Types of ENSO in Conjunction with Cloud Feedbacks in Climate Model Simulations

(Zusammenhang zwischen ENSO Typ und Wolkenfeedbacks in Klimasimulationen)

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Abstract

Through an evaluation of the historical experiment of the Climate Model Intercomparison Project (CMIP5) over the time period 1900-2004, the zonal drift between warm-pool (WP) and cold-tongue (CT) El Niño is investigated. The aim is to find out, whether this zonal drift of the El-Niño-Southern-Oscillation (ENSO) is correlated with cloud properties in the southeast Pacific in climate models. The resulting drift of El Niño towards the western basins of the Pacific ocean in conjunction with higher sea surface temperatures (SSTs) and frequent occurrences of WP events appears simultaneous with a reduced cloud cover and a negative shortwave cloud radiation effect (SWCRE) in the subsident pool of the southeast Pacific (SEP). In the two utilised realisations of the ensemble a connection between net SWCRE and ENSO is clear, whereas cloud cover is not correlated with ENSO in climate models. CT and WP indices increase with higher net SWCRE, whereas the westward shift of El Niño correlates with negative net SWCRE, respectively. Besides, the intermodel spread has the widest range concerning radiative cloud feedback in this region. The role of internal variability in General Circulation Models (GCMs) cannot be ignored, however, due to the fact that two realisations establish similar correlations, climate noise is not dominating the calculated trends. Determining that the southeast Pacific interacts with ENSO needs further investigation and improvement of the representation of thermodynamic processes in general circulation models.
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1 Introduction

Climate change is affecting the earth's oceans and atmosphere continually. Considering tropical circulations in the Pacific, thermal convection is the main contributor for both equatorial, Hadley and Walker circulations (Holton and Hakim, 2013). Changes in the total sea surface temperature (SST) pattern are determining circulation patterns, thus triggering the Walker cell. Closely linked to the variability of SST is the El-Niño-Southern-Oscillation (ENSO). While El Niño is approaching, not only anomalous cyclones and anticyclones begin to develop but also a rotation of the Hadley cell is obvious (Wang, 2002). Many studies (Oort and Yienger, 1996; Holton et al., 1989) agree with the inversely correlated anomalies of the Hadley cell during El Niño.

Since the development of El Niño it is mentioned as a dominant source of interannual climate variability (Trenberth, 1997). In recent decades it is reported that the major action centre of the canonical El Niño is shifted from the eastern Pacific westwards to the central Pacific (Yeh et al., 2009) (dataset from 1854-2006). For this reason the eastern Pacific (EP) El Niño is referred to as Niño-3 and the central Pacific (CP) El Niño as the Niño-4 region. Since the climate shift in 1976/77 the CP El Niño occurs more frequently (Sohn et al., 2013). Yeh et al. (2009) found out that the occurrence ratio of CP El Niño before and after 1990 is 0.01 and 0.29 per year.

Furthermore, the Trans-Niño-Index (TNI) was introduced to evaluate the difference in normalized anomalies of SST between Niño-1+2 and Niño-4 regions. While Niño-3.4 is quite stable throughout the twentieth century, TNI shows changes after the climate shift (Trenberth and Stepaniak, 2001).

So several indices have been compared with the result that they do not capture the flavours of ENSO well. Therefore, a coexistence of two ENSO like modes is assumed. Bejarano and Jin (2008) distinguished between a low quadrennial (cold phase) and a higher-frequency quasi-biennial mode (warm phase) in the Pacific. Also, westward flows dominate. Considering warm and cold phases of CP El Niño, it is clear that La Niña and El Niño are described by a similar physical process. Although, in case of EP El Niño the two phases have a significantly different in-
1 Introduction
tensity and propagation (Kao and Yu, 2009).
Taking into account any findings of CP and EP El Niño trends (Lee and McPhaden, 2010; Li et al., 2013), it is necessary to define new indices for types of ENSO. First, cold-tongue (CT) (warm-pool (WP)) events are assigned to the Niño-3 (Niño-4) region. One event is included if their corresponding boreal winter Niño-3/4 index is above 0.5 degree Celsius. Here Kug et al. (2009) agree with Kao and Yu (2009) that cold events cannot easily be separated during a WP El Niño because of the already available westward shift of La Niña. Whereas Kug et al. (2009) and Yeh et al. (2009) defined a CT (WP) event if "the winter Niño-3 index is greater (smaller) than the winter Niño-4 index", Ren and Jin (2011) used a coordinate transform into the Niño-3 and Niño-4 phase space. Due to this simple transformation the new indices are modestly correlated with each other. Thereby, it is noteworthy that the transformed indices capture, on the one hand, original WP and CT indices and on the other, a connection between the regions - if necessary, depending on the relation of Niño-3 and Niño-4 phase spaces. Before the climate shift indices are simultaneous, however, afterwards the WP El Niño tends to intensify since the past three decades. Hence, it is concluded that a new WP type of ENSO emerges additional to the CT El Niño.

Of particular interest is the adjustment of tropical circulations. Generally, one expects higher SSTs, more water vapour and thus a strengthened water vapour transport associated with climate change. The East Pacific stratocumulus deck with its enhanced rainfall (due to sulphate aerosols, predominantly) seems to stabilize the water column of the ocean and to weaken the thermohaline circulation (Allen and Ingram, 2002). So enhanced water vapour transport as a consequence of higher SSTs simultaneous with a weakening of the Walker circulation exists. Other studies, which act as well on the assumption that mass exchange is tied to thermodynamic processes, prove the weakened circulation (Vecchi et al., 2006; Held and Soden, 2006). Originating from the law of Clausius-Clapeyron, the much smaller rainfall increase of 2% per degree opposite to an increase of water vapour of about 7% per degree would imply an enormous decrease of the vertical mass flux. This requires a slowdown of the Walker circulation (Held and Soden, 2006). Vecchi et al. (2006) proposed a reduced zonal SLP gradient based on observations and model simulations also confirming the thesis of a weakened zonal circulation.
Sohn and Park (2010) and Sohn et al. (2013), who argued that due to the enhanced water vapour flux the circulation would strengthen, only relate to the years 1979 until 2008, the time period in which the WP El Niño begins to occur. Sohn et al. (2013) found out that the increase in the east-west SST gradient is consistent with anomalies of deep convection, upper tropospheric moistening and sea level pressure (SLP). Introducing the concept of the effective wind derived from water vapour flux as the Walker circulation strength index (CSI), yields enhanced easterly winds - thus supporting the theory of intensification between 1979 and 2008 (Sohn et al., 2013).

Uncertainties in modelling arise from natural variability which dominates the tropical Pacific (Sohn et al., 2013). Possible causes for the discrepancy in simulations are the lack of data sets that may be not suitable for a representation of long term trends. Besides, one can not exclude the natural variability, the temperature trend associated with climate change contributing to higher anomalies of SST. Additionally, internal variability of climate models plays an important role as well as the chosen time period has to be considered in comparing different results.

Cloud properties are an enormous contributor in regulating thermodynamic processes. Frequently, anomalies of total cloud fraction (CLT), cloud top altitude and cloud optical depth are reported yielding a strong linear relationship between long- and shortwave net radiation fluxes (Sun et al., 2012). This interdependence of single El Niño events captures a non-linear response of cloud properties attributed to types ENSO, hence either to a strengthened or a weakened Walker circulation (Loyola et al., 2006; Su and Jiang, 2013). Lacagnina and Selten (2013) used SST and mid-tropospheric pressure velocity $\omega_{500}$ in 500 hPa as a proxy in a bivariate approach. Inter alia, the $\omega_{500} - \text{SST}$ phase space proposes a non-linearity between these proxies in the Tropics (30°N-30°S) which gives rise that other processes may be included additionally. During El Niño opposing cloud feedbacks are observed, for example lower (higher) CLT is associated with cold (warm) SST anomalies and stronger (weaker) subsident motion implying lower (higher) net cloud radiation effect (Lacagnina and Selten, 2013). Large uncertainties and high sensitivity of models exist concerning low clouds. They contribute to the intermodel spread in cloud feedback, especially over regions with large scale subsident motion. In particular, Soden and Vecchi (2011) pointed out that the southeast Pacific (SEP) has
the widest range of intermodel spread in global mean net cloud feedback which is attributable with cloud amount. Figure 1 displays the local change in cloud feedback regressed against the global mean cloud feedback. Areas, in which models produce a strong positive cloud feedback are referred to an increase in marine boundary layer cloud amount.

This study focuses on the transformation of indices introduced by Ren and Jin (2011). The transformation of CT and WP indices are applied to time series analyses of the historical run referring to the fifth phase of the Climate Model Intercomparison Project (CMIP5). In addition, cloud properties in the South east Pacific are examined. A possible connection to the variability of ENSO is proposed. Therefore, the correlation between the shift of El Niño and cloud properties in the southeast Pacific is analysed. As cloud properties here only the total cloud fraction and the net cloud radiation effect are taken into account.

The structure of the study is as follows: To further understand the context, fundamentals are covered in Section 2. Therefore, a description of large-scale circulations and climate feedbacks is required. Section 3 covers the methods, beginning with a description of climate model simulations including their uncertainties. All data used is obtained from CMIP5, so this intercomparison project is mentioned as well as the method of analysing the data. Section 4 covers an examination of El Niño and its shift by applying the transformed CT and WP indices to the historical ex-

![Figure 1: Intermodel regression of the global mean cloud feedback against the local cloud feedback. Black contours represent the ensemble mean 500 hPa pressure velocity (adapted from Soden and Vecchi (2011)).](image)
periment of CMIP5. Section 5 focuses on cloud properties in the southeast Pacific which may play an important role in triggering ENSO. Finally, in Section 6 the connection between the shift of El Niño and the aforementioned cloud cover as well as the net shortwave radiation feedback in the southeast Pacific is investigated. At last a brief summary is given.
2 Theoretical background

2.1 Large scale circulations

2.1.1 Interdependence of Hadley and Walker circulation

The meridional global circulation in the Tropics and Subtropics is characterized by the diabatic forced heating of the Hadley cell. Zonal equatorial currents also form a thermal driven circulation, the Walker cell. Figure 2 displays the mean state and anomalous atmospheric cells during ENSO. While El Niño is approaching air masses of the Hadley cell converge in the tropical Eastern, upper-tropospheric winds flow northward, air masses start sinking in the mid latitudes and return to the Tropics in the lower troposphere. So Wang (2002) describes the variation of the eastern (western) Pacific Hadley Cell during the mature phase of El Niño as a clockwise (counter clockwise) rotation. Further on, the mid latitude zonal

Figure 2: Representation of circulations. (Additional to the Hadley cell also the Walker and the mid latitude zonal cell are shown.) (adapted from Wang (2002))
cell (MZC), which results from divergent wind fields and mid tropospheric vertical velocity, and the inter tropical convergence zone (ITCZ) are shown. The equatorward converging surface winds have a westward drift due to the Coriolis force, thus affect atmospheric and oceanic motion in the Pacific which weakens or strengthens the Walker circulation (McWilliams and Gent, 1978). Because the northern hemisphere is more affected by insolation than the southern hemisphere, SSTs as well have great longitudinal gradients. Not only the zonal SST gradient, but also the meridional SST difference plays a significant role by regulating the Walker circulation system, so characterizing a shift of ENSO (Liu and Huang, 1997).

2.1.2 The El-Niño-Southern-Oscillation (ENSO)

El Niño is characterized by an anomalous warming of the surface layers in the equatorial Eastern and Central Pacific. Overlain on this fluctuation of SST is the Southern Oscillation Index (SOI), which describes the normalized difference in surface pressure between Tahiti and Darwin, Australia. Considering normal conditions higher pressure over Tahiti and lower pressure over Darwin is observed implying an eastward flow in the equatorial region. High SOI indicates stronger trade winds, so La Niña conditions, whereas El Niño is associated with low values. Combining the atmospheric and ocean system one can define the El-Niño-Southern-Oscillation (Trenberth, 1997; Julian and Chervin, 1978; McCreary Jr. and Anderson, 1984).

With reference to the Walker circulation in the tropical Pacific, phases of inter annual variability can be classified (see Fig.3).

Figure 3: ENSO, normalized Walker circulation, La Niña and El Niño conditions. Adapted from: National Oceanic and Atmospheric Administration
Trade winds induced by the thermal direct circulation along the equator drive global ocean currents. By upwelling of cold water from the depths of the Humboldt current, simultaneously warm water in the western Pacific begins to pile up. The associating deep convection supports the forming of low-pressure areas in the western Pacific region. The lower SOI in the eastern regions effectuates divergences establishing high-pressure areas, hence strong subsidence in this area. These normal conditions of the Walker cell are dominated by a stronger upwelling resulting in a rising of the thermocline, the interface between cold and warm water masses. Colder (warmer) SSTs advance sinking (rising) motion leading to a stronger pressure gradient than normal. This effect strengthens the trade winds, and thus the Walker cell and is referred to as La Niña conditions (Trenberth, 1997).

At intervals of two to seven years trade winds slacken, leading to a deepening of the thermocline in the eastern Pacific, so that warm surface currents flow eastward. In the Indo-Pacific high-pressure areas are developing and South America is influenced by a new build low due to the elevation of the thermocline. The anomalous warming contributes to an inversion of the Walker circulation. Usually El Niño lasts 12-18 months and causes enormous flooding in South America and strong dryness in Indonesia and Australia (Schur and Hegerl, 2003).

According to the National Oceanic and Atmospheric Administration (NOAA) there is consensus for El Niño (La Niña) conditions "as a phenomenon in the equatorial Pacific Ocean characterized by a positive (negative) sea surface temperature departure from normal (for the 1971-2000 base period) in the Niño-3.4 region greater than or equal in magnitude to 0.5°C, averaged over three consecutive months" (National Oceanic and Atmospheric Administration).

2.1.2.1 Types of ENSO

To capture the flavours of ENSO, the Pacific is divided into different regions. Latitude and longitude ranges of these are illustrated in Fig. 4. The Niño-1+2 (0°–10°S, 90°–80°W), Niño-3 (5°N–5°S, 150°–90°W), Niño-3.4 (5°N–5°S, 170°–120°W) and Niño-4 (5°N–5°S, 160°E–150°W) regions define SST area averages (Hanley et al., 2003). Events with their centre of major activity in the Niño-3 region are referred to as eastern Pacific or cold-tongue (CT) El Niño, whereas the Niño-4
index is appropriate towards the central Pacific or warm-pool (WP) El Niño (Kug et al., 2009; Lee and McPhaden, 2010). Many studies agree that the WP El Niño emerges more frequently in recent decades and additional to the canonical EP El Niño (Yeh et al., 2009; Kug et al., 2009; Lee and McPhaden, 2010). Amongst others, Kug et al. (2009) figured out that the WP El Niño is rather a stochastic event due to its first occurrence after the climate shift in 1976/77. Furthermore, a co-existence of different kinds of modes gives rise to distinguish between quadrennial and quasi-biennial modes of ENSO (Bejarano and Jin, 2008). Since none of these indices capture the properties of the new type of ENSO well, a transformation of WP and CT indices is needed. With this transformation introduced by Ren and Jin (2011) CT and WP events can be considered independently from each other. For further explanation see Section 3.2.

2.2 Feedbacks

In general, changes in global mean surface temperature indicate changes in climate parameters (i.e. albedo, SST, etc.) defined as feedbacks. They do influence the Earth’s radiation budget by either amplifying or diminishing global mean temperature changes (Stocker et al., 2013). An amount of feedbacks exists, i.e. the lapse-rate, water-vapour, the feedback from Arctic cloud interactions with sea ice as well as the cloud radiative feedback. This study elaborates on the latter, which
dominates the southeast Pacific.

2.2.1 Cloud Radiative Feedback

Clouds affect longwave and shortwave radiation immediately. The sum of both, incident longwave (positive sign) and outgoing shortwave (negative sign) fluxes is defined as net radiation effect of clouds in Watts per square meter (Ramanathan et al., 1989).

On the one hand high, optically thin clouds like Cirrus have a low reflection and absorption but high transmission of solar radiation. Warming in the terrestrial spectral range dominates the moderate cooling due to solar radiation.

On the other hand low, optically thick clouds like Cumulus ensure a net cooling effect. They cause high reflection but low absorption and transmission of shortwave radiation. Longwave radiation, however, contributes to only a slight warming. In the southeast Pacific shallow cumuli have a horizontal large extension and further, they ensure a small longwave warming.

So in general shortwave cloud radiation effect (SWCRE) is sensitive to low, optically thin clouds, whereas longwave cloud radiation effect (LWCRE) is more sensitive to high, optically thin clouds (Stocker et al., 2013). Currently, a mostly net (reflective) cooling due to cloud radiation feedback is reported. In future also other weightings of fluxes could lead to changes in feedbacks. For example, the cloud radiation feedback decreases as cloud top temperature rises and increases as optical depth decreases (Bretherton and Hartmann, 2009).
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3.1 Climate model simulations

3.1.1 General

In a climate system processes are bound to laws of energy, mass and momentum conservation. Numerical climate models solve them, although, still the parametrization of clouds is a significant issue.

Present climate models are General Circulation Models (GCMs) which couple atmospheric processes with ocean, land surface, sea ice and the carbon cycle. Responses to feedbacks vary with each GCM, just because of the way physical processes are parametrized.

Aims of modelling are primarily exploring the climate response to radiative forcing which includes making projections of the past and future climate either on seasonal or decadal time scales. As well, it is of interest to study the difference between observations and model outputs to reduce uncertainties and errors in parametrizations. The largest uncertainty still arises from cloud feedbacks (Stocker et al., 2013).

To improve models, simulations are performed as an ensemble. All models of an ensemble have identical experiment conditions but are initialized from different points. So several realisations are produced covering a wide range of climate trajectories. Strong deviations in calculated realisations are connected to inconsistencies with observations. Here, the multimodel ensemble of CMIP5 is used involving a variety of coordinated model experiments (Taylor et al., 2012).

3.1.2 Discrepancy of cloud feedbacks in model simulations

Parametrizations of cloud properties exhibit the largest uncertainties in GCMs. Microphysical processes and turbulent properties of clouds - especially in mixed-phase clouds - lead to a challenge in parametrization because they still need more investigation and scales are smaller than the grid boxes of the GCM (Stocker et al., 2013).
Most of the intermodel spread actually arises from subtropical marine boundary layer clouds in large-scale subsidence regions. Climate models underestimate the contribution of low cloud cover to a change of temperature and albedo. Especially, the sensitivity of marine boundary layer (MBL) clouds to current climate change remains the main source of uncertainty (Soden and Vecchi, 2011; Bony and Dufresne, 2005). Due to global warming, in future low clouds will be optically thicker and vertically as well as horizontally more extensive (Bretherton and Hartmann, 2009), so yielding a great field of inquiry. According to Andrews et al. (2012) who differentiates between rapid adjustments and feedbacks, one should better focus on the transient than on the equilibrium climate sensitivity. As well, it is evident that models fail to simulate the non linearity of thermodynamic processes (Held and Soden, 2006). Thereby, it is difficult to find the cause of errors because of the strong relation of processes. It is suggested that discrepancies are associated with double ITCZ or the excessive equatorial Pacific cold tongue, an error in representing cold SSTs most GCMs suffer from (Li and Xie, 2014).

3.1.3 The Climate Model Intercomparison Project (CMIP5)

Since 1995 coordinated climate model experiments were promoted by the World Climate Research Program (WCRP). The current fifth phase of the Climate Model Intercomparison Project (CMIP) is based on atmosphere-ocean global climate models (AOGCMs).

The project mainly consists of long and near term experiments to determine mechanisms of climate change. Long term integrations cover an atmospheric model intercomparison project (AMIP) run, a coupled control run and a historical run. For the evaluation in this study, the historical run is used, referring to the years 1850-2005 using AOGCMs and earth system models (ESMs) that combine AOGCMs with biogeochemical components of the carbon cycle (Taylor et al., 2012).

The limits of simulation in these models potentially evoke complex issues. Especially important for ENSO is the discussion of unforced variability. According to Taylor et al. (2012) internal climate variations depend on arbitrary initial values.
So here in the historical evaluation, actual years of El Niño coincide inadequate with dates calculated by the model. But AMIP simulations for example which are based on observations match, however still limited by atmospheric variability. Due to the slow adjustment of the ocean a larger time period for the control simulation is needed to correct climate drift and bias. Besides, it has to be noted that a mismatch in downscaling exists. CMIP5 grid cells measure about a 100 km grid, so local observations have to be treated with caution.

### 3.1.3.1 List of used models

In this study following data is obtained from CMIP5: NorESM1-M, MPI-ESM-LR, IPSL-CM5A-LR, HadGEM2-ES, CSIRO-Mk3-6-0, CanESM2 and GFDL-CM3 (references in Table 1).

For all models the time series from 1900 to 2004 is investigated. The chosen experiment is a historical run initialized in 1850 until 2005 for two realisations (r1i1p1, r2i1p1).

<table>
<thead>
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<th>Model</th>
<th>Institution</th>
<th>Reference</th>
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<td>Met Office Hadley Centre</td>
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<th>Description</th>
<th>Website</th>
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<tbody>
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<td>Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) Marine Atmospheric Research</td>
<td><a href="https://wiki.csiro.au/display/CSIROMk360/Home">https://wiki.csiro.au/display/CSIROMk360/Home</a></td>
</tr>
<tr>
<td>GFDL-CM3</td>
<td>NOAA Geophysical Fluid Dynamics Laboratory</td>
<td><a href="http://nomads.gfdl.noaa.gov/">http://nomads.gfdl.noaa.gov/</a></td>
</tr>
</tbody>
</table>

Table 1: References for CMIP5 models

3.2 ENSO indices

Since the occurrence of a new type different from the canonical EP or CT El Niño, there have been various suggestions in representing the variability of ENSO. As already mentioned, CT and WP events are described using \( N_3 \) and \( N_4 \) indices which represent anomalies of SST. Through following indices, where \( N_{CT} \) and \( N_{WP} \) display the \( N_3 - N_4 \) phase space, hence no temperature anomalies, cold-tongue and warm-pool events can be treated independently from each other (Ren and Jin, 2011).

\[
\begin{cases}
N_{CT} = N_3 - \alpha N_4 \\
N_{WP} = N_4 - \alpha N_3,
\end{cases} \quad \alpha = \begin{cases}
\frac{2}{3}, & N_3 N_4 > 0 \\
0, & \text{otherwise}
\end{cases}
\]

If one event cannot be strictly allocated to a specific region, when \( N_3 N_4 > 0 \), an approximation with the parameter \( \alpha \) is used. Besides, \( N_{CT} \) and \( N_{WP} \) are a suitable proxy in capturing \( N_3 \) and \( N_4 \) indices as well. Through considering the deviation, even the temperature trend caused by natural variability does not falsify the correlation much in quality.

On the basis of these indices the monthly area average of SST is calculated and weighted for every grid point of Niño-3 and Niño-4 regions. Resultant, a movement
of the El Niño phenomenon is observed. The shift of ENSO is defined as follows:

\[
\text{Shift (}N_{CT} \text{Minus} N_{WP}) = N_{CT} - N_{WP}
\] (2)

Negative values depict a westward shift, whereas positive yield an eastward shift. Trends of \(N_{CT}\), \(N_{WP}\) and the shift are calculated using least square linear fits with the aim to minimize the sum of square residuals.

### 3.3 Net shortwave radiation

Apart from applying the method of least square linear fits to the total cloud fraction, as well incident and outgoing shortwave radiation at the top of atmosphere (TOA) are investigated. Via the difference of incident and outgoing shortwave (SW) radiation at the TOA, the net shortwave cloud radiation is calculated. The variation of outgoing SW depends on cloud properties, so an increase indicates optical thick and extensive clouds, thus strong cloud albedo (Bretherton and Hartmann, 2009). Since the anomaly of incident SW varies modestly, it is sufficient to only show net SW radiation here. Trends are calculated as mentioned in Section 3.2. A negative trend then depicts high reflection of clouds so yielding a net SW cooling effect.

### 3.4 Connection of parameters

Furthermore, the connection between investigated parameters is analysed. In order to get a correlation, parameters are plotted against each other in a scatter plot. Each point describes one model; values of the variables are determined to the x-axis and its appropriate y-axis.

Primarily, the first realisation of the multimodel ensemble is considered for the conjunction of \(N_{CT}\), \(N_{WP}\) and the shift towards the total cloud fraction and net SW effect. Secondly, the results are compared to the model outputs of the second realisation. As well, the incomplete beta function (with the use of a students t-test) is calculated to get the probability whether the connection between parameters is
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significant.
4 Shift of ENSO

Over a period of 104 years (1900-1004) the historical experiment of CMIP5 is utilised to analyse the time series of temperature anomalies for cold-tongue and warm-pool El Niño indices. An increase of SST as a consequence of the accumulative warming trend forced by the carbon cycle is obvious in most of the models. Additionally, a westward shift of the major action centre during El Niño years is denoted (Fig. 5).

Figure 5 describes trends of $N_{CT}$ and $N_{WP}$ indices as well as the yielded drift ($N_{CT} \text{Minus} N_{WP}$). On the one hand, the cold-tongue index has a range of $-1.5$ to $+1.5$, on the other hand, according to the warm-pool region, the index has only a range of circa $-1$ to $+1$, for some models of the ensemble even minor. If $N_{CT}$ is greater than $N_{WP}$, events are shifted westward and otherwise. The calculated range of the anomaly of CT and WP phase spaces in listed models is comparable to the study of Ren and Jin (2011), who obtained their data from the Climate Prediction Centre in National Oceanic and Atmospheric Administration (NOAA) (http://www.cpc.ni0aa.gov/data/indices/sstoi.indices). Since anomalies of phase spaces are obtained from Niño-3 and Niño-4 indices based on SST, their ranges are comparable to the anomalies of these indices denoted by other studies and behave similarly (Kao and Yu, 2009; Kug et al., 2009; Lee and McPhaden, 2010).

In general, different peaks are not comparable because the natural variability is superimposed by internal variability. Just because of (deterministic) dynamics and interactions in a system, the variability of the climate alters from model to model. This is also called climate noise Schur and Hegerl, 2003. Besides, each model has varying initial conditions. Although single phenomena are quite distinguishing in model simulations, there is still significance that trends are similar.

In all three presented models, the WP index becomes stronger whereas the CT index tends to weaken in recent decades. Furthermore, WP events tend to have no strong following cold phase after their decay and so contribute to accumulative warming of the Pacific (Fig. 5). In studies of Sohn and Park (2010) and Yeh et al. (2009) one can observe a similar behaviour of the WP El Niño, whereby the
Figure 5: Trend of cold-tongue and warm-pool indices. The x-axis shows the years from 1900-2004, the y-axis displays the anomaly of phase spaces: $N_{CT}$, $N_{WP}$ and the shift ($N_{CT} - N_{WP}$).

The intensity of trends naturally depends on the chosen time period. By examining the slight westward drift many causes can act triggering (Yeh et al., 2009). During the second half of the twentieth century, the ocean heat content has increased in the upper layers (Stocker et al., 2013). Due to the slow adjustment of the ocean, the warming slightly weakens the Walker circulation by i.e. reducing the sea level pressure gradient. The warming is regulated by the thermocline feedback. In the western Pacific the thermocline rises, whereas it is deepening in the eastern Pacific. This shoaling may produce advantaging conditions for WP El
4 Shift of ENSO

Niño, hence favouring frequent occurrences of this type of ENSO and triggering the drift of events (Yeh et al., 2009; Kug et al., 2010).
5 The southeast subsidence zone

Especially the southeast basins of the pacific ocean (0°N-50°S, 120°W-70°W) are characterized by cold SST anomalies and an extensive stratocumulus deck. The region is maintained by strong coastal upwelling, dry and warm air of the subtropical high and radiative cooling through stratocumulus clouds. The large scale sinking motion in this area is driven by the subsidence of Hadley and Walker circulation branches, besides, it is enhanced due to the orography of the Andes. Many sources of error contribute to systematic failures in simulations, e.g. diurnal circulations are not fully understood (Mechoso et al., 2014).

Moreover, Bretherton et al. (2004) showed that marine boundary layer clouds, predominant associated with the southeast Pacific (SEP), have strong gradients in cloud droplet concentration which could influence the radiative budget. Due to deficient representation of microphysical processes and the increase of low-level marine boundary layer clouds, the widest intermodel spread concerning the net shortwave cloud radiation effect (SWCRE) is ascribed to the SEP (cf. Fig. 1). In common, during El Niño, the region responds with less upper-level clouds. Thus, a reduction in cloud cover and in its net SWCRE are consequences (Lacagnina and Selten, 2013).

5.1 Total cloud fraction

The southeast Pacific is dominated by a decrease of the total cloud fraction (Fig. 6). Most of the used CMIP5 models record a slight reduction, others like the NorESM1-M or GFDL-CM3 exhibit no significant trend. It should, however, be noted that models fail to simulate the interaction between thermodynamic processes (Held and Soden, 2006), see Section 3.1.2, thus leading to such opposing results.

While analysing the trend in cloud cover, the stronger increase of low clouds attracts attention, whereas high and middle cloud amount decline. If the reduction of cloudiness is accompanied with cold SSTs, just like in this region, one can gather further information by examining the net radiation (Sec. 5.2).
5 The southeast subsidence zone

5.2 Net cloud radiative feedback

Although most models display positive SW radiation anomalies (not shown here) and negative net SW CRE, only some few as IPSL-CM5A-LR or the CanESM2 (not shown here) coincide with the observational positive net CRE indicated by Bellomo et al. (2014) (Fig. 7).

Negative (positive) values of outgoing SW reduce (strengthen) cloud albedo, so cool (warm) the atmosphere. The reduced simulated cloud cover in that region correlates with warmer SST and a decrease in SW CRE.

Lacagnina and Selten (2013) pointed out that the negative SW CRE anomaly in the subsident cold basins of the SEP are caused by the transition from stratocumulus to scattered cumulus. For this reason clouds scatter less solar radiation, hence the surface warms more rapidly. This happens prevalent in the development
phase of El Niño, whereas during El Niños decay phase the opposing effect damps warm SST.
6 Possible connections of ENSO and cloud properties

In this chapter, primarily, trends of total cloud fraction (Sec. 5.1) and the net SW radiation effect (Sec. 5.2) are correlated with the shift of ENSO and secondly, with the rise of $N_{WP}$ and $N_{CT}$ indices (Sec. 4). Therefore different realisations are considered. The aim is to gather possible conjunctions between ENSO indices and cloud properties.

Considering CLT in SEP and the shift due to ENSO indices in Figure 8, there is no significant connection. However, it has to be noted that models depict a westward and some, as well, an eastward shift accompanied by a reduced cloud cover. If CT and WP indices are separately taken into account, most models are located in the same range (only a small decrease in CLT, see Fig. 8) except CanESM2 and IPSL-CM5A-LR, which depict a higher decrease in cloud cover accompanied with increasing $N_{WP}$ and $N_{CT}$ phase space.

Instead, there is a relation between net SW radiation and $N_{WP}$ and $N_{CT}$ indices, thus with the shift. Apparently, the net radiation decreases when a westward drift is detected. Indeed, exceptions exist, actually the two models which have been conspicuous before (IPSL-CM5A-LR, CanESM2) are outliers. These two models, however, have the highest significance in representing variables (Tab. 2). Concerning single indices, the net SW radiation is quite well correlated with them. The increase of temperature anomalies correlates with a positive SWCRE, respectively.

In general, for the trend of WP El Niño higher values than for CT El Niño are calculated over the years. In this reanalysis the recent but frequent occurrences of WP El Niño are already significant, although this phenomenon first appears since the climate shift.

Table 2 displays statistical significances which are identical for r1i1p1 and r2i1p1. Anomalies of cloud cover show the lowest significance, hence great uncertainties of parametrization of clouds in models are dominant. The HadGEM2-ES shows the lowest significance, whereas the others, in general, are significant. So ENSO indices are quite well represented, whereas the shift of El Niño is depicted only by some models as significant.
6 Possible connections of ENSO and cloud properties

Figure 8: Correlation of parameters for the first realisation r11p1. First row: Shift of ENSO (NetMinusNwp), anomaly of $N_{CT}$ and $N_{WP}$ (units in K $(100 \text{ years})^{-1}$) plotted with total cloud fraction (units in % $(100 \text{ years})^{-1}$), respectively. Second row: same order of x-axes but plotted with the net shortwave radiation (Net SW Rad.) (units in $W m^{-2} (100 \text{ years})^{-1}$).

While considering the scatter plots of the second realisation (Fig. 9), it is obvious that some differences exist. Due to climate noise, changes of properties and their connection can be detected but not their stochastic occurrence ratio. For this reason two members of the ensemble are taken into contrast to better distinguish between natural and internal variability. The changed order of model outputs is traced back to internal variability. Thus, since both signals are similar, one can argue that at least a connection between the change in net shortwave radiation and in El Niño indices is clear.
6 Possible connections of ENSO and cloud properties

<table>
<thead>
<tr>
<th>Models</th>
<th>$N_{CT}$</th>
<th>$N_{WP}$</th>
<th>Shift</th>
<th>CLT</th>
<th>net SW radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>NorESM1-M</td>
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<td>67,74</td>
<td>6,48</td>
<td>98,49</td>
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<tr>
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<td>98,7</td>
<td>85,57</td>
<td>89,2</td>
<td>34,5</td>
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<tr>
<td>CanESM2</td>
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<td>99,99</td>
<td>87,63</td>
<td>95,63</td>
<td>62,61</td>
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<tr>
<td>HadGEM2-ES</td>
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<td>55,09</td>
<td>3,57</td>
<td>37,77</td>
<td>97,32</td>
</tr>
<tr>
<td>GFDL-CM3</td>
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<td>93,48</td>
<td>45,91</td>
<td>1,86</td>
<td>96,69</td>
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<tr>
<td>CSIRO-Mk3-6-0</td>
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<td>1,81</td>
<td>61,33</td>
<td>79,31</td>
<td>99,59</td>
</tr>
</tbody>
</table>

Table 2: Statistical significances of investigated parameters for each model (obtained from the incomplete beta function) (units in %).

Though the response is weak, it must be mentioned that seven models are not sufficient in representing a trend. Besides, various intermodel deficiencies need a correction, i.e. the new study of Zhang et al. (2014) proposes to add more observational data to the poorly presented South Pacific in models. Evidently, this region is an important factor of developing the ENSO-like variability. After Zhang et al. (2014) the presence of a South and North Pacific meridional mode triggers the canonical and the central Pacific El Niño related to the CT and WP El Niño introduced by Ren and Jin (2011). Unfortunately, used CMIP5 models provide no distinct statement, although in fact a certain connection between parameters, which needs further investigation - especially in improving simulations.
Figure 9: Correlation of parameters for the second realisation r21p1. First row: Shift of ENSO (NetMinusNwp), anomaly of $N_{CT}$ and $N_{WP}$ (units in $K (100 \text{ years})^{-1}$) plotted with total cloud fraction (units in $\% (100 \text{ years})^{-1}$), respectively. Second row: same order of x-axes but plotted with the net shortwave radiation (Net SW Rad.) (units in $Wm^{-2} (100 \text{ years})^{-1}$).
7 Summary

This study examines whether clouds in the east Pacific are influenced by the zonal shift of ENSO. Hundred-four years (1900-2004) of historical simulations for seven CMIP5 models are analysed.

The results show that cold-tongue and warm-pool indices of ENSO after Ren and Jin (2011) have increased in the entire period, especially the WP El Niño emerges frequently in recent decades. The propagation of El Niño towards the west indicated by further occurrences of WP events since the climate shift additional favours an accumulative warming of the tropical Pacific. Thus, increased SST based on CMIP5 data contribute to a weakening of the Walker circulation as other studies have shown (Held and Soden, 2006; Vecchi et al., 2006).

Predominantly, the SEP is of particular interest because amongst others Zhang et al. (2014) and Van Loon and Shea (1985) ascribed a triggering role for ENSO events to this region. From the results of this study it emerges that the variability of cloud cover has no significant connection with ENSO, whereas it is well correlated with net shortwave radiation feedback. One can say that the westward shift of El Niño corresponds to reduced net SW CRE. Furthermore, increasing trends of both indices coincide with higher net SW radiation. Albeit some models present a reduced cloudiness in the SEP, hence a lower net SW CRE due to the accumulation of marine boundary layer clouds and stronger cloud albedo, only two out of seven models match with observations compared with the study of Lin et al. (2014), who analysed the time period 1979-2005.

Simulations depend on internal and natural variability. To better separate climate noise, two realisations have been considered. Due to similar results, in fact, a connection at least between net SW radiation and $N_{CT}$ and $N_{WP}$ can be denoted (see Fig. 8 and Fig. 9) - despite internal variability.

The discrepancies of results originate from the insufficient representation of low clouds causing a large intermodel spread. Models overestimate the reduction of clouds in the SEP, even the examination of radiation yields anti-correlated results with observations in the southeast Pacific. The insufficient presented cloud amount then leads to weaker SWCRE (Sun et al., 2012). As well, volcanic eruptions can
influence radiation at TOA, if they are included in models. Simulating clouds effectively, especially MBL clouds, which dominate this area, is a great issue and needs further investigation. For example, Lin et al. (2014) proposed to apply cloud top radiative cooling to drive boundary layer turbulence to improve simulations of stratocumulus in CMIP5 models. Still, more observational data of the southeast Pacific has to be added. However, the non-linearity between various thermodynamic processes maintains one of the greatest problems in parametrization concerning GCMs (Held and Soden, 2006).
References


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Sohn, B. J. et al. (2013). “Observational evidences of Walker circulation change over the last 30 years contrasting with GCM results”. In: Clima. Dyn. 40.7-8, pp. 1721-1732. DOI: 10.1007/s00382-012-1484-z.


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1. Intermodel regression of the global mean cloud feedback against the local cloud feedback. Black contours represent the ensemble mean 500 hPa pressure velocity (adapted from Soden and Vecchi (2011)).

2. Representation of circulations. (Additional to the Hadley cell also the Walker and the mid latitude zonal cell are shown.) (adapted from Wang (2002)).


4. El Niño regions (adapted from International Research Institute for Climate and Society).

5. Trend of cold-tongue and warm-pool indices. The x-axis shows the years from 1900-2004, the y-axis displays the anomaly of phase spaces: $N_{CT}$, $N_{WP}$ and the shift ($N_{CT} - N_{WP}$).

6. Anomaly of total cloud fraction in the southeast Pacific, see Fig. 5, only the y-axis is changed to the anomaly of total cloud fraction in % as unit.

7. Anomaly of net shortwave radiation in the southeast Pacific, see Fig. 5, only the y-axis is changed to the anomaly of net shortwave radiation in $W m^{-2}$ as unit.

8. Correlation of parameters for the first realisation r11p1. First row: Shift of ENSO ($N_{CT} - N_{WP}$), anomaly of $N_{CT}$ and $N_{WP}$ (units in $K$ (100 years)$^{-1}$) plotted with total cloud fraction (units in % (100 years)$^{-1}$), respectively. Second row: same order of x-axes but plotted with the net shortwave radiation (Net SW Rad.) (units in $W m^{-2}$ (100 years)$^{-1}$).
Correlation of parameters for the second realisation r2i1p1. First row: Shift of ENSO (NctMinusNwp), anomaly of $N_{CT}$ and $N_{WP}$ (units in K (100 years)$^{-1}$) plotted with total cloud fraction (units in % (100 years)$^{-1}$), respectively. Second row: same order of x-axes but plotted with the net shortwave radiation (Net SW Rad.) (units in $W m^{-2}$ (100 years)$^{-1}$).

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Erklärung

Ich versichere, dass ich die vorliegende Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

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Leipzig, den 15. September 2014

(Mareike Löffler)