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Synoptic climatology of cut-off low events that produced extreme precipitation in Valencia, Spain

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Abstract: A seasonal synoptic climatology of cut-off lows (COLs) that produced extreme precipitation in the Valencia region of Spain during 1998-2014 is presented. COLs were shown to be the main producer of extreme precipitation in the region, especially during the transition seasons. The strongest raining COL events occurred during September-November. Six-day composites of lower and upper tropospheric winds, geopotential, sea-level pressure and precipitation show that COLs that produce extreme rainfall in this region remain stationary over Spain for 2-3 days and produce rainfall over the Valencia region for at least two days. In the low levels these COLs are characterized by low pressure over the Mediterranean sea and winds with an easterly, onshore component. Another interesting aspect of the composites is that transition season COLs are characterized by the presence of a filament of moisture that extends from the tropical Atlantic to Spain suggesting a role for remote moisture transport to feed COL rainfall. Further analysis is needed to confirm this hypothesis.

Keywords: cut-off low, extreme precipitation, seasonal climatology

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1. Introduction

The Iberian Peninsula (IP) is a region of contrasts. It experiences strong spatial and temporal precipitation extremes ranging from the wet northwestern Cantabric coast to the dry Levante region along the Mediterranean Sea in the southeast. While precipitation in the wet Cantabric coast is associated with the passage of frontal systems, in the Levante region precipitation can be more episodic and extreme with a few precipitation events causing a large portion of the total annual precipitation. One common scenario for the occurrence of precipitation extremes along the Levante region is the presence of a cut-off low in the upper troposphere, a phenomenon locally known as a 'gota fría', referring to the presence of very cold air within the cut-off low. At the surface, winds with an easterly component blow over the warm Mediterranean sea pushing warm humid air upward along the intricate topography of eastern Spain [1]. Such events can bring extreme precipitation amounts to locations along the coast producing river flooding (locally knowns as 'riadas'), such as the one in the Rio Seco of El Campello, Spain on 8 September 2015 pictured in Figure 1.

Study [2] used 10 years of warm season ERA Reanalysis to study COLs in the Mediterranean region. They found that deep cut-off lows tend to produce the most intense and widespread rain episodes, mainly distributed to the south of the cut-off low center. Shallow COLs on the other hand produce weak convective precipitation near the center of the system, or no precipitation at all. A 41-year study [3] found that an average of 2.3 COLs affect the Iberian Peninsula each year. COL systems located in the western half of the Iberian Peninsula and adjacent Atlantic Ocean bring rainfall to a large portion of Spain, including the Valencia Province. COLs in the southwestern quadrant of the IP and adjacent Atlantic and Morocco bring the largest precipitation amounts (30-40 mm) while COLs located in the northwestern quadrant and adjacent Atlantic bring less precipitation (20-30 mm) to the Valencia Province. About a third of COLs that affect the IP produce no rain while a third produce generalized rain over the entire [3]. Most COLs occur in Spring and Summer, with the fewest COLs occurring in the wintertime when the jetstream is located further south and Spain is in the cyclonically sheared side of the jet, inhibiting upper-level thinning troughs [4] and the formation of COLs. As climate changes the Mediterranean region of Spain is projected to become drier [5,6].

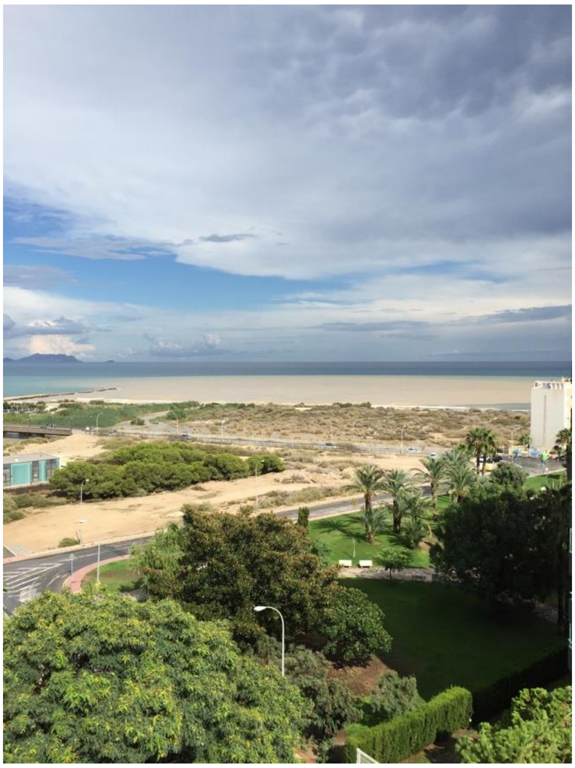

Figure 1: Rio Seco flooding in El Campello, Spain during a COL event on 8 September 2015. Note the large amount of sediment deposited on the Mediterranean Sea by the flood.

The question of how COLs, which bring a substantial amount of precipitation to the region, will change as the climate warms, is an important issue for this already water-stressed touristic region of Spain. The objective of this study is to create a seasonal synoptic climatology of COLs that produce extreme precipitation in the Valencia region of Spain. This work will serve as a benchmark for a future modeling study of the effect of climate change on COL events that produce extreme rainfall in the region.

2. Datasets and Methodology

The datasets used in this study are the high-resolution NASA TRMM (National Aeronautics and Space Administration's Tropical Rainfall Measuring Mission) precipitation and the NCEP (National Center for Environmental Prediction) reanalysis from 1998-2010. The TRMM-3B42 daily precipitation dataset provides homogeneous spatial and temporal precipitation coverage from 50°N to 50°S at 0.25° resolution [7]. The NCEP Reanalysis [8] is a global, daily 2.5° horizontal resolution blend of observations and model. In this study the NCEP Reanalysis sea-level pressure, winds and geopotential anomalies, and the TRMM daily precipitation are used to construct composites of the lifecycle of COLs that produced extreme precipitation amounts over Valencia, Spain.

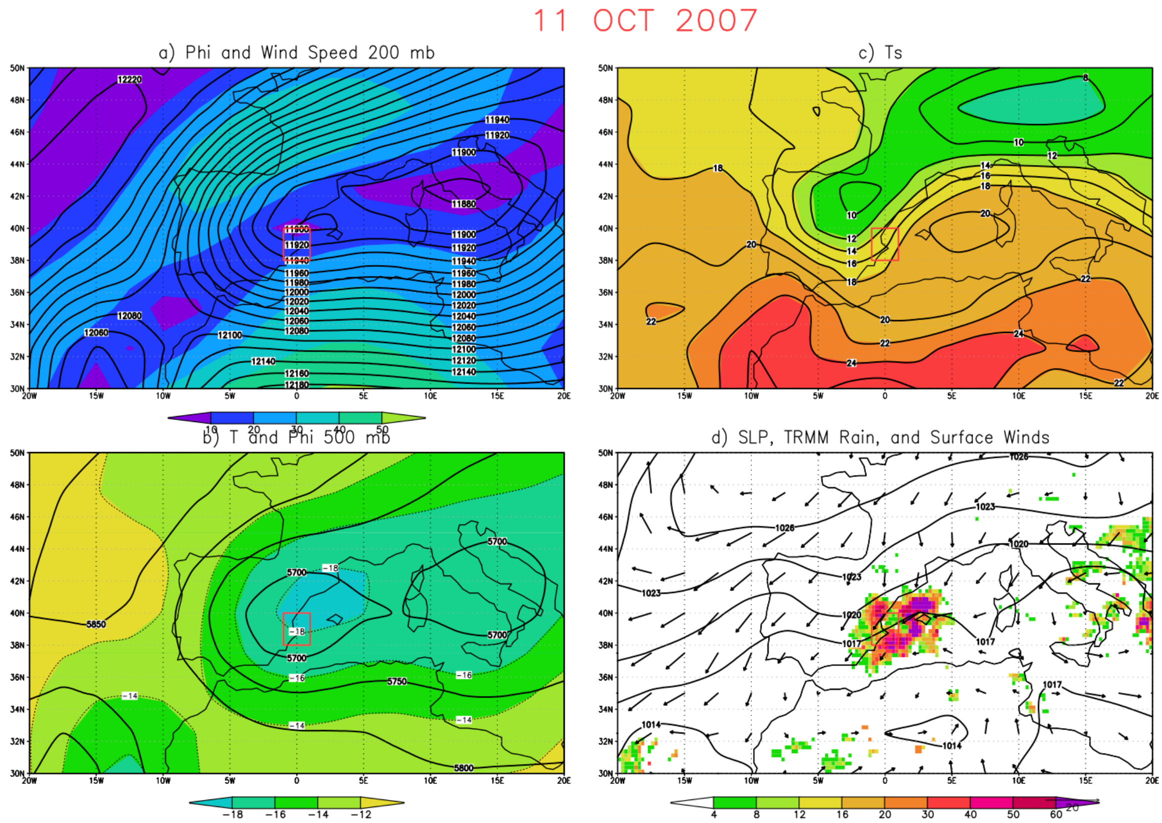

Figure 2: NCEP Reanalysis a) 200 mb geopotential height (Phi, in m) and wind speed (m/s), b) 500 mb temperature (°C) and geopotential, c) surface temperature (°C) and winds, and d) sea level pressure (mb), surface winds (m/s) and TRMM rainfall (mm) for the COL event that produced extreme rainfall in the *Valencia box* on 11 October 2007. The *Valencia box* is outlined by a red square.

Daily TRMM rainfall values from 1998-2014 were averaged for the dataset box that encompasses Valencia (38-40°N, 1°W-1°E, hereafter the *Valencia box*). For the purposes of this study an extreme event was defined as an event that produced more than 20 mm of precipitation in one day, a threshold that represents the top 1% of the distribution. Subjective analysis of the daily NCEP Reanalysis upper-level winds and geopotential was used to determine whether a COL was present at the time when each extreme event occurred. Figure 1 below shows the COL that occurred on 28 September 2012. In that event a closed low or COL system is present was present at 200 (Figure 2a) and 500 mb (Figure

2b) and strong precipitation (Figure 2c) occurred in the southeast quadrant of the IP. All COL events included in the composites presented herein had a closed cold low at 200 and/or 500 mb on the day of the extreme rainfall. Extreme rain events that were clearly caused by frontal systems that propagated across the IP were not included.

Daily TRMM rainfall and NCEP Reanalysis were used to calculate six-day composites of precipitation, sea-level pressure (SLP), 925 mb humidity and moisture flux convergence, 200 mb winds and 200 mb geopotential for the COL events that produced extreme precipitation in the *Valencia box* during March-May (MAM), September-November (SON), and December-February (DJF). The composites were calculated for the day of the extreme rainfall in the *Valencia box* (day0) and for the n^{th} day prior to its passage (day-n) and the n^{th} day after its passage (day+n).

3. Results

The total rainfall in the Valencia box between 1998-2014 was 6,853 mm, or about 400 mm/year. A total of 46 extreme events, or about 2.2 events per year, occurred in the *Valencia box*. Those extreme events produced 1,412 mm of rain, or about 20% of the total rain. COLs were the most common type of extreme rainfall producing events (Table 1) and they produced 1,046 mm of rain (Table 2), or about 75% of the extreme rainfall. The majority of the extreme rain events occurred in the transition seasons (32% in MAM and 48% in SON) and no extreme precipitation event occurred during the summer in the study period.

Table 1. Number of extreme rainfall events detected in the *Valencia box* between 1998-2014. Events are distinguished into those produced by COLs and other phenomena.

Season	COLs	Other
MAM	12	3
JJA	0	0
SON	16	6
DJF	5	4

Table 2. TRMM rainfall (mm) from COLs in the *Valencia box* between 1998-2014.

Season	COL Rainfall
MAM	359
JJA	0
SON	556
DJF	131
Total	1046

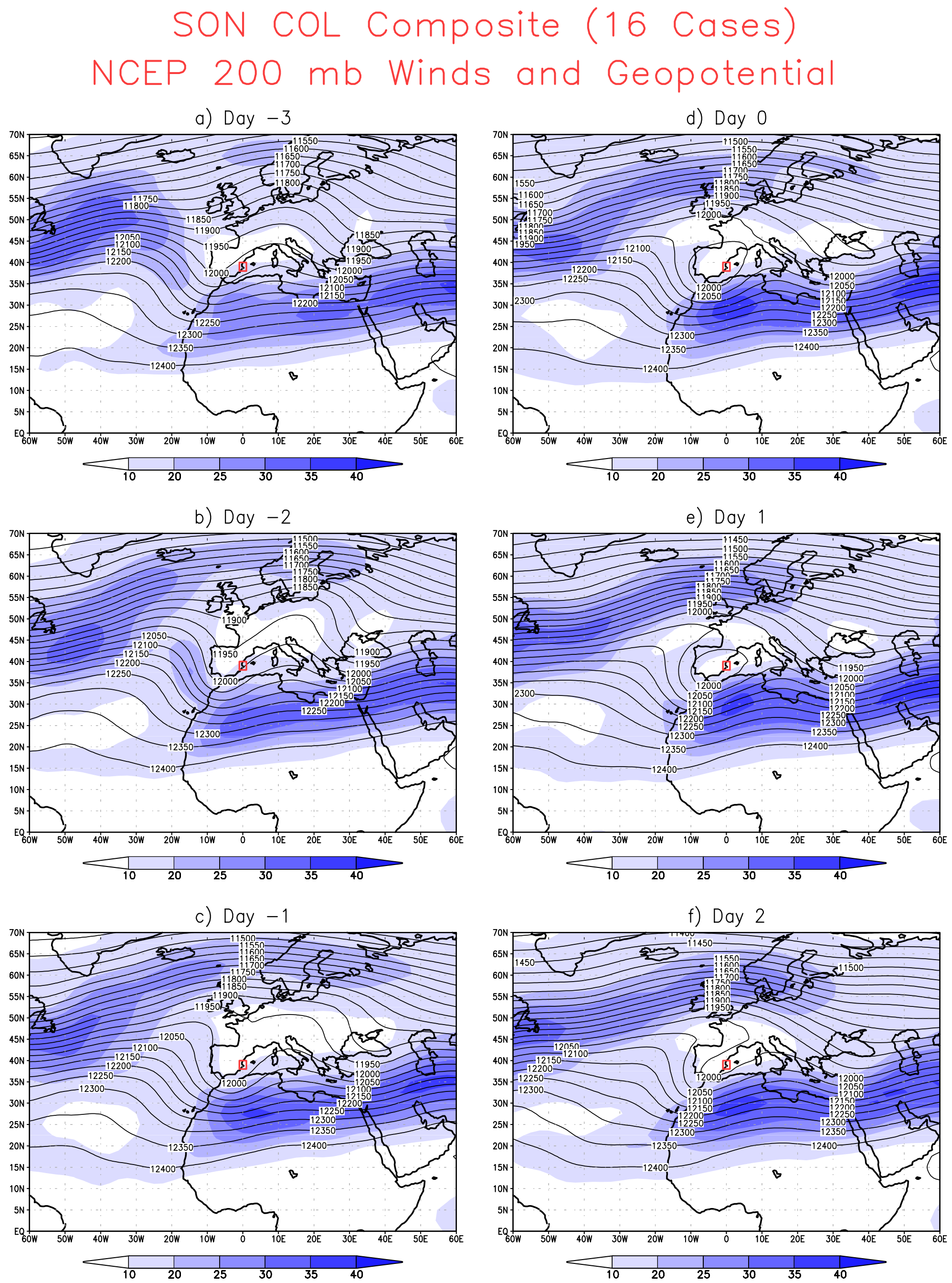

Figure 3. Composite 200 mb winds (shaded in blue) and geopotential heights (contours) for the 16 COL events that happened durint SON. Location of the *Valencia box* is shown in red. Composite plots for day-3 through day+2 are shown.

3.1. Composites

The lower and upper tropospheric composites for the SON, MAM and DJF COL events that produced extreme precipitation in the *Valencia box* during 1998-2014 are analyzed below. Figure 3 shows the

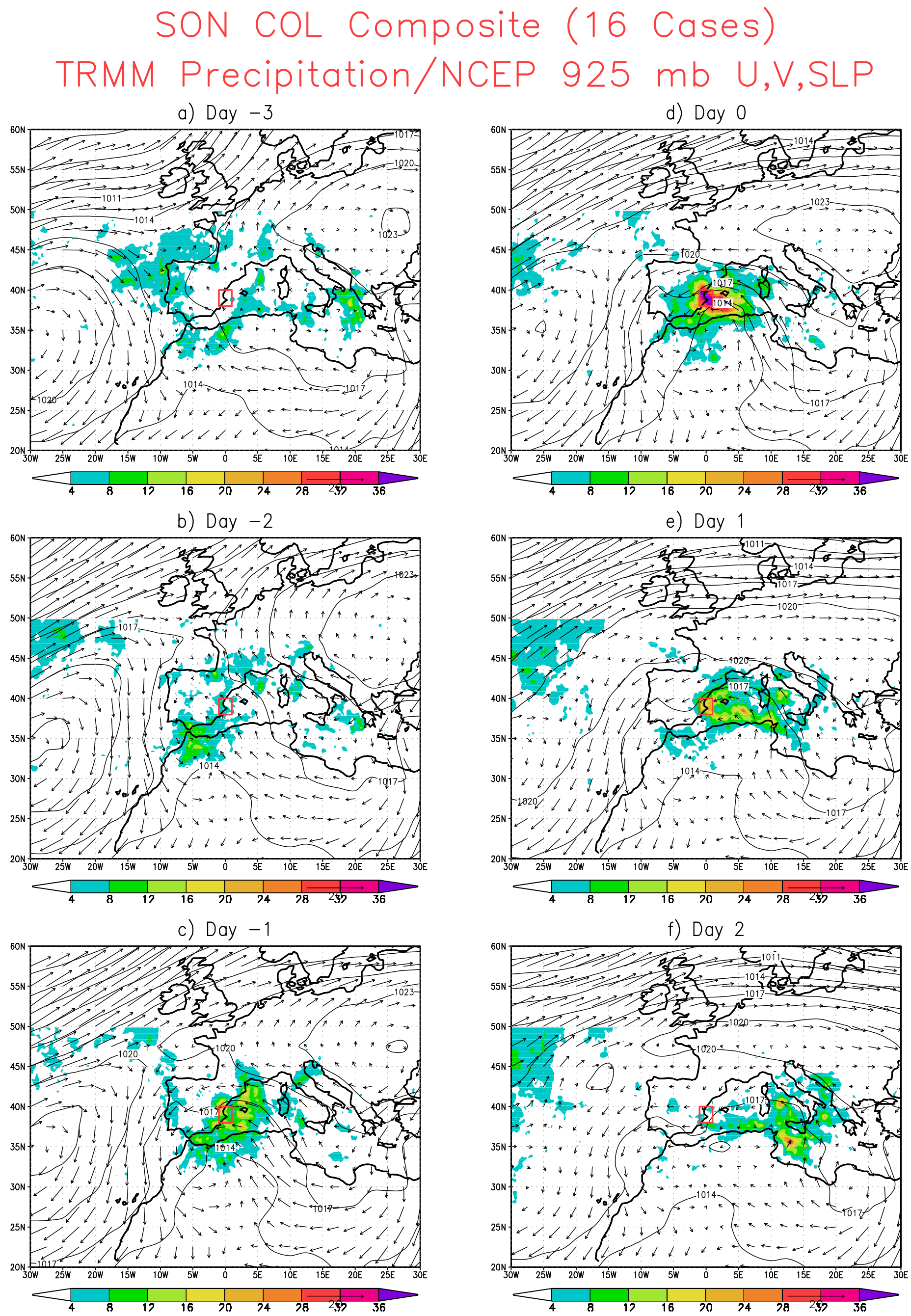

Figure 4. Same as Figure 1 but for NCEP Reanalysis SLP (contours) and 925 mb winds (vectors), and TRMM rainfall (shaded).

200 mb wind speed and geopotential height composites for the 16 COL events that produced extreme rainfall in the Valencia box during SON. A shortwave trough that is present over Spain on day-3 to day-1 is cut off from the mean westerlies and becomes stationary over Spain on day0 and day+1. The COL occurs on day0 and day+1 in a region of weak upper tropospheric winds and low meridional shear that falls between the subtropical and polar jets. The weak winds and low meridional shear favor the formation of a stationary COL. Figure 4 shows the TRMM precipitation, SLP and 925 mb winds composite for the SON COLs. The composite SLP shows an inverted trough over northern Africa that digs northward and produced rainfall in southern Spain, northern Algeria and Morocco on day-2 (Figure 4b). As this low-level trough continues to dig northeastward, its associated closed low at 925 mb produces onshore northeasterly winds along the eastern coast of Spain from day-1 to day+1 (Figure 4c-e). The composite COL produces rainfall in the *Valencia box* and adjoining Mediterranean Sea on day-1 through day+1. The *Valencia box* received rainfall in excess of 80 mm during a typical three-day rain episode (Figure 5c).

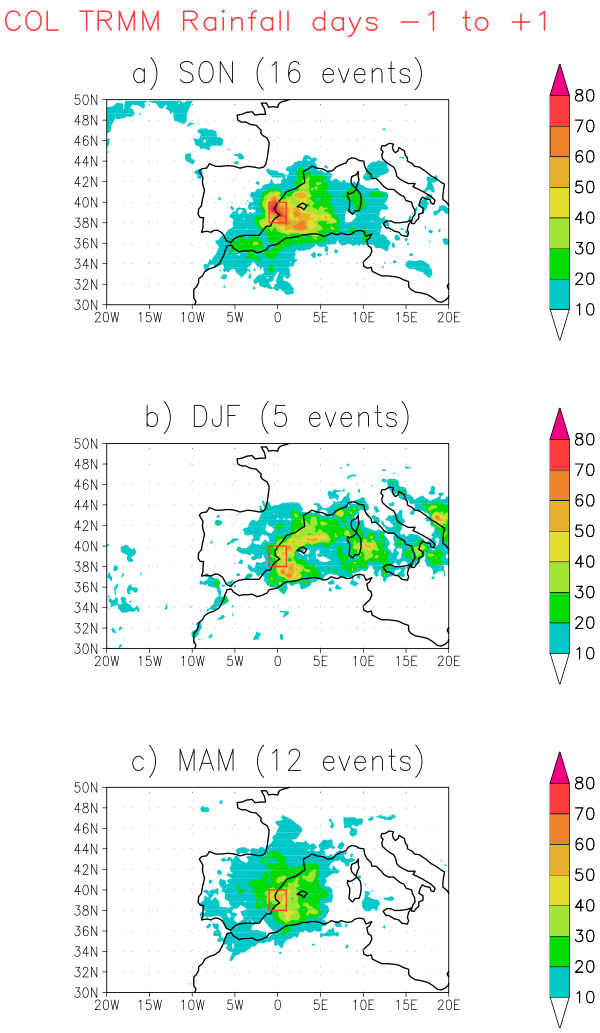

Figure 5. Accumulated day-1 to day+2 composite COL rainfall (in mm) for each season.

At 925 mb on day-2, day-1 and day0 a filament of high humidity streams northwestward from the moist tropical Atlantic toward eastern Spain (Figure 6), where a concomitant strong moisture flux convergence occurs at 925 mb. This suggests that remote moisture sources may play a role in fueling extreme rainfall in the *Valencia box* during COL events.

The MAM composites (not shown) are very similar to the SON composites described above. However, the total amount of precipitation produced by these COLs over the duration of the event is lower, at about 50-60 mm (Figure 5b), with most of the rain occurring on day0. This makes sense in view of the fact that sea-surface temperatures in the Mediterranean are cooler and the air is much drier in MAM than SON. The composite for the 5 COL events that occurred during DJF (now shown) is also similar to the SON and MAM composites. Although the wintertime sample is small, it indicates the presence of a blocking pattern at 200 mb that lasts from day-1 to day+2, likely contributing to the formation of the COLs. Similarly to the MAM COL events, the bulk of the precipitation during the wintertime events occurred on day0. The averaged total rainfall during the wintertime COL events was about 20-30 mm, a value that is the lowest of the three composites and is in line with the fact that the Mediterranean sea surface temperatures and specific humidity is much lower in winter than during the rest of the year.

4. Discussion

As climate warms the Iberian Peninsula is expected to become warmer and drier and precipitation extremes are predicted to increase [5]. The effect of climate change on extreme precipitation in Spain is therefore a subject of active interest. Given the importance of COLs in producing extreme rainfall it is important to study of how COL precipitation might change as the climate warms. Some preliminary simulations to address this question were undertaken as part of this study. Present and future climate simulations of six COL events during SON were produced using the Weather Research and Forecasting (WRF) model. Future climate simulations were performed using the pseudo global warming (PGW) approach in an implementation similar to [9] and [10], but with a 10 km horizontal resolution innermost grid. Under present climate conditions WRF represented well the amounts and distribution of precipitation as well as the location and strength of the COLs. However, a comparison between the future and present climate simulations did not show a consistent increase or decrease in precipitation associated with these COL events, pointing to the need of a more detailed study of the effect of climate change on COL precipitation in the IP.

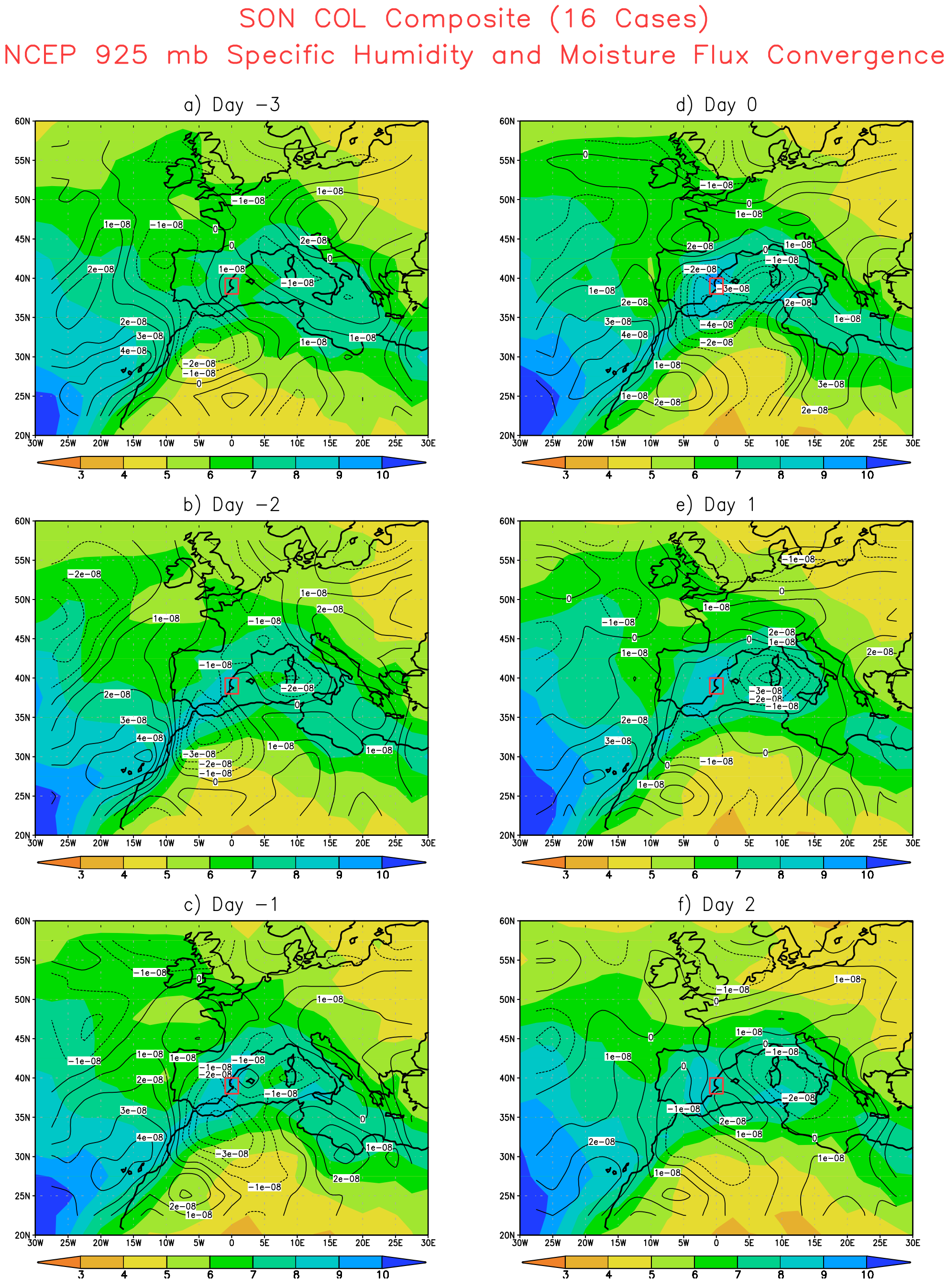

Figure 6. Same as Figure 1 but for NCEP Reanalysis 925 mb specific humidity (shaded in g kg^{-1}) and moisture convergence (contours in g m kg^{-1} s^{-2}).

The composite analyses above shows important characteristics of COLs and extreme rainfall in the Valencia region for the present climate. The question of how COLs and extreme rainfall will change in a future warmer climate is of utmost importance for the region.

4. Conclusions

This study presents results from a seasonal synoptic climatology of COLs that produced extreme rainfall events in Valencia, Spain during 1998-2014. Precipitation data from the TRMM satellite and NCEP Reanalysis data were used to produce 6-day composites of COL systems that produced extreme rainfall over the *Valencia box*. It was found that COLs produced 33 of the 46 extreme rainfall events detected in this study and 75% of the extreme rainfall in the *Valencia box*. The rainiest COLs occur in SON, followed by those in MAM and DJF. No extreme rainfall events were detected during the summer. The mean annual rainfall over the region was 400 mm/year, of which about 20% were produced by extreme events. The vast majority of the extreme rain events occurred in the transition seasons, namely 32% in MAM and 48% in SON, and no extreme precipitation event occurred during the summer in the study period. The upper-level composites clearly show a COL that lasts at least 2 days (3 days in MAM) in the 200 mb geopotential. The COLs form in a region of weak upper level winds between the subtropical and polar jets. At the surface the SON and MAM composites show an inverted trough over northern Africa that extends northward producing rainfall in Spain from day-2 to day+1. According to the composites a typical COL episode produced rain in the Valencia box on day-1 through day+1, with the strongest rain falling on day0. A filament of high humidity that streams northwestward from the moist tropical Atlantic toward eastern Spain on COL days suggests that some of the moisture that feeds rainfall during a COL episode is imported from the tropics. A detailed analysis of the moisture budget of a COL is needed to determine the relative importance of local and remote sources of moisture for rainfall in this dry region of the world.

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Conflicts of Interest: The author declares no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

COL: Cut-off low
DJF: December-February
IP: Iberian Peninsula
JJA: June-August
MAM: March-May
NASA: National Aeronautics and Space Administration
NCEP: National Center for Environmental Prediction
PGW: Pseudo global warming
SON: September-November
SLP: Sea level pressure
TRMM: Tropical Rainfall Measuring Mission

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