A MECHANISTIC UNDERSTANDING OF THE EVOLUTION OF THE NORTH AMERICAN MONSOON

Ehsan Erfani[1], David L. Mitchell[1] and Dorothea C. Ivanova[2]

1. Desert Research Institute, Reno, Nevada

2. Embry-Riddle Aeronautical University, Prescott, Arizona

ABSTRACT

The North American Monsoon (NAM) is a large-scale synoptic feature having a strong impact on summer rainfall patterns and amounts over North America. For example, anomalously wet NAMs in Arizona are strongly anti-correlated with anomalously dry summers in the mid-west. Although regional climate models have succeeded in reproducing some features of the NAM, its onset, strength and regional extent are not well predicted, and a physical understanding of key processes governing its evolution remain elusive. A correct physical understanding of the NAM is thus likely to improve the prediction of summer precipitation over North America in regional and global scale models.

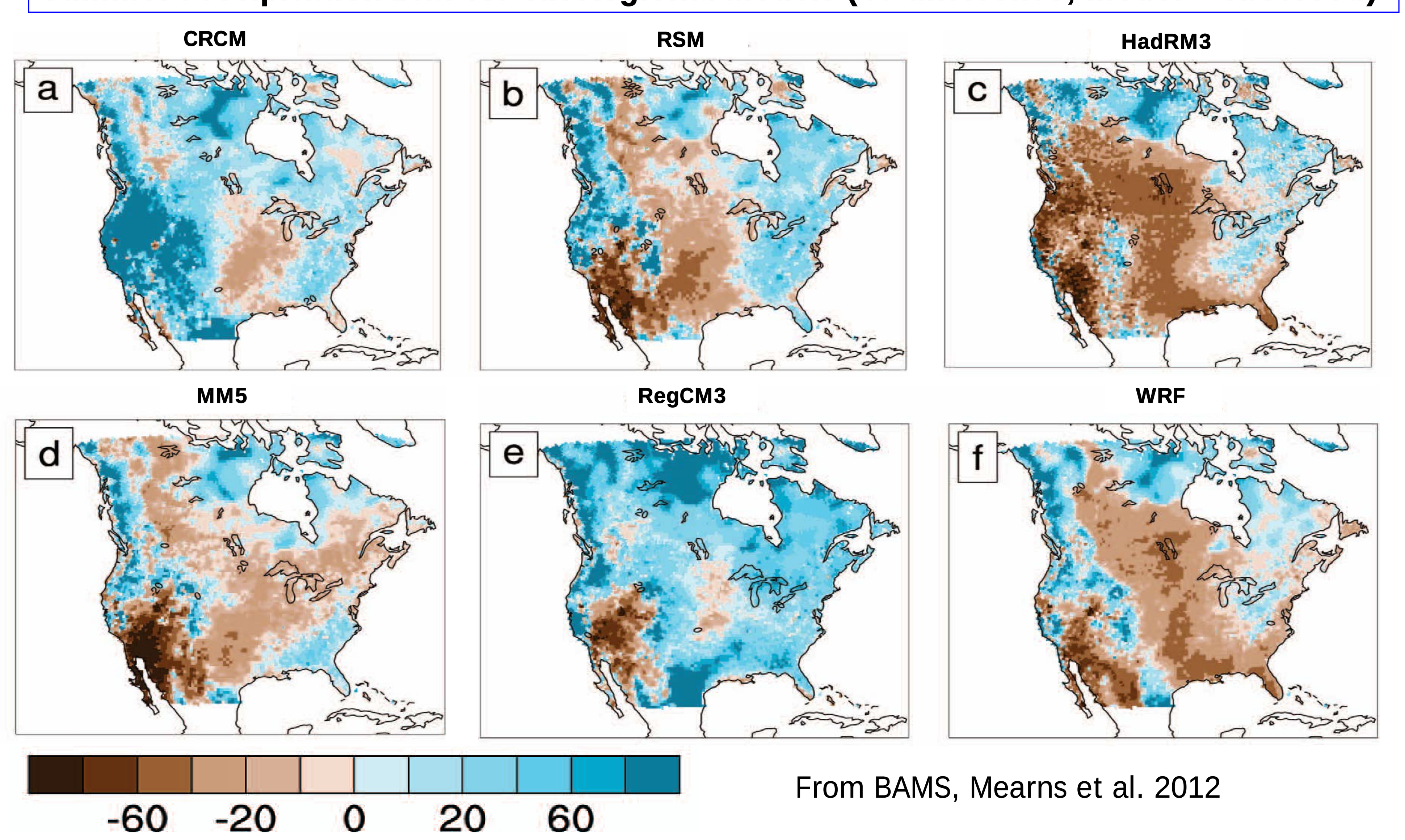
Here we propose a partial mechanistic understanding of the NAM incorporating local- and planetary-scale processes. The proposed hypothesis is supported with satellite observations of sea surface temperature (SST), sea surface height (SSH) and rainfall amount; temperature and humidity profiles from soundings launched over the Gulf of California (GC); climatologies of SST, outgoing longwave radiation (OLR) and 500 hPa streamline reanalysis; regional scale modeling of the NAM region.

On the local-scale, these measurements and modeling demonstrate that relatively heavy summer precipitation in Arizona generally begins within several days after northern GC SSTs exceed 29°C. The mechanism for this relates to the marine boundary layer (MBL) over the northern GC. For SSTs < 29°C, GC air is capped by an inversion ~ 50-200 m above the surface, restricting GC moisture to this MBL. The inversion weakens with increasing SST and generally disappears once SSTs exceed 29°C, allowing MBL moisture to mix with free tropospheric air. This results in a deep, moist layer that can be advected inland to produce thunderstorms.

On the synoptic scale, climatologies of NAM region SST, OLR and NCEP/NCAR 500 hPa streamline reanalysis support the hypothesis that relatively warm SSTs (≥ 27.5°C) are generally required for widespread deep convection to initiate in the NAM region, and that the poleward evolution of the monsoon anticyclone during June-July is driven by the associated descending air north of the convective region. As warm Pacific SSTs propagate northwards up the Mexican coastline, deep convection accompanies this northward advance, advancing the position of the anticyclone. This evolution brings mid-level tropical moisture into the NAM region.

This understanding of the NAMs evolution may provide a basis for more productive NAM research, which could greatly improve summer rainfall forecasts over North America.

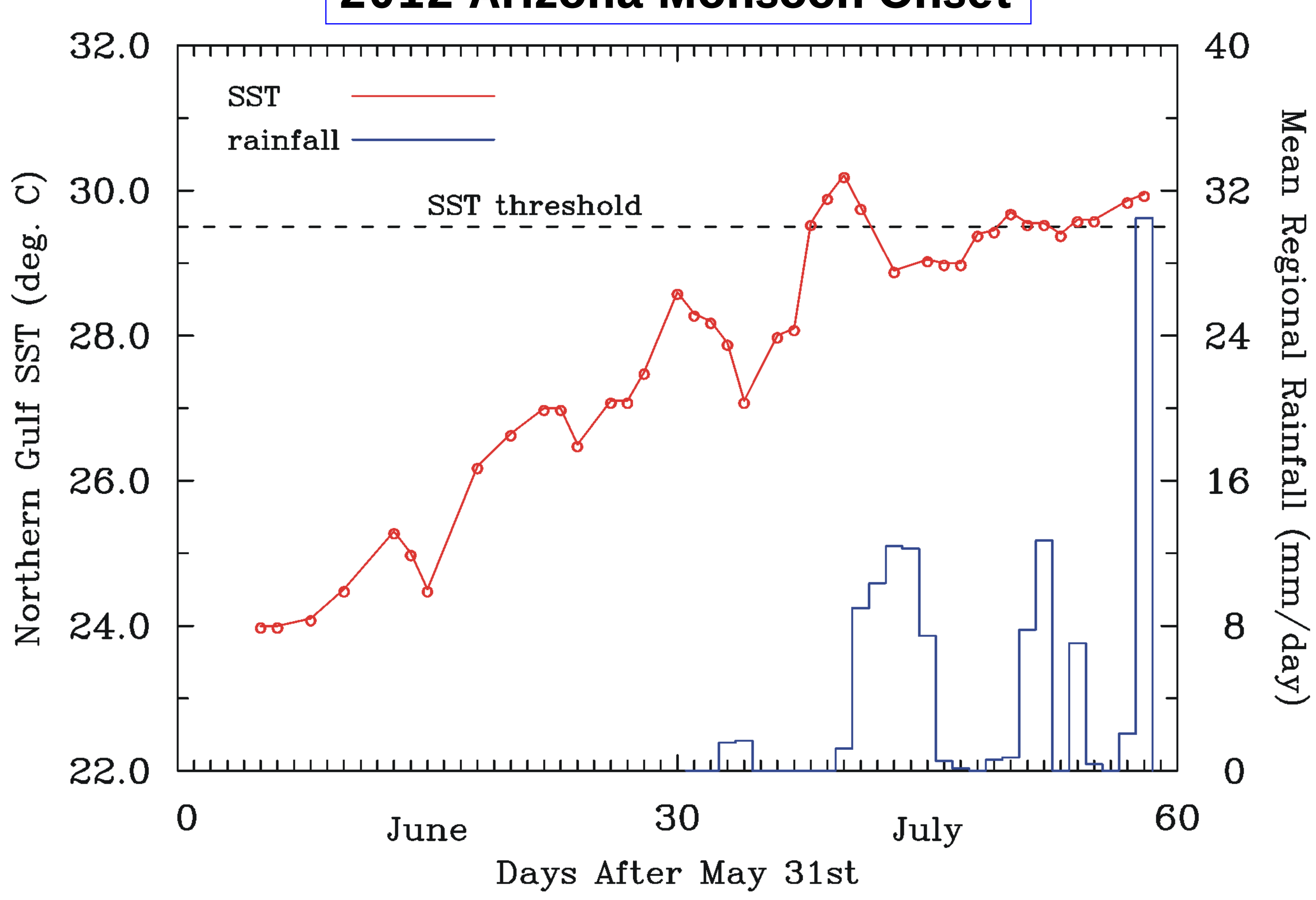
Summer Precipitation Bias for Six Regional Models (% difference; model – observed)



From BAMS, Mearns et al. 2012

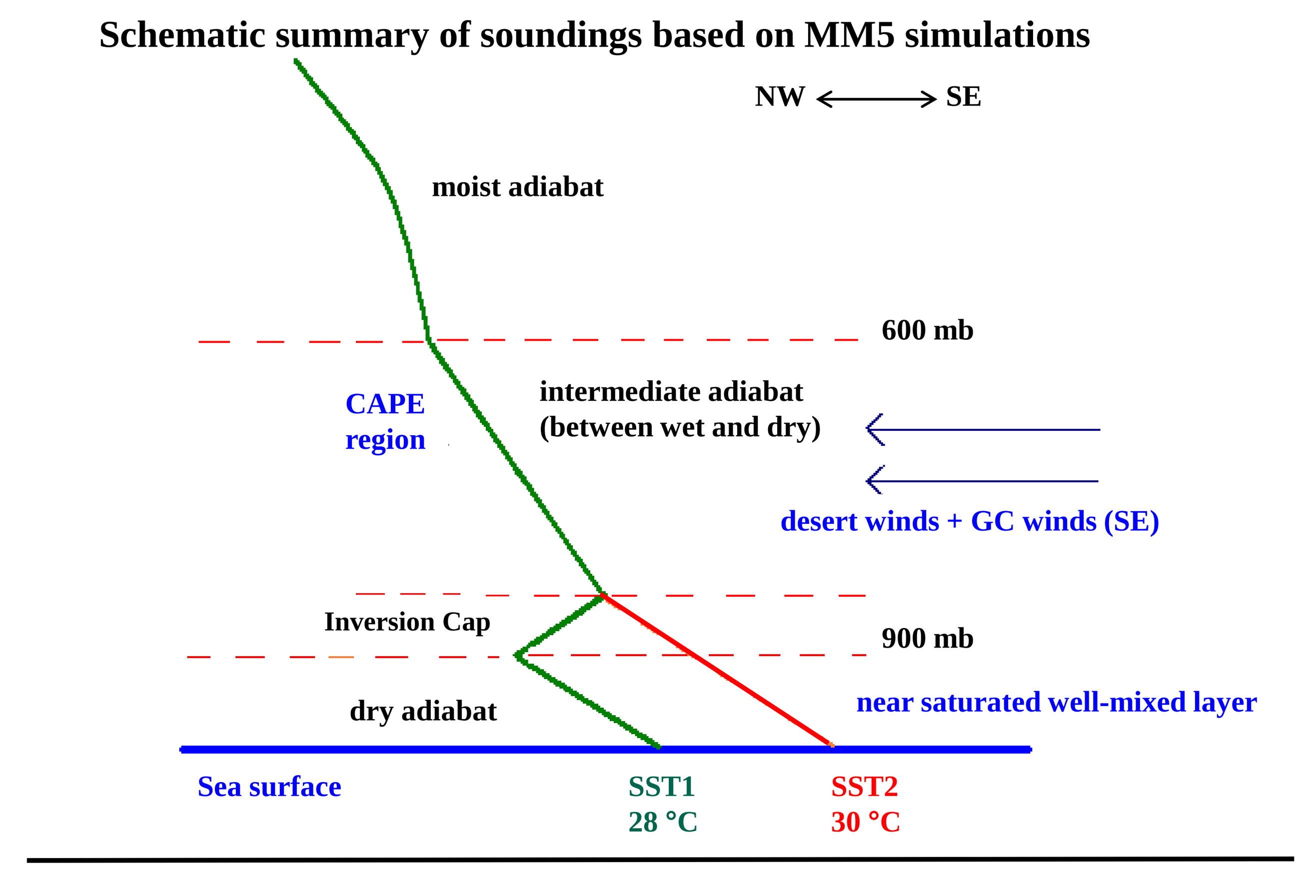
The above results are from a recent climate model inter-comparison study that indicates summer rainfall is generally most under-predicted in the NAM region. Knowledge of the processes governing NAM rainfall onset, amount and extent should improve such predictions as well as summer rainfall prediction over North America in general (shown by several studies).

2012 Arizona Monsoon Onset

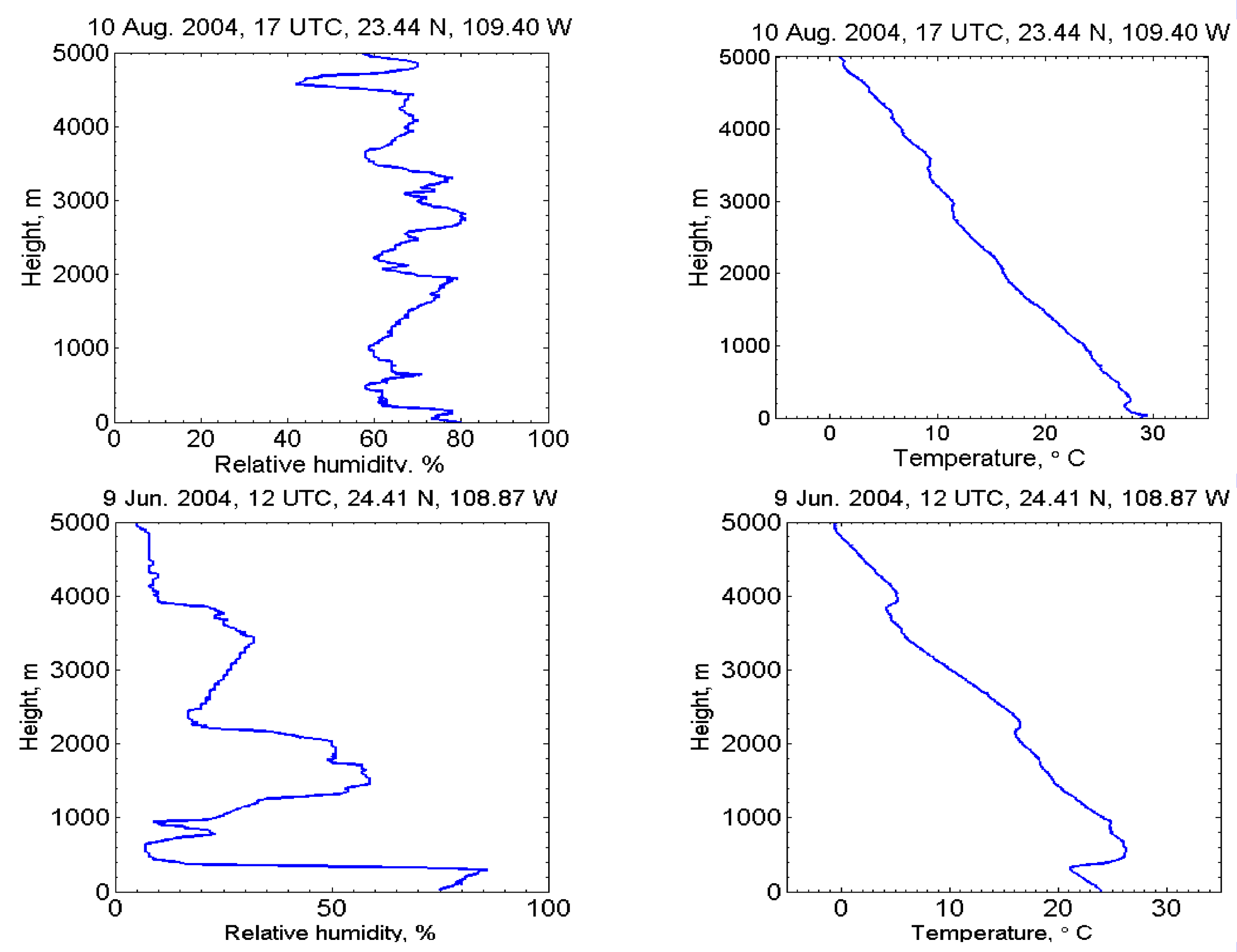


One of 9 case studies of the NAM onset in Arizona related to SSTs in the northern Gulf of California (GC). All cases show relatively heavy rainfall begins after the N. GC SST exceeds 29.5°C. See Mitchell et al. (2002, J. Climate).

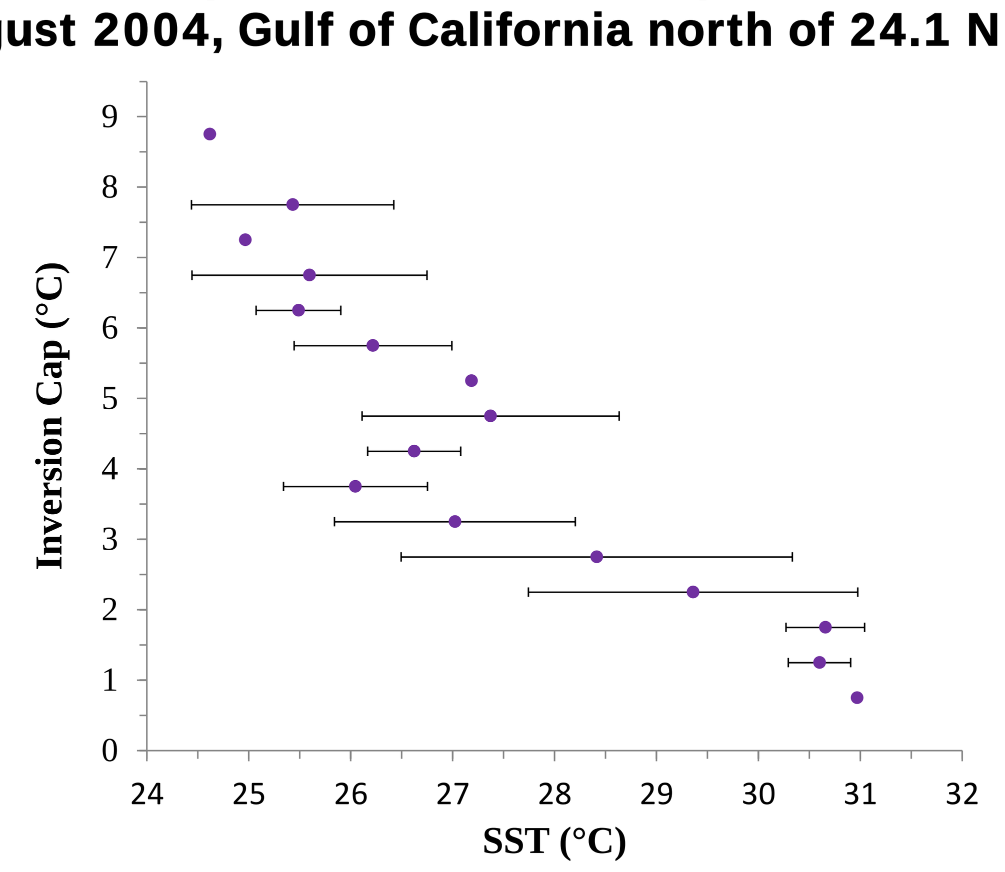
Dependence of Gulf MBL Inversion on SSTs



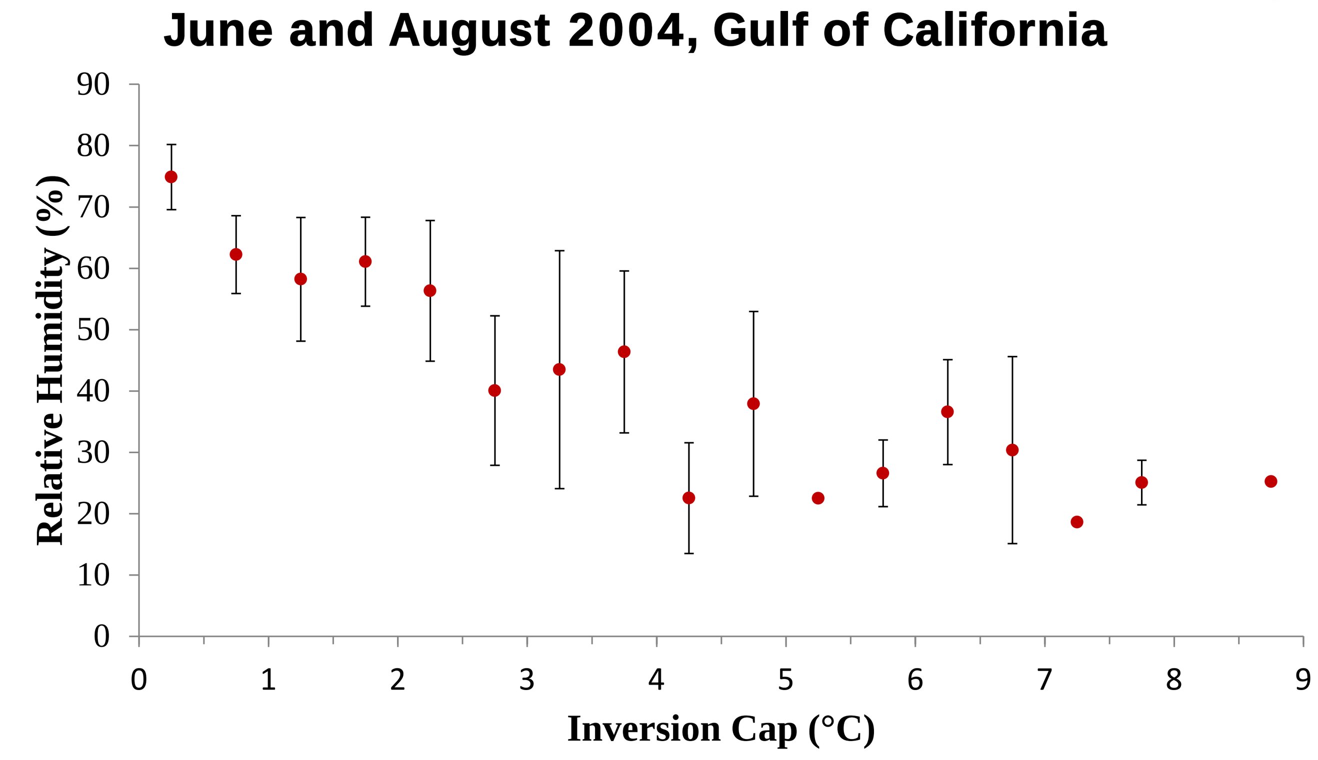
Temperature and relative humidity from ship balloon launches during NAME 2004; SST from GHRSST satellite data.



Inversion cap vs. sea surface temperature, June & August 2004, Gulf of California north of 24.1 N lat.

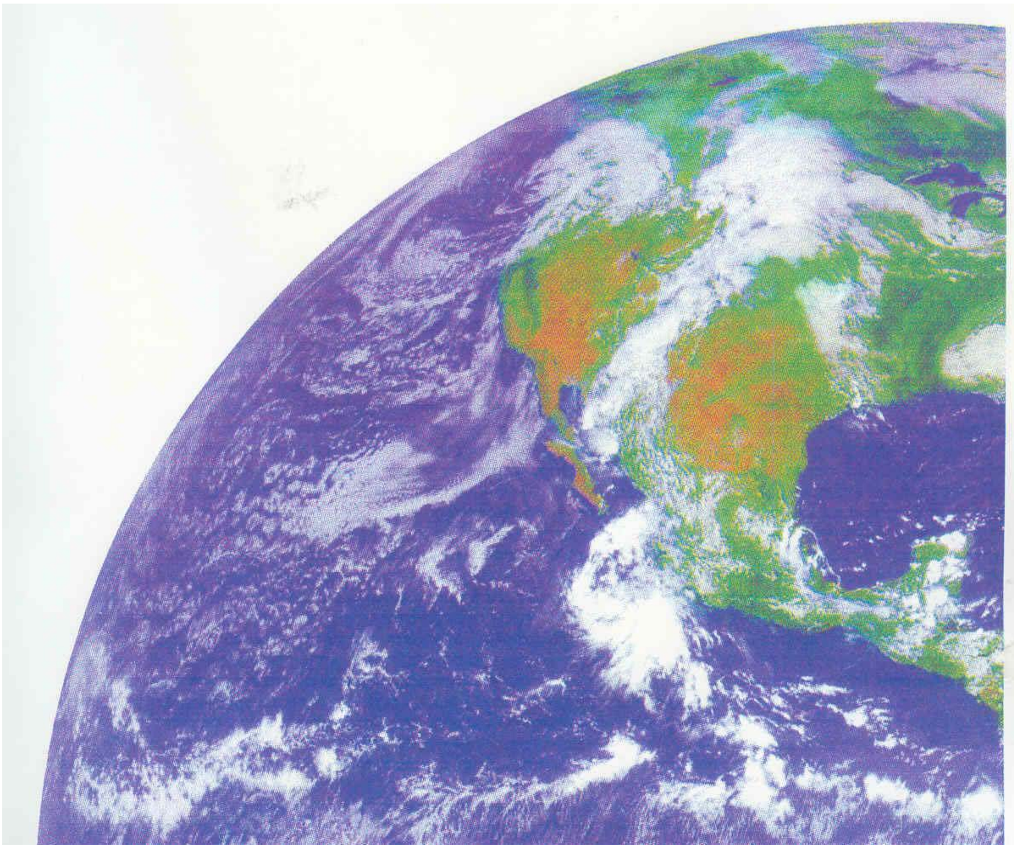


Mean relative humidity of lower 2000 m vs. inversion cap, June and August 2004, Gulf of California

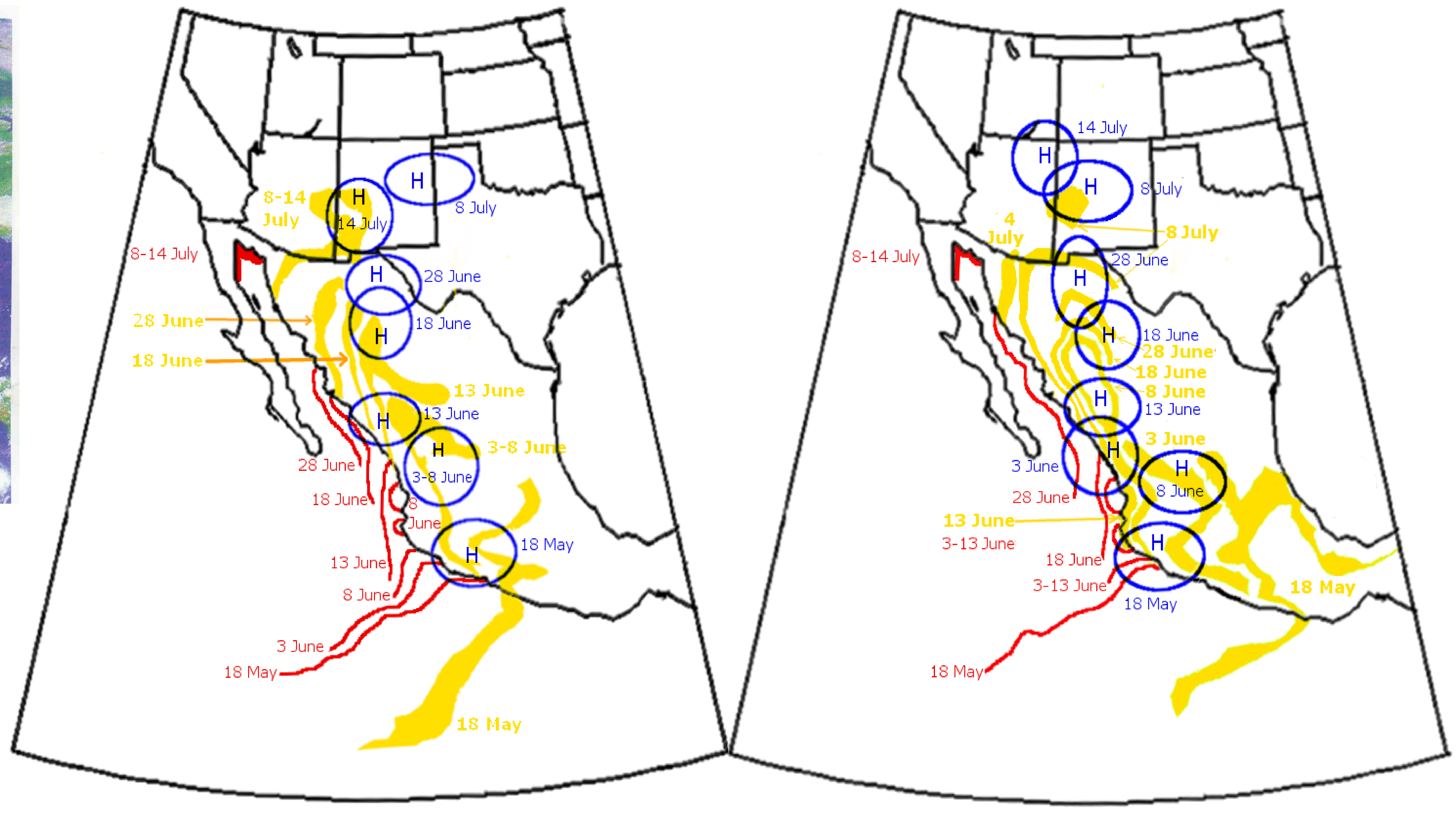


A strong near-surface inversion during June over the GC traps the moisture in the shallow MBL (marine boundary layer). Increasing SSTs lead to weaker MBL inversions. The higher the SST, the smaller the inversion cap. For inversion caps < 5°C, the mean RH in a 2 km layer over the GC tends to increase with smaller inversion caps. Note SSTs ≥ 29.5°C (i.e. SSTs ≥ threshold SST) correspond with inversion caps < 2.5°C, which correspond with mean RH > 55% in lowest 2 km (this was generally true for higher levels too). Numerical simulations reinforce these findings.

Postulated Dependence of the 500 mb Anticyclone on SSTs and Deep Convection



Satellite image showing a tropical easterly wave offshore of Mexico and a strong moisture surge from the Gulf of California into the southwestern US and northward into Canada.



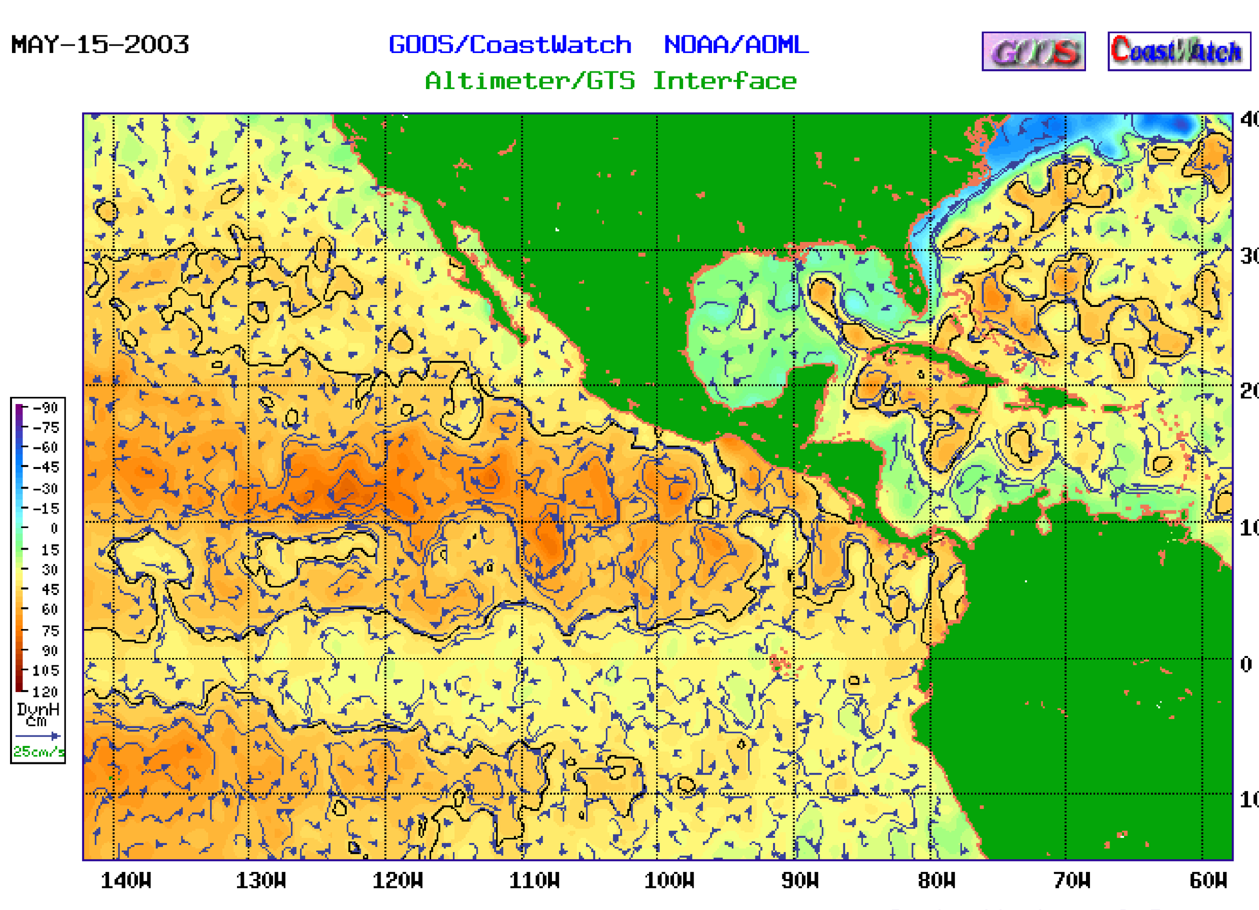
SST Climatology, 27.5 C isotherm: 1983-2000
OLR Climatology, 240-250 OLR gradient (W/m2): 1983-2000
500 mb Geopotential Height Climatology: 1983-2000

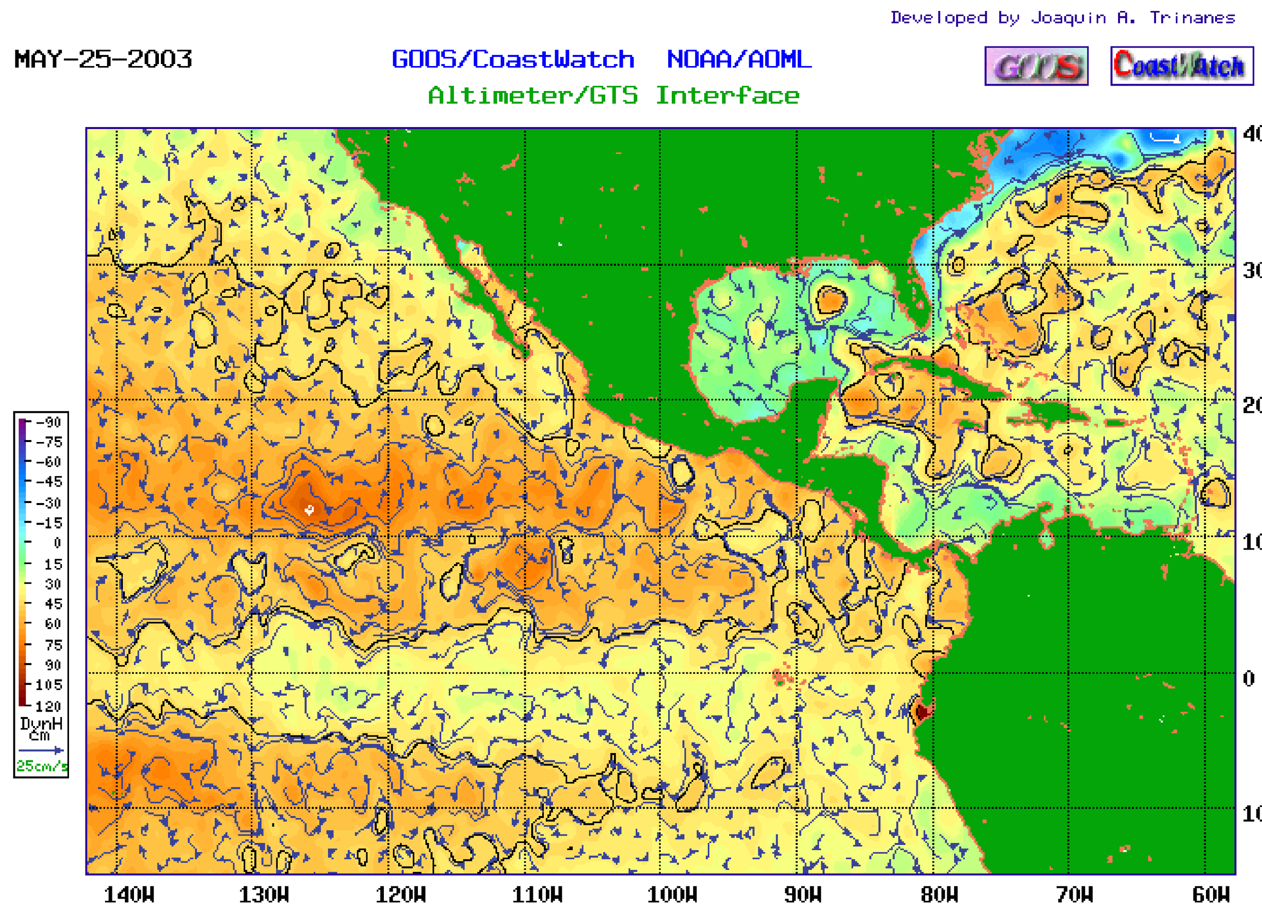
SST Climatology, 27.5 C isotherm: 2001-2010
OLR Climatology, 240-250 OLR gradient (W/m2): 2001-2010
500 mb Geopotential Height Climatology: 2001-2010

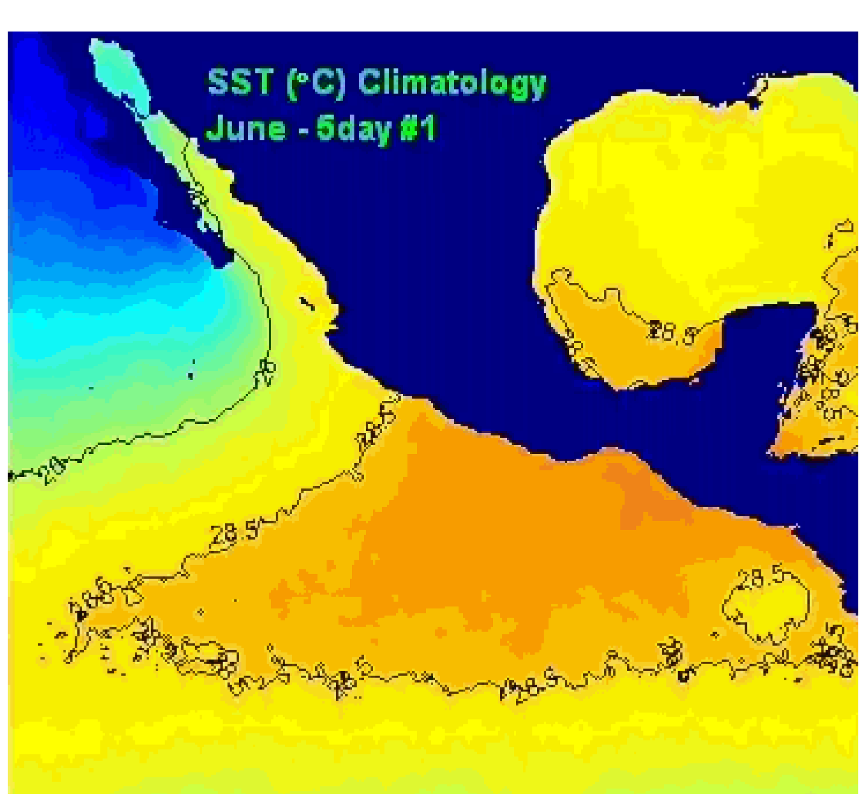
Climatological evolution of the 27.5°C isotherm (red), the 500 mb anticyclone center (blue), and the 240-250 W/m^2 OLR gradient (yellow). The latter approximates the NAM boundary; a transition between regions of rising air (wet) and descending air (dry). The red band at the top of the GC indicates the 27.5°C SST isotherm has advanced throughout the entire GC.

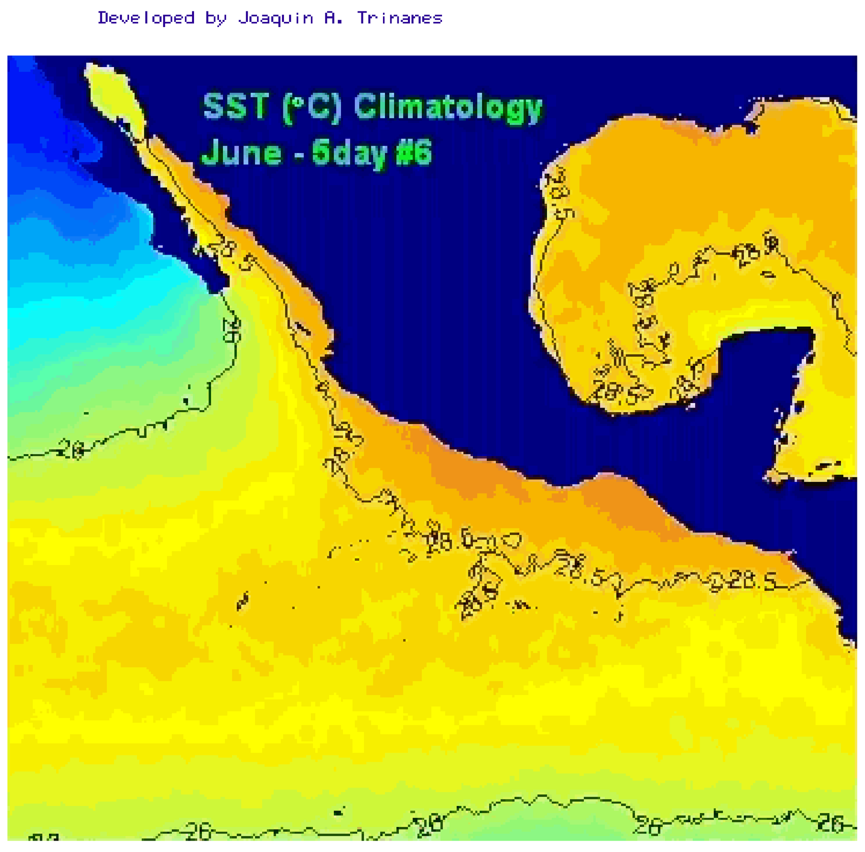
As the SST isotherm advances poleward, deep convection develops in the region and may be influenced by prevailing southeasterly winds. The Rossby wave response to the monsoon heating forms a region of adiabatic descent and anticyclone. Descending air driven by convection farther south may fix the position of the anticyclone. As convection advances poleward, so also does the anticyclone. In summary, the poleward advance of the anticyclone appears slaved to the advance of warm SSTs along the coast. One exception in the OLR pattern is observed June 8th in the new climatology (2001-2010).

Export of Tropical Surface Water from the Eastern Pacific Warm Pool into the Gulf of California



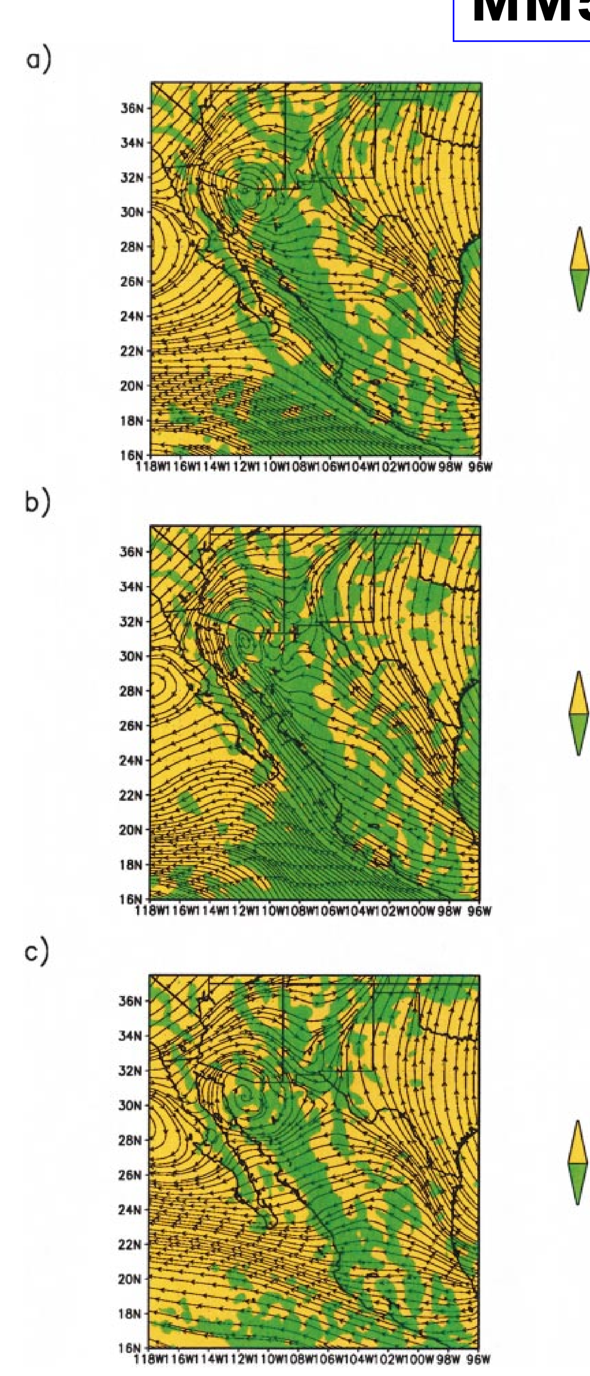






Upper two panels show sea surface height (SSH) topography with the 50 cm contour in black. The blue arrows indicate geostrophic current velocities. In late May or early June, the SSH topography changes about the time the surface winds in this region slacken, directing geostrophic currents into the GC instead of down the coast. The lower panels show the evolution of the 26^{o}C and the 28.5^{o}C isotherms, based on SST climatology (1983-2000) from JPL/PO.DAAC at 18 km resolution. Images are 5-day means centered on 3 June and 28 June, courtesy of Dr. Miguel Lavin at CICESE. The altered circulation in late May-early June may explain the rapid retraction of the 28.5^{o}C isotherm toward the coast in late June, and the corresponding intrusion into the GC.

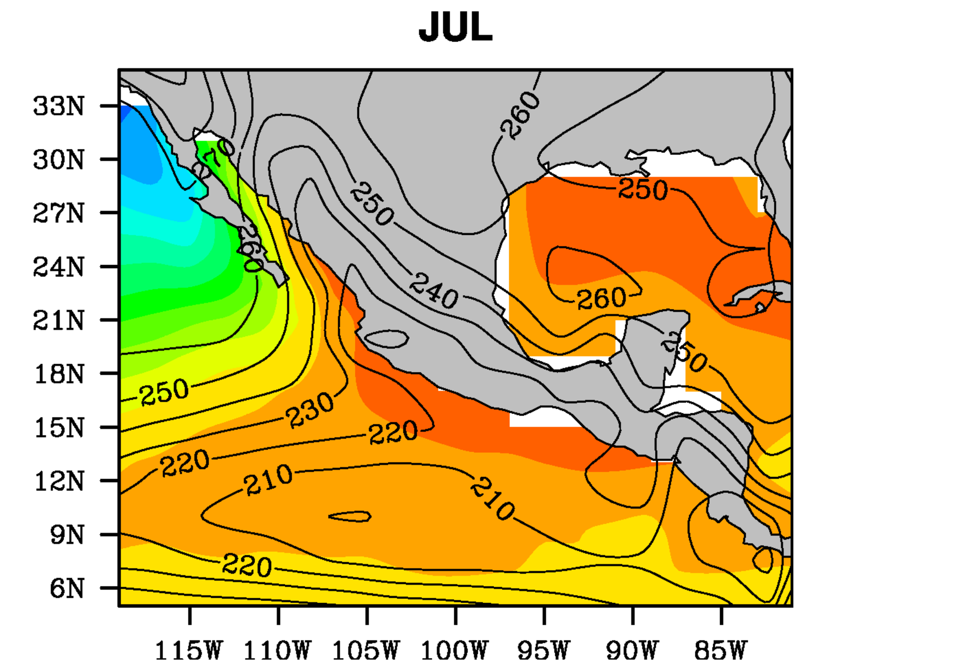
MM5 Modeling Evidence for the Hypothesis



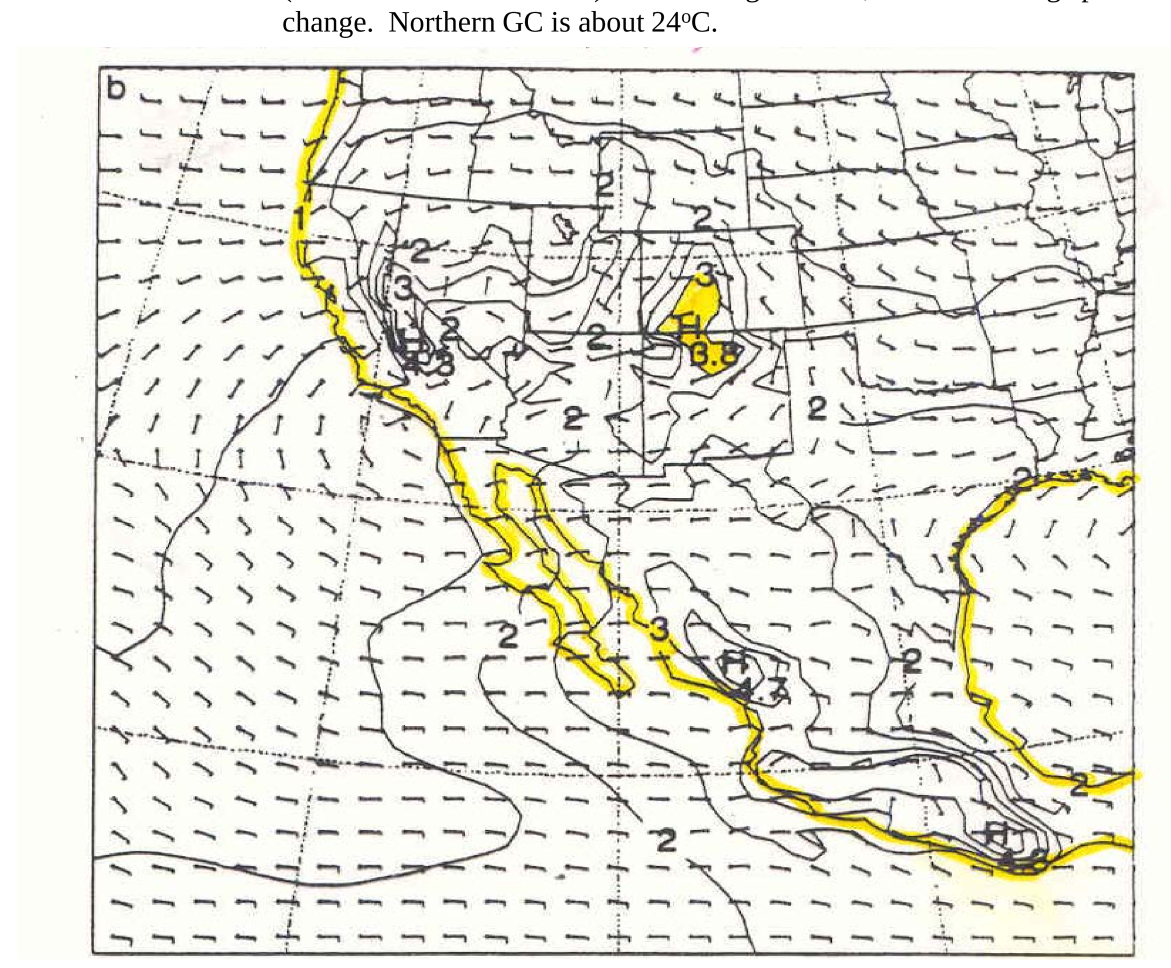
The July mean surface-600 mb pressure integrated divergence (s^{-1}) and surface-600 mb pressure integrated streamline pattern.

MM5 simulations of the anticyclone at 600 mb for July, using 3 convection schemes: (a) Betts-Miller-Janjic, (b) Kain-Fritsch and (c) Grell. Taken from Gochis et al. 2002, *Sensitivity of the Modeled North American Monsoon Regional Climate to Convective Parameterization*, Mon. Wea. Rev., Vol. 130, 1282-1298.

Simulations based on Reynolds-Smith SST data (optimum interpolation method), which under-estimate the GC SSTs by 2-6^{o}C during July, especially in the northern GC. The position of the anticyclone below US-Mexico border is consistent with hypothesis that its position depends on the latitude of the warmest coastal SSTs.



Reynolds-Smith climatological SSTs (1974-1993) for July with OLR fields (numbers and solid curves). Dark orange = 29^{o}C, with 1^{o}C change per color change. Northern GC is about 24^{o}C.



Mean 500 mb circulation showing anticyclone center (in yellow) and mixing ratios. Based on MM5 simulation for 10 July – 10 August, where GC SST = 29.5°C. Taken from Stensrud (1995; J. Climate).