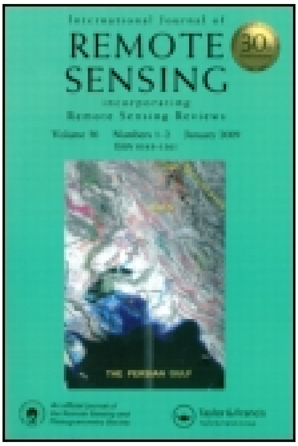

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Interannual variability of cirrus clouds in the tropics in El Niño Southern Oscillation (ENSO) regions based on International Satellite Cloud Climatology Project (ISCCP) satellite data

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The percentage of the interannual variance of cirrus clouds, explained by the variability of the El Niño Southern Oscillation (ENSO), the Quasi-biennial Oscillation (QBO) and solar activity over the tropics, is presented in this article. Analysis is focused on the eastern and western tropical Pacific Ocean, which is strongly affected by the ENSO. It is shown that over the eastern tropical Pacific Ocean, the amplitude of the ENSO in cirrus-cloud cover (CCC) is about 8.0%. The amplitude of the annual cycle is about 0.8% and the amplitudes of the QBO, solar cycle and long-term trends are the order of 1.0%, 0.1% and 0.3%, respectively. Using as an index of convective activity in the upper troposphere the vertical velocities at 300 hPa, we have calculated a vertical velocity related to cloud component. It is shown that the total contribution, from all related cloud components examined explains about 65% of the variance in cirrus clouds over the eastern Pacific and about 50% of the variance in cirrus clouds over its western part.

1. Introduction

Large-scale natural fluctuations, such as the El Niño Southern Oscillation (ENSO), alter the distribution of large-scale weather patterns and affect the variability of various atmospheric parameters such as temperature, pressure and precipitation. The ENSO is a natural oscillation of the ocean–atmosphere system in the tropical Pacific Ocean with important consequences for weather around the World. Its impact, however, on the natural variability of cirrus clouds has been less investigated, and much less is known on the relationship between Quasi-biennial Oscillation (QBO), solar activity and cirrus clouds.

Cirrus clouds are the most common form of high-level clouds forming in the vicinity of the tropopause (Zerefos *et al.* 2003). In the tropics, their formation is mainly triggered by convective activities (Jensen *et al.* 1996). Over the northern middle

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latitudes, their formation is linked to synoptic and frontal weather systems (Sassen and Campbell 2001) and to the existence of large ice supersaturated regions in the upper troposphere (Gierens *et al.* 2000). Cirrus-cloud formation depends on the existence of small particles that provide the nuclei for the formation of ice crystals (Jensen and Toon 1997). Thin cirrus clouds are of significant climatological importance because they produce net heating of the planet (Lynch 1996).

Previous studies examining the effects of El Niño on upper tropospheric cirrus clouds have based their results on satellite observations (Wang *et al.* 1996, Mergenthaler *et al.* 1999, Sandor *et al.* 2000, Cess *et al.* 2001). Massie *et al.* (2000) examined the effects of El Niño in 1997 over the mid-Pacific and over Indonesia using aerosol extinction data from the Halogen Occultation Experiment (HALOE). Wang *et al.* (2003) used Stratospheric Aerosol and Gas Experiment (SAGE) II measurements to show above-normal high-altitude cloud occurrence over the eastern tropical Pacific and an opposite situation over the Pacific warm pool, which is generally consistent with the pattern of the tropical sea surface temperature and precipitation anomalies.

In the present study, we calculate the percentage of the interannual variance of cirrus-cloud cover (CCC) that can be attributed to interannual natural variability such as the ENSO, the QBO, the 11 year solar cycle and long-term trends. To account for the dynamical influence on CCC variability, cirrus-cloud averages have been studied in relation to variations in large-scale vertical winds in the upper tropical troposphere. Such parameters are commonly used as proxies for natural variability (e.g. Zerefos *et al.* 1994, Chandra and Varotsos 1995, Gernandt *et al.* 1995, Kondratyev and Varotsos 1996, Tourpali *et al.* 1997, Efstathiou *et al.* 1998, Zerefos *et al.* 2003, 2007, Chipperfield *et al.* 2007). The areas of interest are the eastern and western tropical Pacific Ocean. The analysis is based on satellite cloud data from the International Satellite Cloud Climatology Project (ISCCP), which provides global cloud coverage based on remote-sensing data. The data used in this study include more than two decades of cloud cover from the ISCCP, which include several ENSO and QBO cycles and two solar cycles. This allows us to conduct a detailed study of the time and space scales of variability of CCC along with an analysis of the dynamic influences on the CCC. The availability of this long satellite cloud dataset and the completeness of the analysed time and space scales and dependencies distinguish this work from previous studies. To evaluate the quality of our results over the examined regions, we compare the variability in ISCCP CCC with the variability in cirrus-cloud reflectance from Moderate Resolution Imaging Spectroradiometer (MODIS) Terra remote-sensing data.

2. Data and method of analysis

The cloud dataset analysed in this study was produced by the ISCCP (Rossow *et al.* 1996). The data are based on observations from the suite of operational geostationary and polar-orbiting satellites. Visible radiances are used to retrieve the optical thickness of clouds and infrared radiances to retrieve cloud-top temperature and pressure. The D2 dataset used in this study has a spatial resolution of 280 km (2.5° at the equator) and provides monthly averages of cloud properties of 15 different cloud types. The cloud types are derived based on radiometric definitions that rely on cloud optical thickness and cloud-top pressure. Cirrus clouds are defined as those with optical thickness less than 3.6 and cloud-top pressure less than 440 hPa. In this study, we made use of the cirrus-cloud data for the period 1984–2005.

Multiple linear regression is typically used to estimate statistical model parameters (e.g. Zerefos *et al.* 1994, Chipperfield *et al.* 2007). Seasonal cycle, southern oscillation, solar flux and QBO indices are commonly used as proxies for natural variability. Characteristics of volcanic aerosols, such as aerosol optical depth, are used in some models to account for effects of volcanic eruptions, particularly for the El Chichón and Mt. Pinatubo eruptions. In our study, due to the contamination of the ISCCP satellite retrievals caused by the Mt. Pinatubo eruption in 1991 (Rossow and Schiffer 1999, Luo *et al.* 2002), cirrus-cloud data taken between 1991 and 1992 were not used in our analysis, and therefore it was not possible to study the effects of volcanic eruptions on cirrus clouds.

The effects of seasonal, the ENSO and other climatological variations on cirrus variations have been examined using the following multiple linear-regression model for the cirrus-cloud variations:

$$(\mathrm{CCC})(i,j) = (\mathrm{S})(i,j) + (\mathrm{ENSO})(i,j) + (\mathrm{QBO})(i,j) + (\mathrm{SE})(i,j) + (T_{\mathrm{r}})(i,j) + (\mathrm{residuals}), \quad (1)$$

where i denotes the month and j is the year of the CCC and its components, that is, the seasonal (S), the ENSO, the QBO, the solar-cycle effect (SE) and finally, the long-term trend term (T_{r}), as described by Zerefos *et al.* (1994) and Tourpali *et al.* (1997). CCC data were deseasonalized by subtracting the long-term monthly mean (1984–2005) pertaining to the same calendar month. The ENSO signal appears significant mainly in the tropical region. As an index of the ENSO in the tropics, we made use of the Southern Oscillation Index (SOI) that was provided by the Bureau of Meteorology of the Australian Government (http://www.bom.gov.au/climate/current/soi2.shtml). The QBO component on cirrus clouds was examined by using the monthly mean equatorial winds at Singapore at 30 hPa and at 50 hPa. The zonal wind data were provided by the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA) at http://www.cpc.ncep.noaa.gov/data/indices/. The relationship between solar activity and cirrus clouds was examined using the monthly averaged 10.7 cm wavelength solar radio flux (in 10^{-22} J s^{-1} m^{-2} Hz^{-1}) from the National Geophysical Data Center of NOAA at http://www.ngdc.noaa.gov/stp/SOLAR/FLUX/flux.html.

Cirrus-cloud changes could also be related to variability in convective activity. As an index of convective activity in the tropics, we made use of the monthly mean vertical velocities at 300 hPa computed on a 2.5° grid from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset. The level of 300 hPa is the lowest pressure with vertical velocities reported in the NCEP reanalyses for the upper troposphere. For brevity in this study, the term VV300 is used to represent the vertical velocities at 300 hPa.

The ISCCP cloud properties have been tested extensively both against other satellite cloud retrievals and against surface cloud observations (Rossow and Schiffer 1999). In the latest (D-series) version of the ISCCP dataset, changes in the retrieval thresholds and the inclusion of an ice microphysics model for retrieval of optical thicknesses and top temperatures of cold clouds, have improved the agreement of cirrus-cloud amounts with both surface observations (Rossow and Schiffer 1999) and High-Resolution Infrared Sounder (HIRS) data (Stubenrauch *et al.* 1999). An underestimate of the ISCCP cirrus clouds amounts (~15% in the tropical warm pool) compared to HIRS results is caused by missed detection of very thin clouds (Rossow and Schiffer 1999, Stubenrauch *et al.* 1999). High cloud amounts from this dataset have been compared with those from SAGE II (Liao *et al.* 1995). It has been shown that the frequency of high-level clouds from SAGE II is about three times higher than the cloud amount from the ISCCP, with little seasonal variation. Despite this large systematic difference, it was noted that the correlation between the zonal mean curves is high, 0.88 (99.99% confidence level) for July and 0.82 (99.99% confidence level) for January, which strengthens our results.

3. Results and discussion

3.1 *Cirrus-cloud climatology in the tropics*

Figure 1 shows the annual mean CCC (%) in the tropics for the period 1984–2005. The highest amounts of cirrus clouds are found over the inter-tropical convergence zone. In the tropics, the annual mean cirrus coverage (according to ISCCP) exceeds 20%. The lowest and highest coverages in the tropics are estimated to about 18% and 22%, respectively, corresponding to the summertime and springtime averages. High cirrus amounts in the tropics are also observed over the south Pacific convergence zone, the Amazon area and central Africa as a result of strong upward air motions and high amounts of upper tropospheric humidity. Regions with low cirrus amounts in the tropics are observed at latitudes between 20°–30°, corresponding to the persistent high-pressure systems over these regions. These features are consistent with previous studies (Wang *et al.* 1996, Wylie and Menzel 1999, Bourassa *et al.* 2005).

Cirrus-cloud variability in the tropics is correlated to variability in deep convective clouds and vertical winds (Zerefos *et al.* 2007). At some locations, there is a correlation coefficient of $r = -0.7$ between the large-scale vertical-velocity field and CCC, which means that variations in the large-scale vertical-velocity field are the origin of up to half of the local variability in CCC. The remaining variability can probably be explained by unresolved dynamics (meso-scale and micro-scale) and unresolved variations in the humidity, temperature and aerosol fields. In addition, cirrus clouds detached from the convective activity contribute to the remaining

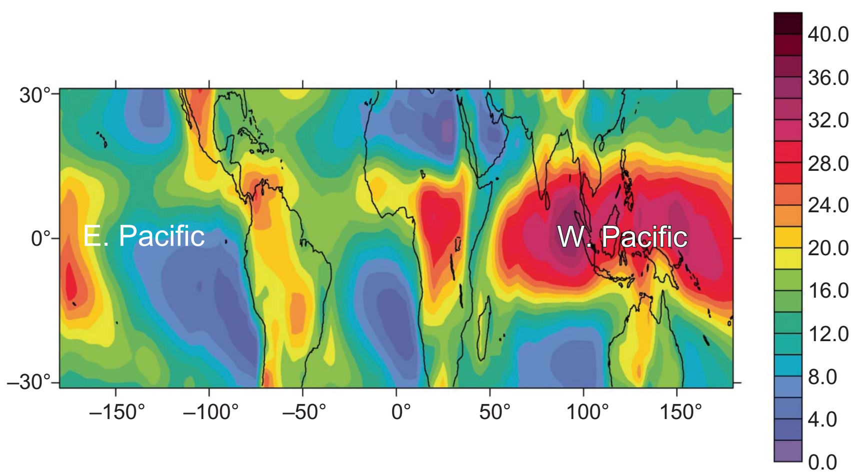

Figure 1. Mean cirrus-cloud cover (CCC) from 1984 to 2005 in the tropics by ISCCP (in %).

variability (Eleftheratos *et al.* 2007). The high correlations in the tropics can be attributed to seasonal variations, the ENSO and other climatological variations.

3.2 *Correlation with natural perturbations in the tropics*

Figure 2 shows the correlation coefficients between the CCC and ENSO in the tropics after removing the seasonal cycle and long-term trends from the time series of cirrus coverage. From this figure, it appears that CCC is strongly anti-correlated with SOI over the eastern tropical Pacific Ocean ($r = -0.7$) and positively correlated ($r = +0.6$) over its western part.

Figure 3 illustrates the contribution of different explanatory variables to cirrus fluctuations. It shows monthly mean CCC over the eastern and western tropical Pacific Ocean estimated from ISCCP data (top panels) and the contribution (in percentage of CCC) of major components of the cirrus variability to the total integral: the seasonal cycle, ENSO, QBO, solar-cycle-related signal, long-term trends and an estimated vertical-velocity-related cloud component. The vertical-velocity-related cloud term indicates variations in cirrus clouds due to possible variations in convective activity in the upper troposphere.

The percentage of the interannual variance of CCC explained by the variables used in equation (1) was calculated for the case of the ENSO by reconstructing the time series of CCC from the various indices, using the following linear-regression model:

$$\text{reconstructed CCC}(i,j) = a\,(\text{SOI})(i,j) + b, \qquad (2)$$

where a is the slope and b is the intercept of the correlation analysis between the deseasonalized and detrended time series of CCC and SOI. Accordingly, we have calculated the percentage of the interannual variance of CCC explained by the QBO, 11 year solar cycle, long-term trends and vertical-velocity variations. The annual mean CCC and the amplitudes of the different natural components contributing to cirrus fluctuations over the regions studied are summarized in table 1.

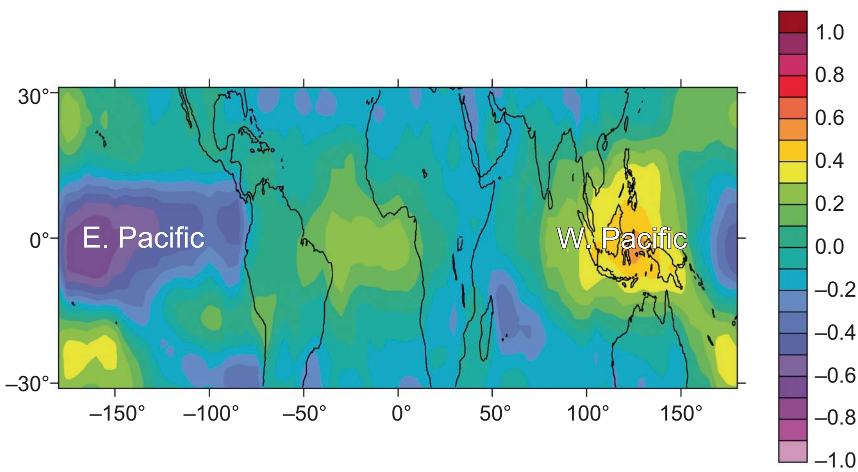

Figure 2. Map of correlation coefficients between CCC and SOI in the tropics for the period 1984–2005. Cirrus-cloud averages have been studied over the eastern and western tropical Pacific Ocean.

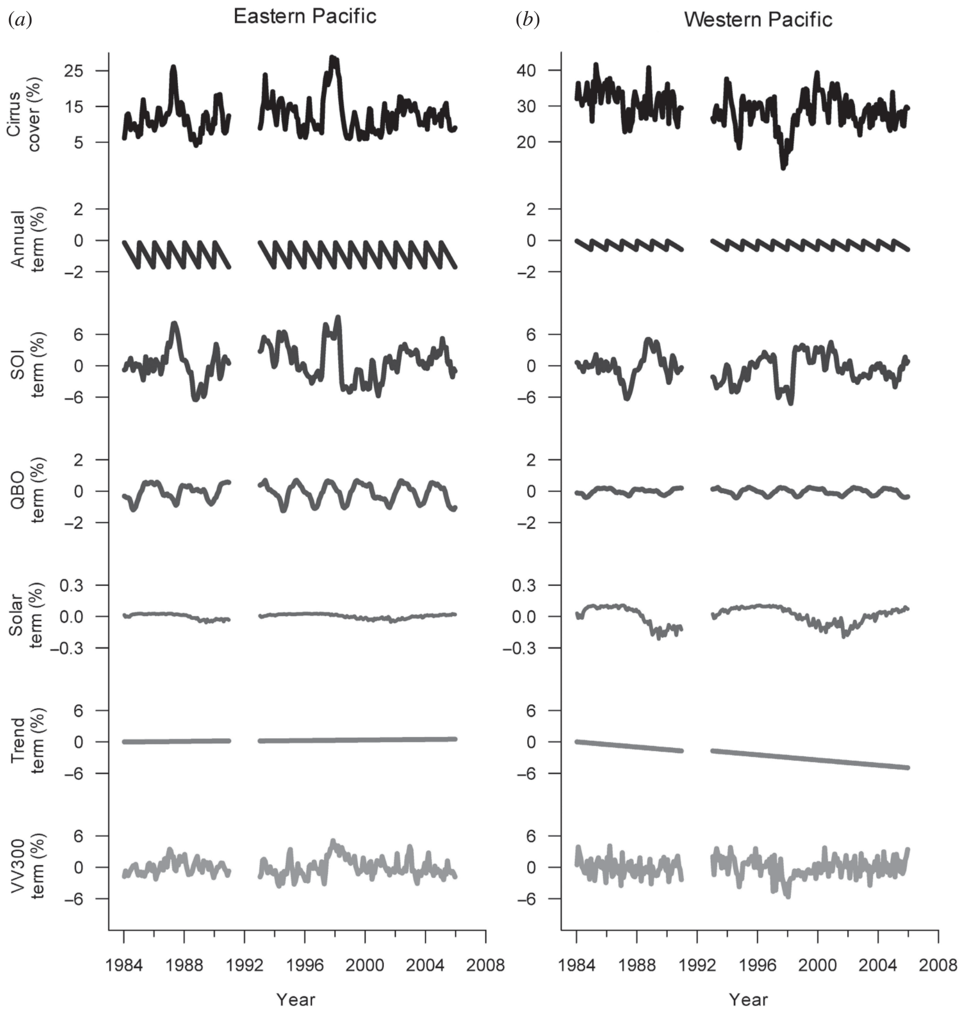

Figure 3. Contribution of different variables to cirrus fluctuations obtained from multiple linear regression analysis over (*a*) the eastern and (*b*) the western tropical Pacific Ocean. Units: percent (%) of cirrus-cloud cover.

Table 1. Mean cirrus-cloud cover ± 2σ (%) and amplitudes ((maximum value – minimum value) / 2) of seasonal, ENSO, QBO, 11 year solar cycle, long-term trends and vertical velocity related cloud components over the regions examined (eastern Pacific; 10° S–10° N, 80° W–180° W, western Pacific; 10° S–10° N, 80° E–150° E). Underlined contributions are statistically significant at the 95% confidence level and σ = standard deviation.

	Cirrus cover (%)	Contribution of major components to cirrus fluctuations (in % of cloud cover)					
1984–2005	Mean ± 2σ	Annual	ENSO	QBO	Solar	Trend	Vertical velocities
Eastern Pacific	12.3 ± 9.5	0.8	7.9	1.0	0.1	0.3	4.4
Western Pacific	29.3 ± 9.5	0.3	6.2	0.3	0.2	2.5	4.9

As can be seen, although the annual cycle is the dominant mode in all latitudes and longitudes its amplitude can be exceeded during strong El Niño/La Niña events. After removing from the time series of cirrus coverage the variability related to the seasonal cycle and long-term trends, the ENSO signals become dominant over the eastern and western tropical Pacific Ocean, determining the highest part of the cirrus-cloud interannual natural variability. The amplitude (i.e. (maximum value – minimum value) / 2) of the ENSO in cirrus clouds over the eastern Pacific is estimated to about 8.0%, contributing the highest part to the interannual variability of cirrus clouds. The amplitude of the annual cycle in cirrus clouds as calculated by the model is about 0.8% of the CCC. The amplitudes of the QBO, 11 year solar cycle and long-term-trend-related cloud components are estimated to about 1.0%, 0.1% and 0.3%, respectively. Finally, the amplitude of the vertical-velocity-related cloud term is estimated to be 4.4%.

Accordingly, over the western tropical Pacific, we estimate an ENSO-related amplitude in cirrus clouds of about 6.2%. The amplitudes of the seasonal cycle, QBO, 11 year solar cycle, long-term trend and vertical-velocity-related cloud components are of the order of 0.3%, 0.3%, 0.2%, 2.5% and 4.9%, respectively.

The total contribution of these components to CCC fluctuations over the regions examined is presented in figure 4. As can be seen from this figure, in both regions, there

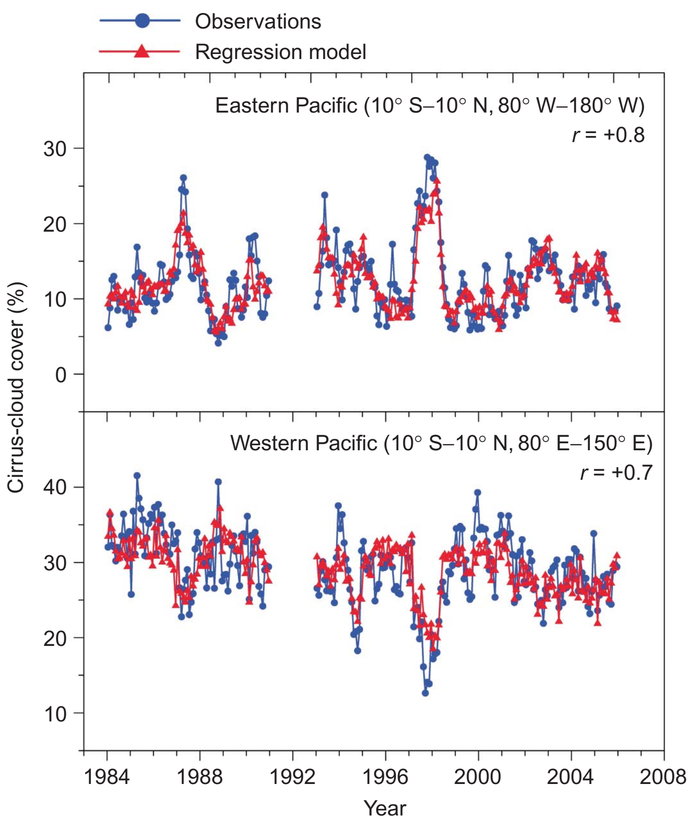

Figure 4. Correlation between observed and regressed cirrus-cloud cover over the two ENSO regions.

is good agreement between the observed and regressed cirrus-cloud data obtained from equation (1). A linear correlation coefficient of $r = +0.8$ between observed and regressed data is obtained over the eastern tropical Pacific Ocean, indicating that 65% of the observed variance in cirrus clouds is explained by the ENSO and other natural fluctuations. Similarly, the correlation coefficient between the observed and regressed cirrus-cloud data over the western Pacific is estimated to about +0.7, explaining 50% of the variance in cirrus clouds.

To evaluate the quality of our results over the examined regions, we have compared the variability in the ISCCP CCC with the variability in cirrus-cloud reflectance from MODIS Terra remote-sensing data. Cirrus reflectance data from MODIS Terra were downloaded from the Giovanni online data system, developed and maintained by the National Aeronautics and Space Administration (NASA) Goddard Earth Sciences Data and Information Services Center (GES DISC) at http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=MODIS_MONTHLY_L3.

MODIS Terra has provided cirrus-cloud reflectance data since 2000. In this study, we made use of the data for the period 2000–2005. Figure 5 shows the comparison

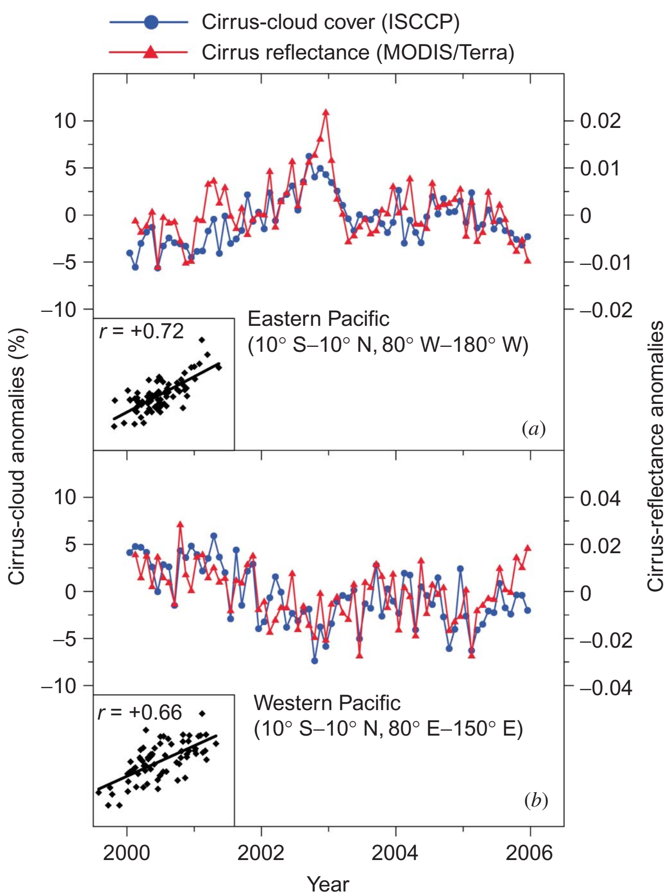

Figure 5. Comparison between deseasonalized ISCCP cirrus cloudiness and deseasonalized MODIS Terra cirrus reflectance over the two tropical regions.

of the variability in deseasonalized ISCCP CCC with the variability in deseasonalized MODIS Terra cirrus reflectance over the two examined tropical regions. As can be seen from figure 5, there are strong correlations between the time series of the two independently produced cloud datasets over the two examined regions, which strengthen our results. Both correlation coefficients (+0.72 and +0.66 over the eastern and western tropical Pacific regions, respectively) are statistically significant at the 99% confidence level.

4. Summary and conclusions

This study analysed cirrus-cloud data for the period 1984–2005 and calculated the percentage of the interannual variance of cirrus clouds, which can be attributed to interannual variabilities such as the ENSO, the QBO, the 11 year solar cycle and the vertical-wind regimes in the tropics.

We have introduced a multiple linear-regression model to account for the seasonal cycle, southern oscillation, solar-cycle-related signal, QBO, long-term trends and a vertical-velocity-related cloud component for the cirrus-cloud fluctuations over the eastern and western tropical Pacific regions. It is shown that the ENSO explains the highest part of the interannual variability of cirrus clouds. The amplitude of the CCC due to the ENSO over the eastern tropical Pacific Ocean is estimated to be about 8.0%. The amplitudes of the annual, QBO, 11 year solar cycle, long-term trends and vertical-velocity-related cloud components are estimated to be 0.8%, 1.0%, 0.1%, 0.3% and 10.1%, respectively.

There is a good agreement between the observed and regressed cirrus-cloud data. A linear correlation coefficient of $r = +0.8$ between observed and regressed data was obtained over the eastern tropical Pacific Ocean and a correlation coefficient of about +0.7 over its western part. The remaining variability can probably be explained by unresolved dynamics (meso-scale and micro-scale) and unresolved variations in the humidity, temperature and aerosol fields.

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