of about  $-20 \text{ Wm}^{-2}$ , are observed in the central Pacific near the dateline and within the Niño-3.4 region for the NDJ period, but in a more confined region compared with the corresponding values during the ENSO warm phases.

The absolute value of NSL shows less variability compared with DLR. The highest values of the enhancement of NSL during warm ENSO phases compared with cold ENSO phases, appear south of the Niño-3 and Niño-3.4 regions and are about  $15 \text{ Wm}^{-2}$ .

The Niño-3.4 index is very often used to define the phase and strength of ENSO events. We calculated the correlation coefficient given by linear regression of the time-series of the monthly DLR anomaly, referenced to the whole study period 1984–2004, in each  $2.5 \times 2.5$  degree grid-box and the Niño-3.4 index, and found values higher than 0.5 over the central and eastern tropical Pacific. Values higher than 0.85 are observed in the Niño-3.4 region. Thus, the average DLR anomaly in the Niño-3.4 region (DLR-A [3.4] index), is a very useful index to describe and study ENSO events and can be used to assess whether or not El Niño or La Niña conditions prevail. It is important to note that DLR is an easily measurable quantity using a pyrgeometer and contains information both for oceanic (i.e., SST) and atmospheric (i.e., water vapour) processes.

We further investigated the DLR anomaly time-series in the western Pacific using the DLR-A [3.4] index time-series as our reference. We found a significant anti-correlation between the two time-series over the ocean north of Australia up to the equator. There is a region in the western Pacific over Indonesia and western Java (15–0 S, 105–130 E) where the DLR anomaly leads the corresponding anomaly in the Niño-3.4 region by 3–4 months. Thus, DLR measurements in this region will be very useful for the study of the time evolution of El Niño events.

*Acknowledgements.* The ISCCP-D2 data were obtained from the NASA Langley Research 12912

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Center (LaRC) Atmospheric Sciences Data Center (ASDC). The NCEP/NCAR Global Reanalysis Project data were obtained from the National Oceanic and Atmospheric Administration (NOAA) Cooperative Institute for Research in Environmental Sciences (CIRES) Climate Diagnostics Center, Boulder, Colorado, USA.

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**Table 1.** Definition of symbols representing radiation parameters used throughout this paper.

Symbol	Definition
DLR	Downward longwave radiation at surface
NSL	Net longwave radiation into the surface defined as $\text{DLR} - \varepsilon\sigma T^4$ where the second term is the surface longwave emission
$\text{DLR}_{EN}$ , $\text{DLR}_{LN}$ , $\text{DLR}_{NE}$	Mean DLR when El Niño, La Niña, or neutral conditions prevail respectively
$\text{NSL}_{EN}$ , $\text{NSL}_{LN}$ , $\text{NSL}_{NE}$	Mean NSL when El Niño, La Niña, or neutral conditions prevail respectively
$\text{DLR-A}_{LN}$	El Niño DLR anomaly with respect to the mean DLR for the La Niña years equal to $\text{DLR}_{EN} - \text{DLR}_{LN}$
El Niño $\text{DLR-A}_{NE}$ , La Niña $\text{DLR-A}_{NE}$	Difference of the mean DLR of the El Niño or La Niña years, with respect to mean DLR for the neutral years defined as $\text{DLR}_{EN} - \text{DLR}_{NE}$ and $\text{DLR}_{LN} - \text{DLR}_{NE}$ respectively
$\text{DLR-A}_{NE}$	DLR anomaly with respect to all years DLR
$R_{NE}$	Ratio of El Niño $\text{DLR-A}_{NE}$ to the standard deviation of the $\text{DLR}_{NE}$
$R_{EN}$	Ratio of El Niño $\text{DLR-A}_{NE}$ to the standard deviation of the $\text{DLR}_{EN}$
$R_{LN}$	Ratio of La Niña $\text{DLR-A}_{NE}$ to the standard deviation of the $\text{DLR}_{LN}$

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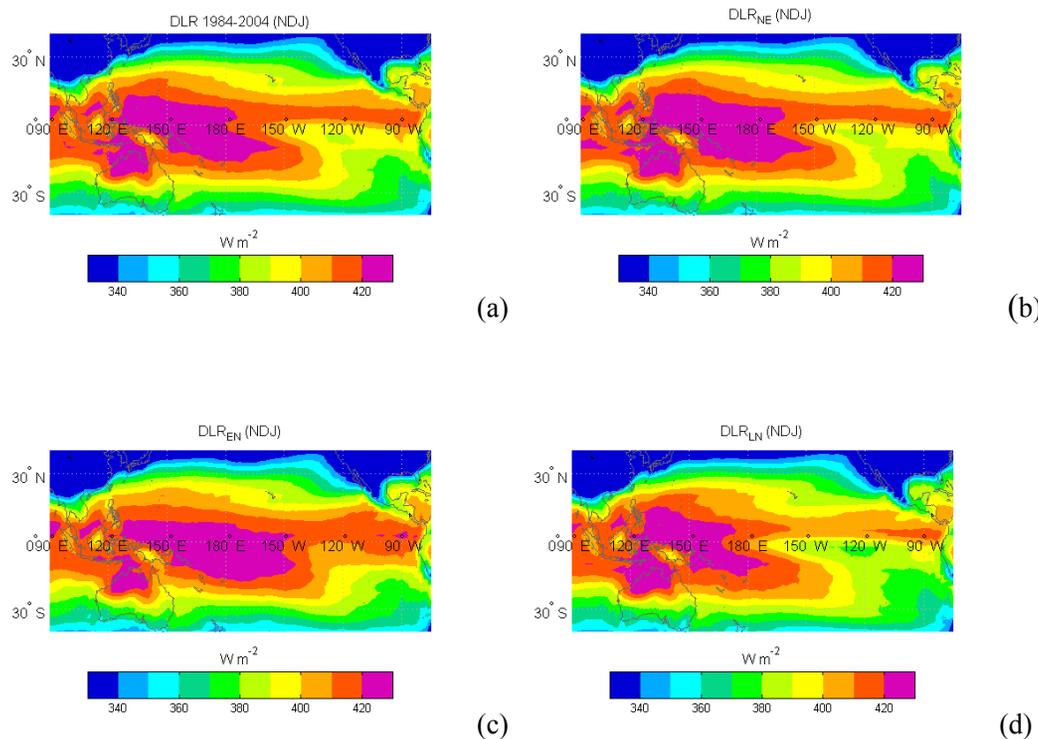
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**Fig. 1.** The distribution of downward longwave radiation (DLR), over tropical and subtropical Pacific for the three month period November, December, January (NDJ); **(a)** long-term average (1984–2004), **(b)** average for eleven neutral (non-ENSO) years, **(c)** average for five El Niño years, **(d)** average for five La Niña years.

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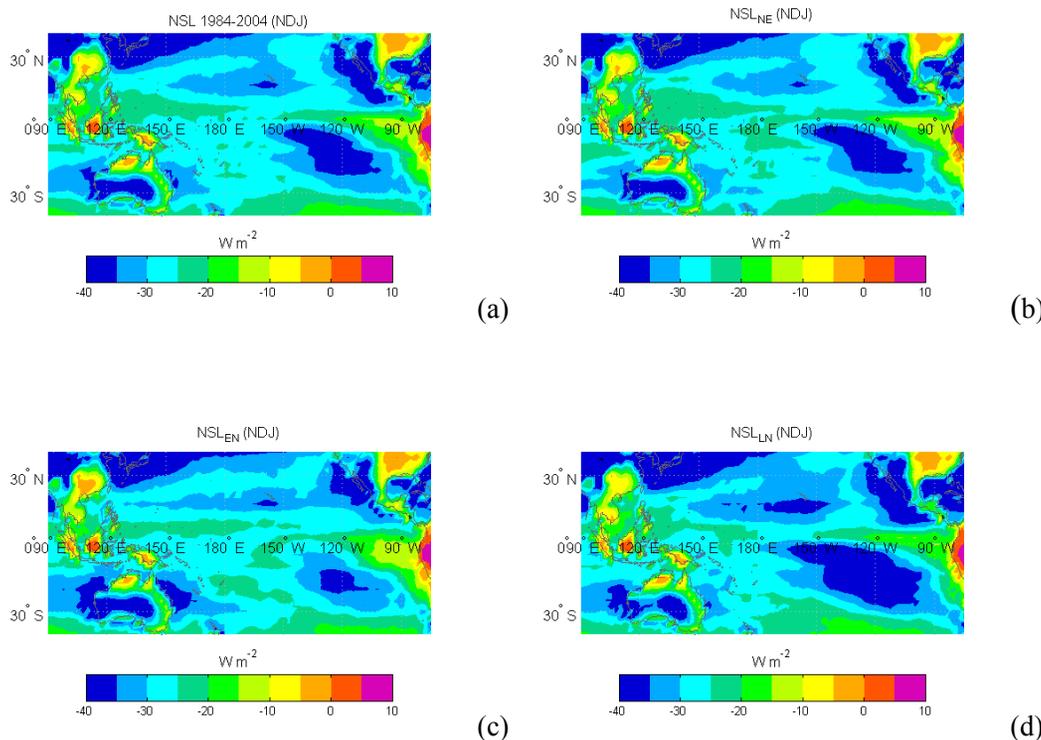
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**Fig. 2.** The distribution of net surface longwave radiation (NSL), over tropical and subtropical Pacific for the three month period November, December, January (NDJ); **(a)** long-term average (1984–2004), **(b)** average for eleven neutral (non-ENSO) years, **(c)** average for five El Niño years, **(d)** average for five La Niña years.

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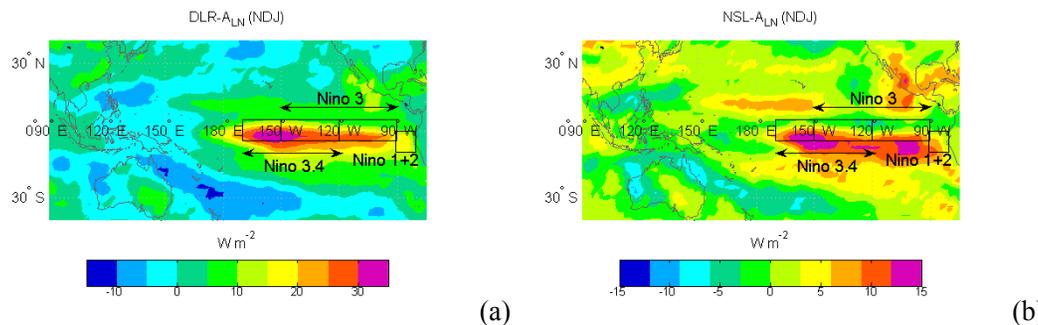
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**Fig. 3.** (a) Differences in the mean downward longwave radiation (DLR), between the El Niño and La Niña years, over tropical and subtropical Pacific for the period of November, December and January (NDJ), (b) The same but for NSL.

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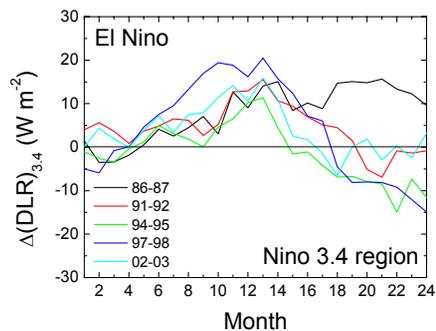
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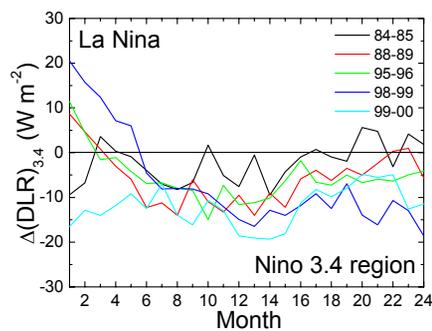
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(a)



(b)

**Fig. 4.** DLR differences between the warm ENSO phase and neutral years; **(a)** in the Niño-3.4 region (5S–5N, 170–120W) from January of each ENSO development to December of the following year, **(b)** the same but for the cold ENSO phase.

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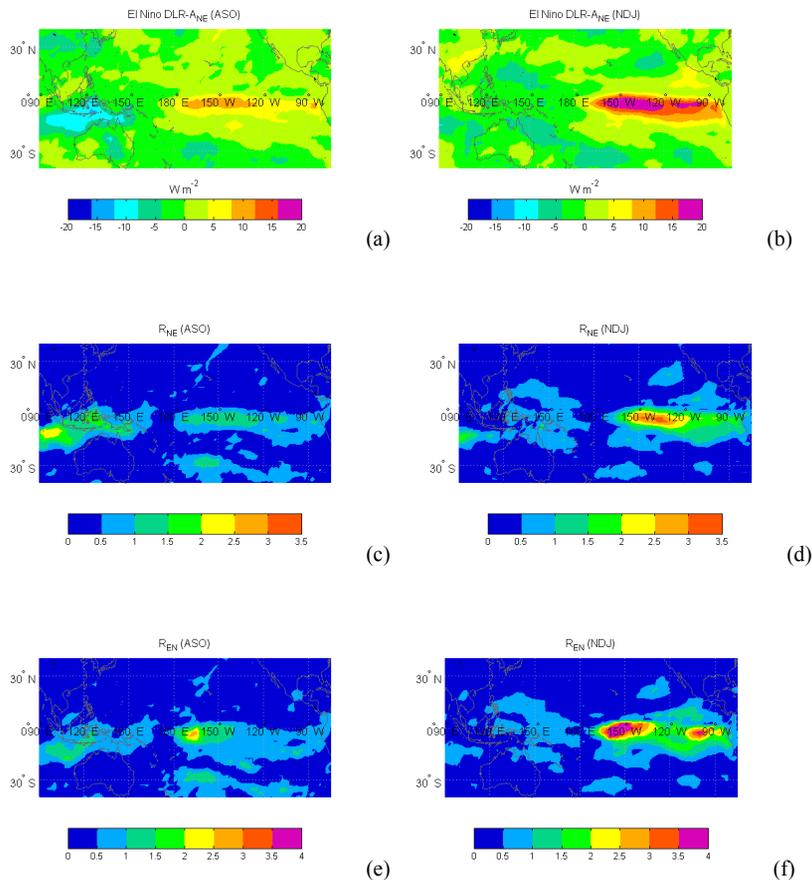
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**Fig. 5.** Top Panel: The distribution at  $2.5 \times 2.5$  spatial resolution of El Niño  $DLR-A_{NE}$  for ASO and NDJ. Middle panel: The distribution of the ratio ( $R_{NE}$ ) of the El Niño  $DLR-A_{NE}$  to the standard deviation of  $DLR_{NE}$ . Bottom Panel: The distribution of the ratio ( $R_{EN}$ ) of the El Niño  $DLR-A_{NE}$  over the standard deviation of the  $DLR_{EN}$ .

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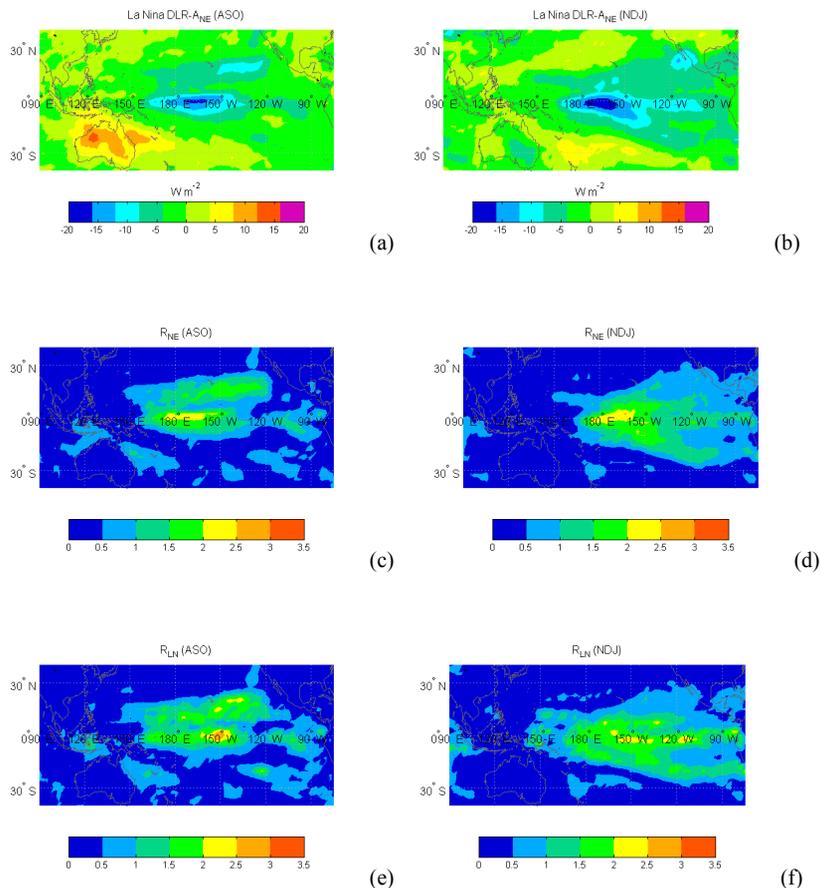
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**Fig. 6.** Top Panel: The distribution at  $2.5 \times 2.5$  spatial resolution of La Niña  $DLR-A_{NE}$  for ASO and NDJ. Middle panel: The distribution of the ratio ( $R_{NE}$ ) of the La Niña  $DLR-A_{NE}$  to the standard deviation of  $DLR_{NE}$ . Bottom Panel: The distribution of the ratio ( $R_{EN}$ ) of the La Niña  $DLR-A_{NE}$  over the standard deviation of the  $DLR_{EN}$ .

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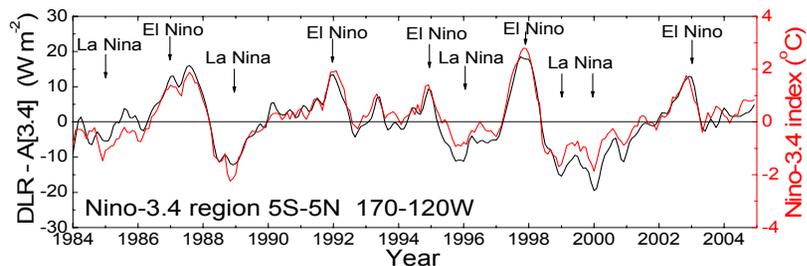
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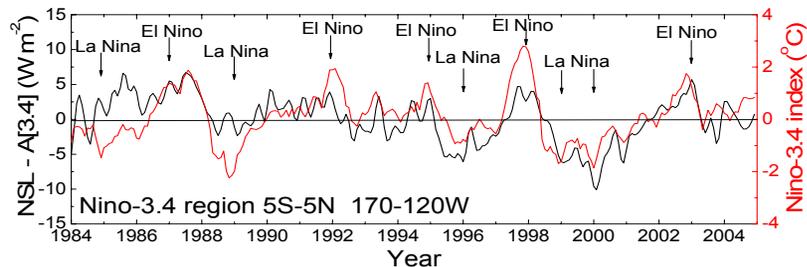
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(a)



(b)

**Fig. 7.** Time-series of downward longwave radiation (DLR-A[3.4]), and net surface longwave radiation (NSL-A[3.4]) anomaly (defined with respect to the average monthly DLR for the whole study period 1984–2004) in the Niño-3.4 region (black line). Overlaid is the time-series of the Niño-3.4 index (red line).

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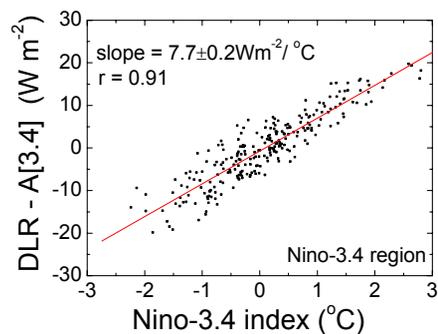
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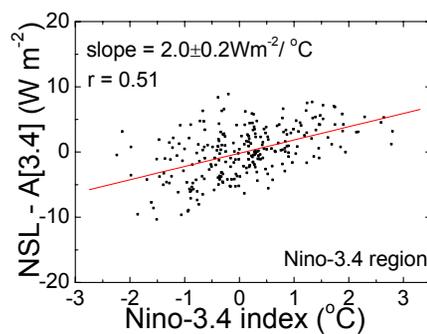
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(a)



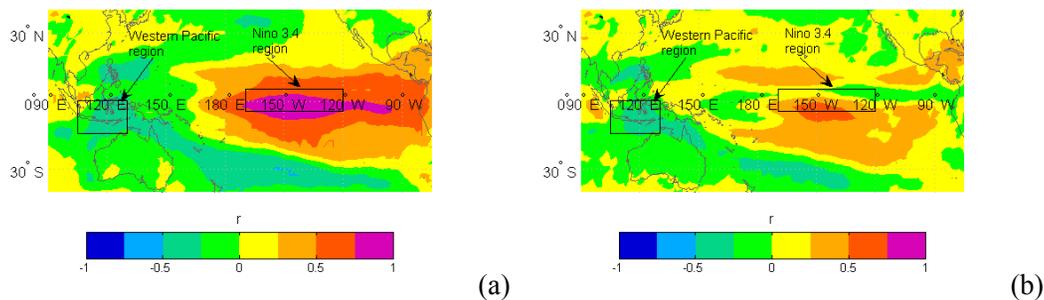
(b)

**Fig. 8.** (a) Scatter plot between the DLR-A[3.4] and the Niño-3.4 index, (b) between the NSL-A[3.4] and the Niño-3.4 index.

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**Fig. 9.** (a) Geographical distribution of correlation coefficient between the DLR-A and the Niño-3.4 index, (b) between NSL-A and Niño-3.4 index.

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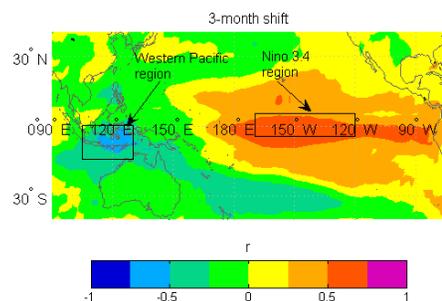
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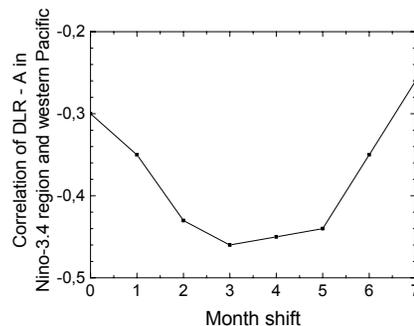
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(a)



(b)

**Fig. 10.** (a) Geographical distribution of correlation between the DLR-A and the DLR-A[3.4] in the Niño-3.4 region with a 3-month shift, (b) correlation coefficient of the DLR-A in the western Pacific and the DLR-A[3.4] as a function of the number of months shift of the DLR-A[3.4].

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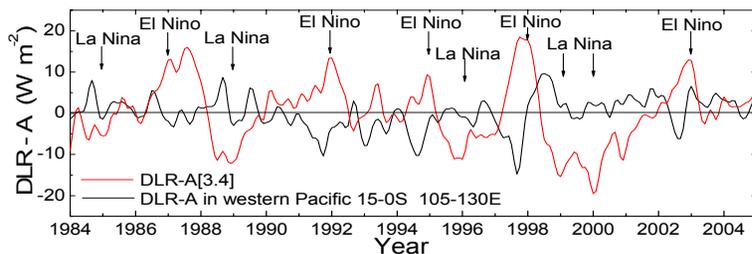
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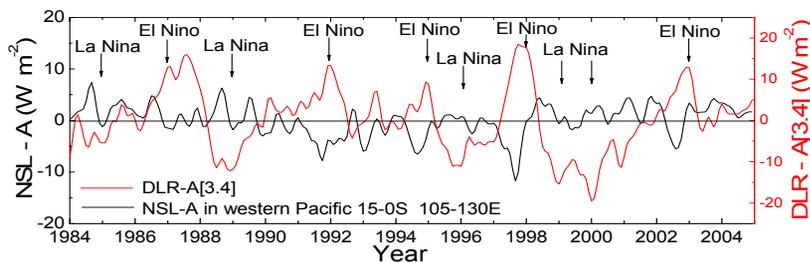
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(a)



(b)

**Fig. 11.** Downward longwave radiation (DLR), and net surface longwave radiation (NSL) anomaly time series in the western Pacific region 15 S–15 N, 120–140 E (black line) compared with DLR anomaly in Niño-3.4 region (red line).

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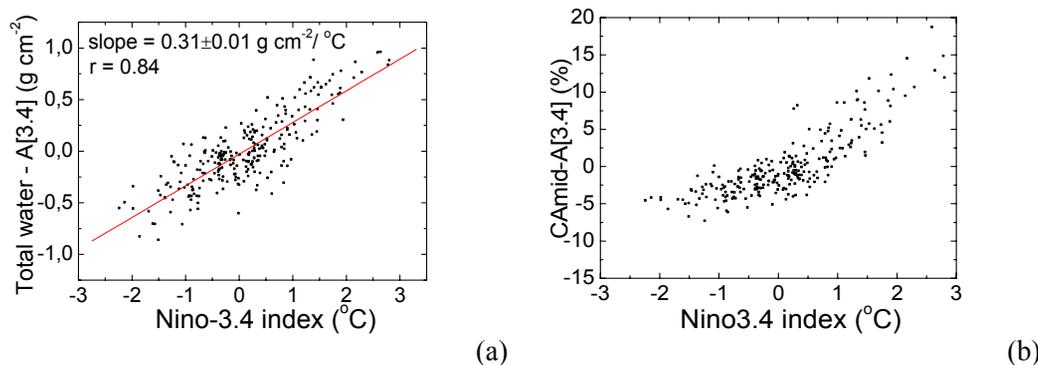
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**Fig. 12.** (a) Scatter plot between the total column water vapour in the Niño-3.4 region and the Niño-3.4 index, (b) scatter plot between the middle cloud amount in the Niño-3.4 region and the Niño-3.4 index.

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