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CLIMATOLOGICAL ASPECTS OF THE 1991/1993 EL NIÑO IN ECUADOR

Jörg, BENDIX [*], *Astrid BENDIX* [**]

Abstract

In the scope of the project *ENPEX* (El Niño Precipitation Experiment), the spatial distribution and temporal development of severe precipitation in Ecuador and northern Peru during the 1991/1993 El Niño event have been investigated mainly based on satellite data (METEOSAT-3). The distribution of heavy rains is determined by the Convective-Stratiform-Technique (CST) which has been adjusted to METEOSAT-3 geometry as well as the KED interpolation method. The validation of the adjusted CST scheme reveals an encouraging accuracy also for extreme rainfall amounts up to 300 mm per 3 days. The extraction of cloud motion winds (CMW) by means of cross correlation technique which is applied to sequences of METEOSAT imagery provides additional information on circulation patterns which are related to severe precipitation. The analysis have shown that the 1991/1992 event is stronger than the 1972/1973 but significantly weaker than the 1982/1983 event. Severe precipitation occurs mainly in the coastal plain of Ecuador and north Peru up to the 1000 m contour line. Deep convection is originated by the land-sea-breeze phenomenon on most of the investigated days. In this case, heavy precipitation is locally confined and shows a clear diurnal cycle. Precipitation starts over land in the evening and is shifted to the coastal waters during night. A nocturnal center of heavy precipitation is the Gulf of Guayaquil due to the shape of the coastline which favours convergence and the frequently increased SST's. in this area. Severe precipitation without any diurnal cycle which is characterized by great spatial extension occurs during main El Niño (March-April) due to an extended atmospheric instability of the lower troposphere. Deep convection is often organized in mesoscale convective complexes (MCC) which are related to extended areas of SST's >28°C. During these situations, a strong meridional stream flow (Hadley circulation) could be observed.

Key words: *Precipitation dynamics, Meteosat-3, Convective-Stratiform Technique (CST), Cloud Motion Winds (CMW), Ecuador, north Perú.*

ASPECTOS CLIMATOLÓGICOS DE EL NIÑO 1991/1993 EN EL ECUADOR

Resumen

En el alcance del Proyecto ENPEX (El Niño Precipitación Experimental), han sido investigadas la distribución espacial y el desarrollo temporal de precipitaciones severas en el

[*] Institute of Geography, University of Bonn, Meckenheimer Allee 166, D-53115 Bonn-Germany Telf: (++49-228) 73-2093, Fax: 73-7506, e-mail: bendix@beauty.giub.uni-bonn.de

[**] Academy of Science and Literature, Mainz, Dep. of Geoecology at University of Bonn, Meckenheimer Allee 166, D-53115 Bonn-Germany, astrid@beauty.giub.uni-bonn.de

Ecuador y norte de Perú durante el evento de El Niño, el cual está basado en información satelital (METEOSAT-3). La distribución de fuertes precipitaciones se determina mediante la Técnica Estratificada Convectiva (CST) la cual ha sido ajustada a la geometría del METEOSAT-3, así como también al método de interpolación KED. La validación del esquema ajustado CST revela una exactitud alentadora además para cantidades de lluvia extremas de hasta 300 mm por 3 días. La extracción de vientos de movimientos de nubes (CMW) mediante la técnica de correlación cruzada, la cual se aplica a la secuencia de imágenes METEOSAT, provee de información adicional en patrones de circulación, los cuales están relacionados a precipitaciones severas. El análisis ha mostrado que el evento 1991/1992 es más fuerte que el evento 1972/1973 pero significativamente más débil que el evento de 1982/1983. La precipitación severa ocurre principalmente en la planicie costera del Ecuador y norte del Perú hasta la línea de nivel de los 1 000 m. La convección profunda se origina por el fenómeno brisa-mar-tierra en la mayoría de días investigados. En este caso, la precipitación fuerte está confinada localmente y muestra un ciclo diurno claro. La precipitación se inicia sobre la tierra en la tarde y se cambia sobre las aguas costeras durante la noche. Un centro nocturno de fuerte precipitación es el Golfo de Guayaquil debido a la forma de la línea de costa, la cual favorece la convergencia y la frecuentemente creciente temperatura de la superficie del mar en esta área. La precipitación severa, sin ningún ciclo diurno, caracterizado por una gran extensión, ocurre durante El Niño importante (marzo-abril) debido a una inestabilidad extendida de la troposfera más baja. La convección profunda se organiza a menudo en complejos convectivos de mesoescala (MCC) los cuales están relacionados a amplias áreas de temperatura de la superficie del mar superiores a 28 grados centígrados. Durante estas situaciones, se pueden observar fuertes flujos de corrientes meridionales (circulación de Hadley).

Palabras claves: *Dinámica de precipitaciones, Meteosat3, Técnica convectiva-Stratiforma (CST), viento de desplazamiento de nubes (CMW), Ecuador, norte del Perú.*

ASPECTS CLIMATOLOGIQUES DU EL NIÑO 1991/1993 EN ÉQUATEUR

Résumé

Dans l'optique du projet ENPEX (*El Niño Precipitation Experiment*), nous avons étudié la répartition spatiale et temporelle de très fortes précipitations en Équateur et dans le nord du Pérou au cours du El Niño de 1991/1993, en utilisant surtout des données satellite. La répartition des fortes pluies a été déterminée par la technique Convective-Stratiforme (CST) qui a été adaptée aux images de METEOSAT-3, et par la technique d'interpolation de KED. La validation du schéma CST s'est révélée d'une précision encourageante, y compris pour des totaux pluviométriques extrêmes dépassant 300 mm sur 3 jours. L'extraction des vents par suivi de nuage (CMW) par des techniques de corrélations croisées, appliquées à des séquences d'images METEOSAT a fourni des informations supplémentaires sur les modes de circulation associés aux très fortes précipitations. L'analyse a montré que l'événement de 1991/1992 est plus fort que celui de 1972/1973, mais nettement moins fort que celui de 1982/1983. Les très fortes précipitations sont surtout survenues dans la plaine côtière d'Équateur jusqu'à l'altitude de 1 000 m. On a observé une convection profonde, générée par un phénomène de brise dans la plupart des cas. Dans ce cas, les fortes précipitations sont localisées et suivent clairement un cycle diurne. Les précipitations commencent sur terre dans l'après-midi et se déplacent sur les eaux côtières dans la nuit. Un centre de fortes précipitations nocturnes dans le Golfe de Guayaquil, dû à la forme de la ligne côtière, qui favorise la convergence et l'augmentation de la température de surface de l'océan dans cette zone. De très fortes précipitations, sans aucun cycle diurne et caractérisées par une grande extension spatiale, surviennent au coeur du El Niño (mars-avril), à cause d'une instabilité étendue de la basse troposphère. Une convection profonde s'organise souvent dans des complexes convectifs à méso-échelle (MCC), qui correspondent à d'importantes surfaces où la SST est supérieure à 28°C. Dans cette situation, on observe un fort flux du sud (circulation de Hadley).

Mots-clés : *Dynamique des précipitations, Météosat3, Technique Convective-Stratiforme (CST), vents de suivi de nuage (CMW), Équateur, Pérou du Nord.*

INTRODUCTION

The spatial distribution and temporal formation of heavy precipitation in Ecuador and northern Peru during El Niño events is not finally known until today (Bendix, 1994). Available studies which are mainly based on rain gauge data do not provide an exact overview over the patchy structure of the local rainfall distribution. Yet less known are the local circulation patterns which cause heavy precipitation within the mentioned area. Whereas some authors attribute anomalous El Niño precipitation in the arid environments of south Ecuador and north Peru to an extreme southward shift of the ITCZ due to increased SST's (e.g. Miller & Laurs, 1975), other investigations point out the importance of local circulation patterns (e.g. an extended land-sea-breeze phenomenon) for rainfall formation (e.g. Schütte, 1968; Horel & Cornejo-Garrido, 1986). The aim of the present investigation is to examine the interrelations of spatial rainfall distribution, circulation patterns and positive SST anomalies in Ecuador by means of a synergy of remote sensing techniques, ground based observations as well as spatial interpolation techniques and numerical modelling for the 1991/1993 El Niño event.

1. METHODOLOGY

Figure 1 gives an overview over the data sources and techniques which are used for the present investigation.

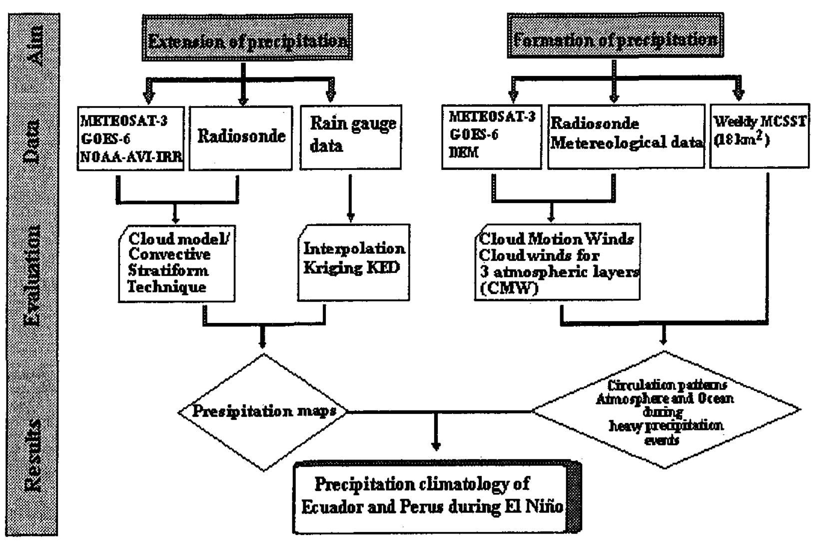

Fig. 1 - Aim, data and methodology of the current investigation.

The spatial distribution of precipitation is estimated applying an adapted version of the *C*onvective-*S*tratiform-*T*echnique (hereafter *CST*) of Adler & Negri (1988) to METEOSAT-3 data. Additional information concerning rainfall distribution is obtained by the application of a special interpolation technique (KED Kriging, Deutsch & Journel, 1992) to rain gauge observations.

To derive the circulation patterns during single events of heavy precipitation, wind observations and radiosonde data are combined with cloud-motion winds (CMW) which are extracted from sequences of METEOSAT-3 IR imagery by means of cross-correlation technique as described by Schmetz *et al.* (1993). This cloud tracking method provides the wind field of three atmospheric layers (850-700, 500-400, 200-100 hPa). Weekly data of multichannel sea surface temperatures (MCSST) derived from NOAA-AVHRR data which are available from the JPL-PO.ODAC archive (McClain *et al.*, 1985) complete the investigations.

1. 1. The CST Method

The CST rain retrieval technique was originally developed for the calculation of convective rainfall in Florida by means of GOES-6 IR-radiometer. The divergent viewing geometry of Meteosat-3 IR which observed Ecuador during the 1991/1993 El Niño as well as the dissimilar climate of Ecuador require some adjustments to the original CST parameterisation (for further details of the CST procedure and the adjustment scheme refer to Bendix, 1997; Bendix, & Bendix, A. 1996):

> The relation between cloud temperature as seen from the Meteosat-3 IR radiometer and the convective rain rate/rain area is provided by the computation of a 1D-cloud model using local radiosonde data (Fig. 2, left).

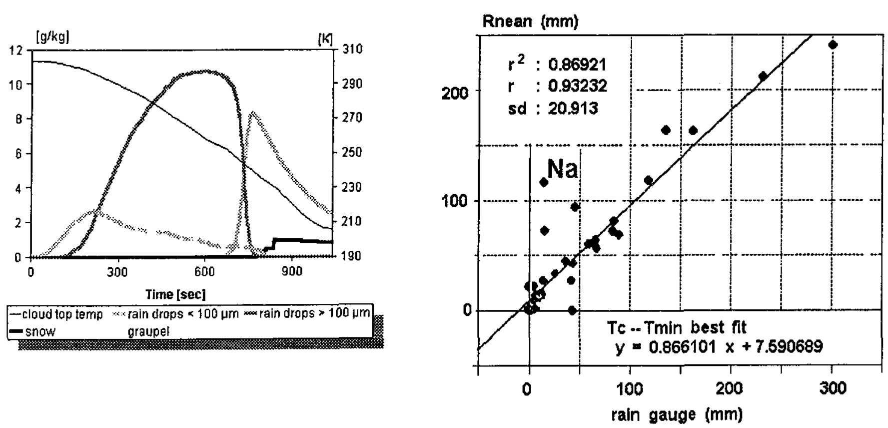

Fig. 2 - (Left) Cloud model microphysics at 30 April 1992 using radiosonde data of San Christobal, Galapagos - (Right) comparison of rain gauge data and calculated rain rate (CST) for 29 April to 1 May 1992.

A field-of-view correction between cloud model temperature (T_c valid for 1 km^2 resolution) and the temperature derived from Meteosat-3 IR data (T_{min} valid for 4.7x5.7 km^2 resolution) has to be performed. This is done by comparing temperature minima derived from NOAA-AVHRR (1.1 km^2 nominal pixel resolution) to a Meteosat-3 image of the same scan time.

A discriminant function to separate young and mature storms and to distinguish between raining and non-raining T_{min} pixels in the stratiform cloud area (*i.e.* simple life cycle test) has been adapted to the spatial resolution of Meteosat-3 IR.

Validation of the adjusted CST scheme has been performed by comparing rain gauge data of 50 meteorological stations to rainfall calculated from 101 METEOSAT images (half hour interval) for the corresponding pixel locations (Fig. 2, right). The rain retrieval by means of the adjusted CST reveals a good accuracy (r2 = 0.87, SD = 20.9 mm). It should be noted that also great amounts of rainfall up to 300 mm can be calculated by the adjusted scheme. However, a slight underestimation of heavy rainfall > 200 mm by the CST has been found. The outlier Na represents the station Naranjal (Ecuador) which has been proved as unreliable during several rainfall events by means of plausibility tests based on surrounding rain gauge stations.

1. 2. Interpolation technique

A well known method for the spatial interpolation of precipitation maps from rain gauge data is the Kriging technique. However, the common ordinary Kriging technique often provides only unsatisfactory results because rainfall extension in the Tropics depends on various factors as e.g. the altitude. To account for topographical effects, the *K*riging method with *E*xternal *D*rift (*KED*, Deutsch & Journel, 1992) has been chosen for the current study. The KED technique comprises three overall steps:

A variogram analysis to examine the spatial variability function of precipitation. The form of the function can be linear, spherical, exponential etc.

An anisotropy correction to describe the spatial coherence of various rain fields. The spatial coherence can have a more zonal or meridional component. Due to the north-south orientation of the Andes, a meridional correction has been chosen.

The consideration of an external drift variable. All interpolation within the current study have been performed by accounting for the external drift variable altitude (asl) which has been taken from a *D*igital *E*levation *M*odell (DEM) of Ecuador an north Peru..

Table 1 shows the result of sensitivity test for different Kriging settings using the complete data set of 84 rain gauge stations for the 1982/1983 El Niño event. Precipitation maps have been interpolated using KED with only 71 stations. Subsequently, the results for 13 independent stations have been compared to the real observations to determine the accuracy of the technique as well as the sensitivity in relation to single settings.

Table 1 - Validation of Kriging algorithm using rain gauge data from 71 dependent and 13 independent meteorological stations (Dec 1982 - May 1983).

Kriging settings:				
Variogram adjustment	on	on	on	on
Anisotropy	on	off	on	off
External drift	on	on	off	off
r2	0.94	0.92	0.88	0.84
R	0.97	0.96	0.94	0.91

The results reveal clearly a major importance of the drift variable altitude with which the correlation between observed and interpolated precipitation can be significantly increased. The importance of external drift additionally increases if only marginal stations are considered for sensitivity test. The test results an improvement of correlation from r2=0.74 to r2=0.94 for 7 marginal of the 13 independent stations.

1. 3. Extraction of cloud motion winds

Wind field maps of several atmospheric layers could be derived for every day with heavy precipitation by applying the cross-correlation technique after Schmetz *et al.* (1993).

Table 2 - Average deviation of wind speed and wind direction between 42 CMW'S and wind observations from the radiosondes San Christobal, Galapagos and Lima (1991/1993 El Niño).

	upper level	mid level	lower level
wind speed [m sec^{-1}]	±2	±1	±0.5
wind direction [°]	±15	±16	±23

The CMW's have been calculated for the low (850-700 hPa), mid (700-300 hPa) and upper atmospheric level (<300 hPa). For details of this technique refer to Schmetz *et al.* (1993) and Bendix & Bendix (1996). Information concerning the accuracy of this technique within the study area are presented in Table 2.

2. OVERALL CHARACTERISTICS OF PRECIPITATION

The interpolated maps of precipitation as well as the corresponding rainfall anomalies for the 1991/1992 and the 1992/1993 event are presented in figure 3. The greatest rainfall amounts have been observed in the coastal plains of north and central Ecuador but a secondary maximum is found in the arid region of south Ecuador close to the 1000 m contour line. Obviously, precipitation during the 1991/1992 event extends more to the south especially in the coastal area of northern Peru (Sechura desert). On the other hand, the inter-Andean basin as well as the Amazon region of Ecuador had been significantly dryer during the 1991/1992 event as in 1992/1993, especially in the northern part of Ecuador.

The rainfall anomalies also points out to a more intense event of 1992. Up to 1000% more precipitation could be observed in the arid coastal parts of north Peru especially between Tumbes (940%) and Talara (944%). On the other hand, only up to 300% surplus of rainfall could be measured during 1993 close to the 1 000 m contour

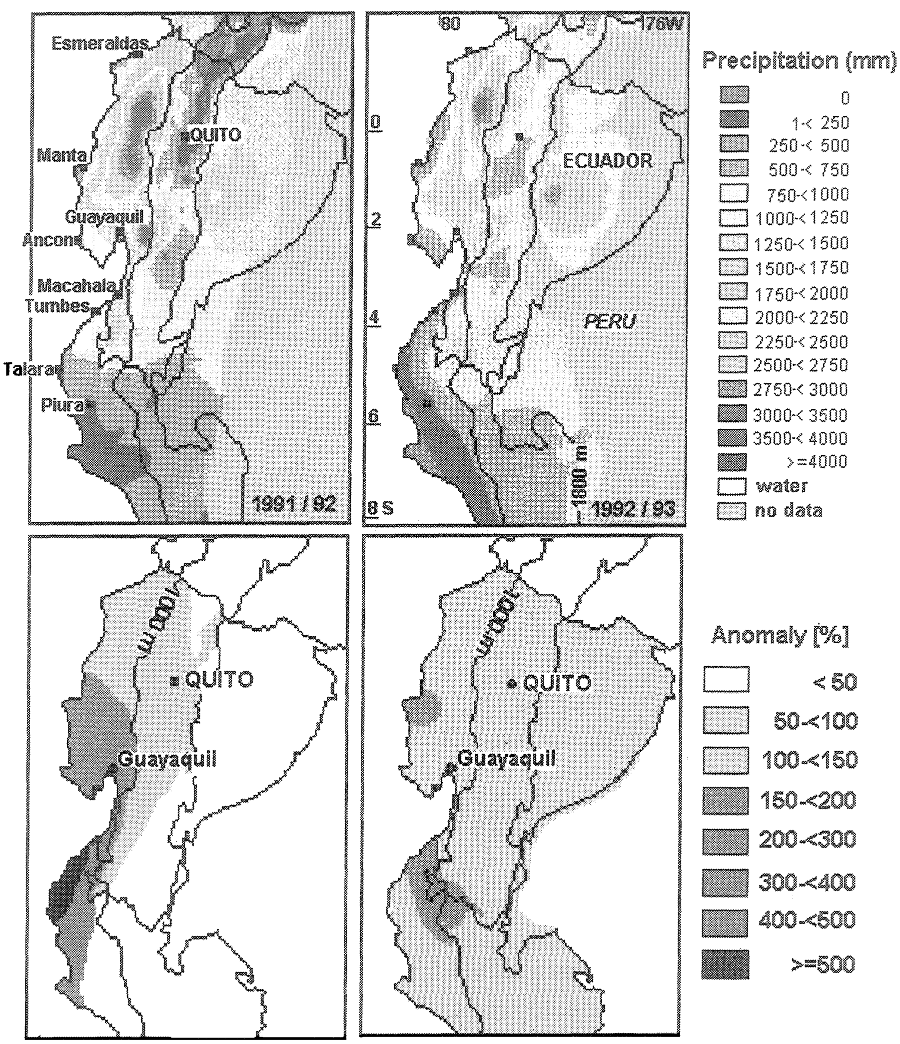

Fig. 3 - KED-interpolated precipitation maps for the 1992 and 1993 events (January-June) and corresponding anomalies.

line at the border between Ecuador and Peru. Generally, the 1992 event was weaker than the 1982/83 Niño (e.g. Talara = 8071%) but stronger than 1972/1973 (Bendix, 1994). The 1993 continuation is only of local importance.

A more detailed overview over the spatial extension of heavy precipitation also including the marine environment provides the CST map which was calculated for the 45 days (i.e. 1087 Meteosat-3 images) with the heaviest rainfall during 1992 (Fig. 4). The CST map generally affirms the precipitation maximum as seen in the interpolated map. Greatest amounts are also observed in the coastal plains up to the 1000 m contour line but the calculated spatial rainfall distribution is more patchy. It can be noted that local rainfall maximum are often related to the weak elevations of the coastal cordillera (<500 m asl) and hence, forced convection seems to be involved in rainfall formation. A remarkable local maximum can be observed over the Gulf of Guayaquil where convection is expected to be intensified due to more frequently increased SST's >28°C.

Further interesting features are generally weaker precipitation over the adjacent Pacific as far as the Galapagos Islands as well as the dry area at the eastern slope of the Ecuadorian Andes which is also present during a normal rainy season (Bendix & Lauer, 1992).

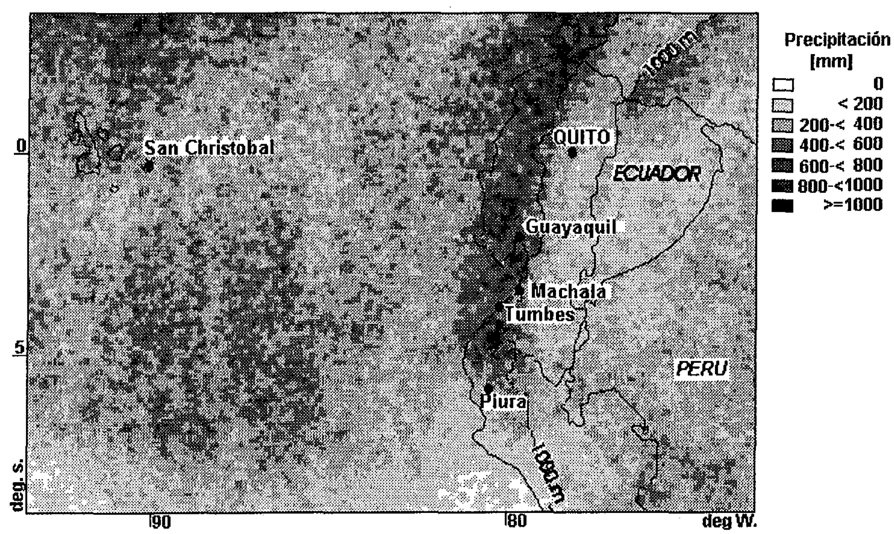

Fig. 4 - CST-precipitation map for the region of Ecuador and Peru for 45 days of heavy rains (1991/1992 El Niño event).

3. PRECIPITATION FORMATION

Some theories which accounts for the formation of severe precipitation in Ecuador and north Peru have been derived from preceding EN events:

Local precipitation formation due to the land-sea-breeze system (e.g. Horel & Cornejo-Garrido, 1986). Deep convection is sometimes intensified due to an outburst of convective activity from the Amazon basin across the Andes (e.g. Goldberg *et al.*, 1987).

Extensive atmospheric instability due to an increase in sea surface temperature (SST) in combination with a southward shift of the Inner Tropical Convergence Zone (e.g. Miller & Laurs, 1975; Caviedes & Endlicher, 1989)

3. 1. Precipitation patterns due to the land-sea-breeze

The most of the 45 days with severe precipitation are characterized by a weak land-sea-breeze phenomenon which mainly causes local precipitation. Land and sea breeze in the arid coastal plains of south Ecuador and north Peru are only developed at increased SST during Niño situations. In normal years, the greate thermal contrast between cold up-welling and heated desert causes a divergent coast parallel stream flow (thermo-tidal wind, see Horel & Cornejo-Garrido, 1986.) The typical course of deep convection is presented in Fig. 5.

The sea-breeze is developed at 10 LT (Manta) and initiates convection within the coastal plain until 19:00 LT especially in northern and central Ecuador. Cloud free is the

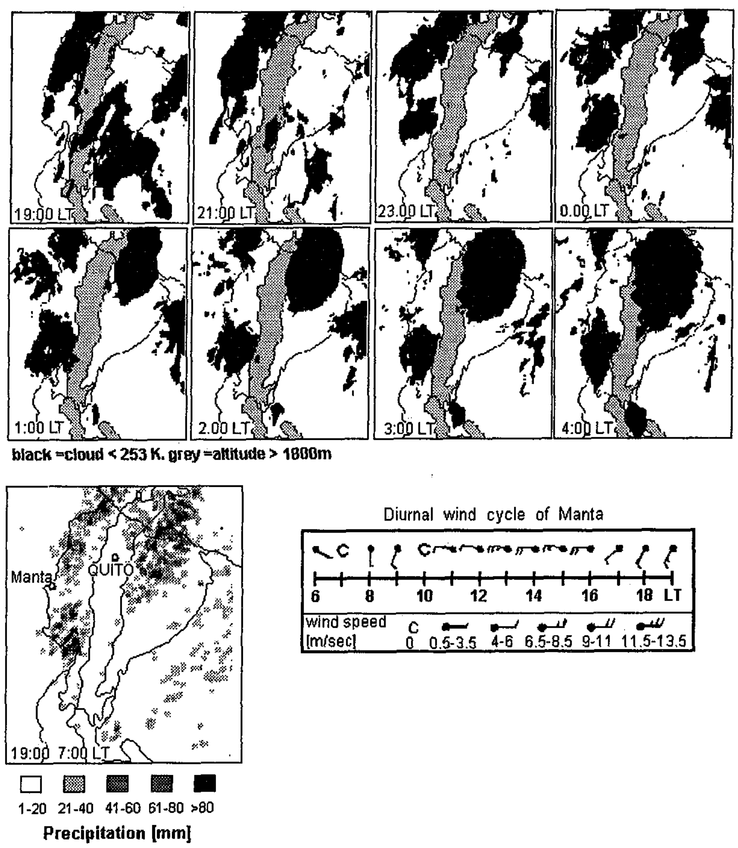

Fig. 5 - Cloud formation, precipitation (CST) and wind observations (station Manta) 29/30 May 1992.

area in the vicinity of the Gulf of Guayaquil because the shape of the coastline favours a divergent stream flow. Later at night, the areas of deep convection are shifted off the coastline due to the well developed land-breeze which can be observed e.g. at the station Manta (6:00 LT). Especially convection over the Gulf of Guayaquil is again influenced by the shape of the coastline which favours a convergent land breeze. The CST map shows that the areas of precipitation >80 mm 12 hours^{-1} are locally confined to just a few places with its maximum over the Gulf of Guayaquil.

3. 2. Precipitation patterns due to extended atmospheric instability

A typical weather situation for the central El Niño period during March-April is presented in figure 6.

Centers of heavy precipitation are the eastern Amazon, the Pacific area north and south of the Galapagos Islands as well as the coastal plains of Ecuador and north Peru.

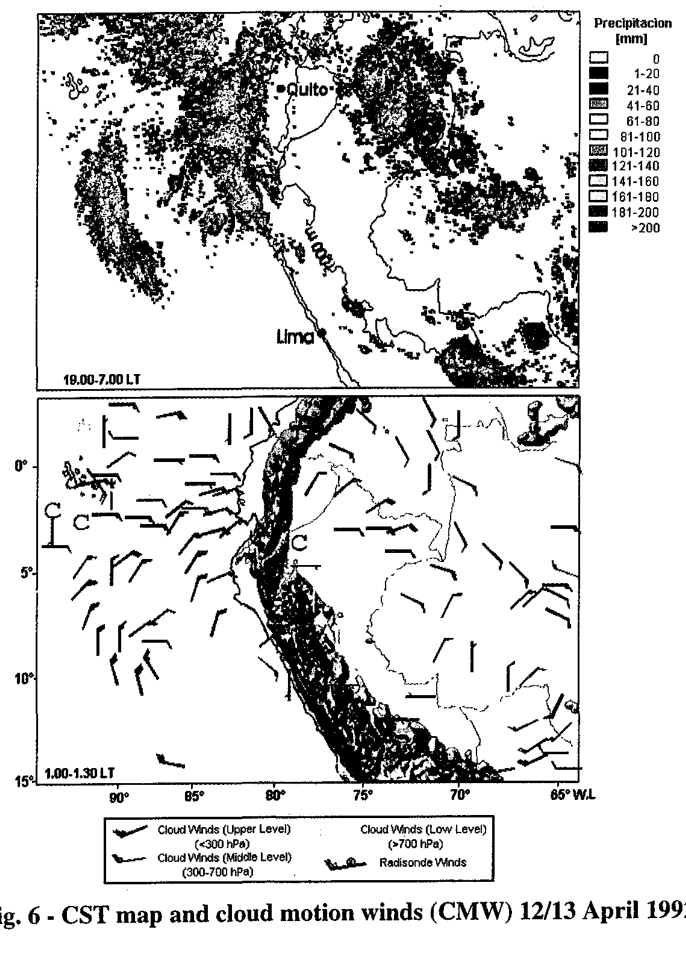

Fig. 6 - CST map and cloud motion winds (CMW) 12/13 April 1992.

The severest rainfall >200 mm 12 hours^{-1} occurs within the Sechura desert close to Piura as well as on the peninsula Sta. Elena and the adjacent coastal waters. Deep convection is organized in mesoscale convective complexes (MCC) which are related to an extended instability of the lower troposphere over areas of SST's 28°C mainly due to the suppression of coastal up-welling off the coast of Ecuador and Peru. The MCC's show no well-defined diurnal cycle as it is observed for precipitation formation due to the land-sea-breeze phenomenon.

The circulation patterns in the upper level are characterized by easterly winds along the equator but a meridional wind direction (from north) over the precipitation field south of Galapagos. This meridional stream flow replaces the trades of the south Pacific anticyclon which are normally well developed in this area. It represents a weak Walker in relation to an intensification of the Hadley circulation due to a great meridional contrast in SST which is also typical for the main El Niño phase (Kousky & Ropelewski, 1989). Convection in this area is sometimes originated from convective cloud lines which indicate an extended instability and are only observed during El Niño situations (Goldberg *et al.*, 1987).

4. CONCLUSIONS

The present investigation has shown that satellite data are an appropriate tool to examine the extension, formation and dynamics of severe precipitation in Ecuador and Peru during El Niño situations. The maximum of precipitation could be found within the coastal plains and the adjacent ocean as well as over the Gulf of Guayaquil with the greatest anomalies in the normally arid regions of Ecuador (peninsula Sta. Elena) and north Peru (Sechura desert). The formation of severe precipitation is either local due to the land-sea-breeze phenomenon or more extended due to deep convection which is frequently organised in MCC's. However, the overall spatial structure of rainfall reveals significant analogies to a normal rainy season even if its southward extension is much greater. On the other hand, satellite-based case studies of the 1982/1983 Super Niño have shown some deviations to the situation of a normal Niño. Therefore, the expected strong event of 1998 provides a good opportunity to compare a normal (1991/1992) and an extreme Niño situation.

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