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California Heat waves

Are observations enough?
How can models help?

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Contents

Abstract 3

1. Introduction: The 2006 heat wave over California 4

   Definition 4
   Synoptic situation 5
   The role of the soil's state 6

2. Capturing the event with observations 8

   In situ data 8
   Satellite data: Skin Temperature 10
   Relationship between skin and air Temperature 12

3. How can models help? 13

   Weather Research and Forecasting Model 13
   Land Information System 14

4. Results and Future work 16

   WRF runs 16
   Improving the land surface initialization 17
   Future work 18

References 19

Abstract

In July 2006, California experienced a record-breaking heat wave. This type of extreme weather events is expected to become more frequent, more intense and longer lasting in the 21st century.
The characteristics of the 2006 heat wave over California are investigated using satellite and stations observations as well as modeling. The factors favoring the spreading of the heat wave and the temporal and spatial distribution of the temperature fields are analyzed and described. It is found that in average, the diurnal temperature range increases by 2.2°C between the coldest and the hottest days.
The use of satellite images for monitoring heat events over California requires a trade-off between spatial and temporal resolutions. A way of dealing with this downside of observation data is discussed with the possibility of a very high spatial and temporal resolution product generated from the blending of satellite and station data. The creation of such a product would require an investigation of the relation between standard air temperature and skin temperature.
The WRF model is run for 24 hours runs during the 2006 heat wave event using the NCEP Final Analysis data for initial and boundary conditions. WRF is found to have a warm bias and to reproduce better the morning and early afternoon temperatures than the late afternoon and night ones. The use of the Land Information System could provide a high resolution initialization field which is expected to improve the capture of the heat wave by WRF.

Introduction: The 2006 heat wave over California

The IPCC report of 2007 (IPCC 2007) projects an increase in the frequency and intensity of extreme heat events over the century both in Europe and North America. In agreement with these predictions, (Meehl and Tebaldi 2004) find that ongoing increases in greenhouse gases concentration in the atmosphere intensifies the current circulation patterns responsible for heat waves over Europe and North America, therefore predicting more intense, more frequent and longer lasting heat waves in the 21st century.

If it is impossible to attribute the record-breaking heat waves of 2003 over Europe and 2006 over the USA to climate change only, these events along with the conclusions of IPCC2007 have contributed to raise the awareness about this kind of extreme weather events.

Heat waves and the associated hot sustained temperatures have been known to have notable impacts on human mortality, ecosystems, economies and energy supply.
As an example, during the heat wave of 2006 over California, the 24th of July set an all-time single day record electricity demand with 50,3GW used and several regions within California were left without power from hours to days due to infrastructure failures (Miller, Hayhoe et al. 2008). During the same event, 140 deaths were directly attributable to the heat wave, (Gershunov and Cayan 2008)

Definition

There is no universal definition of a heat wave, but in regard of their economic and human impacts, no one would question the classification of the 2003 and 2006 extreme heat events in Europe and California as such. Several studies have used different definitions to identify and characterize heat waves.
The first definition that can be thought of is a definition based on an absolute temperature threshold. This definition can be appropriate for a small area with little spatial differences in temperatures but not for a domain the size of California with such topographical and geographical heterogeneity. Indeed, as described in (Grotjahn and Faure 2008), a temperature of 40°C is not uncommon in the Central Valley while 35°C is very unusual in San Francisco.
In order for a definition to be meaningful, it needs to include the possible impacts of the heat wave. The impact factor is related with how unusual an event is at a given location and thus how ready the population is.
For this reason, the definition used here is based on both the temperature anomaly and the duration of the event. Therefore, heat waves are here defined as a time period with **at least 3 consecutive days with a temperature anomaly above 5°C and at least one day with a temperature anomaly above 7°C.**

Synoptic situation

The first factor for the development of a heat wave is related to the synoptic situation. Extreme heat events are generally associated with upper level high pressure patterns aloft that generate large scale descending air and compressional heating.

The climatology of California for the month of July is influenced by a high pressure system over northeast Pacific. California is dominated by strong onshore flows from the Pacific high to thermal low pressure over the hot desert interior (figure 1).

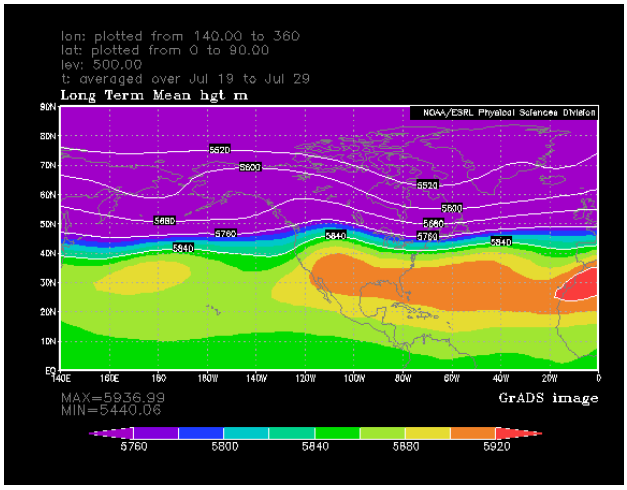

Figure 1: Climatological 500mb Pressure field for July 19th to 29th. Winds over California are mainly westerly.

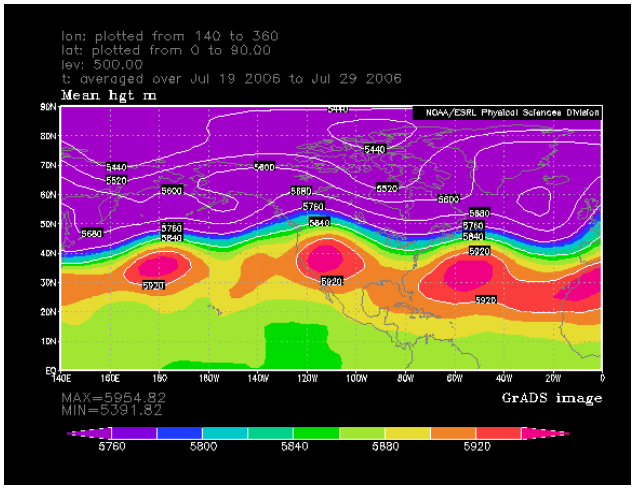

Figure 2: 500mb Pressure field averaged over the 2006 heat wave event: July 19th to July 29th. Winds over California are south-easterly.

A study from (Kozlowski and Edward 2007) provides a detailed description of the synoptic situation during the 2006 California heat wave.

Figure 2 represents the synoptic situation averaged from the 19th to the 29th of July 2006. Compared with Figure 1, it shows that during this period, the semi permanent summertime high was displaced westward and strengthened. The high which is usually located over the Central southern United States and Mexico was unusually persisting over California.

This shift of the high pressure pattern above California had two main consequences.

First, the presence of a strong high pressure pattern increases the surface air temperature by 1/ bringing clear skies hence increasing the received radiation, and 2/ creating a compressional heating situation at the surface.

Second, the westward shift of the high pressure system changed the flow situation and therefore the moisture conditions over the state. The southerly flow bringing the moist air from the Gulf of California and the Pacific is usually located to the east of California. However, during the

2006 heat wave event, because of the westward shift of the high pressure feature, the usual westerly flow over California shifted to southerly and easterly allowing an influx of moisture over the state, hence increasing the severity of the heat for the population.
Indeed, the discomfort felt by the populations during extreme heat events is not only due to the extremely high temperatures but also to the humidity of the air. The reason for this is that the way for the body to prevent its internal temperature from reaching dangerous levels is to release water (sweat), which evaporation releases energy through latent heat. When the water content of the air is high, then the evaporation process is not as efficient to cool the body down and the risks for the health are more important.
In order to take the humidity factor into account, the Heat Index (HI) has been created. Based on Temperature and Relative Humidity, it measures the level of discomfort that is felt by the body. It is also called 'Apparent temperature'. For the 2006 Heat wave, even if the dew point temperatures were unusually high reflecting the high moisture content of the air, the relative humidity remained pretty low. The HI being based on relative humidity could therefore not capture that aspect of the event.

The geography and topography of California is complex. The Coastal range separates the Central Valley from the Coast and prevents the marine air from the Pacific Ocean to penetrate inland. Thus, the Central Valley (Sacramento Valley in the northern half and San Joaquin Valley in the southern half) experiences very high temperatures and suffers more from heat than the rest of the state. This study will therefore focus on the Sacramento and San Joaquin Valley which are more affected by the heat waves such as the one in 2006.

The role of the soil's state

The synoptic situation is not the only factor that favors the development of heat waves. Several recent papers (Fischer, Seneviratne et al. 2007; Zampieri, D'Andrea et al. 2009) have used models to investigate the role of precipitation deficit and soil moisture in the spreading of heat waves, especially in Europe.
Fischer, Seneviratne et al. 2007 analyzed the soil-atmosphere interactions during unusually hot summers with regional climate simulations and Zampieri, D'Andrea et al. 2009 investigated the sequence of regional climate processes involved in the northward progression of heat and drought as initiated by dry spring conditions.

Both studies found a chain of processes including positive feedbacks which could lead from an early season precipitation deficit to an extreme heat event during the summer.
This chain of processes is illustrated in figure 3.

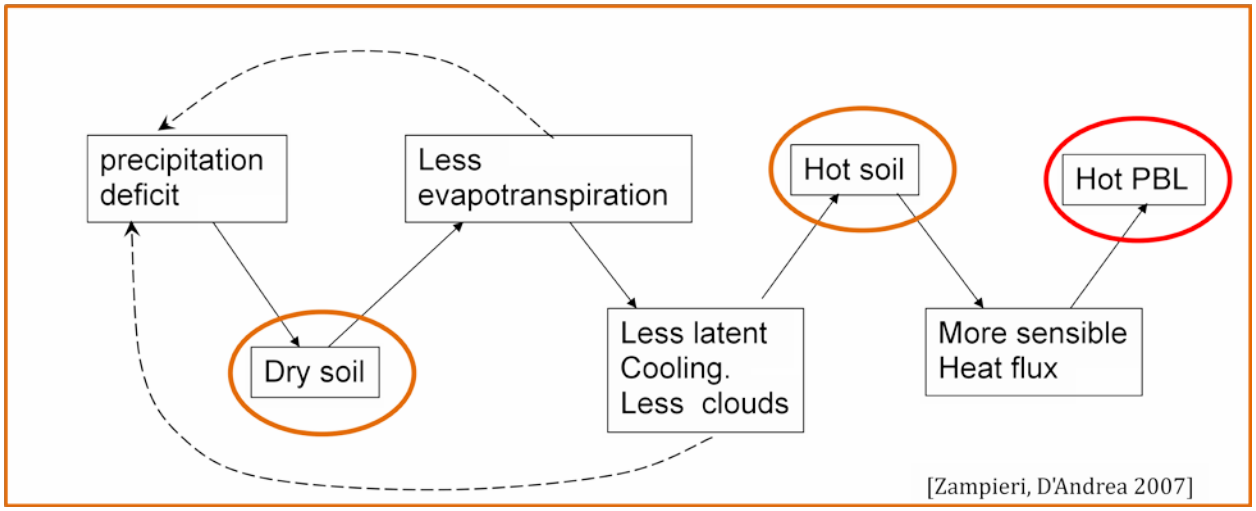

Figure 3: Chain of processes and feedbacks contributing to the intensity and persistence of the 2003 European heat wave

A deficit in precipitation in spring results in a drier soil resulting in 1/ higher sensible heat fluxes, hence surface warming, and 2/ drier air masses carrying less humidity, preventing clouds formation and increasing evaporation, amplifying the drought situation. (Zampieri, D'Andrea et al. 2009)

1. Capturing the event with observations

In situ data

For this study, the time period and the characteristics of the2006 heat wave over California are identified based on the measurements from the CIMIS weather stations network. (Hart).
The California Irrigation Management Information System (CIMIS) program was introduced by the California Department of Water Resources and the University of California, Davis in 1982.
The original goal of CIMIS was top provide evapotranspiration data to California's growers to improve water use by helping irrigation scheduling. There are over 130 computerized stations weather stations located at key agricultural and municipal sites throughout California providing comprehensive and timely weather data to a large users group including firefighters, engineers, researchers, meteorologists.

The hourly data that are used for this study are recorded by data loggers, interrogating the sensors every minute and averaging 60 consecutive readings.

The first step in identifying the heat wave event was to create a climatological temperature field consistent with the stations measurements.
For that, long term daily means (LTDM) of daily maxima temperature have been calculated for each station with more than 10 years of record.
Since most stations do not have many years of record, the year to year variability was still noticeable and was removed through a fitting of the data to polynomial functions.

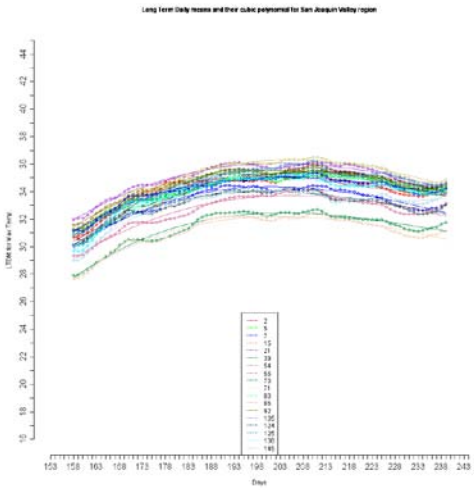

Figure 4: Long Term Daily Means (LTDM) fitted to polynomial functions so that to remove the year-to-year variability (Days are Julian days: 153=June 1st)

Temperature anomalies are then calculated based on the difference between the daily maximum temperature and the LTDM for this day (figure 4).

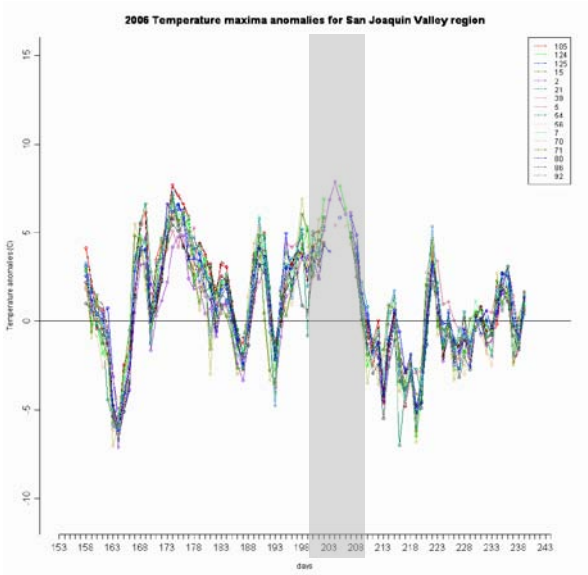

Figure 5: Daily maximum temperatures from the months of June, July and August 2006 for the San Joaquin Valley region. The grey area is the heat wave event on which this study focuses.

The summer time series of daily maxima temperatures (figure 5) shows the unusually high temperature anomalies which are identified as a heat wave by the definition previously chosen.
The day with the maximum daily maximum temperature is day 204 (23rd of July). We choose to extend the period of study from the 19th of July until the 29th of July.

This time series shows an oscillation between hot and cold anomalies which are interpreted as the signal of the alternating unusually deep high and low pressure patterns in the upper-level flow.

The very high temporal resolution of the data also allows us to obtain a precise retrieval of the diurnal cycle of temperatures from which several characteristics of the heat wave event can be deduced (Figure 6).
This figure allows us to determine some quantitative characteristics of the heat wave which will then be compared with the model's output.

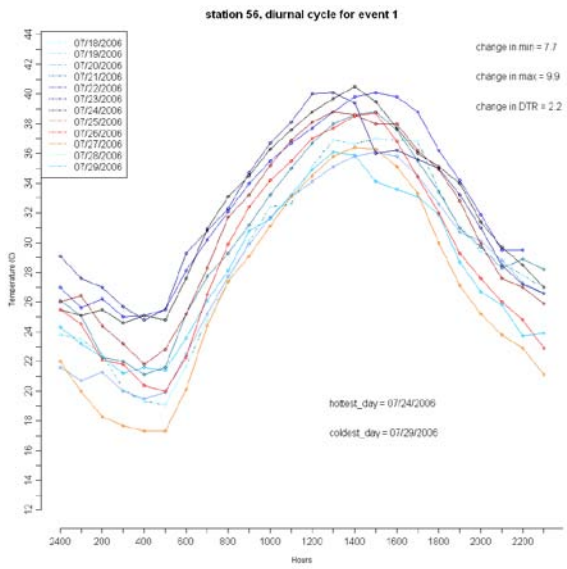

Figure 6: Diurnal cycle of temperatures for every day of the heat wave as observed at station 56

Figure 6 represents the diurnal cycle of temperatures as measured at station 56 during the approximate period of the heat wave.
The general shape of the diurnal cycle of temperature is not symmetric. The part of the graph showing an increase in temperature is convex whereas the part showing a decrease in temperature is concave.

Also, out of 44 stations in the Central Valley, 41 have an increase in their Diurnal Temperature Range (DTR: Difference in temperature between the maximum and minimum temperatures).
This increase in the DTR is due to a larger increase in the maximum temperature than in the minimum temperature between the day of maximum and the day of minimum temperature.
The average increase in the DTR for all the stations is found to be 2.2°C.

Satellite data: Skin Temperature

Station data are very accurate and reliable but lack spatial resolution. A way of getting high spatial resolution information on the distribution of the temperature field is to use satellite data. Two sets of data are appropriate to be used as a satellite observation field: MODIS Level 3 Land Surface Temperature product and GOES Skin Temperature product.

Both retrievals are based upon a split-window technique first developed to retrieve Sea Surface Temperature from satellite data based on the differential absorption in two adjacent infrared channels and was then applied to land surface. One of the major limitations to Thermal Infrared Imagery is cloud contamination. The detection and elimination of partly or totally pixels is

performed through the use of cloud detection algorithms which usually perform tests on several visible and IR channels.

Satellite retrieved land temperature has multiple uses. First of all, it can be used to determine the spatial variations and boundaries of near surface temperature fields. Color enhancements provide a quick and easy way of tracking changes in the temperature field over time. Also, because this temperature corresponds exactly to the temperature of the interface between land and atmosphere, it is related with, and contains a lot of information about the processes of exchange of energy, and water between land and air.

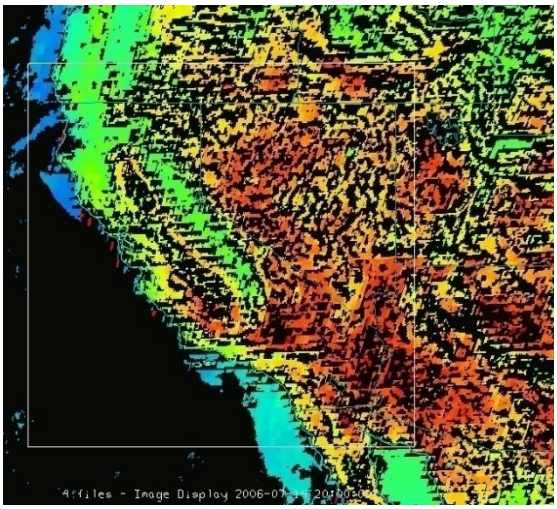

Figure 7: GOES11-SKT product for July 24th, 2006, 2pm LT

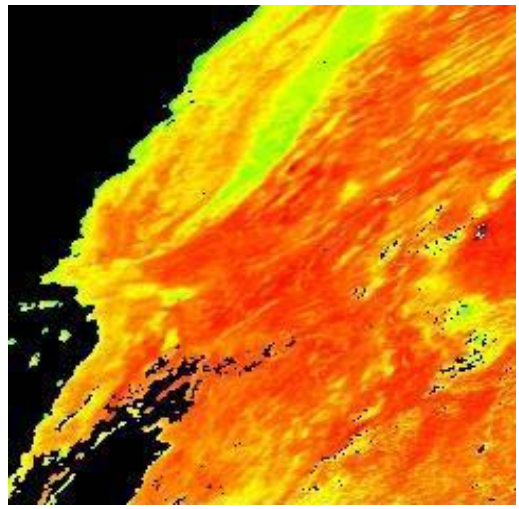

Figure 8: MODIS/AQUA MYD11A1, July 24th, 2006, 1:55pm LT

Geostationary Operational Environmental Satellite (GOES)

A Land Skin Temperature product can be retrieved using the Infrared bands 4 (10.7µm) and band 5 (12.0µm) of the Imager and Sounder onboard GOES.

$$T_S = T_{10.7} + \eta(T_{10.7} - T_{12})$$

$$\eta = \frac{1 - \tau_{10.7}}{\tau_{10.7} - \tau_{12}}$$

Where τ is the atmospheric transmittance calculated from radiative transfer code MODTRAN.
The data are averaged over 50km boxes consisting of 187 fields of view (fov, area seen by the satellite).

Thanks to its geosynchronous orbit, GOES satellite provides a continuous coverage and therefore the skin temperature product, along with other derived products, is available hourly.
This very high temporal resolution is of high interest when it comes to study the diurnal cycle of temperatures.

Moderate Resolution Imaging Spectroradiometer (MODIS)

The Land Surface Temperature (LST) product derived from MODIS observations are generated using two methods.

One is also a split-window algorithm (Wan7Dozier 1996). This algorithm utilizes the longwave window channels 31 (10.8–11.3 μm) and 32 (11.8-12.3 μm) and unlike GOES, it uses coefficients varying with the viewing angle.

$$T = C + \left(A_1 + A_2\frac{1-\varepsilon}{\varepsilon} + A_3\frac{\Delta\varepsilon}{\varepsilon^2}\right)\frac{T_{11\mu} + T_{12\mu}}{2} + \left(B_1 + B_2\frac{1-\varepsilon}{\varepsilon} + B_3\frac{\Delta\varepsilon}{\varepsilon^2}\right)\frac{T_{11\mu} - T_{12\mu}}{2}$$

$$\boldsymbol{\varepsilon = 0.5\left(\varepsilon_{11\mu} + \varepsilon_{12\mu}\right)}$$

$$\boldsymbol{\Delta\varepsilon = \varepsilon_{11\mu} - \varepsilon_{12\mu}}$$

The emissivities ε are estimated from land cover types and may vary even within a land cover type. The coefficients Ai, Bi, and C depend on viewing zenith angle (in range of 0-65o) and also depend on ranges of the air surface temperature and column water vapor. Only pixels identified as clear-sky are processed.

The spatial resolution of the products retrieved with this method is 1km.

The second method is the MODIS day/night LST algorithm (Wan & Li, 1997).

Daytime and nighttime LSTs and surface emissivities are retrieved from pairs of day and night MODIS observations in seven TIR bands. The product is comprised of LSTs, quality assessment, observation time, view angles, and emissivities.

Two MODIS sensors are currently operating onboard the polar orbiting satellites Aqua and Terra. Each of these satellites has two overpasses every day (one ascending and one descending) which leads to a MODIS temporal resolution of 4 overpasses a day.

Relationship between skin and air Temperature

Before using the satellite retrieved temperature fields quantitatively along with the stations data, it is important to understand that these temperatures are two physically different quantities (Norman and Becker 1995).

The skin temperature measured by the satellites is derived from the radiance emitted by the surface and received by the sensor in various wavelengths. Thus, the “skin temperature” or “land surface temperature” refers to the temperature of the thin layer of the Earth that is visible to the satellite and which corresponds to the penetration depth of the electromagnetic radiation used to measure it (Norman and Becker 1995). Because only the most superficial layer of the surface is measured, land cover is a key factor of the retrieved quantity as well as the land-atmosphere processes.

This temperature is not to be confused with the standard surface air temperature as defined by the World Meteorological Organization (WMO) and measured by ground weather stations. These measure the temperature of a thicker layer of relatively homogeneous air approximately 2m above the ground.

As described in part 1, the soil's state plays an important role in the development of a heat wave. However, these weather events are most of the time only studied and referred to with standard air temperature measurements. Because skin temperature is measured at the interface between soil and atmosphere, it must include the information about the heat wave and might be able to help us monitor the event.

2. How can models help?

Weather Research and Forecasting Model

The Weather Research and Forecasting Model (WRF) is a next-generation mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs.
Previous studies have shown that the WRF's output is less accurate for summertime high temperature situations (Fovell 2008; Caldwell, Chin et al. 2009). We want to evaluate the performance of WRF at reproducing the 2006 California heat wave. The output variables 'Temperature at 2m' and 'Skin Temperature' are especially relevant and will be compared with observations to assess the accuracy of the WRF predictions.

The domain of the run has been chosen to encompass all of California at a resolution of 4km (figure 9).
27 vertical levels are considered on the vertical. The lateral boundary conditions are taken from the global NCEP GFS (0.5 × 0.5 degree) forecasts, at six hours frequency. WSM 6-class graupel scheme is chosen for microphysics, MYJ PBL and Noah LSM surface schemes are respectively used for planetary boundary layer and surface physics. No cumulus parameterization is used. Rapid Radiative Transfer Model (RRTM) longwave and Dudhia shortwave radiation schemes are chosen. The model is run for every day of the heat wave event for 24h runs starting at 00Z.

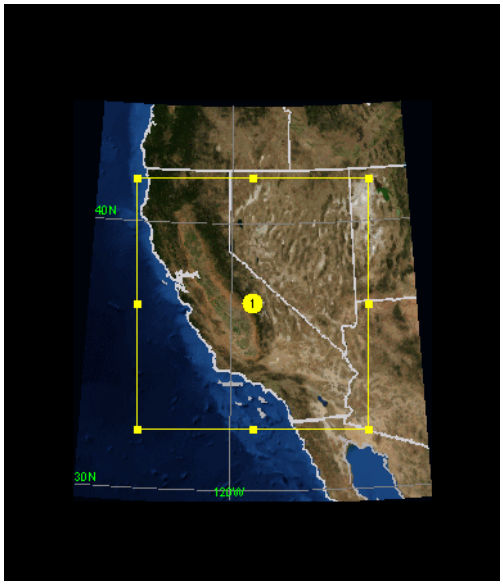

Figure 9: WRF Domain, resolution of 4km

Errors in models are due to several reasons which include: imperfect model physics, an uncertainty in model parameters, a stochastic behavior in inputs, errors in measurements.

Temporal and spatial resolution along with forecasting possibilities make models essential to the understanding and capture of weather events such as heat waves. However, to improve WRF's capture of the HW, (Cheng and Steenburgh 2005) suggest to improve the soil initialization to obtain a better overall result.

Land Information System

As described before, the processes involved in the development of heat waves are the result of a complex contribution of atmospheric and soil states and dynamics. Therefore, a way to improve the modeling of extreme heat events might be to improve the modeling of the soil's state.

The development of heat waves is highly dictated by the water and energy fluxes between the land and atmosphere.
These fluxes are predicted by Land Surface models (LSM)
LSM requires 3 types of input

- Initial conditions (initial state of the land)
- Boundary conditions (upper and lower fluxes and states also called atmospheric and soil forcings)
- Parameters

From these input, LSMs solve the governing equations of the soil-vegetation-snowpack medium and predicts the fluxes and soil states.

The Land Information System is a software framework which uses satellite-derived datasets, ground-based observations, and model reanalysis data to force a variety of LSMs. The input data used by the LIS are the best available data at resolutions as high as 1km. The LIS can be run in a coupled or an offline mode.

When run offline, LIS uses various atmospheric forcings to run one of the available LSM and produces a high resolution initialization field for WRF runs.

When run coupled with WRF, LIS allows the integration of high resolution land datasets such as MODIS-derived vegetation fields as parameters or forcing data.

Offline spin-up simulation

The goal of the spin-up is for the Noah LSM to reach “equilibrium”, meaning that the state of the soil at the end of the spin-up has no memory of the initial first-guess fields.

According to previous studies (Case, LaCasse et al. 2007), a 18-months spin-up is sufficient for our case.

LIS is therefore run uncoupled for 18 months in order to provide an initialization field independent of the initial first-guess fields.

3. Results and Future work

WRF runs

WRF is run uncoupled for 24 hours every day of the period of study (19-29 July 2006) at a resolution of 4 km.

The comparison of Figure 10 and Figure 11 shows that WRF reproduces well the general patterns of the skin temperature over land that can be observed on the corresponding MODIS/Terra satellite. In both images we can see the highest temperatures of the Central Valley located in its southern half along the mountain ranges with colder temperatures in the Sierra East and North of the Valley. Also, the very high temperatures of Southern California, Arizona and Mexico are well represented in the WRF output.

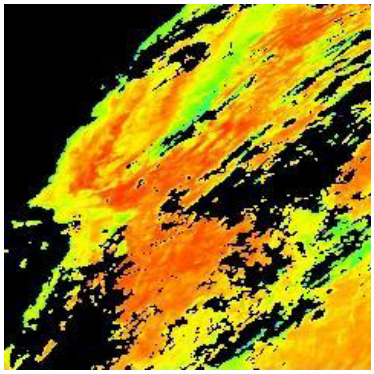

Figure 10: MODIS/Terra image from July 19th 2006, 19:30Z overpass

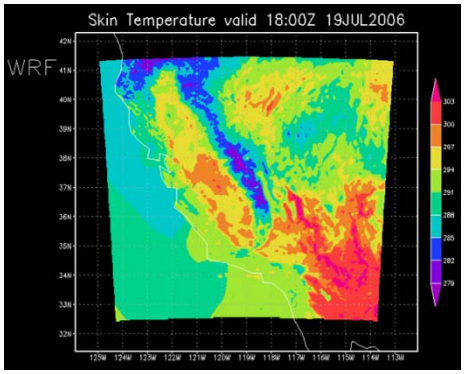

Figure 11: WRF simulation of skin temperature valid July 19th 2006 18:00Z

Using the station data gives us a more quantitative assessment of the precision of the model.

Figure 12 shows the comparison between the diurnal cycle at station190 located in the center of the San Joaquin Valley calculated by WRF versus measured by the CIMIS station.

From figure 12, we see that the accuracy of WRF is not constant during the day. Most of the time, WRF is warmer than the observation but the amplitude of this bias is more important in the late afternoon and night when the temperature is decreasing than in the morning and early afternoon when the temperature is increasing.

The times of maximum and minimum temperatures are well reproduced.

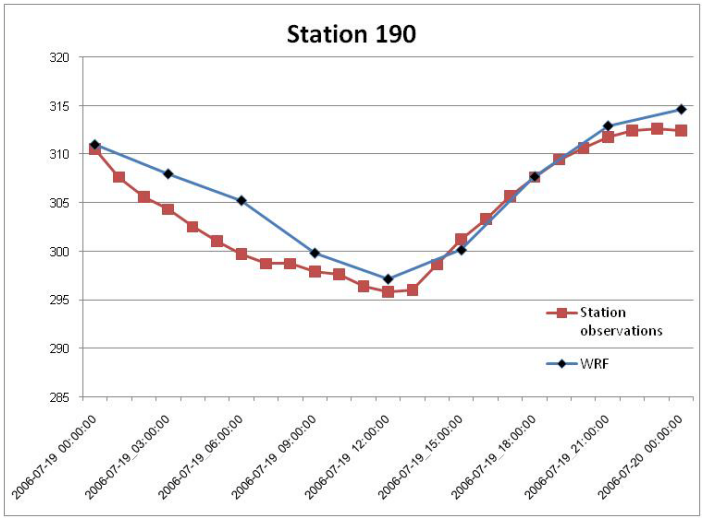

Figure 12: Comparison of station observations and WRF generated standard 2m air temperature for station 190, valid 2006/07/19

Improving the land surface initialization

WRF is run by itself with initial and boundary conditions from NCEP Final Analysis at 1° ·1° lat./long. resolution, every 6hours.

The initial soil moisture field is showed in figure 14 and compared with the soil moisture field of the same Noah soil layer 4 as generated by the LIS spin-up.

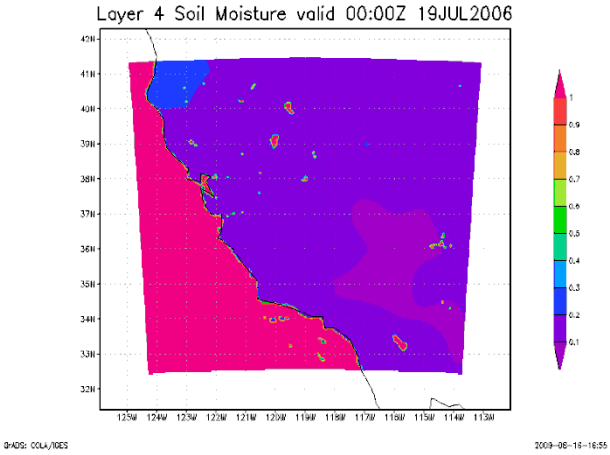

Figure 13: Initial Soil Moisture field generated by WRF preprocessor using NCEP FNL data. Valid at 00:00Z 2006/07/19

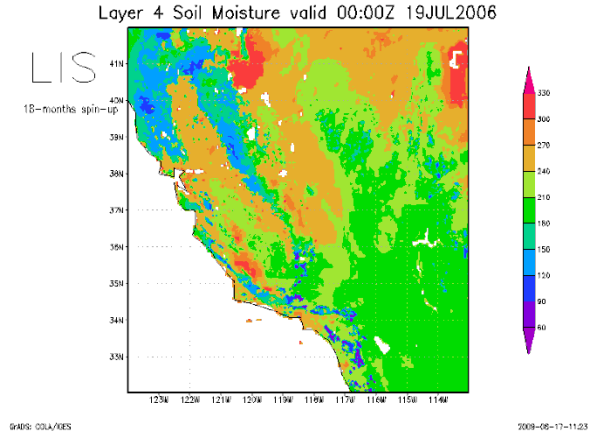

Figure 14: Soil Moisture field generated by 18-months long spin-up run of LIS. Valid at 00:00Z 2006/07/19

The initial field based on the NCEP FNL data is very uniform with a coarse resolution, whereas the output of the LIS spin-up displays fine-scale features closely associated with soil's type distribution (not showed here).
Using this high resolution field to initiate the WRF runs will impact the simulation of the meteorological fields and therefore should lead to a more accurate representation of the weather patterns.

Future work

These preliminary results suggest that heat waves can be modeled by WRF with an improved accuracy by using a high resolution initiation field provided by the LIS framework developed at Goddard Space Flight Center.
As far as the choice of the duration of the spin-up the choice of a length of 18 months is based on Case, LaCasse et al. 2007. However, their study was located over Florida which soil and meteorological situation are different. It would therefore be interesting to carry out a series of test runs to determine which length of spin-up allows the model to reach thermal equilibrium.
When the appropriate duration of the spin-up runs is determined, LIS-WRF will be run for the duration of the heat wave event.
Also, more stations will be used to control the accuracy of the WRF outputs and more characteristics of the heat wave need to be tested, like the change in the Diurnal Temperature range during the heat wave.

Another step is to merge the satellite and station data in order to obtain a high spatial and high temporal resolution observation field for better evaluation of WRF outputs.

4. Acknowledgements

I am very grateful to the NASA Graduate Student Summer Program for giving me the opportunity to work in such a stimulating environment. It was a wonderful experience.
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