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Mediterranean climate change and Indian Ocean warming(*)

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Summary. — General circulation model (GCM) responses to 20th century changes in sea surface temperatures (SSTs) and greenhouse gases are diagnosed, with emphasis on their relationship to observed regional climate change over the Mediterranean region. A major question is whether the Mediterranean region's drying trend since 1950 can be understood as a consequence of the warming trend in tropical SSTs. We focus on the impact of Indian Ocean warming, which is itself the likely result of increasing greenhouse gases. It is discovered that a strong projection onto the positive polarity of the North Atlantic Oscillation (NAO) index characterizes the atmospheric response structure to the 1950-1999 warming of Indian Ocean SSTs. This influence appears to be robust in so far as it is reproduced in ensembles of experiments using three different GCMs. Both the equilibrium and transient responses to Indian Ocean warming are examined. Under each scenario, the latitude of prevailing midlatitude westerlies shifts poleward during the November-April period. The consequence is a drying of the Mediterranean region, whereas northern Europe and Scandinavia receive increased precipitation in concert with the poleward shift of storminess. The IPCC (TAR) 20th century coupled ocean-atmosphere simulations forced by observed greenhouse gas changes also yield a post-1950 drying trend over the Mediterranean. We argue that this feature of human-induced regional climate change is the outcome of a dynamical feedback, one involving Indian Ocean warming and a requisite adjustment of atmospheric circulation systems to such ocean warming.

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1. – Introduction

There is convincing evidence that the evolution of global sea surface temperatures (SSTs) has played a significant role in North Atlantic/European climate change since 1950. Results from various atmospheric GCMs subjected to the monthly variations of observed SSTs during 1950-1999 reproduce the trend pattern of that region's atmospheric

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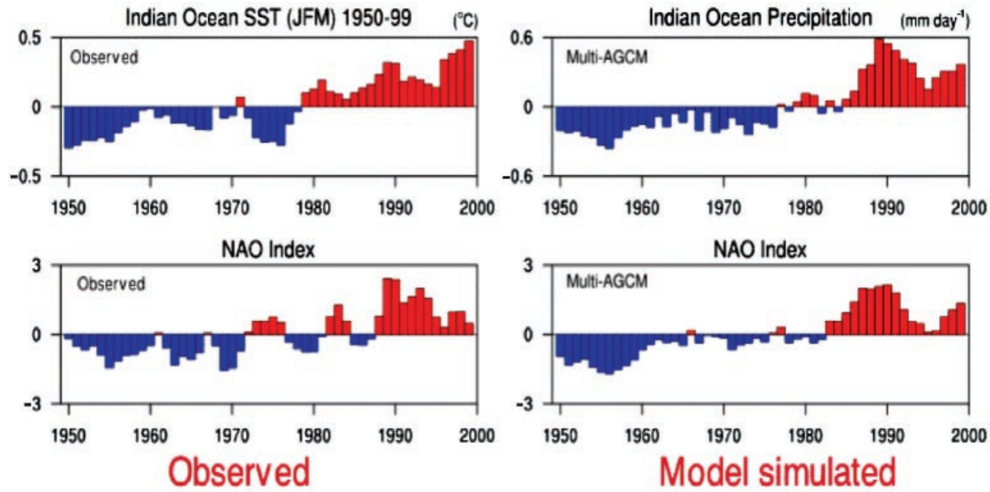

Fig. 1. – 1950-1999 time series of the January-March averaged observed Indian Ocean SST anomalies for 15°N-15°S (top, left) and NAO index (bottom, left). The AGCM simulated time series of Indian Ocean rainfall (top, right) and AGCM simulated NAO index (bottom, right). The NAO index is the difference in 500 hPa heights averaged over a southern (30°N-50°N, 80°W-20° E) minus a northern (60°N-80°N, 80°W-20° W) domain. The model data are the ensemble means of 67 AGCM members across 4 different models, each forced with the observed monthly and global variations of SSTs and sea ice for 1950-1999. All anomalies are relative to the respective JFM 1950-99 climatologist.

circulation, one that resembles a trend toward the positive polarity of the North Atlantic Oscillation (see [2] and references therein). Recent attribution evidence is illustrated in fig. 1, drawn from the two papers by [2], and [1] (hereafter referred to as HH). There is a strong correspondence between the observed time series of an NAO index and the simulated time series of the same NAO index using a 67-member AGCM ensemble. The additional time series shown in fig. 1 are of Indian Ocean SST and rainfall changes shown in fig. 1, each bearing striking resemblance to the NAO time series. This latter resemblance is not coincidental. Additional model experimentation reported in HH confirmed the causal nature of this link.

In this presentation, given at the First US-Italy Workshop on Mediterranean Climates and their Change during October 5-6 2004, we summarize the evidence for the Indian Ocean's influence on European Mediterranean climates that was first set forth in the papers of HH. We present new, and detailed evaluation of the sensitivity of Mediterranean precipitation to warming of the Indian Ocean, and also to increasing greenhouse gas concentrations. We update the analysis to include the period 1950-2002.

2. – Mediterranean climate

The notion of climatic zones emerged from early 20th century classification efforts. In these, a "Mediterranean climate" was included among a group of subtropical climates typified by dry summers. In the spirit of these early classical efforts, we apply a Fourier harmonic analysis to the climatological monthly precipitation data, based upon the Climate Research Unit's (CRU) 0.5° gridded analyses for 1901-2002. We define a region's

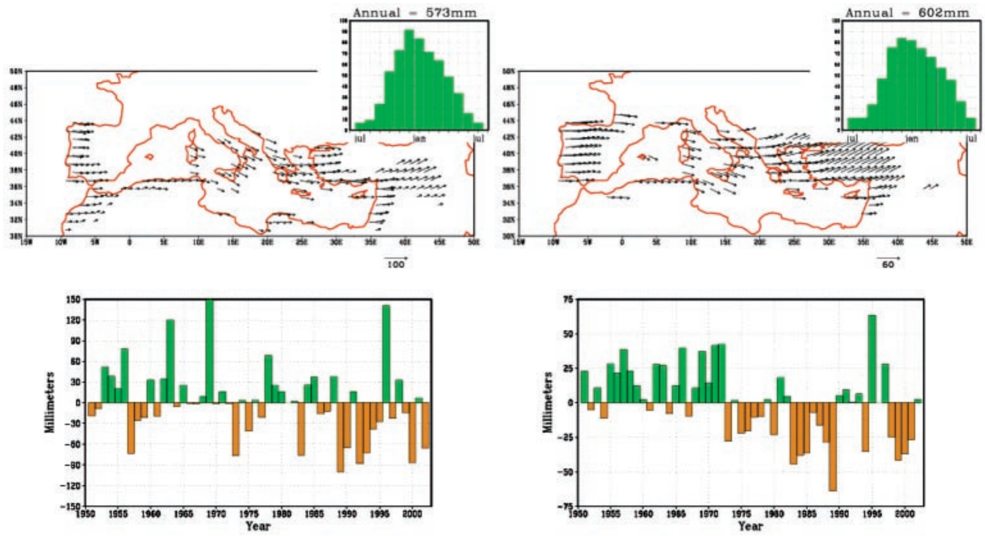

Fig. 2. – Top panels analyze the climatological annual cycle of precipitation over the Mediterranean region. Vectors plot points where the first harmonic of the annual cycle of precipitation accounts for at least 80% of the annual total, and has a winter peak. January peak indicated by vectors pointing to the right, late Fall (early Spring) peak occurs where vectors point down (up). Inset is the annual cycle of precipitation averaged over all points for which vectors have been plotted. This is our defined Mediterranean climate zone. Lower graphs are the November-April time series of 1950-2002 precipitation anomalies, relative to a 1950-2002 climatology. Left panels are based on observations, and right panels based on atmospheric GCM simulations. Three different models are used, including ECHAM4, GFDL-AMp12, and NASA-GMAO, with a total of 42 simulations. The simulated time series is based on the 9-member NASA model runs.

climate to be “Mediterranean” if the first harmonic of the seasonal cycle has a winter maximum (December-March), and that this first harmonic accounts for at least 80% of the annual total precipitation. The top left side panel of fig. 2 plots vectors at all grid points satisfying the above criterion. Vector arrows pointing to the right indicate a January peak in the first harmonic. The insets show the seasonal cycle of precipitation averaged over these plotted grid points. The adjacent top right side panel repeats the analysis, but using output from a large suite of three different atmospheric GCM simulations forced by the 1950-2002 observed SST variations. Despite their course resolution (roughly 250 km), they realistically define a Mediterranean climate, including a realistic seasonal cycle of precipitation in this region.

The time series of November-April (hereafter referred to as winter) precipitation, averaged for the Mediterranean climate zone, captures the wet decades of the 1950s and 1960s, followed by a generally dry period since 1980. The simulated time series has very similar low frequency variability, confirming that global SSTs have played a role in the drying trend.

3. – Indian Ocean influence

A 10-member ensemble of idealized, transient Indian Ocean warming experiments are analyzed in fig. 3. These experiments complement the equilibrium warm anomaly runs

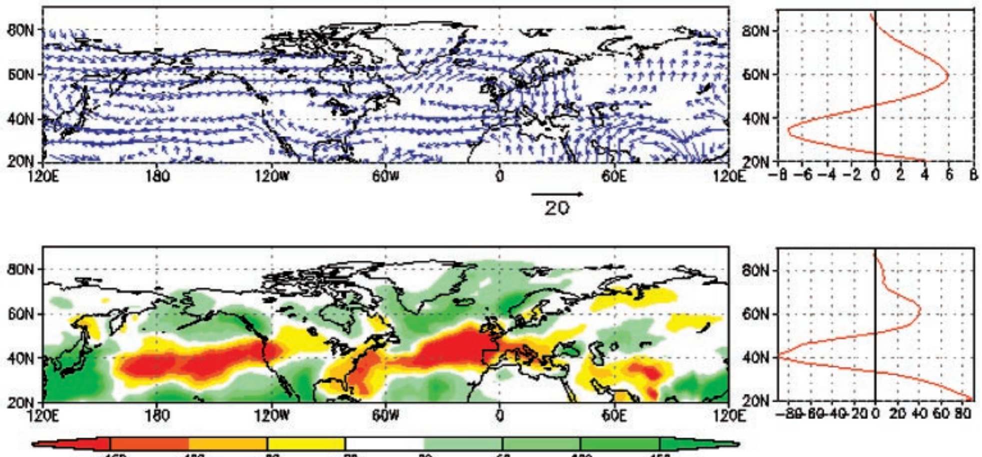

Fig. 3. – The AGCM simulated trend of November-April 200 mb winds (top) and precipitation (bottom) occurring in a 10-member ensemble subjected to a linear warming trend of Indian Ocean SSTs (see text for details). Right side plots are the zonal average of 200 mb u-wind trend (top) and precipitation trend (bottom). Wind (precipitation) trends are plotted as m/s/10years (mm/10 years). Simulations based on NCAR CCM3.

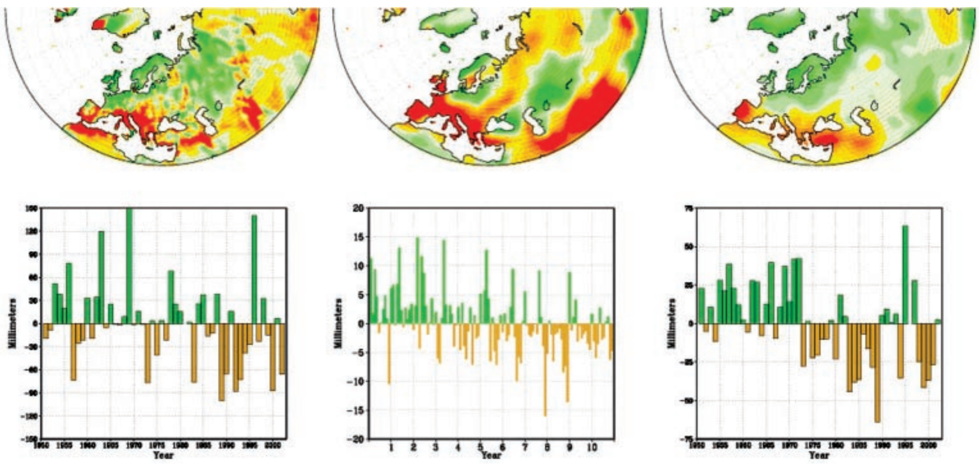

Fig. 4. – The trend and time series in November-April averaged precipitation for 1950-2002 observed (left) and simulated as a response to greenhouse gas forcing (right). Middle panels are November-April precipitation trend due to a specified linear warming of Indian Ocean SSTs using the NCAR CCM3 (see text for details). The time series of the idealized Indian Ocean warming runs spans all 120 months of the 10-year integration, and is based on a 10-member ensemble. The GHG runs are from the IPCC (TAR) experiments, and the analysis uses a 17-member ensemble drawn from 8 different coupled models.

studied in HH. In these new runs, Indian Ocean SSTs between 25 N-25 S warm at a linear rate of 0.2°C/year for a period of 10 years. Figure 3 analyzes the linear trend in the GCM's ensemble mean response. For winter, the top panel displays the 200 mb vector wind trends, whereas the lower panel displays the precipitation trend. The zonal average of each field is plotted to the right of each plot.

A striking feature of the wind response is the zonally uniform weakening of subtropical westerlies, and a commensurate increase in westerlies in sub-polar latitudes. Precipitation decreases throughout much of the region of weakened westerlies, especially in the vicinity of the European Mediterranean climate region, but also in the so-called California Mediterranean climate region. The substantial annularity of the atmospheric wind response is thus seen to illicit a coherent disruption of the typically wet winter climates of the US and European Mediterranean regions.

The warming of Indian Ocean SSTs during the latter half of the 20th century is very likely the response to increasing greenhouse gases. The study of HH compared the time series of Indian Ocean SST of three different greenhouse gas (GHG) forced coupled ocean-atmosphere models to observations, and found a striking agreement in the low frequency Indian Ocean SST change among them. In so far as fig. 3, and the earlier experiments of HH, have established Indian Ocean warming to be an attributable cause for Mediterranean drying, the question becomes whether this drying is ultimately due to human-induced climate change.

We have analyzed the 1950-2002 Mediterranean climate region's precipitation response to observed and projected changes in GHG-forcing. Our analysis uses the available IPCC (TAR) simulations. The total available ensemble size is 17 runs, and we compute the precipitation trend, and the Mediterranean time series of this 17-run average. The results are shown on the right side plots for fig. 4. For comparison, the left side plots repeat the observed 1950-2002 precipitation trend, and the Mediterranean-zone time series. The middle plots are the results from the aforementioned 10-year transient Indian Ocean warming experiments. Its time series shows all 120 months of simulated Mediterranean zone precipitation anomalies that span the 10-year period during which the Indian Ocean warms at the linear rate of +0.2°C/year.

We find remarkable agreement among the spatial patterns of the observed and simulated trends in precipitation. The GHG-forced signal is considerably weaker than the observed change, in part owing to run to run variations in the trends. Nonetheless, the similarity in temporal evolution of the GHG-forced Mediterranean and observed precipitation changes is unlikely due to chance. The fact is that the Indian Ocean warming simulations also yield a drying trajectory over the European Mediterranean. It is our interpretation that a Indian Ocean warming in the GHG-forced coupled runs, similar to that imposed in our idealized AGCM experiments, is responsible for Mediterranean drying in those experiments.

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