Tropospheric Kelvin waves and extreme rainfall events in Piura, northwestern Peru, during El Niño - DRAFT

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ABSTRACT

Day to day variability in heavy rainfall in Piura, in northwestern Peru, during El Niño conditions is associated with large-scale perturbations in the tropospheric circulation. An empirical analysis is presented that suggests that these perturbations are associated with convectively-coupled tropospheric equatorial Kelvin waves, as depicted in filtered outgoing longwave radiation data.

The coherence these waves present while propagating from the Pacific to the coast of South America, makes it possible to anticipate their arrival with a lead time of at least 2 days, but possibly up to 4-5 days. Therefore, this is a potentially useful source of predictability of extreme rainfall events in Piura and perhaps elsewhere in the equatorial Pacific coast of South America.

1. Introduction

The northern coast of Peru is normally arid, with the notable exception of summer and fall during El Niño events, during which near-coastal sea surface temperature (SST) is anomalously high and heavy rainfall takes place. This relationship between monthly rainfall and near-coastal SST is statistically robust and can, therefore, be used to predict monthly rainfall given SST forecasts (Woodman, 1999).

However, rainfall in these warm periods does not occur uniformly in time, but tends to occur in very strong episodic events, which can then lead to floods and heavy impacts on the infrastructures. Therefore, it is of practical, as well scientific, interest to understand the mechanisms leading to day-to-day variability since this can lead to improved predictability of these events. In a previous analysis, the present author (Takahashi, 2004; hereafter referred to as T04) showed that, during two periods with El Niño conditions (December 1997 - April 1998 and March - April 2002), rainy events were associated with a strengthening of the sea-breeze circulation due to perturbations in the large scale circulation; it was suggested that these perturbations might have been associated with convectively-coupled equatorially-trapped tropospheric Kelvin and $n = 1$ Rossby waves (Wheeler and Kiladis, 1999).

In this work, the hypothesis of T04 is evaluated using global outgoing longwave radiation (OLR) data decomposed into the previously mentioned waves, and statistically relating this to rainfall indices over northwestern Peru for the same periods considered by T04.

2. Data

We will use the same rainfall indices as T04, which consist in daily rainfall averaged over northern Peru for December 1998 to April 1998 (digitized from Figure 2 from Douglas *et al.*, 2000); and instantaneous discharge from Piura river measured every two hours from Puente Ñácara (5.10°S, 80.17°W). Unfortunately, daily rainfall observations or proxy data were not available to the author for other El Niño periods.

The equatorial-convective-wave data for the 1995-2000 period was kindly provided by Dr. Matthew Wheeler (Bureau of Meteorology, Australia). It is diagnosed from daily global OLR data, which is filtered in time and space on the bands corresponding to different wave modes as described by Wheeler and Weickmann (2001).

3. Local relationship

The time series for the rainfall indices and the Kelvin- and $n = 1$ Rossby-wave OLR anomalies at the grid point closer to Piura (5°S, 80°W) are shown in the upper panels of Figs. 1 and 2. The linear correlation coefficient (r) between the rainfall indices and the Kelvin-

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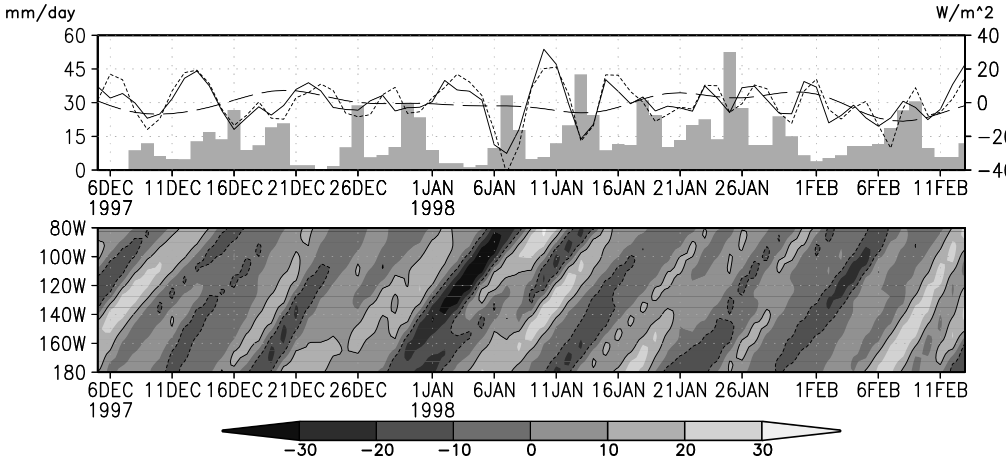

FIG. 1. Upper panel: Daily rainfall averaged over northern Peru (mm day^{-1}; bars) and OLR anomalies (Wm^{-2}) at 5°S, 80°W associated with Kelvin and $n = 1$ Rossby waves (solid and dashed lines, respectively) for the period December 1997-March 1998. The Kelvin-wave OLR anomalies for 5°S, 120°W lagged by 2 days are shown dotted. Lower panel: Kelvin-wave OLR anomalies along 5°S as a function of time and longitude. The -20 and 20 Wm^{-2} contours are included for reference.

wave anomalies is -0.36 and -0.41 for the 1997-98 and 2002 periods, respectively, indicating that there is indeed a relationship between Kelvin-waves and day-to-day modulation of rainfall in Piura. The negative sign of the coefficients was expected since low OLR approximately indicates the presence of deep convection. On the other hand, the relation between Rossby waves and rainfall was not significant. Although it may appear that linear correlation analysis is not ideally suited to deal with daily rainfall data, which tends to have a non-gaussian distribution, it will be seen that it gives a fair and clear lower bound on the strength of the relationship.

A closer inspection of the time series for 1997-98 (Fig. 1, upper panel) suggests that the relation was stronger in the earliest half of the period. In fact, it was found that $r = -0.58$ for the period ending mid-January 1998, while it was $r = -0.25$ for the rest of the period. This degradation can be partly explained by the reduction in importance of the topographic lifting associated with the sea-breeze for triggering deep convection (Ordinola *et al.*, 2001[1]), probably due to the increase in SST to values high enough to support extended instability. In this different regime, the atmosphere is probably unstable enough that convection can also occur without the triggering by Kelvin waves. In contrast, in 2002, r is larger in the latter part of the period ($r = -0.52$ for the period starting in mid-March). Because of the briefness of this period, it is more appropriate to discuss this in terms of individual events. In Fig. 2 (upper panel) we see that the three major rainy events of 19 March, 28-29 March and 6-7 April 2002 were associated with the largest negative Kelvin-wave OLR anomalies. During the first half of March, however, there were two minor rainfall events and one negative Kelvin-wave OLR anomaly which did not have a counterpart in OLR or rainfall, respectively. Since the condition of high SST for convection appeared to be satisfied (T04), the reason for this indiscrepancy is unclear.

At this point it is pertinent to recall that the hypothesis of T04 called for the enhancement of the low level westerly flow (sea breeze circulation) by the Kelvin waves. Therefore, it is important to verify that the OLR anomalies we have found to be related to rainfall are also proxies for zonal wind anomalies. Wheeler *et al.* (2000) analyzed the three dimensional structure of these Kelvin waves and found that, indeed, they feature low level westerly flow associated with low OLR. A question may arise from this: Can the rainfall in Piura be explained just by the dynamics of Kelvin waves without having to rely on topographic lifting? One argument against this idea is that convection in Piura tends to be initiated near the western slopes of the Andes and then propagates westward, which is the opposite of what we would expect from a Kelvin wave. However, perhaps it would be desirable to address this issue from a numerical modelling perspective.

4. Predictability

In the lower panels of Figs. 1 and 2 we see the Kelvin-wave OLR anomalies along 5°S as function of time and

[1] Ordinola, N., Douglas, M., Yauri, H. and Flores, L., 2001: Distribución de lluvias en el norte del Perú y sur de Ecuador durante el episodio El Niño 1997-1998, unpublished document

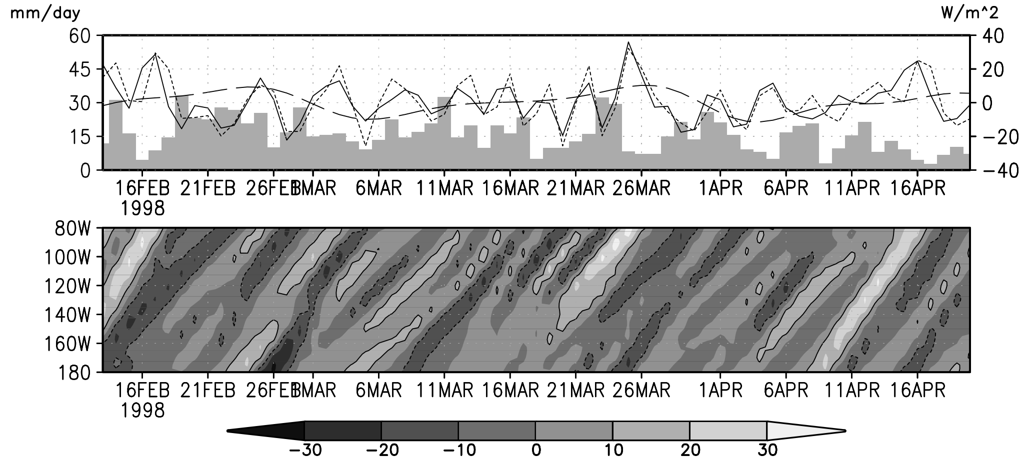

FIG. 1. Continued.

longitude. These perturbations propagate from west to east at typical speeds of 10-15 m s^{-1} (Wheeler and Kiladis, 1999) and those which impinge on the coast of South America can be tracked back to at least 120°W.

In Table 1 we present lagged correlation coefficients between the rainfall indices and Kelvin-wave OLR anomalies at 5°S and different longitudes, corresponding to the lead-times which give the largest magnitude of r. If we consider the Kelvin-wave anomalies at 100°W, we see that they give a correlation with rainfall two days later as good as that obtained using collocated anomalies at zero-lead. The lead time of two days is consistent with the typical propagation speeds mentioned previously.

The correlations are significant out to 120-140°W and to leads of 4-5 days, which could allow for a lead time of 4 to 5 days for predicting the arrival one such disturbance from just monitoring these on real-time. In fact, the NOAA-CIRES Climate Diagnostic Center maintains a web site[2] which allows for real-time monitoring of these waves and which also provides forecasts of these using the technique described by Wheeler and Weickmann (2001). According to these authors, these predictions might be skillful in our region of interest for up to 4 days lead.

Furthermore, we can see that, in 2002, the magnitude of r actually increased with distance and lead time with maximum value at 140°W and 5-day lag. An inspection of the data suggests that this was due to having coastally-restricted short-lived negative OLR events which had no apparent impact on rainfall (in particular, the one observed in the first week of April), which suggests that they may be spurious, and also to having long-lived disturbances propagating from afar, most remarkably the one that hit the coast on the second week of April. During the 1997-98 period, on the other hand, the correlations were more coastally-restricted, probably because the eastern tropical Pacific was very warm and acted as a source of Kelvin-waves, as suggested by the lower panels of Fig. 1.

[2] http://www.cdc.noaa.gov/map/clim/olr_modes

TABLE 1. Lagged correlation coefficients (r) between rainfall indices and Kelvin-wave OLR anomalies at 5°S and different reference longitudes, at the lead-time (days) which gives the largest correlation. Correlations significant to the 95% level are shown in bold*.

Reference longitude	1997-98 r (lead)	2002 r (lead)	Both periods r (lead)
80°W	**-0.36** (0)	**-0.41** (0)	**-0.38** (0)
100°W	**-0.36** (2)	**-0.50** (2)	**-0.39** (2)
120°W	**-0.27** (4)	**-0.53** (3)	**-0.30** (4)
140°W	-0.14 (5)	**-0.55** (5)	**-0.24** (5)
160°W	-0.06 (8)	-0.36 (7)	-0.11 (8)

* Effective sample sizes were calculated as $N^* = N(1-\alpha)/(1+\alpha)$ where N is the sample size and α is the lag-1 autocorrelation (e.g. Wilks, 1995). The significance of the correlations where tested using Fisher's Z transformation.

5. Conclusions

A clear relationship was established empirically between day-to-day variability in intense rainfall in Piura and the action of convectively-coupled equatorially-trapped tropospheric Kelvin waves, confirming the hypothesis put forward in a previous study (Takahashi, 2004). This relationship is particularly strong when the El Niño conditions are not too severe, probably due to the lack of need of a triggering mechanism during very warm conditions. The influence of equatorial $n = 1$ Rossby waves appears to be negligible.

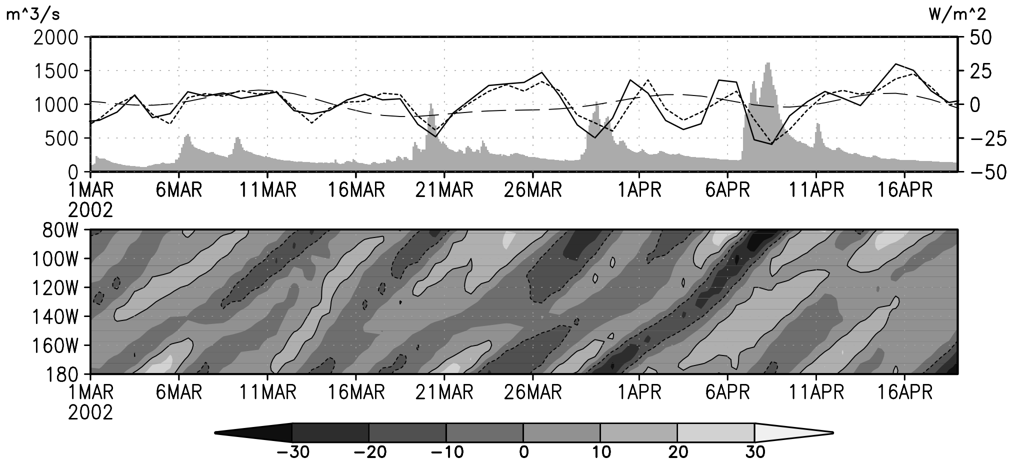

FIG. 2. As in Fig. 1 but for the period March - April 2002 and instantaneous discharge (m^3 s^{-1}) for Piura river is shown instead of precipitation

Real-time monitoring of the Kelvin waves waves may allow for forecasts of extreme rainfall events in Piura, and potentially along the coasts of Ecuador and western Colombia, with lead times of at least 2 days, but possibly up to 4-5 days.

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