Assessment of the CFS on the Predictability of the North American Monsoon

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1. Introduction

The North American Monsoon (NAM) is a difficult region for weather and climate prediction because although it encompasses a small region, it has an intricate terrain. The region stretches from central Mexico into Arizona and New Mexico with the Gulf of California and Baja peninsula to the west and the Gulf of Mexico to the east. In addition, the Sierra Madre Occidental stretches along the west coast of Mexico with the Sierra Madre Oriental to the east. This combination of mountains, water bodies, and the Baja peninsula make the NAM an interesting system.

Two similar studies focusing on the NAM system have been compiled. The first study investigates the ability of NCEP's Climate Forecast System (CFS) to simulate the NAM using different atmospheric physics, horizontal resolutions, and lead times. The second study highlights results gathered during the NAM Experiment Model Assessment Project 2 (NAMAP2). For NAMAP2, six global models, including NCEP's CFS and Global Forecast System (GFS), and four regional models were gathered and analyzed. The results presented for both studies focus only on precipitation and the general circulation in the region. These studies aim to determine 1) how the predictability of the monsoon system by the CFS changes with different variations of the model and 2) how the CFS compares to other global and regional models.

2. CFS Variations Simulating the NAM

In the first study, a test version of the CFS (Saha et al. 2006), which may be used for the next generation CFS, is run at three different horizontal resolutions: T62, T126, and T382. These single runs use May 15th for their initial condition. In addition, the current operational CFS forecast, run at T62, is used. These operational runs are 15-member ensemble means using both a 1-month lead (May) and a 3-month lead (March). For observational comparison, a Unified Rain Gauge Dataset (URD) for North America (Higgins et al. 2000) is used for precipitation and the North American Regional Reanalysis
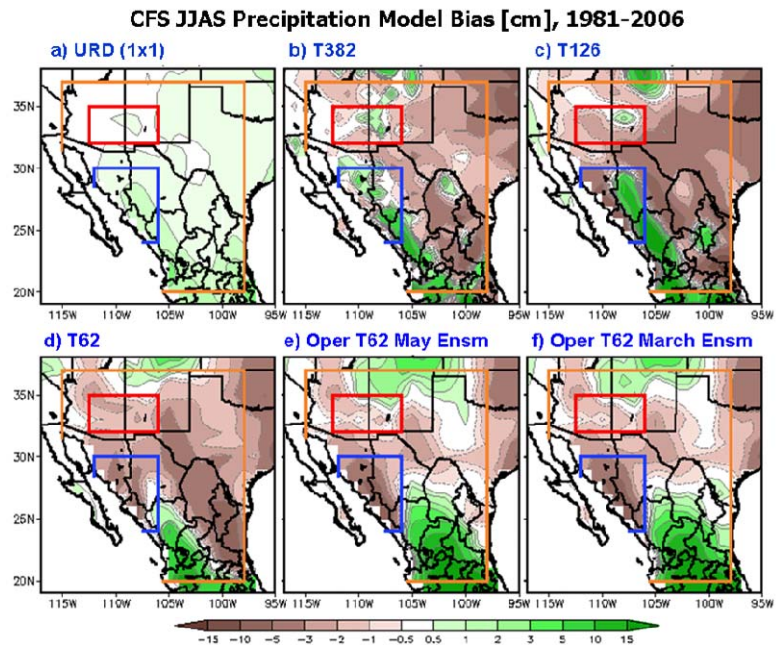

Figure 1 Spatial maps of the JJAS Precipitation Model Bias [cm] for CFS from 1981-2006 for b) CFS at T382, c) CFS at T126, d) CFS at T62, e) Operational T62 CFS Ensemble with May initial conditions, and f) Operational T62 CFS Ensemble with March initial conditions. The total observed precipitation from which the bias is calculated is shown in a), the URD 1981-2006 climatology. Orange boxes represent the TIER 1.5 region. Blue boxes represent the CORE region. Red boxes represent the AZNM region.

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(NARR) is used for wind velocities (Mesinger et al. 2006).

a) Precipitation

In order to compare the different versions of the CFS, we first look at the model precipitation bias compared to the total rainfall represented by the URD (Figure 1). The bias shows that both operational versions of the CFS (Fig 1e and 1f) have a wet bias in central Mexico and a slight dry bias in northern Mexico into the southwest U.S. Also unlike observed climatology (Fig 1a), the precipitation is not contained in a swath following the mountains along the west coast (CORE region, blue box). Instead, this region is extremely dry. Figure 1d shows that the T62 CFS (next generation) is more organized along the mountain range and begins to bring rain into this CORE region, although not far enough north. In addition, the dry bias in Texas is more extreme, reaching down into northern Mexico. Finally, the T382 and T126 runs (Figs 1b and 1c) continue to have this dry bias in Texas and northern Mexico, but the precipitation becomes more organized along the western coast, bringing a healthy swath of precipitation northward. The high resolution of the T382 run leaves a small patch of wet biases along this swath; however, it is important to note that the observations are based on rain gauges and therefore may miss small areas of intense rainfall. Overall, finer resolution and model upgrades are more accurate in simulating precipitation variability in the NAM region.

Figure 2   Seasonal Cycle of precipitation [cm] for the a) AZNM, b) CORE, and c) TIER 1.5 Regions from May to September.

Moving to the seasonal cycle, Figure 2 shows area averages of monthly precipitation from May to September over the three NAM sub-regions. Focusing now on the CORE region (Fig 2b), a clear progression occurs in the CFS model runs, reinforcing the spatial maps in Figure 1. The two operational CFS ensembles at T62 show a much drier monsoon than seen in observations (black line). The T62 with updated physics (red) shows an improvement in the precipitation magnitude, but maintains a precipitation peak in August. The T126 and T382 runs more accurately predict the amount of precipitation; however, only the T382 run correctly simulates the peak in July (versus T126 in August). The T382 does well simulating the monsoon onset from June to July in all three regions, with the onset in the AZNM region being right with observations. In the larger Tier 1.5 region, the two operational CFS ensembles do a better job with the onset and amount of precipitation in the early season than in the AZNM and CORE regions. As seen in Figure 1 by the extreme wet bias to the south, the precipitation is present in these T62 runs, but restricted to the southern NAM region of central Mexico.

Unfortunately, although the CFS does well in predicting the seasonal variability, it does poorly when simulating the interannual variability. Figure 3 shows the correlations for the interannual variability of each model run compared to the URD for each month (left) and seasonal averages (right). Plots of the interannual variability (not shown) are extremely chaotic as can be surmised from the very low or even negative correlations. The next generation CFS at T62 shows improvement over the operational CFS at T62. Increased horizontal resolution also shows improved correlations. Surprisingly, the T382 is not always the most skilled model run. While the T382 run exhibits the most skill in the small AZNM region (Fig 3a and 3d), reaching close to 0.45, it is the T126 run that does better in the larger regions. The T126 run reaches the peak correlation for any CFS run
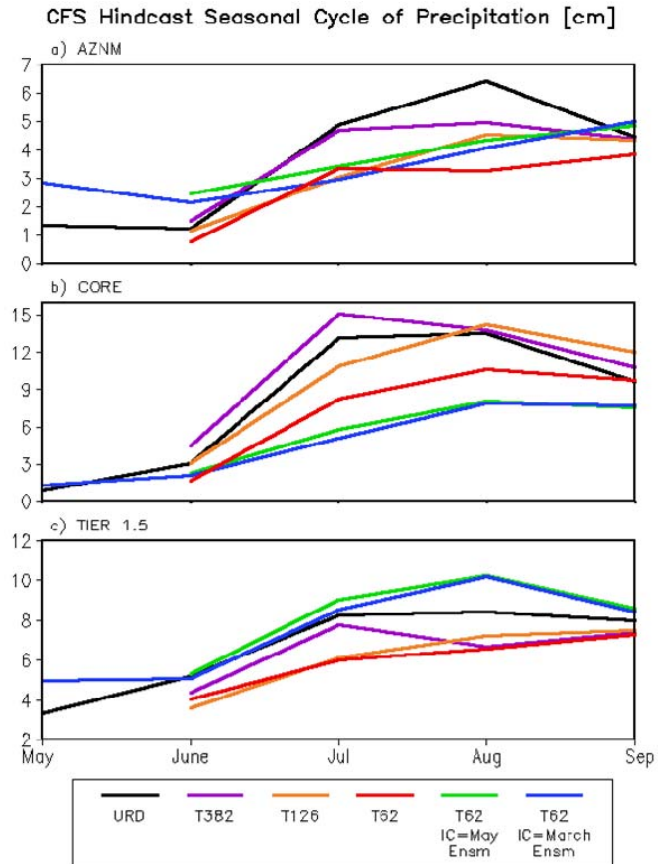
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at 0.51 in the Tier 1.5 region for August. Obviously with these very low correlations, few are actually statistically significant.

b) Winds

The NAM region has three distinct upper and lower level wind features. The first is a large anticyclonic flow located off the west coast of Mexico at 300 mb. This anticyclonic flow seems to come and go throughout the JJA and JAS seasons (not shown). The T382 run correctly produces an intense anticyclone slightly too far south during JJA, but this disappears during JAS. The two operational T62 runs do the opposite. An anticyclonic flow appears late in the monsoon season in JAS. This is consistent with earlier analysis that shows the operational CFS has a tendency to have a late onset of the monsoon. The remaining runs show little to no evidence of the anticyclone near Mexico, but most produce a slight anticyclonic flow far from the area in the southwest Pacific.

The other two important wind features are low-level jets located over the Gulf of Mexico (GoM LLJ) and the Gulf of California (GoC LLJ). At 925 mb, all runs of the CFS produce a robust GoM LLJ bringing warm, moist air into Texas and eastern and central Mexico; however, the CFS does poorly simulating the GoC LLJ. The GoC LLJ brings moist air from the Gulf of California directly into the monsoon region (Figure 4, left). Winds turn from northerly in the Pacific to southerly in the Gulf of California. The CFS produces the northerly flow over the Pacific, but instead of turning to southerly flow over the Gulf, the CFS produces a weak westerly flow. The T382 run is the only run shown in Figure 4 (right), but the wind direction and magnitude is surprisingly consistent between all CFS runs analyzed in this study.
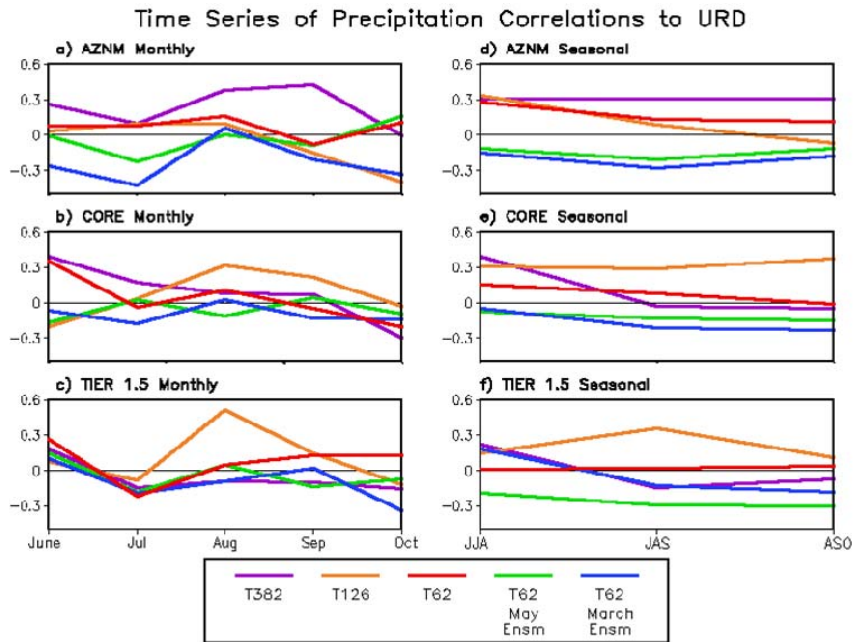

Figure 3 Time series of precipitation correlations to URD for the interannual variability of the NAM from 1981-2006. Correlations are for each month in a) AZNM, b) CORE, and c) TIER 1.5 and for each season in d) AZNM, e) CORE, and f) TIER 1.5.
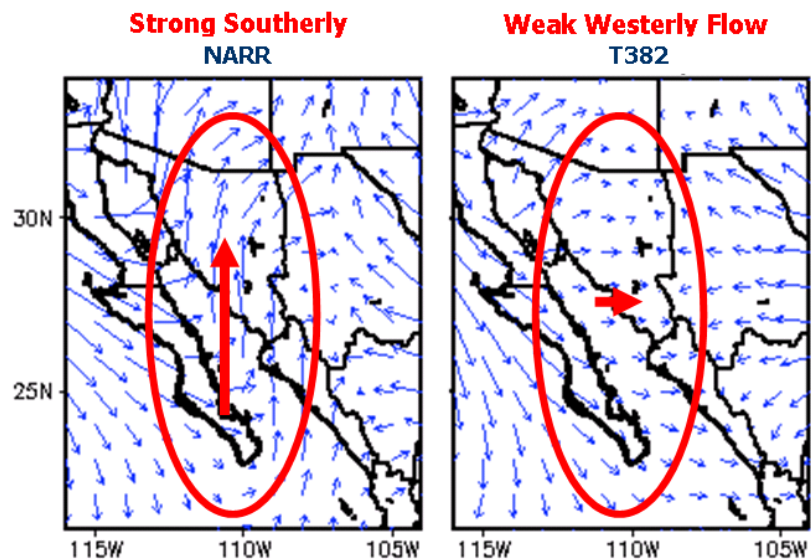

Figure 4 Spatial map of 925mb winds over the Gulf of California region for NARR and CFS T382 averaged for JJA. The main direction of the Gulf of California Low-Level Jet is highlighted by the red vector.

3. NAMAP2

The second study is a snapshot of results gathered during NAMAP2. NAMAP2 is an international collaboration between the United States and Mexico which focuses on the 2004 monsoon season. For this project, modelers were asked to submit simulations for the 2004 summer season from May 15th to September 30th using a new high resolution Multiplatform-Merged (MPM) SST analysis (Wang and Xie, 2007). Ten modelers submitted runs for the study consisting of six global models and four regional models. Model details are illustrated in Table 1 (more complete information on the different models can be obtained from the NAMAP2 web page at http://www.eol.ucar.edu/projects/name/namap2). Most modelers used our requested SST analysis, but a few used their own (RAMS, CAM3b). One modeler submitted two sets of runs, one using the MPM SSTs and one using Era-40 (CAM3c and CAM3a, respectively). There is also a wide range in model resolution and ensemble members.

Model Name	Affiliation / Contact	Horizontal Resolution	Ensemble Size	SST prescription
CFS	NOAA CPC / Schemm	T126 (~1°)	5	MPM
GFS	NOAA CPC / Mo & Wei	T126 (~1°)	4	MPM
CAM3_a	UCSD SIO / Collier & Zhang	T42 (~2.8°)	1	Era-40
CAM3_b	NCAR / Lawrence	1.0°×1.25°	1	Hadley
CAM3_c	UCSD SIO / Collier & Zhang	T42 (~2.8°)	3	MPM
Finite Volume	NASA GSFC / Bosilovich	0.25°×0.36°	2	MPM
GEOS5	NASA GSFC / Lee & Schubert	0.5°	5	MPM
RAMS	*Duke U / Roy*	*64 km*	*1*	*NOAA OI*
RSM	*UCSD SIO / Nunes & Roads*	*30 km*	*1*	*MPM*
MM5_a	*IMTA / Lobato*	*30 km*	*3*	*MPM*
MM5_b	*UNM / Ritchie*	*15 km*	*1*	*MPM*

Table 1   Listing of models participating in NAMAP2 and their key characteristics. The six global models are indicated in non-italic type; the four regional models in italics.

a) Precipitation

Spatial maps of the NAM region show a large discrepancy between models in precipitation magnitude and scope. Figure 5 shows the spatial precipitation maps for each global model and the URD for JJAS in 2004. As in the prior study, three regions are boxed off (AZNM, CORE, and TIER 1.5). The top row (Fig 5a – 5d) shows the URD for comparison and each CAM3 simulation. The two CAM3 simulations from UCSD show precipitation occurring too far south and to the east. The rainfall is not well organized and shows a lack of topographic forcing. These CAM3 simulations are at T42 whereas the NCAR simulation of the CAM3 model (Fig 5d) is at a much finer resolution (~1 degree). At this finer resolution, the CAM3 is able to produce a more accurate representation of the NAM rainfall. Rainfall is confined to a thin region along the western coast of Mexico, moving into the CORE region (blue box). One feature lost in the NCAR contribution is the rainfall present in Texas, Oklahoma, and Arkansas.

Looking now at the bottom row of global model simulations (Fig 5e – 5h), we see a very similar pattern. Here the CFS, FV GCM, GEOS 5, and GFS all capture the swath of precipitation stretching into the CORE region; however, the exact swath location, swath width, and rainfall magnitude vary between models. In addition to the similar precipitation swath, these models all show a dry bias in Texas, Oklahoma and Arkansas.

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Only the GEOS 5 from NASA shows some significant precipitation in the AZNM region (red box) for the global models.

Figure 6 is the same as Figure 5 but for the regional model contributions. Here the effect of increased resolution is evident by the increased detail to the rainfall pattern; however, in addition to this increased detail, the regional models are producing significantly more precipitation than observed. The exception is the RAMS model from Duke which is the coarsest of the regional models and has a more conservative amount of precipitation produced over the NAM region. Northward in the United States, the regional models more accurately simulate the presence of precipitation (albeit too wet), both in the AZNM region and farther east.

Focusing now on the CORE region, the seasonal cycle of precipitation from May to September is shown in Figure 7. For 2004, many different observational tools were available for the NAM region. For comparison, three different products (black lines) are used: a rain gauge dataset, URD, used in the previous study; TRMM, a satellite product (Huffman et al. 2007); and RMOPRH, a satellite-gauge blend (Janowiak et al. 2007). One interesting result of NAMAP2 is the large discrepancy between precipitation products. Although the magnitude of these three products differs greatly, the overall structure is consistent. Each product shows a pronounced increase in precipitation from June to July. All global and regional models, with the exception of one, capture this increase. This is a marked improvement over the previous NAMAP results which indicated delayed onset for most global models. The lone model with delayed onset is the CAM3a submission (dark blue) which produces precipitation too far east

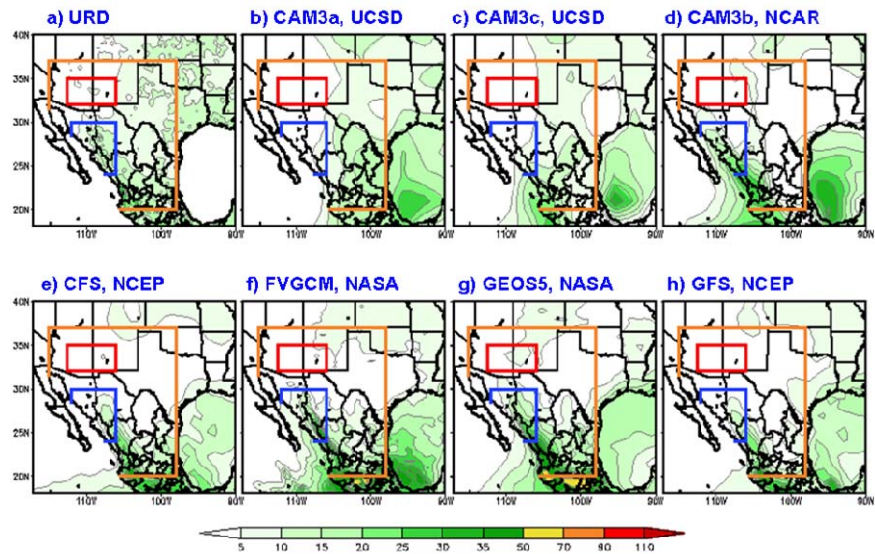**GLOBAL Models - JJAS Precipitation [cm], 2004**

Figure 5 Spatial maps for Global NAMAP2 models and URD. Maps depict JJAS total precipitation [cm] for 2004. Orange boxes represent the TIER 1.5 region. Blue boxes represent the CORE region. Red boxes represent the AZNM region.

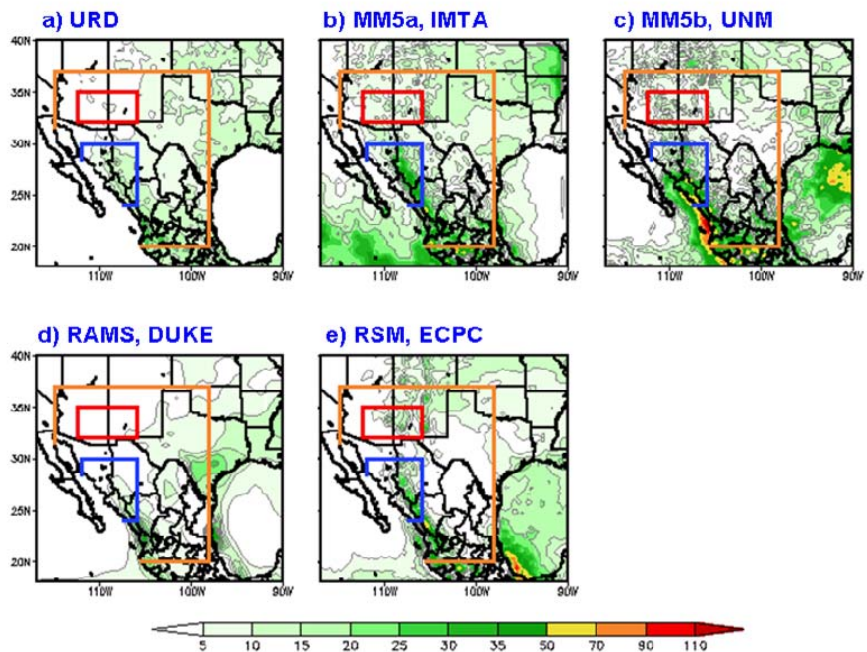**REGIONAL Models - JJAS Precipitation [cm], 2004**

Figure 6 Same as Figure 5, but for Regional Models.

and then slowly moves it into the CORE region late in the season.

Of the global models, only the CFS (red) and GFS (purple) peak in July and then show a decrease in precipitation for the remainder of the season. These two submissions simulate the 2004 monsoon seasonal cycle extremely well. The other five model runs peak in August. This is also true for one regional model (MM5b); however, the other three regional models peak in July. Both the RAMS and RSM simulate the seasonal cycle well. Another interesting feature is the large wet bias in both MM5 submissions seen earlier in the spatial maps. Note the change in scale for the y-axis between the global to regional models.

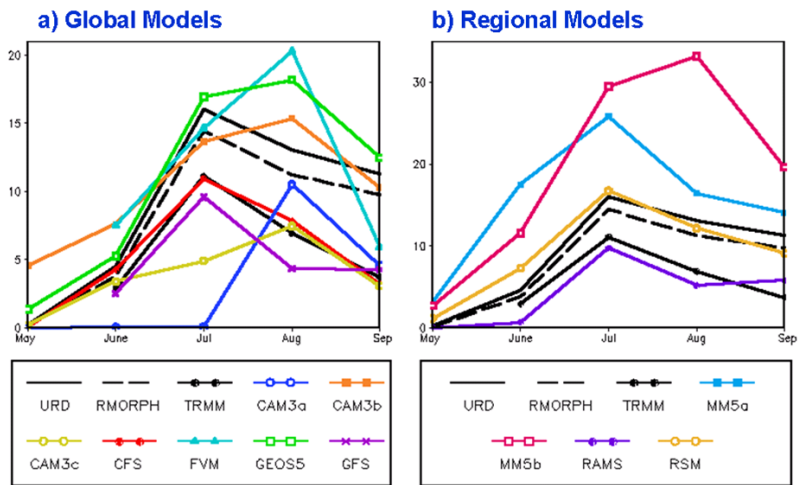**2004 Seasonal Cycle of Precipitation [cm], CORE Region**

Figure 7 Time Series of Monthly Precipitation [cm] averaged over the CORE Region for a) Global models and b) Regional models for May to September. Observations are in black.
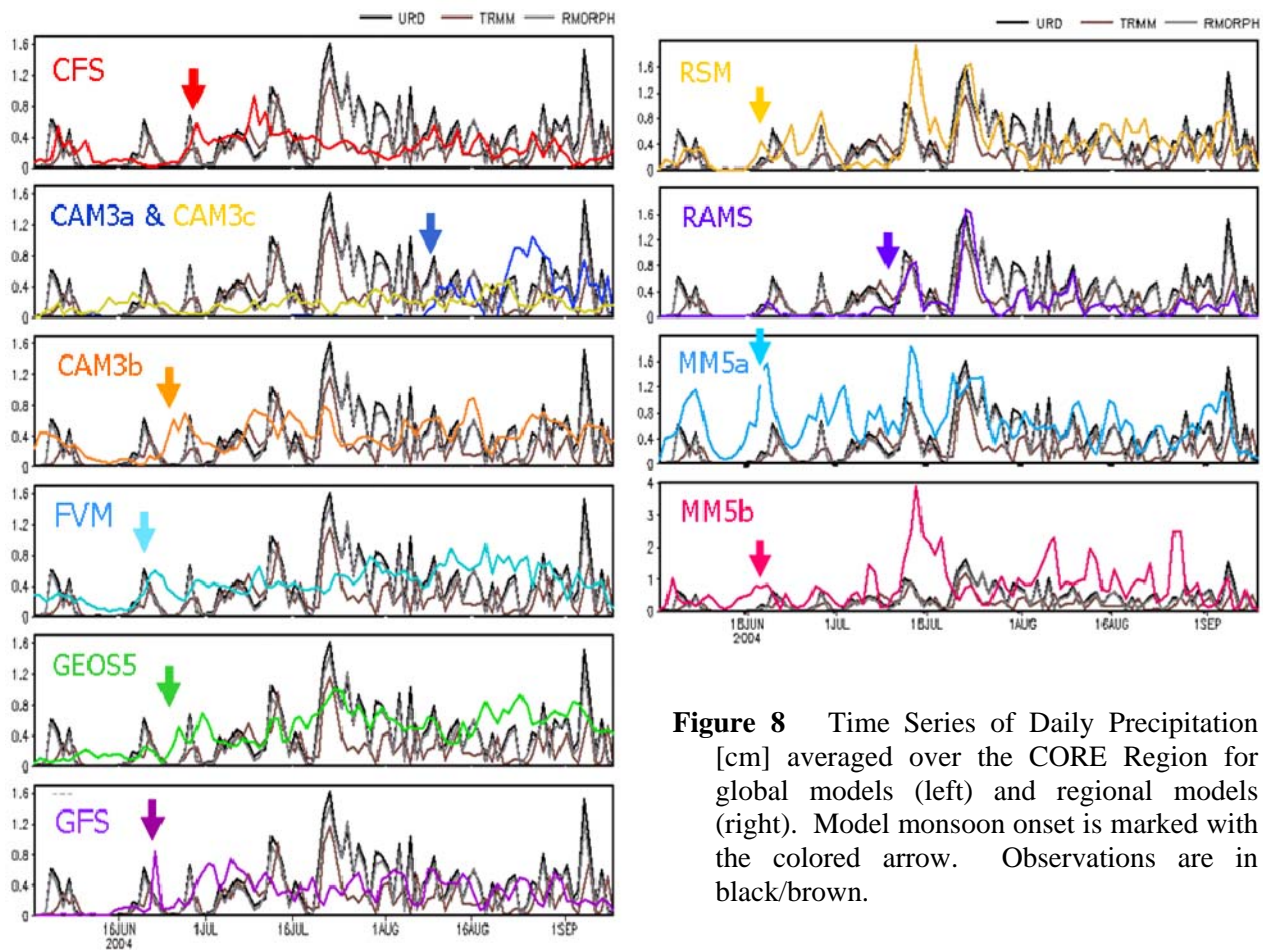

Figure 8 Time Series of Daily Precipitation [cm] averaged over the CORE Region for global models (left) and regional models (right). Model monsoon onset is marked with the colored arrow. Observations are in black/brown.

Figure 8 takes a closer look at the monsoon onset for the CORE region by showing the daily precipitation amounts simulated by each model. Again the same three observational products are shown in the dark colors. Thick colored arrows indicate the monsoon onset for each model, defined as three days of precipitation over 0.5

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mm/day after June 1st. This again shows how well the models are doing at simulating the monsoon onset. In fact, some models even capture the false onset taking place in early June. The CFS, CAM3b, FVM, RSM, and both MM5 simulations show a definite peak in precipitation in early June and then a true onset around June 21st. In addition, the regional models tend to accurately simulate the noisy rainfall pattern throughout the season. Note that the two heavy rainfall events during mid and late July are captured extremely well by the RSM, RAMS, and MM5a (Figure 8, right).

b) Winds

The anticyclonic feature associated with the NAM is represented differently by each model in NAMAP2. At 300 mb, each submission has some anticyclonic flow present in the NAM region; however, many are not located off the western coast of Mexico as seen in observations (not shown). Instead, the center of circulation is found throughout the NAM region including near the US/Mexico border (CAM3 submissions and GEOS5), in eastern Texas (FV GCM), and in central Mexico (MM5a). Both the GFS and CFS produce the anticyclonic flow in the correct location, but with a latitudinally elongated circulation. The RSM produces the most accurate representation of this anticyclonic flow. In addition, as seen in the earlier study, all models do well at simulating the GoM LLJ. The jet shows consistent strength from model to model, but with a slight difference in the angle of flow onto land between model submissions.

Also as seen in the previous study, it is difficult to find a good representation of the GoC LLJ in the NAMAP2 model simulations. Only the MM5b submission from the University of New Mexico shows some sign of the GoC LLJ (not shown). This submission shows a westerly flow that does manage to turn to a southerly flow, albeit weakly, in the very northern portions of the gulf at around 18 UTC.

However, it is important to note some obstacles faced by the models in correctly simulating the GoC LLJ. For NAMAP2, only data at 300, 500, and 850 mb was requested; however, low-level jets are best viewed at pressure levels lower than 850 mb. The GoC LLJ is strongest at approximately 925 mb. Therefore, although the models may not show a jet at 850 mb, there may be one present at lower levels. In addition, the GoC LLJ was weak during the 2004 season which makes it even harder to see at 850 mb. Because the GoM LLJ is such a strong jet, it is easily seen at 850 mb and there is no such problem.

Even with the limitations described above, it is surprising that none of the models can correctly simulate the GoC LLJ. Because of the topography of the region, model resolution was thought to be a main contributor to model weaknesses in simulating the jet. However, with this group of model simulations, many regional models are at considerably fine resolutions. Therefore, limitations in horizontal resolution may not be the actual cause of model error.

Although only total precipitation and general circulation is mentioned here, many other variables were analyzed during NAMAP2. Spatial maps, plots of seasonal and diurnal cycles, and much more are available on the NAMAP2 Online Atlas. This atlas is hosted by the University of Miami located at

http://www.rsmas.miami.edu/personal/pkelly/Research.html.

4. Conclusions

Overall, the CFS has been doing fairly well in simulating seasonal precipitation during the warm season NAM. With horizontal resolutions T126 and finer, the CFS is able to create the swath of precipitation up the west coast of Mexico along the Sierra Madres in the CORE region. The CFS at T62 using the new, test version of the CFS also shows great improvement over the current operational CFS. This test version of the CFS is able to capture the monsoon onset occurring between June and July with greater accuracy as resolution increases. In comparison to other global models examined in NAMAP2 for 2004, the T126 CFS is doing as good if not better than the other submissions.

Even though the CFS correctly predicts this seasonal precipitation, the upper and lower level circulations have serious deficiencies. Because both the GoC LLJ and the upper level anticyclonic flow off the Mexican coast are poorly simulated by the CFS, they bring into question the skill shown by the CFS in predicting precipitation in the NAM region. Although the CFS seems to capture the seasonal cycle of the monsoon, including both magnitude and onset, it seems to be correctly capturing these features for the wrong reasons. The

GoC LLJ is the main source for NAM moisture, and although there is some westerly flow produced over the Gulf of California by the CFS, it is too weak and not pulling from the warmest waters in the southern gulf.

As seen in NAMAP2, this error with the GoC LLJ is also produced by all global and regional models examined. Although complex terrain can be blamed for not capturing the jet at coarse resolutions, when simulations using a grid scale as fine as 15 km fail to capture the jet, other model issues must be responsible. If an additional NAMAP-type study is performed in the future, it would be advantageous to redo the analysis on the GoC LLJ while looking at the correct pressure level of 925 mb to see if this is in fact hampering the analysis.

Finally, the CFS is doing poorly at simulating the interannual variability of the NAM. Although the CFS does well for the 2004 season in NAMAP2, the low correlations presented in Figure 3 show that there is still a significant amount of work to be done on the CFS in the NAM region. Future work involves looking at the general circulation during high and low correlation years to find if there is a connection between a correctly located anticyclone off the west coast of Mexico and a more accurate precipitation simulation. Because there was an anticyclonic flow consistent with observations during the 2004 season, and the CFS correctly predicted the monsoon magnitude and onset, this is a viable analysis.

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