INFLUENCE OF THE ATLANTIC NIÑO ON THE MEDITERRANEAN CLIMATE VARIABILITY

This project was presented for the MedCLIVAR grants to support the exchange of young scientists between institutes for Ms. Teresa Losada Doval, PhD student at the Universidad Complutense de Madrid (Spain), to spend 18 weeks as visiting scientist at the Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste (Italy).

The proposal pursued the understanding of one of the possible mechanisms responsible for the observed Mediterranean climate variability, which is one of the MedCLIVAR aims; and can be included in the main theme of the ESF MedCLIVAR Programme "Connections between Mediterranean and global climate variability".

1. Purpose of the visit

The aim of the project was to improve the understanding of the connection between the tropical Atlantic variability and the Mediterranean climate variability, with special attention on the possible influence of the Atlantic Niño on the Mediterranean area in recent decades (from the late 70s)

Just a few works describe the statistical connection between the TAV and the Mediterranean. Baldi et al. (2004) relate positive SST anomalies in the Tropical Atlantic during summer with colder and wetter conditions in the Western and Central Mediterranean in late summer (July and August), pointing to the perturbation of the Hadley cell and the storm track as key factors in the possible mechanisms linking these two areas. Under the influence of ENSO, Ward (1998) found the same relation; although he also pointed out that some part of this association is independent of ENSO. Ward (1998) found their statistical relationship for the period 1948-1988.

Baldi et al (2004) found a relation between EM and Aug-Sep Med, using data for the period 1986 – 2002. They related warm anomalies in the tropical Atlantic during summer with cold and wet conditions over the Central-Western Mediterranean in late summer. To explain this situation they proposed a mechanism involving changes in the Hadley circulation. Anomalous cold (warm) SST over the tropical Atlantic lead to a more (less) intense monsoon and a northward (southward) shift of the ITCZ, consequently there is an increase (decrease) of the downward motion over the West Med region, an anomalous high (low) pressure over that region and, thus, less (more) precipitation. They also showed how, during august 2002, anomalous warm SST in the tropical Atlantic occur concurrently with a blocking over the Subtropical Atlantic that splits the jet into two parts, leading to a fall-like configuration with storms affecting central and southern Europe.

In addition, number of papers have pointed out the relationship between the Indian SSTs and the Mediterranean (Bader and Latif, 2003, Raicich et al., 2003). Together with Kucharski et al. (2007, 2008 and 2009) results regarding the Atlantic-EM and Indian SST relationship, all these findings could add some insights to the connection between the Equatorial mode and the Mediterranean.

Rodriguez-Fonseca et al. (2009b) have recently found a different a atmospheric response to the

Mediterranean SSTs in relation to WAM when using time series before and after the so-called climate shift (Cane et al. 1997). A relation tested in numerical models by Fontaine et al. (2009). Clarifying the origin of this change in the Mediterranean is also of crucial importance in the context of climate change, regarding the vulnerability of the region described in the literature (Vorosmarty et al., 2000).

Thus, the main objectives of this work are:

1. To study the existence and characteristics of the EM-Late Summer Mediterranean relationship.
2. To establish the grade of the coupling between EM-Med precipitation.
3. To describe the differences in the response before and after the climate shift: when is the relation stronger? Do the characteristics of the response change between periods?
4. To find the key factors determining the changes of this response, if there is any.

2. Description of the work carried out during the visit

The first step of the work was an observational study completing those made by previous authors (Baldi et al., 2004; Ward, 1998), using both regressions onto the Atl-3 index and a new methodology developed by the UCM group: the EMCA described in Polo et al. (2008).

We made a special effort to describe the changes on the Mediterranean response to the Equatorial mode before and after the climate shift, by dividing the whole period of study (1958-1998) into two parts, taking 1979 as the year of the split.

In a second step we analyzed the results of the simulations done with four different AGCM forced with the same Equatorial-Atlantic-like SST anomaly (Losada et al., 2008a) in order to describe the mechanisms underlying the connection between the tropical Atlantic and the Mediterranean region.

The findings of the previous parts of the work led us to perform different simulations with a coupled model available at the host group: the Speedy Atmospheric General Circulation Model (AGCM) coupled to an SLAB ocean model (Kucharski et al., 2006) in the extratropical Atlantic and Mediterranean areas.

3. Description of the main results obtained

<u>Precipitation response to Atl3 before and after 1979</u>

Figure 1 shows the regression of the observed precipitation (CRU data) onto the Atl3 index. The results have been divided in two periods (1958-1978 and 1979-1998). For the second period the regression was also performed for CMAP data.

For both periods the response over Central Europe is similar, with increased precipitation for a warm tropical Atlantic ocean. Nevertheless, the magnitude of the precipitation anomaly in Eastern and Central Europe increases after 1979.

For Western Europe (Iberian Peninsula, British islands and south of France) the response shifts from positive precipitation anomalies during 1958-1978 to negative ones during 1979-1998.

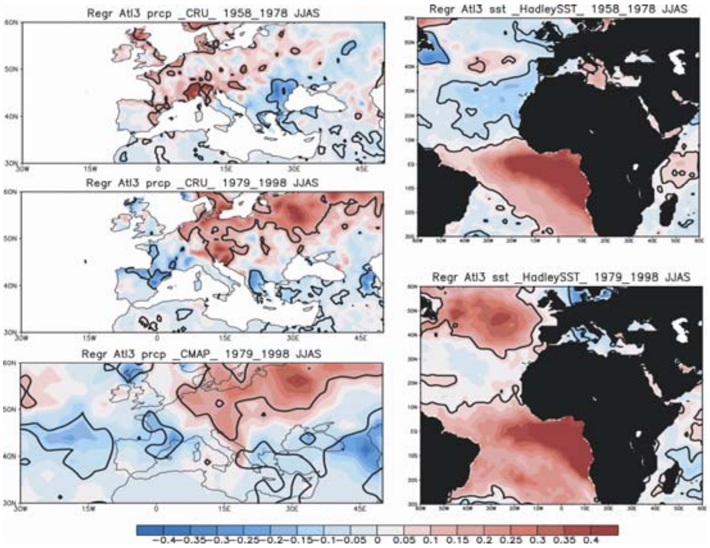


Figure 1: Regression of CRU precipitation (left) and Hadley SST (right), into the Atl3 index, for 1958-1978 (top) and 1979-1998 (center). Bottom:Regression of CMAP precipitation (left) and Hadley SST (right), into the Atl3 index, for 1979-1998 period.

We compare these results with those obtained in a simulation performed with the Speedy AGCM, forcing with monthly SST observed from 1949 to 2002 (Figure 2), we will refer to this simulation as **Speedy GLOB SST**. In this simulation, the speedy model is able to somehow reproduce the observed precipitation anomalies associated with the Atl3 index, specially for the second period: warm Atlantic SST related to increase of the precipitation over central Europe, and decrease of precipitation in the Iberian Peninsula and Southern France and also in Greece. However, the positive precipitation anomalies over central Europe are located a bit too north and the amplitude of the anomalies is weak compared to the observations.

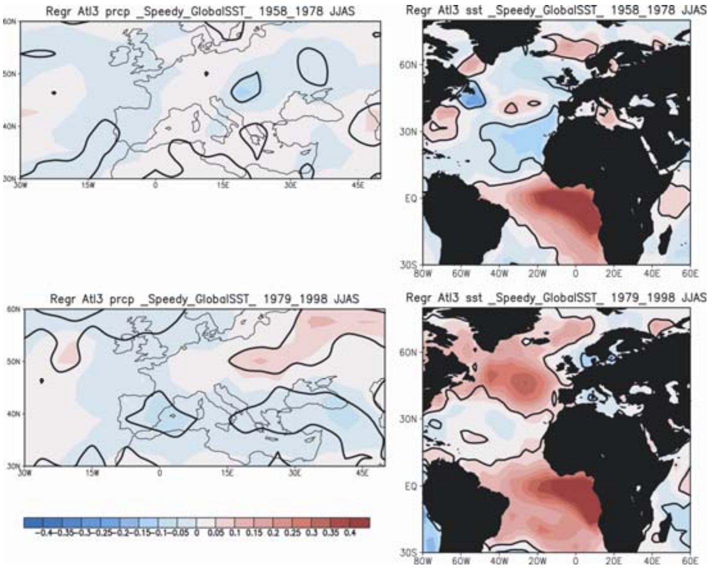


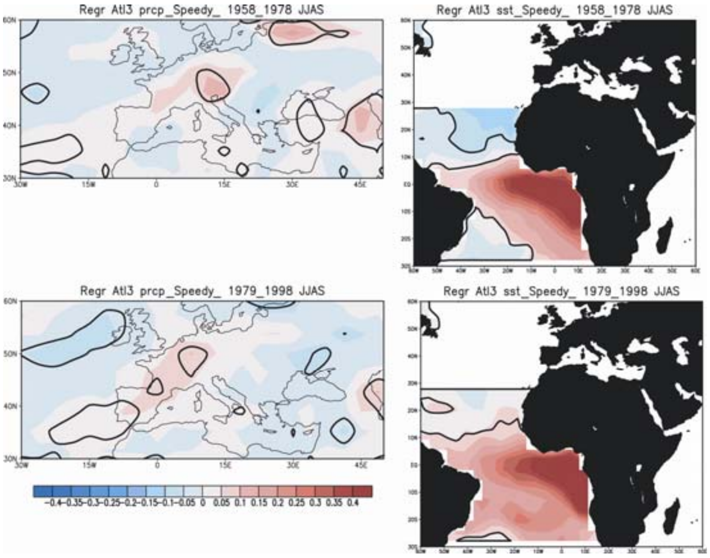
Figure 2: Regression of **Speedy Global SST** precipitation (left) and SST (right), into the Atl3 index, for 1958-1978 (top) and 1979-1998 (center).

It is worth to notice the important differences in the subtropical and extratropical North Atlantic SST anomalies, and in the Mediterranean Sea, between the two periods of the analysis.

To test whether the extra-tropical Atlantic SST anomalies are having an influence in the European precipitation differences between periods, we regress the rainfall response of a Speedy simulation forced with observed SST in the tropical Atlantic and climatology elsewhere, onto the Atl3 index (Figure 3). We will call that simulation **Speedy TATL**

The results of the **Speedy TATL** simulation differ from those of the observations: for the observations, the precipitation show negative values over western Europe (Iberian Peninsula and South of France) during the second period; in **Speedy TATL** results the difference of the response between the two periods is weaker, and precipitation anomalies over western Europe remain positive for the second period. As the tropical SST pattern associated with the Atl3 index doesn't show significant differences between periods, this result points to a forcing external to the tropical Atlantic and, thus, to an interaction between different ocean basins in the second period, opposed to a more “Only-Tropical Atlantic” influence for the first period.

Although these results may be model dependent, they suggest that the Mediterranean response to the EM doesn’t show such an important change before and after the climate shift.


Regr Atl3 prcp_Speedy_ 1958_1978 JJAS

Regr Atl3 sst_Speedy_ 1958_1978 JJAS

Regr Atl3 prcp_Speedy_ 1979_1998 JJAS

Regr Atl3 sst_Speedy_ 1979_1998 JJAS

Figure 3: Regression of **Speedy TATL** precipitation (left) andSST (right), into the Atl3 index, for 1958-1978 (top) and 1979-1998 (bottom).

EMCA analyses

To study the co-variability between the tropical Atlantic SST and the Mediterranean precipitation, an Extended Maximum Covariance Analyses (EMCA, Polo et al., 2008) has been performed between the predictant field (SST) developing from spring to winter (MAMJ to SOND) and the mediterranean (30N-50N, 15W-40E) precipitation in summer (JJAS). This study will help to elucidate if the pattern depict in the Atl3 study is a mode of variability, and how much variability it explains.

The results show a response very similar to the Regressions onto the Atl3 for observations and SPEEDY data.

The square covariance fractions explained by each one of the EMCAs is displayed in table 1. The explained covariance is higher for the second period for both the observational and modelled results.

Table 2 shows the correlation between the two Expansion Coefficients of each EMCA (ruv), indicating the covariability of the two fields explained by the EMCA. It is worth noting that, even though the explained covariance is higher for the second period, the fraction of covariability between the two fields is lower during this second period.

CMAP 79-98	0.4221
CRU 79-98	0.3781
CRU 58-78	0.2807
Speedy GLOB 79-98	0.4839
Speedy GLOB 58-78	0.4665

Table 1: Squared Covariance Fraction of EMCA performed with observations (CMAP and CRU precipitation data) and **Speedy GLOB** model results for the two periods of study

CMAP 79-98	0.5727
CRU 79-98	0.5477
CRU 58-78	0.6072
Speedy GLOB 79-98	0.6370
Speedy GLOB 58-78	0.6480

Table 2: ruv of the EMCAs performed with observations (CMAP and CRU precipitation data) and **Speedy GLOB** model results for the two periods of study.

The spatial patterns of the two EMCAs are very similar (see Figures 4 to 5), consistent with the high correlations between the ECs (see table 3). The correlations between EC of the two EMCA (observations and model) are slightly higher for the second period of study.

	CRU 79-98	**CRU 58-78**
CMAP 79-98	0.99	
Speedy GLOB 79-98	0.8737	
Speedy GLOB 58-78		0.7628

Table 3: Correlation of the global SST ECs obtainded with the EMCA performed with observations (CMAP and CRU precipitation data) and **Speedy GLOB** model results

A comparison with the Atl3 regressions shows very similar precipitation patterns for the observations (compare Figures 1 and 4), as well as for **Speedy GLOB** results (Compare Figures 2 and 5). Overall, we can say that the results are robust enough, as we obtain a similar response with two different analyses.

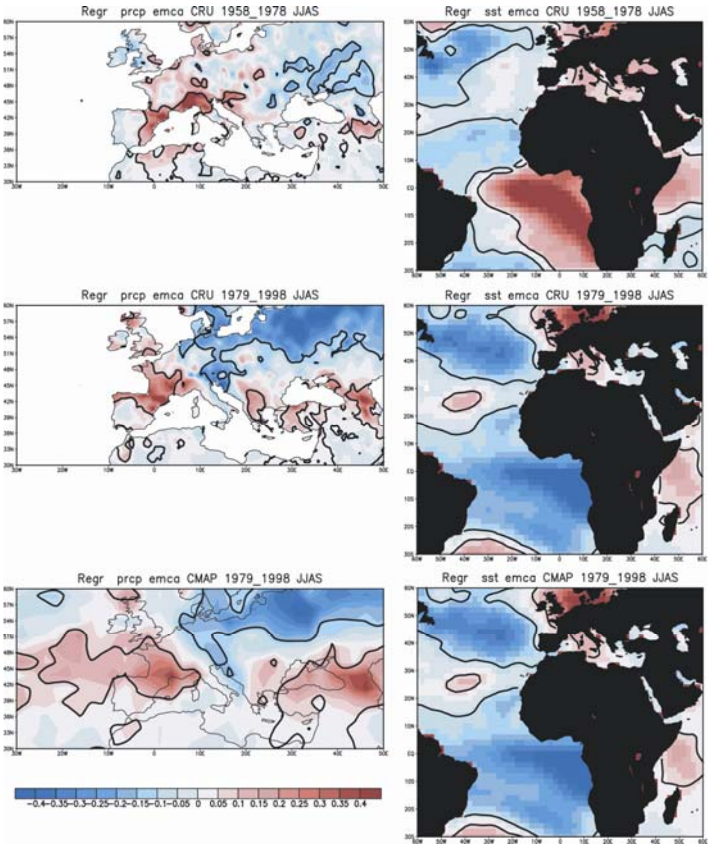


Figure 4: Observations regressions onto SST EC results

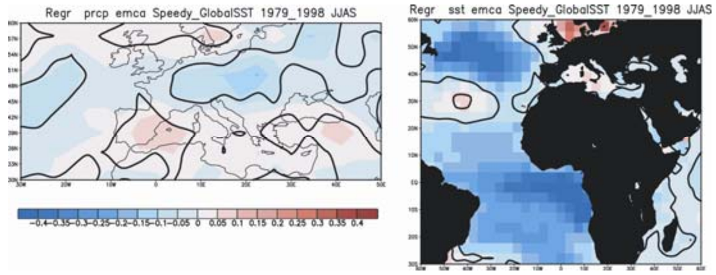


Figure 5: Speedy GLOB regressions onto SST EC results

On the contrary, for the **Speedy TATL** experiment, the precipitation patterns of the EMCAs differ from those of the regression onto Atl3, enhancing the amplitude of the precipitation anomalies in the eastern part of the Mediterranean region.

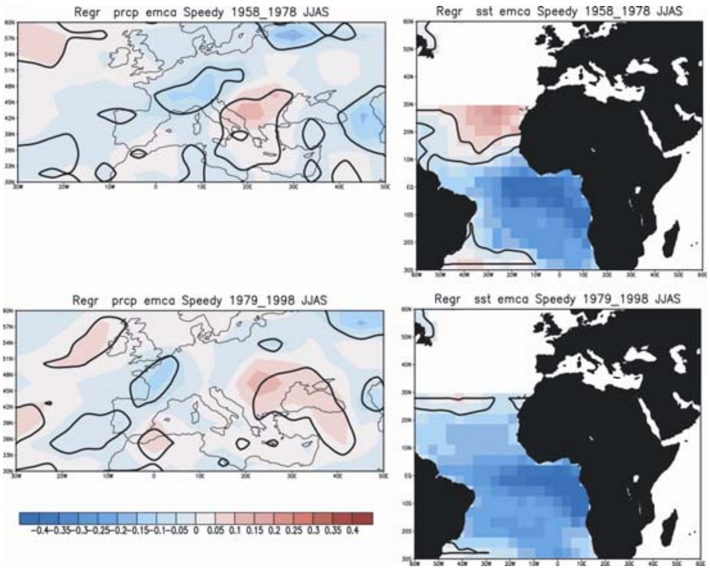


Figure 6: Speedy TATL: Regressions onto SST EC results

These results, similarly to the ATL3 ones, point to the possibility of an “outside Tropical Atlantic region” influence on the region of study.

The confidence of the results is bigger for the second period of study (78-98). For this period, SST variability patterns show stronger loadings in the equatorial West Atlantic, suggesting that the link between tropical Atlantic and Mediterranean area could be through modifications in the convergence of the Amazonian basin.

Baldi et al. (2004), also related warm Tropical Atlantic SST with cold Wester Mediterranean. To test the covariability between the two basins, we perform an EMCA between summer tropical Atlantic SST and summer to winter Mediterranean SST.

The results (see Figures 1 and 4) show how this relationship has changed before and after the climate shift. Before 1979 warm tropical Atlantic SST was related with warm eastern Mediterranean SSTs. After the climate shift, warm conditions over the tropical Atlantic appear together with cold SST anomalies in the western and central Mediterranean Sea. Also, the spatial pattern of the Atlantic SST anomalies resembles more the EM during the second period.

ATMOSPHERIC CONDITIONS RELATED WITH THE EM-MED CONNECTION

To study the atmospheric conditions we regress different spatial patterns onto the Atl3/EMCA-EC. As the results from both methods of study are really alike, for the shake of simplicity from now on we just will show the regressions onto the ATL3 index for both observations and **Speedy TALT** model results, and only for the second period of study.

Observations results (Figure 7) show a barotropic response in the Gulf of Guinea, pointing at the non-direct atmospheric response to the SST anomalies over that area.

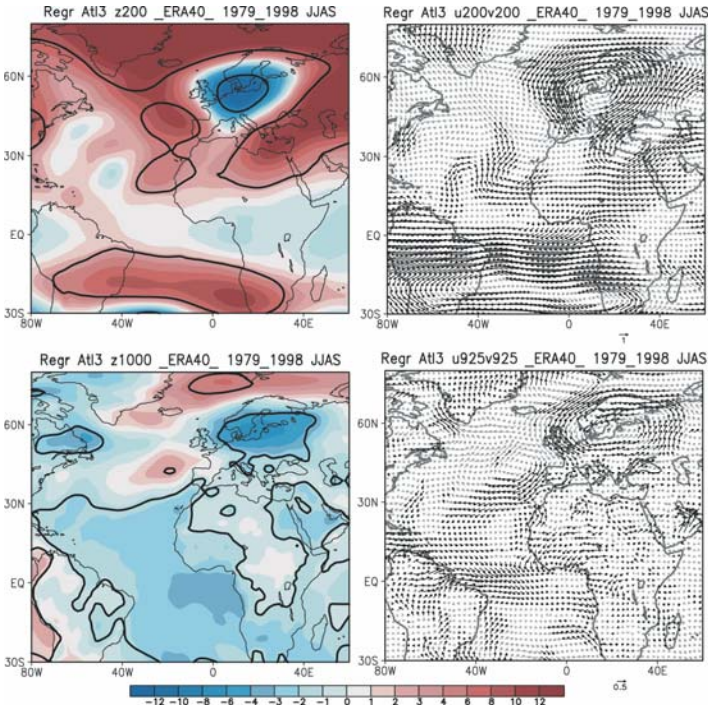


Figure 7: Regression of ERA40 z200 (top, left), z1000 (bottom, left), 200 hPa wind (top, right) and 925 hPa wind (bottom, rigth) onto the Atl3 index, for 1979-1998 period.

The response is baroclinic in the west tropical Atlantic, between 10-20N, and a barotropic response over the extratropics, suggesting a Rossby wave pattern linking the two regions. This response produces a low pressure over central Europe, which leads to an inland influx from the North Atlantic that could be responsible for the increased precipitation. The anomalous high pressure off the Iberian Peninsula has an associated low pressure over Northern Africa and the West Mediterranean that produces a southwesterly wind blowing from North Africa to Central Europe. This flow could bring moisture to the area, adding its effect to that of the cyclonic center located over Central Europe and increasing even more the precipitation over the area.

These results are consistent with the fact that the precipitation pattern of the CMAP regression onto the Atl3 shows positive anomalies over this area (around Sicily). The southerly winds will be responsible of these precipitation anomalies in the southern central Mediterranean. Note that this doesn't appear in CRU results (not shown), due to the lack of data over the ocean.

The results of the **Speedy TATL** experiment are quite different (Figure 8). They show a baroclinc response over the equatorial Atlantic, indicating local forcing. There is also a baroclinic response over the eastern Mediterranean area, but the sign of the anomalies is opposite to the observed one: it shows an anomalous high at the surface and an anomalous low in the upper troposphere over the eastern Mediterranean. The SLP of this simulation also differs from the observed one in the Arabic peninsula. The anomalous Northern low is displaced to the east with respect to observations, in a way that makes the central Europe be affected by an anomalous high, instead of an anomalous low; this high has associated an anomalous low off the Iberian Peninsula that would explain the precipitation anomalies.

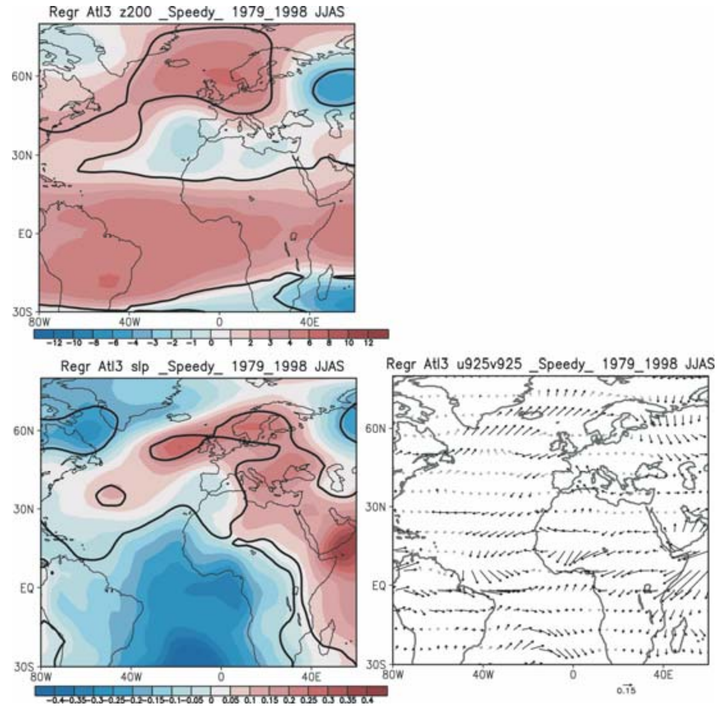


Figure 8: Regression of **Speedy TALT** z200 (top, left), z1000 (bottom, left), and 925 hPa wind (bottom, rigth) onto the Atl3 index, for 1979-1998 period.

COMPOSITE ANALYSIS

Baldi et al (2003) found the response over the Mediterranean for late summer (August, September). So far we have focused on the seasonal response. In order to study the intra-seasonal characteristics of the response, we have computed a composite analysis for both the EMCAs and the ATL3 data. Again, as the results are quite similar, we will show here just those regarding the ATL3 study.

The years chosen for the ATL3 composite are 1984,1987,1988,1998 for the positive phase, and 1980,1982,1983, 1992 for the negative one.

Although the composite results show a very weak statistical significance, we consider them important in order to illustrate the timing of the atmospheric response in study.

The positive precipitation anomalies over Central Europe and the eastern Mediterranean area show a strong signal in September, the month when the barotropic extra-tropical response and the low-pressure system over central Europe are well developed, and when the southwesterly surface flow from Africa to Central Southern Europe appears.

Nevertheless, the east-west dipolar structure of the precipitation is clearer in August, and seems to be related to the anomalous anticyclone located in the North Atlantic Ocean, and the anomalous low center present in central Europe.

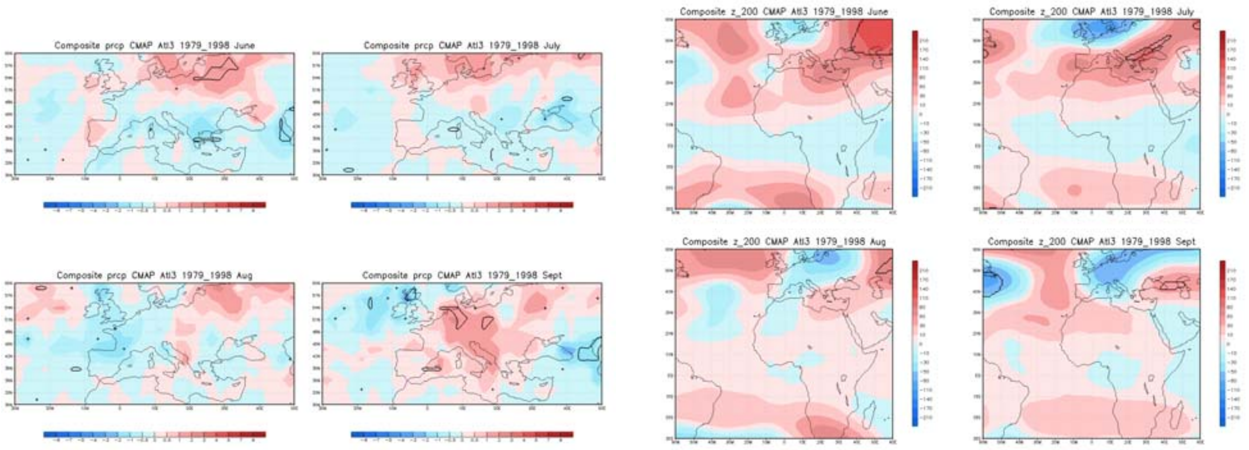


Figure 9: monthly anomalies (from June to September) of a composite of years in which the absolute value of the Atl3 index is greater than one standar deviation, for CMAP precipitation (left). ERA-40 200 hPa (right).

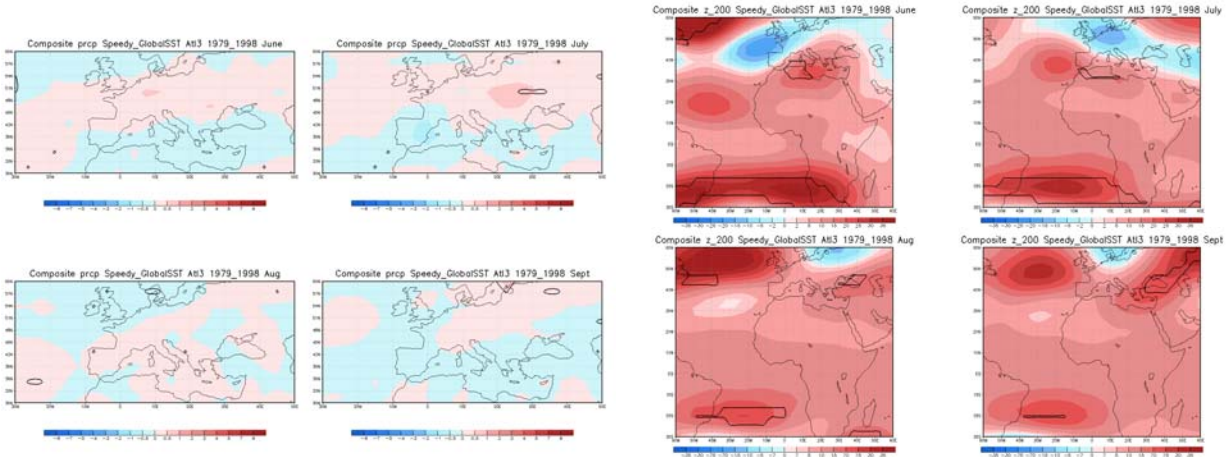


Figure 10: As figure 9, but for **Speedy GLOB** results.

The results of the same analysis performed with the **Speedy GLOB** data (Figure 10) show that the strongest model dipolar response appear in July, when the cyclone in the North Central Europe is well developed, although the spatial pattern of this low is not well simulated, and spreads too far east and south, affecting the Black Sea region. For this simulation, there is no surface flow from North Africa to the Mediterranean, maybe because this lack of reliability of the model in reproducing the southward part of the low pressure located over northern Europe.

It is also worth to notice that the barotropicity of the response in the region of the EM is weaker in the **Speedy GLOB** simulation (not shown) , compared to the observations, pointing to the possibility of a problem of the model in reproducing the atmospheric response to a forcing located far from the region of study.

So far, the results suggest that, associated with the Atlantic EM, there is an anomalous high pressure off the Iberian Peninsula both in the observations and **Speedy GLOB** results. Nevertheless, this anomalous high doesn't appear in the **Speedy TATL** simulation, pointing to a forcing extermal to the tropical Atlantic. The barotropicity of the observational response in the western basin of the tropical Atlantic, together with the barotropic response in the extratropics, also point to a passive role of the tropical Atlantic ocean.

A wave-like pattern appears in the extratropics, showing a low pressure centered over Central Europe that leads to a westerly flow from the North Atlantic into Central Europe that would produce an increase of the precipitation.

Also, there is a south-westerly flow from North Africa to south Italy that would also lead to an increase of the precipitation there. This flow would be related to a relative low pressure to the west of the Subtropical Atlantic High Pressure system.

Regarding the timing of the response, for the observations, it takes place mainly at the end of the summer (August-September). For Speedy model, the response appear earlier, in July.

When looking into the differences between periods, the observational and **Speedy GLOB** simulation analyses show strong differences in the rainfall response between them, but these differences are weaker for the **Speedy TALT** simulation, pointing to the possibility of an extra tropical Atlantic influence into the Mediterranean area for the second period of study

The SSTs in the Mediterranean Sea also show a very different configuration before and after the climate shift. Whether the change in the SST Mediterranean anomalies is due to a change in the Atlantic-Med relation or to other causes needs another kind of analyses, like AOGCM experiments.

SENSITIVITY EXPERIMENTS RESULTS

All the results above point to several uncertainties about the real impact of the EM in the Mediterranean region in late summer. In order to isolate the Mediterranean atmospheric response related to the EM during the second period of study, we next analyze the results of four different atmospheric models (ARPEGE, ECHAM4, LMDZ, UCLA) forced with the leading seasonally varying anomalous tropical Atlantic SST pattern coupled to the Guinean Gulf region (Polo et al., 2008), which corresponds with the Equatorial Mode evolution, form April to September (Figure 11). Details on the computation of the EM, as well as on the characteristics of the models and simulations can be found in Losada et al. (2009a).

As the previous observational analyses have confirmed, in accordance with Baldi et al. (2004), that the atmospheric response is stronger in the late months of the summer, we will divide the summer season in two periods to plot the results of the sensitivity experiments: Jun-July (JJ) and August-September (AS).

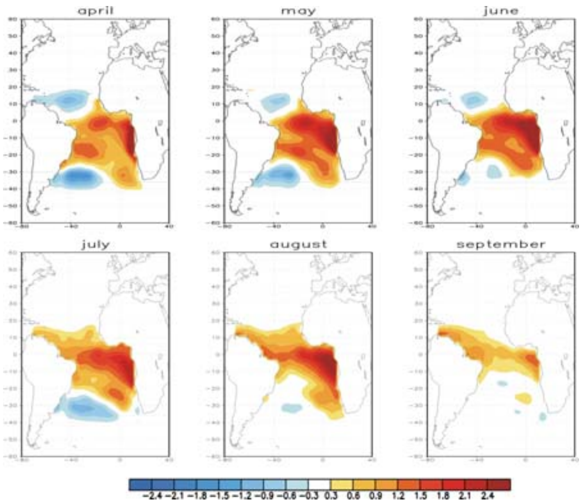
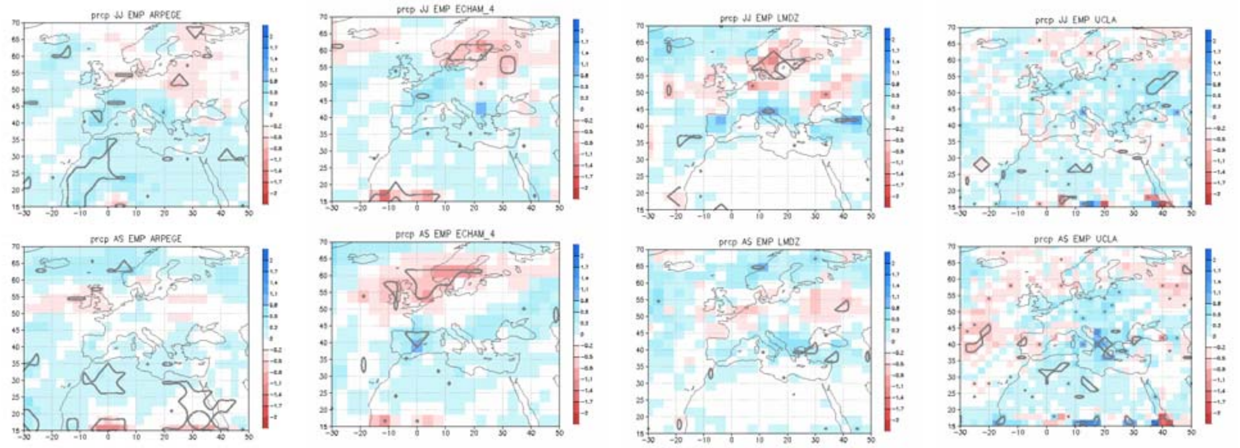


Figure 11: SST anomalies used as boundary conditions in the AGCM sensitivity experiments (from Losada et al., 2009a).

The models rainfall results (Figure 12) show an increase of precipitation in the Mediterranean associated with the Equatorial Mode. This response appears during the whole summer, even though the statistical significance is weak for all of the simulations.



a b c d

Figure 12: JJ (top) and AS (bottom) preciptation anomalies for ARPEGE (a), ECHAM-4 (b), LMDZ (c) and UCLA (d) model results.

The core of the anomalies is located in different areas depending of the model and period: during AS, it appear mostly over the Adriatic Sea and Greece, further east and south than the observed one, but most of the models show also positive precipitation anomalies over the southern part of the Iberian Peninsula (specially ECHAM-4). On the contrary, during JJ, all the models show stronger precipitation anomalies over Western Europe, and there is a presence of a dipole-like precipitation response in every model but

UCLA, very similar to the JJAS regression of the Speedy TALT precipitation onto the Atl3 index.

Regarding the atmospheric response (Figures 13 to 16), all the models show the baroclinic-barotropic structure between tropics and extratropics. Although there is no 200 hPa geopotential height available for LMDZ simulation, the baroclinic extratropical structure can be inferred from the wind response.

All the models show a similar response over North Africa: an anomalous West-East pressure dipole, with anomalous low pressure to the west and anomalous high to the right (east Africa- Arabian peninsula). This configuration lead to a southeasterly flow form east Africa and the Red Sea to the east-central Mediterranean sea. Thus, this flow could be responsible of the increase of precipitation over the area.

Nevertheless, there are important differences between the models responses. For instance, the anomalous high pressure over the Subtropical Atlantic (off the Iberian Peninsula) does not appear in most of the models (just in UCLA in AS).

The configuration of the low-pressure anomaly over the Mediterranean area, which is mostly controlled by the east-west pressure dipole over Africa, seems to be determinant in the location of the precipitation anomalies. For example, ECHAM 4 anomalous low is located further south than ARPEGE and UCLA ones (and also than LMDZ low during JJ), and shows a more latitudinal pressure gradient. Then, the surface wind flow follows a more zonal direction, which could explain the location of the maximum precipitation anomalies further west than for the rest of the models.

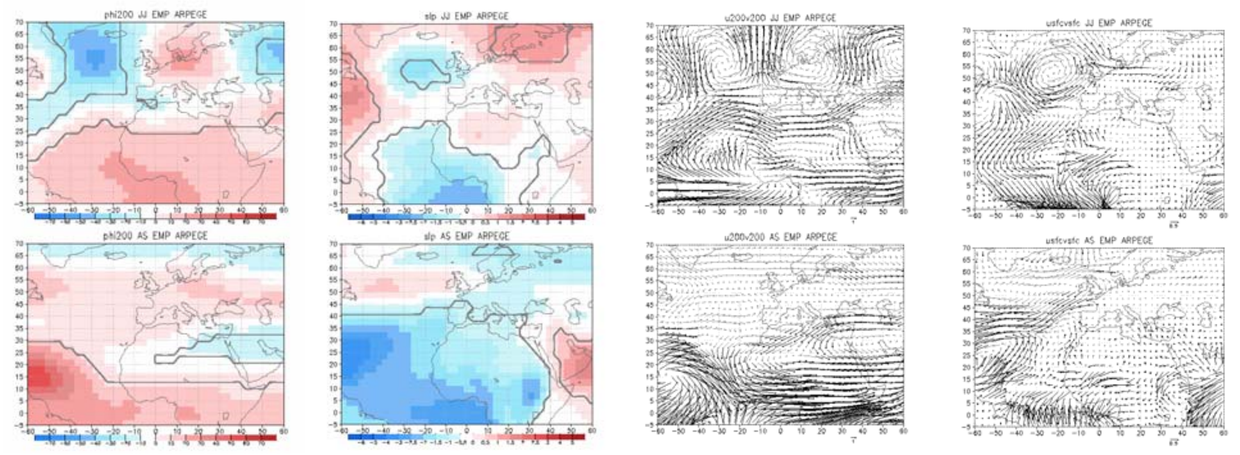


Figure 13: JJ (top) and AS (bottom) 200 hPa geopotential height (top left), slp (bottom left), 200 hPa wind (top right) and surface wind (bottom right) anomalies for ARPEGE simulation.

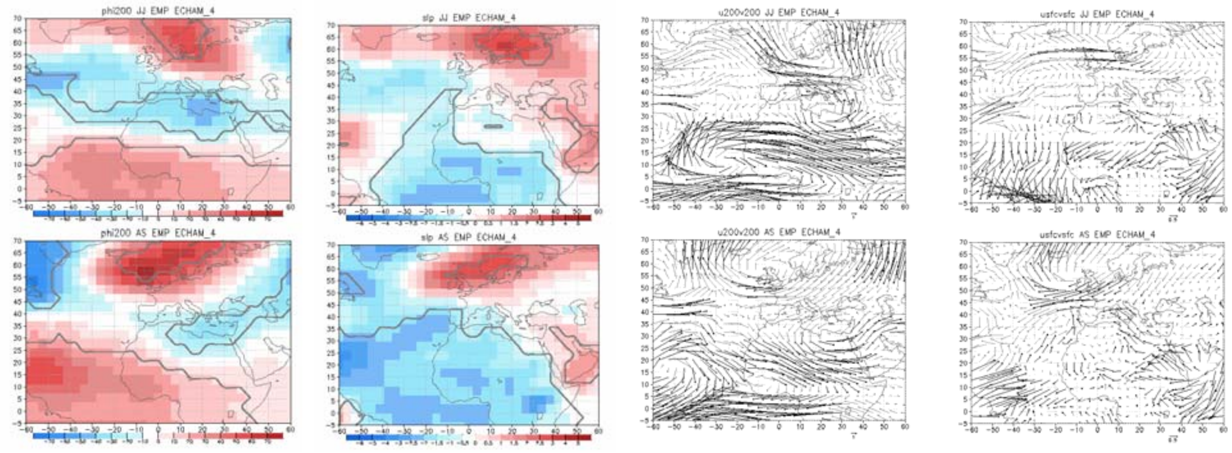


Figure 14: As Figure 13, but for ECHAM-4 simulation

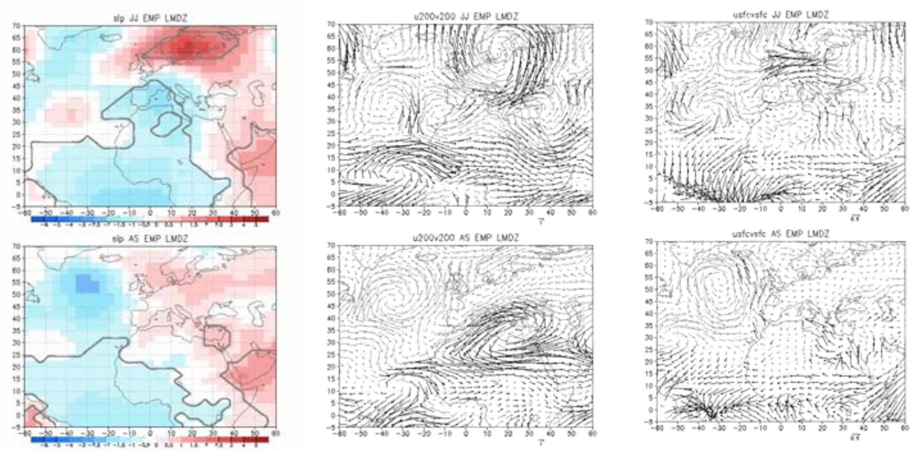


Figure 15: JJ (top) and AS (bottom) slp (bottom left), 200 hPa wind (top right) and surface wind (bottom right) anomalies for LMDZ simulation.

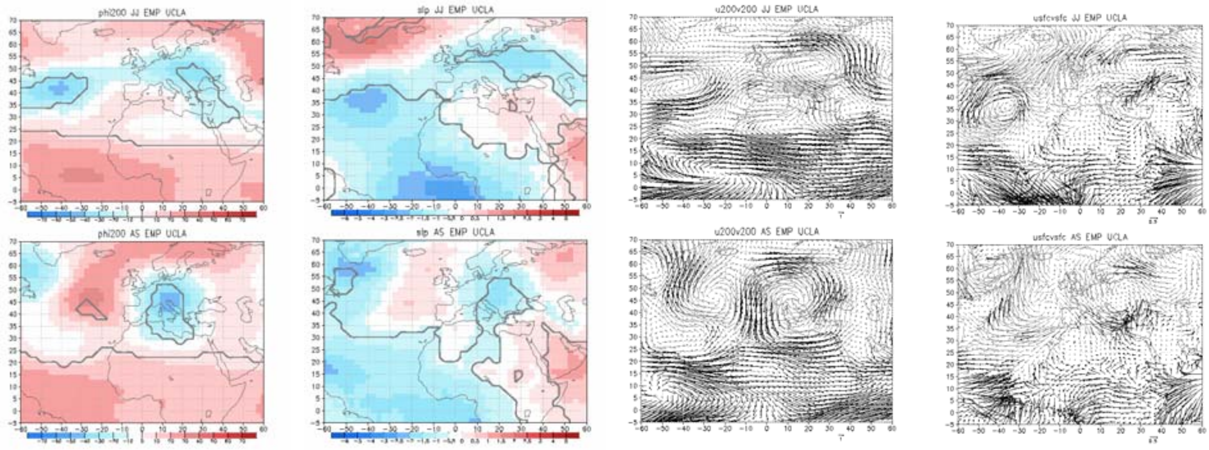


Figure 16: As Figure 13, but for UCLA simulation

The results obtained in the Sensitivity experiments, together with the previous analysis of the regressions lead to the following conclusions about the influence of the EM in the Mediterranean:

Although the EM appears to be related with an increase of the precipitation over the Central Mediterranean area, the responses of the sensitivity experiments differ from that derived of the EMCA and ATL3 studies for Observations and **Speedy GLOB** simulation: The EMCA and ATL3 analyses point to the extratropical wave-like pattern as the key factor in the response, while the sensitivity experiments show the Southeasterly flow from the Red Sea to the Mediterranean as the responsible of Mediterranean precipitation. These differences are very important, as only one model (UCLA) shows a well-formed anticyclone off the Iberian Peninsula as a response to the EM.

The regressions of the **Speedy TATL** simulation onto the Atl3 are more in agreement with the Sensitivity experiment results than they are with the observations: the presence of the North African east-west pressure dipole is apparent also in this simulation.

The differences between the results could be caused by the fact that the EM relation with other ocean basins has changed. Maybe the observed response is produced by SST anomalies from other areas of the oceans.The connection between the Equatorial Atlantic and the Mediterranean can be established through other ocean basins. For example: EM could influence the Indian Ocean or the Pacific area and the South American convergence zone, and then these variations could influence in turn the Mediterranean area.

Whether or not the EM anomalies have an impact in those non-tropical-Atlantic areas can not be stated with this AGCM analyses and coupled model simulations are needed to test this possible influence.

INFLUENCE OF THE NORTH ATLANTIC

In order to study the possible influence of the North Atlantic basin SSTs related to the tropical Atlantic SST variability, we perform the regressions onto the Atl3 index of precipitation and SST fields obtained by performing a simulation with observed SSTs just in the North Altantic (north of 30ºN), and climatological SST elsewhere.

Ir order to compare the results with the previous ones, we perform the regression of the seasonal mean (JJAS) of the different variables onto the Atl3 index.

The precipitation response over central Europe (Figure 17) shows an east-west dipole during the 1979-1998 period, but it is shifted to the east and north with respect to the observations and the Speedy Global SST Exp. results. For this period, in the South of France and the Iberian Peninsula, the precipitation anomalies show the same sign as the observed and the Global SST Exp results. In the eastern part of Europe the response to North Atlantic anomalies is quite similar to the observed one for this second period. Results disagree with observations in Northern Africa, and the Central Mediterranean (Italy and the Adriatic Sea)

Nevertheless, the precipitation response to the extratropical North Atlantic SST during the first period of study is completely opposite to the observed one (see Figure 1), for this period, the **Speedy TALT** experiment shows a much better result, pointing to an increase of the influence of the Atlantic extratropical

SST in the Mediterranean response.

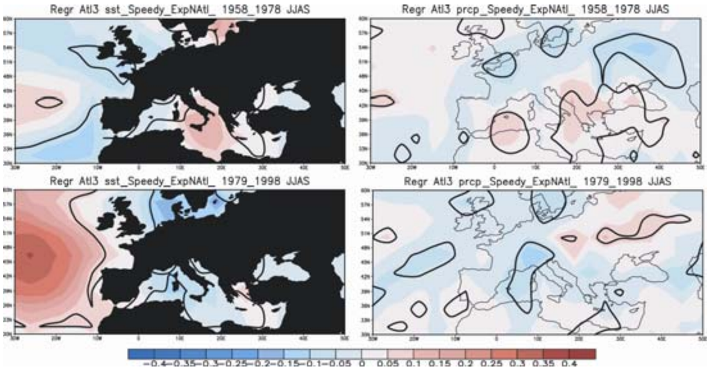


Figure 17: regression of the JJAS precipitation (top) and SST (bottom) of Speedy North Atlantic simulation results onto the Atl3 index, for the 1958-1978 (left) and 1979-1998 (right) periods.

The results point that the extratropical Atlantic SSTs associated to the Atl3 seem to be influencing the Mediterranean precipitation response, at least in the second period of study.

INFLUENCE OF OTHER TROPICAL BASINS AND OF THE INTERACTION BETWEEN THEM

In this next step, we perform several experiments, forcing with observed SSTs over the tropical Atlantic, Pacific and Indian basins, separately, as well as with the tropical Global belt. For each of the basins we run two experiments, one with Speedy AGCM totally decoupled, and a second one coupling the Speedy AGCM to a SLAB ocean model over the Mediterranean Sea and the North Atlantic Ocean. The aim of these new experiments is to analyze the influence of the tropical oceans on the Mediterranean area, as well as on the extratropical North Atlantic SST anomalies, and whether or not the latter possible influence is related with the atmospheric Mediterranean response. Table 4 show a scheme of the different simulations performed.

From now on we will focus just in the second part of the period of study (1979-1998). Several works (Rodriguez-Fonseca et al. (2009a), Polo et al. (2008), etc) have shown how, from the 70's, the relation of the Atlantic and Pacific tropical basins has changed, leading to a connection between the Atlantic and Pacific equatorial anomalies, in a way in that an Atlantic Niño appear together with SST anomalies of the other sing in the tropical Pacific. Indeed, Rodriguez-Fonseca et al. (2009b) have shown how this global mode exists in relation with the West African Monsoon (WAM), and how it became significant after the 70's, explaining more than the 70% of the co-variability between the tropical SST and the WAM.

Following all these results we study the possibility of the existence of an interaction of different tropical ocean SST patterns in association with the EM and how it would affect the Mediterranean region during late summer.

Simulation Name	Period of simulation	Basin on which SSTs observed anomalies are added to climatology	Basin in which the AGCM is coupled to a Slab Ocean Model
Speedy TATL	1949-2002	Tropical Atlantic (30S-30N)	Not coupled
Speedy TATL_SOM	1949-2002	Tropical Atlantic (20S-20N)	North Atlantic and Mediterranean Sea
Speedy TATL_SOMMed	1949-2002	Tropical Atlantic (20S-20N)	Mediterranean Sea
Speedy NATL	1949-2002	North Atlantic (30N-80N)	Not coupled
Speedy TPAC	1949-2002	Tropical Pacific (20S-20N)	Not coupled
Speedy TPAC_SOM	1949-2002	Tropical Pacific (20S-20N)	North Atlantic and Mediterranean Sea
Speedy TIND	1949-2002	Tropical Indian (20S-20N)	Not coupled
Speedy TIND_SOM	1949-2002	Tropical Indian (20S-20N)	North Atlantic and Mediterranean Sea
Speedy GlobTrop	1949-2002	Global Tropics (20S-20N)	Not coupled
Speedy GlobTrop_SOM	1949-2002	Global Tropics (20S-20N)	North Atlantic and Mediterranean Sea
Speedy GLOB	1949-2002	Global SST	Not coupled

Table 4: Simulations performed with the Speedy Model, coupled and uncoupled to a SLAB Ocean Model

As we have shown in the composite analysis that the observed response is stronger in late summer, we repeat our EMCA analysis with the observational data, but performing the EMCA between the evolution of the tropical Atlantic SST (from March-April to November-December) and the Mediterranean (30N-50N, 15W-40E) late summer precipitation (August-September). The squared covariance fraction explained by first mode of the analysis is the 28%, and the correlation between the two Expansion Coefficients of the mode is 0.51.

The spatial pattern of the precipitation (Figure 18, left) obtained with this analysis is almost the same as the previous one (see Figure 4, bottom line). Regarding de SST pattern associated with it (Figure 18, right), we can see how, concomitant with the negative EM-like anomalies in the equatorial Atlantic, there are El Niño-like anomalies in the equatorial Pacific, though they are not really significant in the eastern part of the basin. Also, there are statistically significant SST anomalies in the extratropical North Atlantic and North Pacific regions.

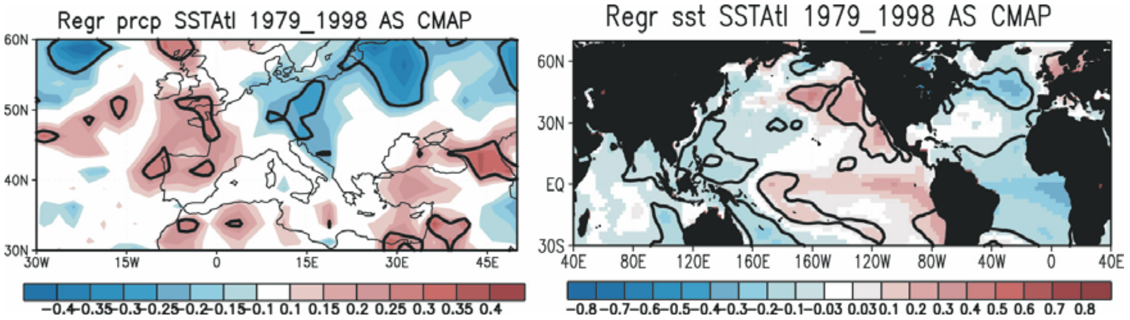


Figure 18: Homogeneous map of the SST (right) and heterogeneous map of the precipitation (left) obtained with the EMCA performed between MA-ND tropical Atlantic SST and AS Mediterranean precipitation.

Regressions of ERA-40 200 hPa geopotential height and SLP onto the EC of the global SST (Figure 19) depict a baroclinc response in the whole tropical basins but in the Indian ocean, where the SST anomalies are very small and non-significant. In the extratropics, conversely, the response is barotropic and shows a wave-like pattern that could be the result of the adding of two wave anomalies departing form the tropical Pacific and the Caribbean region respectively.

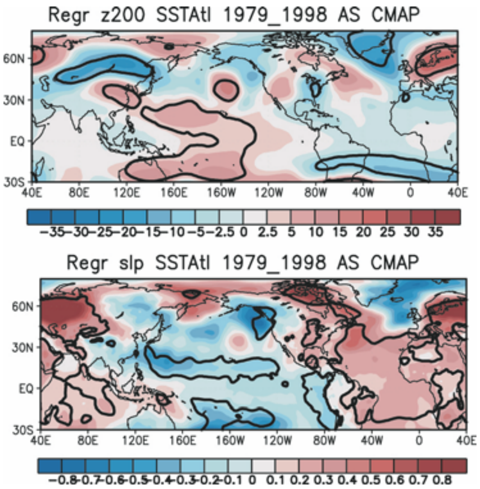


Figure 19: Regression of the ERA-40 200 hPa geopotential height (top) and SLA (bottom) onto the SST global EC of the EMCA performed between MA-ND tropical Atlantic SST and AS Mediterranean precipitation.

In order to understand the different roles of the tropical basins in this response, we will now compare this AS observational precipitation results, with those obtained with the different simulations performed with the Speedy model, coupled and uncoupled to a Slab Ocean Model in the North Atlantic and Mediterranean regions. As we are interested in study the influence of the SST anomalies of the different ocean basins, related to the observed SST pattern obtained in the EMCA, the procedure followed was to regress the precipitation response of each of the simulations into the SST Expansion Coefficient of the observed EMCA.

The results are depicted in Figure 20. It is worth mentioning that, as the composite analysis performed with the **Speedy GLOB** simulation show that the response in the model is stronger in July, we will compare the observed AS results with the modeled JA results. We argue that, due to the SST persistence, the SST anomalous pattern in JA is very consistent with that for AS (compare last panel of Figure 20 with Figure 18, right), and that the model response could appear a month in advance due to the characteristics of the model mean circulation, that make the model atmosphere more sensible to the forcing during July.

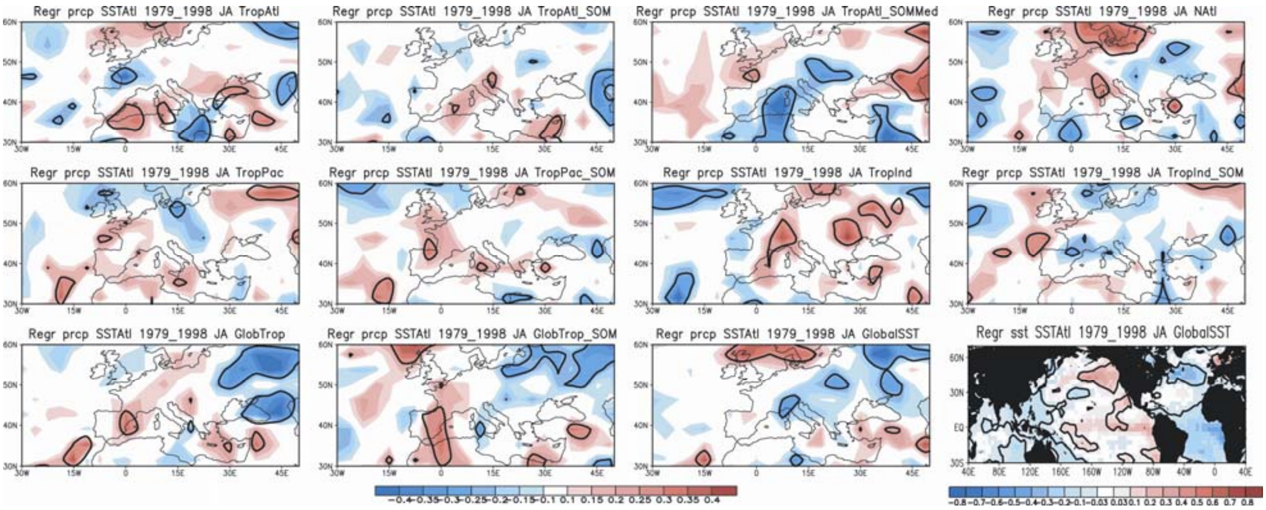


Figure 20: Regressions of the different simulations JA precipitation onto the SST-EC of the EMCA performed between MA-ND tropical Atlantic SST and AS observed Mediterranean precipitation.

Results of figure 20 show how all the simulations performed with observed SST in a single ocean basin fail in reproducing the observed precipitation pattern. From all the uncoupled simulations with observed SST prescribed in just one ocean basin, only the North Atlantic SST one is able to somehow reproduce the dipole-like precipitation over Europe, but fails in the sign of the precipitation anomalies of Northern Africa and the East Mediterranean. The Tropical Atlantic, Tropical Pacific and Tropical Indian simulations show precipitation responses that widely differ from the observed one. On the contrary, the results of the uncoupled simulation in which observed SST were prescribed in the Global Tropics, show a dipolar precipitation pattern, but the positive anomalies of the western part of Europe spread too far into the northern part of the continent.

Regarding the simulations coupled to the Slab Ocean Model, again those forced with observed SST in an isolated tropical basin fail in the precipitation response. The **TATL-SOM** simulation show a kind of a precipitation dipole, but it is too weak; the same occurs to the **TPAC_SOM**. For the **TIND_SOM** the response is too displaced to the west, and not really consistent with the observations. The **GlobTrop_SOM** response, however, shows a rainfall anomalous pattern that is very similar to the observed one, being the simulation that better represent the late summer observed precipitation response related to the EM evolution. If we look at the regression of the SST anomalies of the coupled simulations (Figure 21), we can see how the SST anomalies induced in the North Atlantic-Mediterranean basins in the **GlobTrop_SOM** simulation resemble the observed ones, though the SST anomalous lobes are slightly displaced to the north (see Figure 21, top right, North Atlantic-Mediterranean region), consistently with the northward displacement of the rainfall response observed for this simulation. For the rest of the coupled simulations, the SST anomalies created by the Slab Ocean Model are very small and non significant for the majority of the basin.

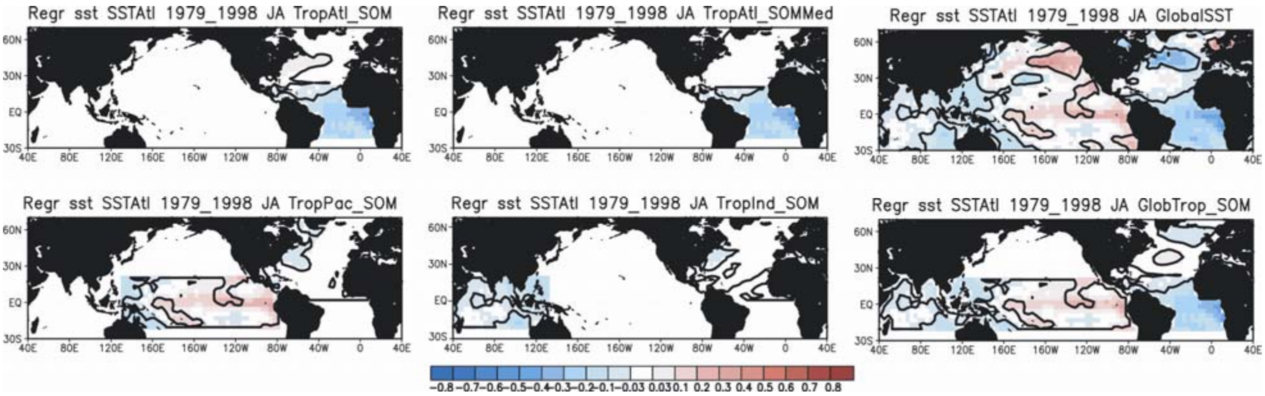


Figure 21: Regressions of the different coupled simulations JA SST onto the SST-EC of the EMCA performed between MA-ND tropical Atlantic SST and AS observed Mediterranean precipitation.

These results appear to confirm the key influence of the North Atlantic SST anomalies in the precipitation response, and point to the action of the global tropical ocean basin as a whole, suggesting that the interaction of the three tropical basins is able to impact onto the North Atlantic Ocean and Mediterranean Sea variability, being the whole picture together (global tropics + North Atlantic extratropics SST) the responsible of the rainfall response.

The fact that the precipitation results of the **GlobTrop_SOM** are more in agreement with the observation records than the **Speedy Glob** results is a striking feature, which could be maybe explained by an erroneous atmospheric response to the extratropical Pacific SST anomalies in the Speedy model.

In order to understand these atmospheric responses we depict the regression of geopotential height at 200 hPa (Figure 22) and SLP (Figure 23) onto de SST EC index. In this plot, we can see how the extratropical wave like pattern in the North Atlantic region is better represented in the **GlobTrop_SOM** than in the **Speedy Glob**. In the observations, an anomalous circulation is located around 160W-30N, to the west of a positive lobe of SST anomalies, pointing to the possibility of the anomalous high being a response to the extratropical SST: the SST gradient between the negative anomalous lobe and the positive anomalies surrounding it, would produce a surface divergence that would create the observed extratropical high. The presence of this anomalous high would have an impact in the modulation of the wave departing from the tropical Pacific producing its distortion.

The effect of the extratropical SST can be underestimated in the **Speedy GLOB** simulation, leading to the appearance of a very small central Pacific anomalous high circulation at the surface; then, the anomalous low in the upper troposphere (160W-30N) would be the first barotropic lobe of the wave pattern formed a response to the anomalous high thermally induced in the tropical belt, being the small surface high a local weak response to the positive SST anomalies, showing a behavior similar to a thermal low. This explanation would be in agreement with the fact that, in the **GlobTrop** and **GlobTrop_SOM** results, the anomalous low is stronger than in the **Speedy GLOB**, and there is not low level high, due to the lack of anomalous SST over that region.

In the **Speedy GLOB** experiment, the incorrect response to the extratropical Pacific SST anomalies, that is also apparent from the anomalous SLP pattern, is reflected in the incorrect modulation of the extratropical wave pattern in the Pacific and North American regions. This pattern is somehow corrected in the North

Atlantic, maybe due to the influence of the Atlantic SST in the atmosphere; the SST anomalies in the tropical Atlantic can trigger a wave from the Caribbean region to central Europe (García-Serrano et al., 2009). This can be also confirmed by looking at the 200 hPa geopotential anomalies for **Speedy TATL** simulation, that shows a wave like pattern similar to the observed in the North Atlantic, but displaced to the west (not shown), leading to a misrepresentation of the precipitation anomalous pattern in this simulation.

In the **Speedy GLOB** simulation there is an anomalous anticyclonic circulation in the North Atlantic around at surface levels, as the North Atlantic SST are prescribed, this can be a direct response to the negative lobe of SST present in the region. In upper levels the circulation, although very weak, is cyclonic, which is contrary to the observations. We argue that the weakness of the **Speedy GLOB** response can be explained if we assume that the North Atlantic SST anomalies are a direct response to the atmosphere: in the real world, the wave patterns arising from both the equatorial Pacific and the Caribbean region interact, leading to an anticyclonic circulation in the North Altantic (~40N), that would be the responsible for the ocean warming observed between 30N-40N (descendant motions are associated with more radiative heating and less evaporation). Nevertheless, in the **Speedy GLOB** simulation, as the SST warm anomalies are already present, they will tend produce an atmospheric response in the form of a low surface pressure, thus operating opposite to the observed atmospheric forcing and leading to a weakness in the modeled response. Regarding the **GlobTrop** simulation, the lack of interaction between the atmosphere and the ocean lead to a misrepresentation of the atmospheric response, with a distorted wave pattern, pointing to the needing of air-sea interaction in order to get the right modulation of the signal.

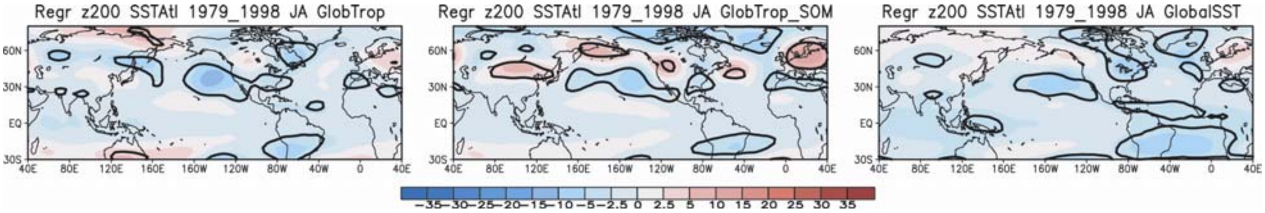


Figure 22: Regressions of the 200 hPa anomalous geopotential height onto the SST-EC of the EMCA performed between MA-ND tropical Atlantic SST and AS observed Mediterranean precipitation. For JA Speedy GlobTrop (top left), GlobTrop_SOM (top right) and SPEEDY Glob (bottom left) simulations, and for AS ERA-40 data (bottom right)

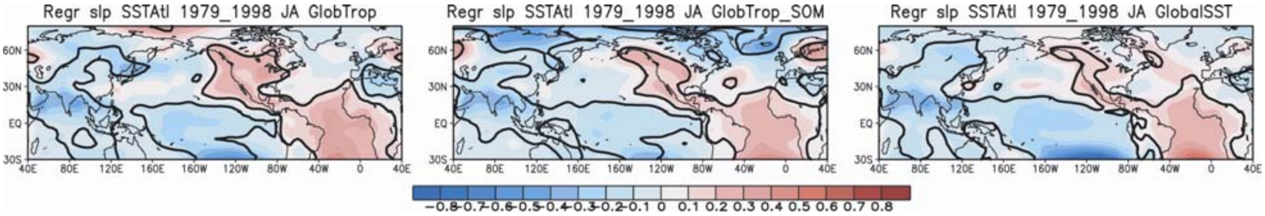


Figure 23: Same of Figure 21, but for mean SLP.

Another difference between the **Speedy GLOB** simulation and the observations is found over the Indian ocean and Eurasia. For the observations there is an anomalous high pressure over the Indian ocean, that can be a direct response to the SST cooling, while for **Speedy GLOB** simulation, the anomalous slp is negative over the Indian ocean and Eastern Asia, and the anomalous high pressure over Europe is very weak. The SST anomalies over the Indian ocean are weak, so are the responses obtained in the Indian experiments (not shown), so the difference of the response between model ad observations could be due to the model not capturing the atmospheric local response to the Indian SST. Instead, for **GlobTrop**, **GlobTrop_SOM** and **Speedy GLOB** simulations the anomalous atmospheric response of the Indian area is barotropic and it is likely to be a response to the atmospheric anomalies generated in the Atlantic region (Kucharski et al., 2007, 2008, 2009; Losada et al., 2009b).

It is also worth mentioning some aspects of the high level atmospheric response over Asia, that show positive lobe over eastern Asia, around 30N-40N; and a negative one further north. This pattern is fairly well represented in the **TropGlob_SON** simulation, and it also appears in the **TPAC_SOM** simulation (not shown), but not in any of the Indian Ocean simulations. It could be an extension of the upper level anticyclonic circulation that appear in the tropical Pacific as a response to the equatorial heating, or a response to the modification of the tropical convection in the Indian Monsoon due to variations in the Walker circulation.

CONCLUSIONS

The results of the work carried out in this visit point to the existence of an impact of tropical Atlantic SST anomalies in the Mediterranean area in late summer in a way that warm SST anomalies would induce a SLP dipole over North Africa, leading to a surface inflow from the Red Sea and the Arabian Peninsula into the central Mediterranean up to Italy, enhancing the precipitation there. This result is present in every of the four sensitivity experiments performed with four different AGCM, although with some differences in the timing and the exact position of the pressure pattern that lead to differences between the magnitude, and spatial pattern of the anomalous precipitation simulated in each of the models. This result is also in agreement those obtained by doing the regression of the Atl3 index onto the outputs of the **Speedy TALT** simulation, but differ from those of the **Speedy GLOB** simulation.

In the **Speedy GLOB** simulation, a warm EM is related to a west-east dipole of anomalous precipitation from the 70's, with negative precipitation over the western Mediterranean and positive precipitation in central Europe. There is a barotropic response in the tropical Atlantic over the maximum SST anomalies, a baroclinic response in the Caribbean region, and again a barotropic response over the extratropics, strongly suggesting the external influence of other ocean basins into the Mediterranean precipitation response.

A composite analysis conclude that the maximum atmospheric response occurs at the end of the summer (AS), but that the Speedy model show its maximum response a month in advance (JA).

The global SST pattern related to the Atlantic EM show, from the 70's, SST anomalies of opposite sign in the equatorial Pacific. In order to study the role of these concomitant SSTs, we do an analysis of different simulations performed with the Speedy AGCM, both coupled and uncoupled to a SLAB Ocean Model in the North Atlantic and Mediterranean. The results of this analysis show how none of the basin to basin simulation obtains a proper precipitation response over the Mediterranean area, and that the simulation that better represents the anomalous rainfall pattern is the **GlobTrop_SOM** simulation.

The results suggest that not only the joined action of the whole tropical basins is necessary to obtain the correct atmospheric response, but it is also necessary to allow the interaction between the extratropical atmosphere and the North Atlantic ocean. The exchange of heating between atmosphere and ocean over the region seems to be a key factor, at least in the Speedy model, which leads to a fine representation of the extratropical wave pattern responsible of the precipitation response. This wave pattern appears to be the result of an interaction between two waves, one departing from the equatorial Pacific, and another one from the Caribbean region. The transference of heat from the atmosphere to the ocean in the North Atlantic produces a positive feedback that enhances the anticyclonic circulation in the extratropical Atlantic off the American coast, leading to the strengthening of the wave pattern created as a response to the tropical belt SST anomalies.

4. Future collaboration with host institution

In collaboration with ICTP institution, we will perform a deeper analysis of the inter-basin relationships found in this work, that will include further analysis of the basin to basin simulations performed during this visit, as well as the realization of coupled AOGCM experiments in order to better determine the characteristics of the interaction between the tropical Atlantic and the rest of the tropical basins, and its influence in the Mediterranean area.

5. Projected publications resulting or to result from the grant

We are preparing a publication showing the main results of this work, to be submitted to GRL: “On the nature of the relationship between tropical Atlantic variability and late summer Mediterranean climate. What has changed in recent decades?”

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