5.2 REGIONAL DRIVERS OF ARIDITY IN SOUTHWEST ASIA AND SENSITIVITY TO SURFACE CHANGE

Benjamin F. Zaitchik*
Jason P. Evans
Ronald B. Smith
Yale University, New Haven, CT

1. INTRODUCTION

Southwest Asia (Figure 1) is a geographically and climatically diverse region that includes cold highlands, humid coastal zones, Mediterranean hills, and semi-arid and arid plains. Mountain ranges frame the region to the north (Taurus and Caucasus Ranges) and to the east (Zagros Plateau and Elburz Mountains). Topography along the western edge of the region is less severe (Lebanon, Media, and Tahama Hills), and the center and south of the region is characterized by broad steppe interrupted by isolated ridges, river valleys, and oases. Large, highly evaporative water bodies surround the region and play an important role in atmospheric dynamics and hydroclimatology.

The most striking climatological feature of Southwest Asia is a strong North to South precipitation gradient, stretching from humid highlands in Turkey (> 1 m yr^{-1}) to deserts in Syria and Saudi Arabia (< 100 mm yr^{-1}). The gradient is interesting from a physical perspective, as it represents the combined influences of latitude, topography, and local evaporation. The relative importance of these drivers is unknown, as is the sensitivity of the gradient to changes in surface properties and large-scale forcings. The gradient is also interesting from a historical and social perspective. Archaeologists suspect that climate variability over the past 10,000 years has played a significant role in the development of civilization in the Fertile Crescent and Mesopotamia, the region is water-stressed and sensitive to drought today, and GCM climate change scenarios predict a warming and drying of Southwest Asia in the coming century that would be coincident with a period of rapid population growth.

A second feature of the region's climatology is that the current regime of winter precipitation and dry summers appears to have changed over time; paleoclimate records from Lake Zeribar (Western Iran) and Soreq Cave (Israel) suggest that summertime precipitation was significant as recently as 6200 ybp (Issar and Zohar 2004). Changes in seasonality as well as quantity of precipitation may have played a role in the ecological and social development of the region, and historic changes in land cover, in turn, may have influenced regional hydrology and climate throughout the Mediterranean and Southwest Asia (Reale and Dirmeyer 2000).

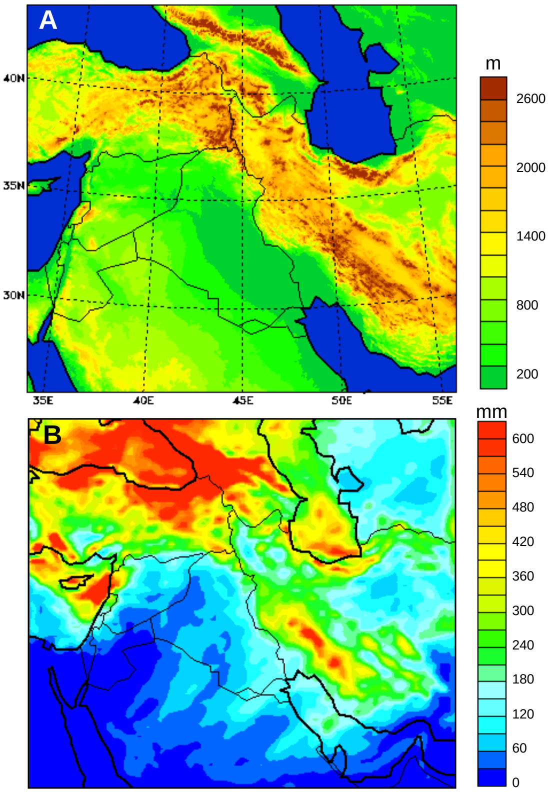

Figure 1: Southwest Asia (A) topography and (B) MM5 predicted annual precipitation for 1999.

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* *Corresponding author address*: Benjamin Zaitchik, Dept. of Geology and Geophysics, Yale University, PO BOX 208109, New Haven, CT 06520-8109
email: benjamin.zaitchik@yale.edu

A firm understanding of the background drivers of climate in Southwest Asia is prerequisite to any investigation of human influence or social response. In the present study we investigate the sensitivity of climate in the region with respect to two hypotheses: (1) that elevated heating by the Zagros Plateau of Iran causes subsidence in the Tigris-Euphrates valley, capping convection and thus enhancing lowland aridity, and (2) that the Persian Gulf is an essential source of water vapor for precipitation events as far north as the Fertile Crescent. We investigate these sensitivities through MM5-Noah simulations with manipulated lower boundary conditions. Such modeling studies provide a foundation for understanding the climate dynamics of the region and also give an indication of potential climate sensitivity to changes in surface features.

2. MM5-NOAH

The PSU/NCAR (Pennsylvania State University / National Center for Atmospheric Research) mesoscale modeling system MM5 is described by Dudhia (1993) and Grell et al. (1994). MM5 is a limited-area nonhydrostatic model that uses a terrain-following vertical coordinate system. It has 2-way nesting capabilities and flexible physics options. In this study MM5 was implemented with the Reisner Mixed-Phase explicit moisture scheme (Reisner et al. 1998), the MRF planetary boundary layer scheme (Hong and Pan 1996), the Rapid Radiative Transfer Model (RRTM) radiation scheme (Mlawer et al. 1997), and, the Grell Cumulus Scheme (Grell et al., 1994).

MM5 is operationally linked with the Noah LSM. Noah is a direct descendent of the Oregon State University (OSU) LSM (Mahrt and Ek 1984; Mahrt and Pan 1984; Pan and Mahrt 1987), a sophisticated land surface model that has been extensively validated in both coupled and uncoupled studies (Chen and Mitchell 1999; Chen and Dudhia 2001). The Noah LSM simulates soil moisture, soil temperature, skin temperature, snowpack depth and water equivalent, canopy water content, and the energy flux and water flux terms of the surface energy balance and surface water balance. In its MM5-coupled form Noah has a diurnally dependent Penman potential evaporation (Mahrt and Ek 1984), a four layer soil model (Mahrt and Pan 1984), a primitive canopy model (Pan and Mahrt 1987), modestly complex canopy resistance (Jacquemin and Noilhan 1990), and a surface runoff scheme (Schaake et al. 1996).

One limitation that we encountered in our application of MM5-Noah on climatological time scales is the absence of an irrigation scheme within the surface flux module. Grid cells classified as irrigated crops or pasture are initialized at 100% soil moisture, but no additional water is introduced during the simulation. This may be appropriate for 2-3 day weather simulations, but for studies of climate some modification is required. A universal irrigation regime would be difficult to emulate as irrigation practices can differ markedly between regions. Here we simulated the flood irrigation practices common in the region for a summer crop by bringing irrigated grid cells to saturation for 30-minutes at 0900 local time once every seven days. The irrigation season began on May 30 and concluded on September 14, in accordance with average cropping patterns in the area (al-Khaier 2003). The length of the saturation period was selected based on local practice as well as trial and error in order to obtain a realistic periodic dry-down throughout the soil column (Figure 2). Some accumulation of water was observed in the bottom soil layer over the length of the growing season, but this is not unrealistic for flood irrigation as it is traditionally practiced (e.g., Sharma and Tyagi 2004).

3. SENSITIVITY TESTS

A large mountain range or plateau can act as an elevated heat source, absorbing solar radiation during the day and warming the air column to temperatures several degrees higher than air at the same height in the free atmosphere. In the proper mesoscale context this heating may drive thermally direct circulations, varying in strength or direction on a diurnal time scale. In the classic “plain-plateau circulation,” elevated heating in the mountains causes strong upslope flow near the surface, lifting along the slopes and ridgetops, and broad return flow aloft. This results in descending air over the plain, potentially capping convection in this zone. Such a circulation is deactivated if the high terrain is snow covered, as high albedo neutralizes the elevated heating source. The Zagros Plateau includes broad areas above 1500 m elevation, and isolated peaks as high as 4000 m. In the current climate permanent snow is limited to the highest peaks, but in a colder climate—the last glacial maximum, the Younger Dryas, or, perhaps, the Little Ice Age—we would expect broader snow cover on the plateau in the warm months. If elevated heating does act to suppress convection in the Tigris-Euphrates basin then we would expect greater convective precipitation in the basin when the Taurus heat source is weakened by snow. To test this in the extreme, we enforce full snow cover at all elevations > 1500 m within the Zagros Plateau for a full year MM5 simulation (Figure 2a). This “Mountain Snow” case is used to examine climate sensitivity to surface change in the Zagros.

The shoreline of the Persian Gulf has shifted dramatically over the course of the Holocene, ranging from a completely dry gulf in the wake of the last glacial maximum to an extended gulf at the time of the Holocene Optimum and subsequent retreat to the current shoreline. The influence of the Gulf as an evaporative source and as a driver of local sea breeze circulations is well established (Warner and Sheu 2000; Shi et al. 2004). In previous modeling studies by our group (Evans and Smith 2005) we found that precipitation events as far north as the Fertile Crescent are fueled by water vapor evaporated from the Gulf. This suggests that the extent of the Gulf may have a significant influence on hydroclimatology over a broad area of Southwest Asia. We test this sensitivity with a “Gulf Removal” MM5 simulation (Figure 2b), broadly representative of the state of the Gulf 18000 ybp (Lambeck 1996).

The Mountain Snow, Gulf Removal, and Control (standard surface conditions) simulations were initialized on model date 1 Nov 1998 and data were analyzed for the 1999 calendar year. Spatial resolution was 27 km in all cases. NCEP-NCAR reanalysis data were used for boundary conditions.

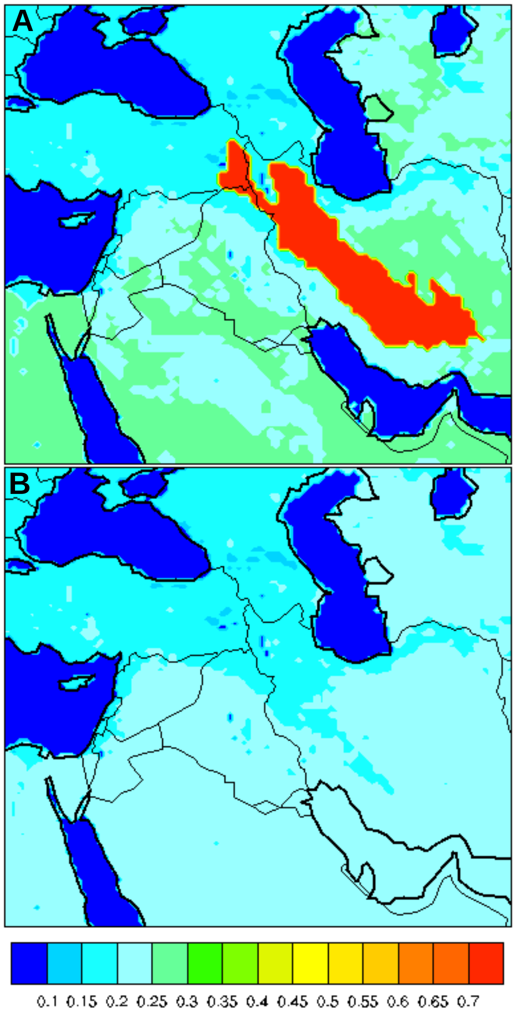

Figure 2: Mean surface albedo for July 1999 in (A) Mountain Snow and (B) Gulf Removal simulations.

4. Results

A general evaluation of the MM5 Control simulation is presented elsewhere (Evans and Smith 2005). Here we compare the Mountain Snow and Gulf Removal simulations to the Control with respect to average atmospheric conditions and precipitation generating events.

As expected, modeled ground temperature over the Zagros Plateau was dramatically reduced in the Mountain Snow case relative to MM5 Control, with the greatest difference in summer (Figure 3). Mountain Snow also had the effect of slightly decreasing daytime temperatures in Mesopotamia and eastern

Iraq and marginally increasing daytime temperatures in Syria. This pattern is related to the considerable influence that Mountain Snow has on the near-surface wind field, as daytime downslope winds bring cool air into Mesopotamia while slowing the prevailing westerlies, thus allowing for greater heating in the upwind region. Night-time temperatures were generally cooler in the Mountain Snow simulation, both on the plateau and in the Tigris-Euphrates Basin.

In the Gulf Removal simulation there is a moderate increase in daytime and night-time ground temperatures in the vicinity of the Gulf, but the strengthening of down-valley winds associated with the loss of the sea breeze circulation actually results in a slight cooling in central and western Iraq and eastern Syria. Loss of the sea breeze also impacts winds on the Eastern shore of the gulf, indicating that diurnally shifting winds in this region are produced by a combination of Zagros heating and Gulf cooling. The upslope daytime winds near the Gulf are considerably weakened in the Gulf Removal simulation; this sensitivity is relevant to precipitation, as forced convection along the Zagros is an important precipitation mechanism within the Tigris watershed.

At 700 mb the impact of Mountain Snow is equally dramatic, as an anti-cyclonic circulation predicted in the Control run is impinged upon by a cyclonic circulation, centered on the Caspian Sea, that dominates flow over the Zagros when the heating source is removed (Figure 4). Gulf Removal has a much smaller impact on wind and temperature at this height. It is also noteworthy that temperatures above the Zagros Plateau are elevated relative to the surrounding free atmosphere during the day and at night (Control case). This is a modification to the classic Plain-Plateau circulation model, which assumes night-time cooling above elevated terrain, and can be attributed to stagnant horizontal flow along the high Zagros. The fact that the atmosphere above the Zagros is warm relative to that of the Tigris-Euphrates throughout the night indicates that during the summer there is a potential for terrain-induced subsidence in the Basin even over night. Indeed, if we consider the pressure velocity (ω) at local noon and local midnight, we see that there is descending motion in the Tigris-Euphrates Basin at both times (Figure 5). In the Mountain Snow case this motion is weakened during the day and reversed at night, due to convergent flow in the valley. The effect is most dramatic in summer.

The influence of Mountain Snow and Gulf Removal on atmospheric stability can also be defined in terms of Convective Available Potential Energy (CAPE). Figure 6 shows average 3pm CAPE for a 10 day period in March and a 10 day period in July. In the March averaging period CAPE is strongest to the south of the region and is also present across the Taurus and Zagros Mountains. Mountain Snow eliminates CAPE over the plateau, as expected, and causes a modest increase in northern Iraq and eastern Syria. Gulf Removal has an extensive impact, causing a reduction in predicted CAPE along the Western ridge of the Zagros Plateau that extends for several hundred kilometers. In July these patterns are even more obvious, as Mountain Snow eliminates CAPE over the Zagros while increasing CAPE over Mesopotamia and the Fertile Crescent, and Gulf Removal reduces CAPE over much of the Zagros Plateau. The impact of Mountain Snow on CAPE is best understood in terms of changes in wind patterns and the location of subsidence zones, while the far reach of Gulf Removal is predominantly a result of reduced humidity.

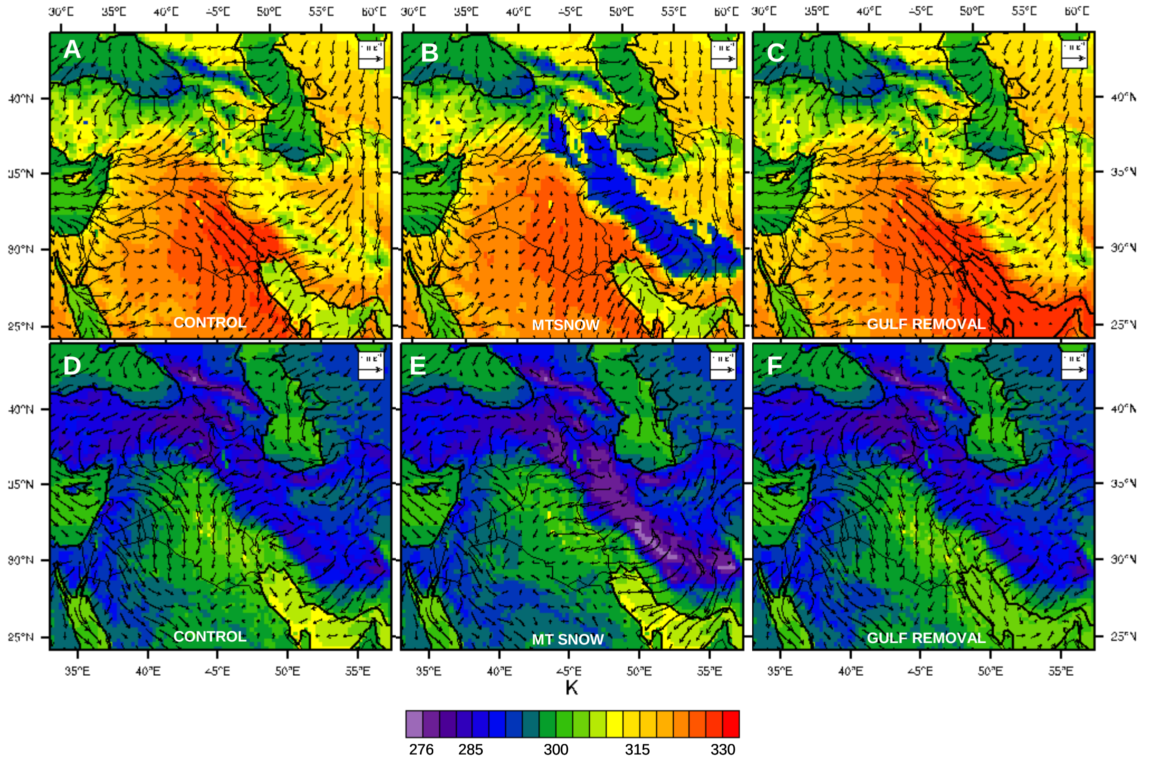

Figure 3: Ground temperature and 10-m winds, time-of-day averages for July-August 1999 at 3pm local time (A-C) and 3am local time (D-F) in the (A,D) Control, (B,E) Mountain Snow, and (C,F) Gulf Removal simulations.

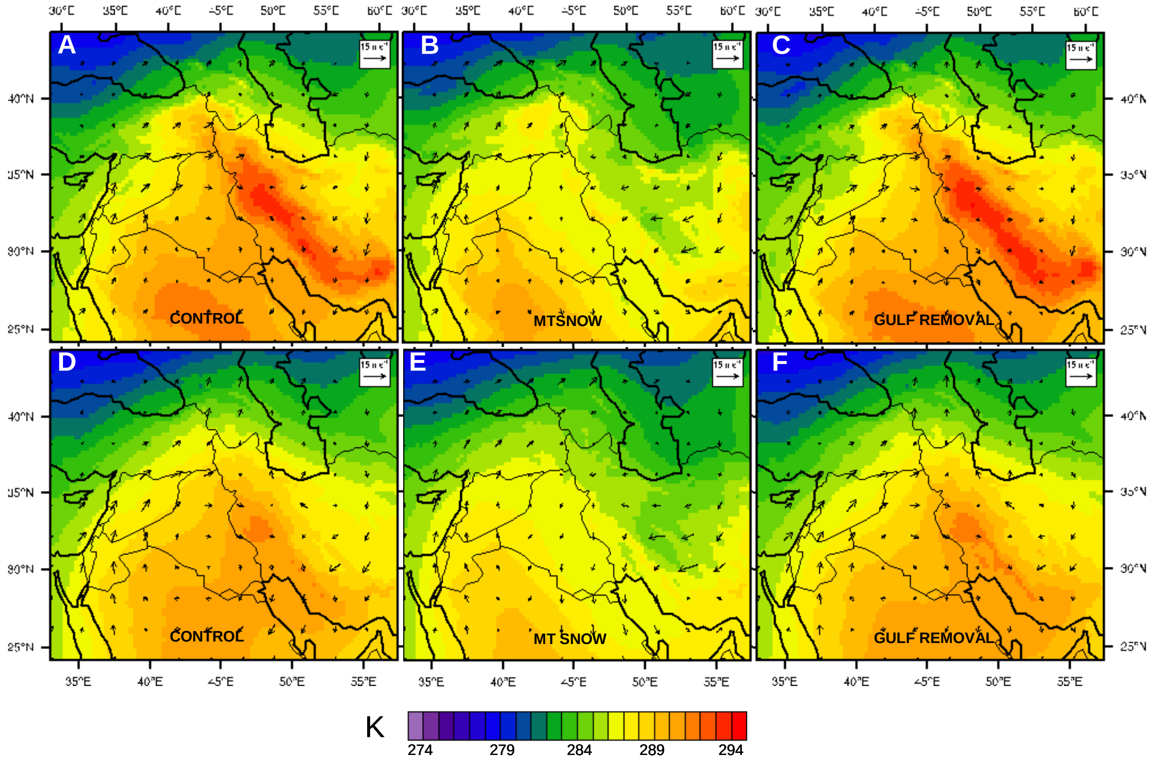

Figure 4: As in Figure 3, but for 700mb winds and temperature.

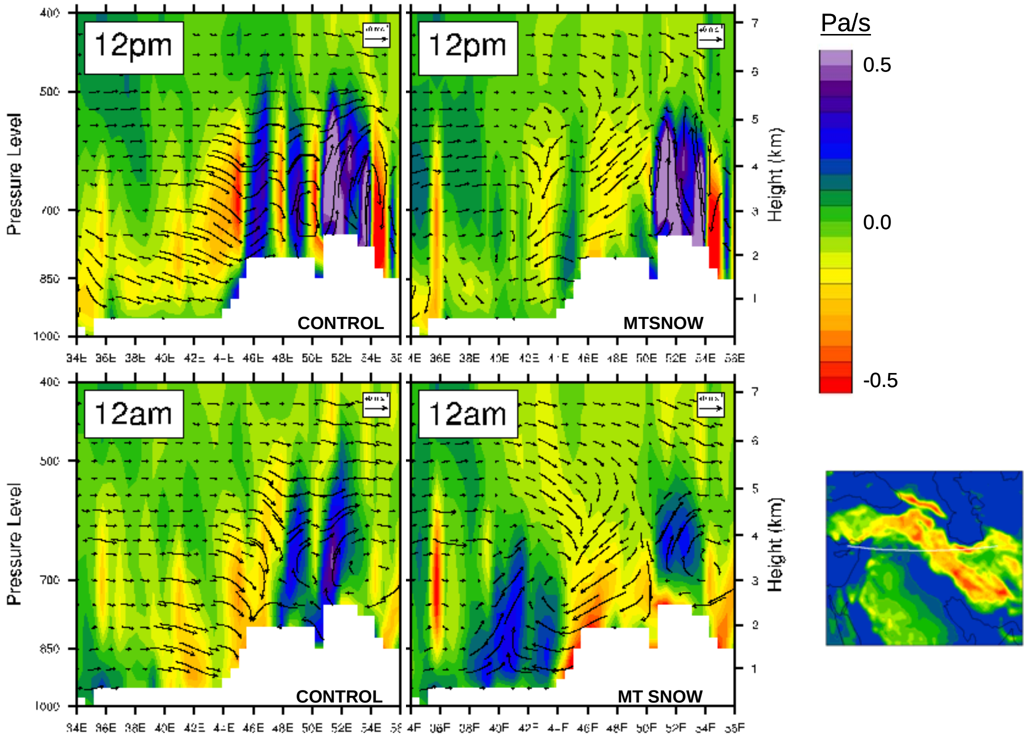

Figure 5: Cross section at 36°N showing winds (vectors) and pressure velocity (colors) at 12pm and 12am local time in the Control and Mountain Snow simulations. All values are time-of-day averages for July and August. Negative pressure velocity indicates upward motion.

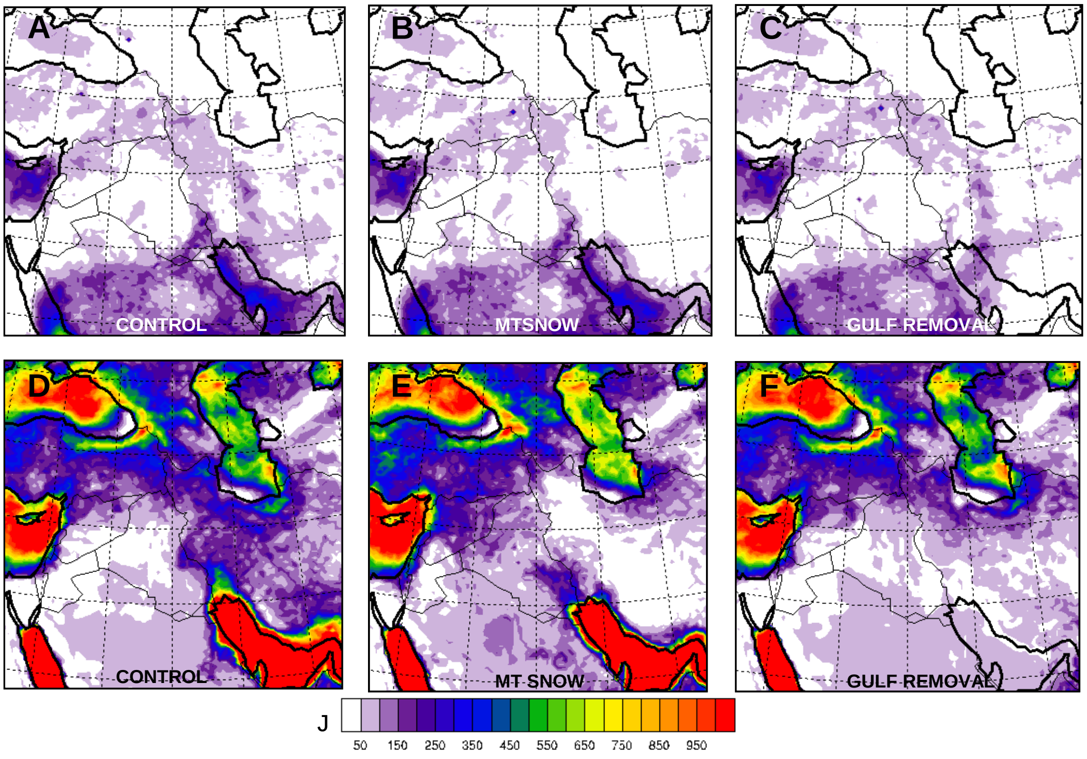

Figure 6: 3pm local time CAPE, averaged for a 10 day period in (A-C) March and (D-F) September.

5. Conclusions

The impact of each simulation on total annual precipitation is shown in Figure 7. The result is noisy, as it is based on only a single year of model data, but there is broad spatial coherence. Mountain Snow results in reduced precipitation over the Zagros and to their East and increased precipitation in the Taurus Mountains and the Tigris-Euphrates Basin. Gulf Removal is associated with a significant reduction in precipitation throughout the Zagros and Taurus Mountains and in portions of Mesopotamia and the Fertile Crescent.

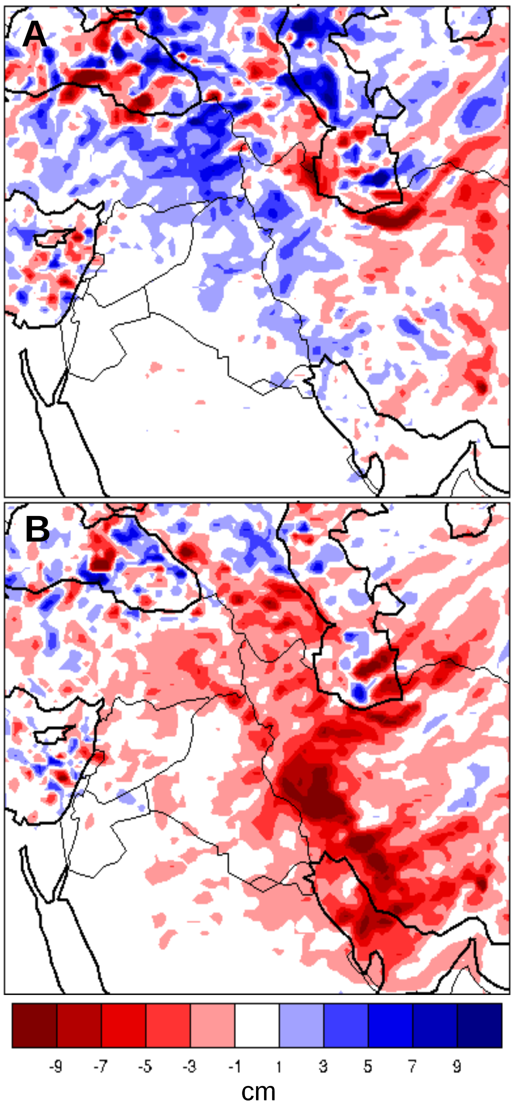

Figure 7: Difference in 12 month accumulated precipitation (1 Jan – 31 Dec 1999) for (A) Mountain Snow - Control (B) No Gulf - Control

These simulations represent extreme cases of surface modification, but they are instructive as to the direction of the impact that increased snow cover or a reduced Persian Gulf may have on circulations and precipitation climatology of the region. Based on these preliminary analyses it appears that the Zagros Plateau and Persian Gulf both have a substantial influence on precipitation patterns in the Tigris-Euphrates Basin, and the role of these surface elements should be considered in any study of climate sensitivity and change in Southwest Asia.

6. Acknowledgements

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