CLIMATE ADAPTATION SCIENCE INVESTIGATION (CASI) AT NASA AMES RESEARCH CENTER: USING THE TERRESTRIAL OBSERVATION AND PREDICTION SYSTEM (TOPS) TO ANALYZE IMPACTS OF CLIMATE CHANGE ON CALIFORNIA ECOSYSTEMS

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ABSTRACT

The study of climate change is important because it is essential that potential problems are identified and mitigated in order to minimize their impact on NASA Ames in accordance with the NASA policy statement on adapting to climate change, and to help achieve the goals of the Climate Adaptation Science Investigation Team (CASI). This project analyzes results from the TOPS model which was run at 1km resolution for the time period 1950-2099 using downscaled GFDL climate projection data for the continental United States. The impacts of climate change on ecosystems are investigated in and around NASA Ames using the TOPS model under the A1B and A2 scenarios for California. The state data were divided into climate zones and watersheds, and for each zone a statistical analysis was completed for temperature, precipitation, gross primary productivity (GPP), evapotranspiration (ET), soil runoff, and vapor pressure deficit. The analysis in this report is limited to the climatology and ecology of the Coyote Watershed near NASA Ames Research Center. Trends produced from this analysis show changes in climate (annual rainfall, dry season length, temperature) and changes to ecosystem functions (GPP, ET, runoff) due to land cover changes.

KEYWORDS: climate, TOPS, ecosystem model, California, GFDL, GPP

INTRODUCTION

It has become necessary for NASA to determine how its facilities will be affected by climate change. According to a Policy Statement released on May 18 2011, (Dominguez, 2011), NASA's goal is to have "climate resilient NASA centers." According to the Intergovernmental Panel on Climate Change (IPCC), a well-known consequence of increased emissions under scenarios A1B and A2 is that the average global temperature is expected to rise (Cayan et al., 2008). Carbon Dioxide (CO_2) is a major contributor to the greenhouse effect, which causes atmospheric warming near the earth. Another effect of increased levels of CO_2 is that plants have increased their rate of CO_2 absorption since 1960 (Le Quéré et al., 2009). However, this rise in CO_2 may also cause reduced rates of transpiration in plants, and therefore increase runoff significantly (Cao et al., 2010). An increase in temperature and evapotranspiration (ET) in the dry season, and in storm and drought intensity, is projected to increase the rate and severity of wildfires and mudslides (Valade, 2010; Ren et al., 2010). The areas at the greatest risk of large wild-fires are coastal and mountain regions as well as much of Northern California under the A2 scenario (Westerling and Bryant, 2008).

An increase in temperature may cause early snow melt in the Sierra Nevada Mountains (Mote et al., 2005) and can cause flooding in the spring which can then exacerbate drought conditions in the late summer or fall (California Natural Resources Agency, 2009). It is also projected that the dry season will start sooner and end later than currently observed which further increases the severity of drought events and wildfires (Pruski and Nearing, 2002; Null et al., 2010; Keithley and Bleier, 2008). Due to the high dependence of gross primary productivity (GPP) on both temperature and precipitation, it can be expected that locations that currently have high GPP values will change under both scenarios (Wang et al., 2010). This may alter the species of plants that an ecosystem can support, as well as cause life within the ecosystem to migrate in order to survive (California Natural Resources Agency, 2009). The increase in wildfire frequency and severity may cause a reduction in GPP because more vegetation is being destroyed and releasing carbon back into the atmosphere (Dale et al., 2001). Land use changes will release even more CO_2 into the atmosphere as impervious surfaces increase with the expansion of cities due to an increase in population (Le Quéré et al., 2009). In addition, creating more impervious surfaces will increase water runoff and may affect water quality because water cannot penetrate into the ground (Le Quéré et al., 2009; Bierwagen et al., 2010). Finally, there are health impacts associated with increased temperature such as sickness due to heat, and sickness from pollution such as ozone (McGeehin and Mirabelli, 2001; Drechsler et al., 2006).

An executive order mandates that all NASA centers find ways to reduce their water consumption (Federal Register, 2009). However, under a warming climate it is expected that there will be a greater demand for water. Within the executive order, it is required that facilities reduce water consumption by 2% annually, with some exceptions according to how the water is being used. It is also suggested that installing metering devices, conducting water audits for irrigation systems, and purchasing more efficient products are ways to reduce water use.

This project uses preliminary data output from the TOPS model (see below) to analyze the projected change to the climatology, hydrology, and carbon cycles under the IPCC (Intergovernmental Panel on Climate Change) A1B and A2 climate scenarios (Nakicenovic et al., 2007) for the Coyote Watershed, and examines how these projections might affect regional water and power availability. The A1B scenario describes a world where there is high energy use, rapid technological growth, low changes to land use, and a balanced approach to resource consumption. The A2 scenario describes a world much like the one today. There is high energy use, slow technological growth, high land use changes, and a resource consumption that varies by location, causing overall greater greenhouse gas emissions than A1B.

METHODOLOGY

TOPS (Terrestrial Observation and Prediction System) is a modeling framework that integrates a multitude of input variables from satellite (land cover, leaf area index, surface temperature, etc.), aircraft (fires, floods, land cover), and ground sensor data (temperature, precipitation, solar radiation, etc.). It also utilizes data from weather, climate, and application models. The resulting output is used to forecast ecosystem conditions, and can be used in applications such as water resources, agriculture, and public health (Nemani et al., 2009). The datasets used for the TOPS report are shown in Table 1.

Table 1. Input variables for TOPS.

Input variable	Dataset	Citation	Note
Impervious Surface Area	SERGoM	(Theobald et al., 2009)	
Climate	GFDL CM2.0 from WCRP CMIP3	(Maurer et al., 2009)	downscaled to 1km with TOPS
Elevation	National Elevation Dataset	(USGS,2011)	resampled to 1km
Leaf Area Index	MODIS MOD15A2 LAI	(Myneni et al., 2000)	
Soils	US STATSGO2 database	(NRCS)	
Land Cover	MODIS MOD12Q1	(Friedl et al., 2002)	
Ecosystem	BIOME-BGC	(Thornton et al., 2002)	

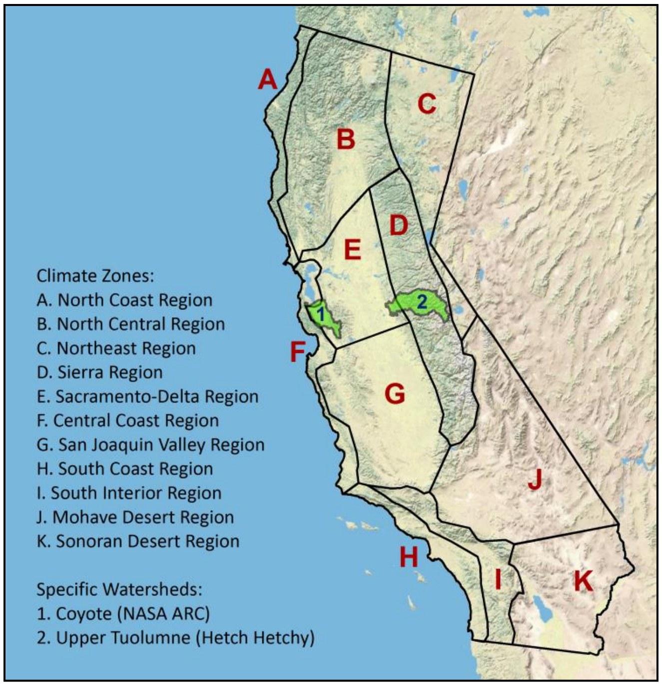

Figure 1. Climate regions of California and specific watersheds of study.

The Geophysical Fluid Dynamics Laboratory (GFDL) global climate model (GCM) is used as the basis for the climate projections in this analysis. The GCM data, originally on a 2.5º longitude by 2.0º latitude grid, was downscaled to 1 km. This high resolution is needed to input the climate data into the TOPS model. Because of the time and computational constraints on downscaling data to this resolution, only the GFDL model is considered here. This poses limitations on the TOPS model output, as usually a multi-model ensemble provides more reliable output than any single model (Randall et al., 2007).

The TOPS model was run at 1km resolution for the time period 1950-2099 using downscaled GFDL A1B and A2 climate and impervious surface projection data for the continental United States. The data for California were extracted from this larger data set, and the state data were divided into regions separated by climate zones based on the work of the California Climate Tracker project (Abatzoglou et al., 2009).

The data gathered were used to determine the climatological and ecological effects given a change in climate under either the A1B or the A2 scenario. For each zone a statistical analysis was completed for temperature, precipitation, GPP, ET, soil runoff, and vapor pressure deficit (VPD). The trends of the variables for each month were calculated over the span of years between 1950 and 2099. These auto-correlated trends are tested for statistical significance at the 95% confidence level to determine if there is a change in the variables for certain seasons. Also, changes between the decades of 1950 - 1959 and 2090 - 2099 were calculated and tested for significant differences to the 95% confidence level and account for autocorrelation. The statistical difference between these two decades will henceforth be referred to as the "decadal differences." However, the decadal differences are not graphically represented in the following figures. It should also be noted that the projected monthly average plots have been smoothed in Figures 7, 8, and 9 to better approximate the inter-monthly values in these yearly cycles.

The analysis was then broken down into specific watersheds, i.e. the watersheds containing the Hetch Hetchy Reservoir (Upper Tuolumne Watershed), and Ames Research Center (Coyote Watershed). These watershed areas were defined using the United States Geological Survey (USGS) Hydrologic Units shapefile at the 1:250K scale (USGS, 2011).

RESULTS

Some variables are projected to increase across the entire state of California, regardless of climate region. The minimum and maximum temperature trends, and their decadal differences, increase significantly in all areas under both climate change scenarios. A time series of projected temperatures for the Coyote watershed is shown in Figure 2a. Also, VPD increases for nearly all months throughout the state under both scenarios. The decadal differences also show an increase in VPD. In general, the daily temperature range (DTR) is projected to increase as well across the areas of interest in nearly all months, with some areas having no change during the spring months.

Though analysis was done for all the climate regions previously listed within California, for the purposes of this study the focus was the Coyote Watershed because NASA Ames Research Center is located within its boundaries.

Within the Coyote Watershed, the yearly average precipitation trend is downward, but is not statistically significant (Figure 2b). However, when looking at monthly trends, under the A1B scenario there is a significant decrease which occurs from April to June (Figure 3). Under the A2 scenario, this decrease occurs earlier in the year, extending from March to May, and also in October. The only period where there is a decrease in precipitation when considering the decadal differences is between March and May under the A2 scenario. There are no significant decadal differences under the A1B scenario.

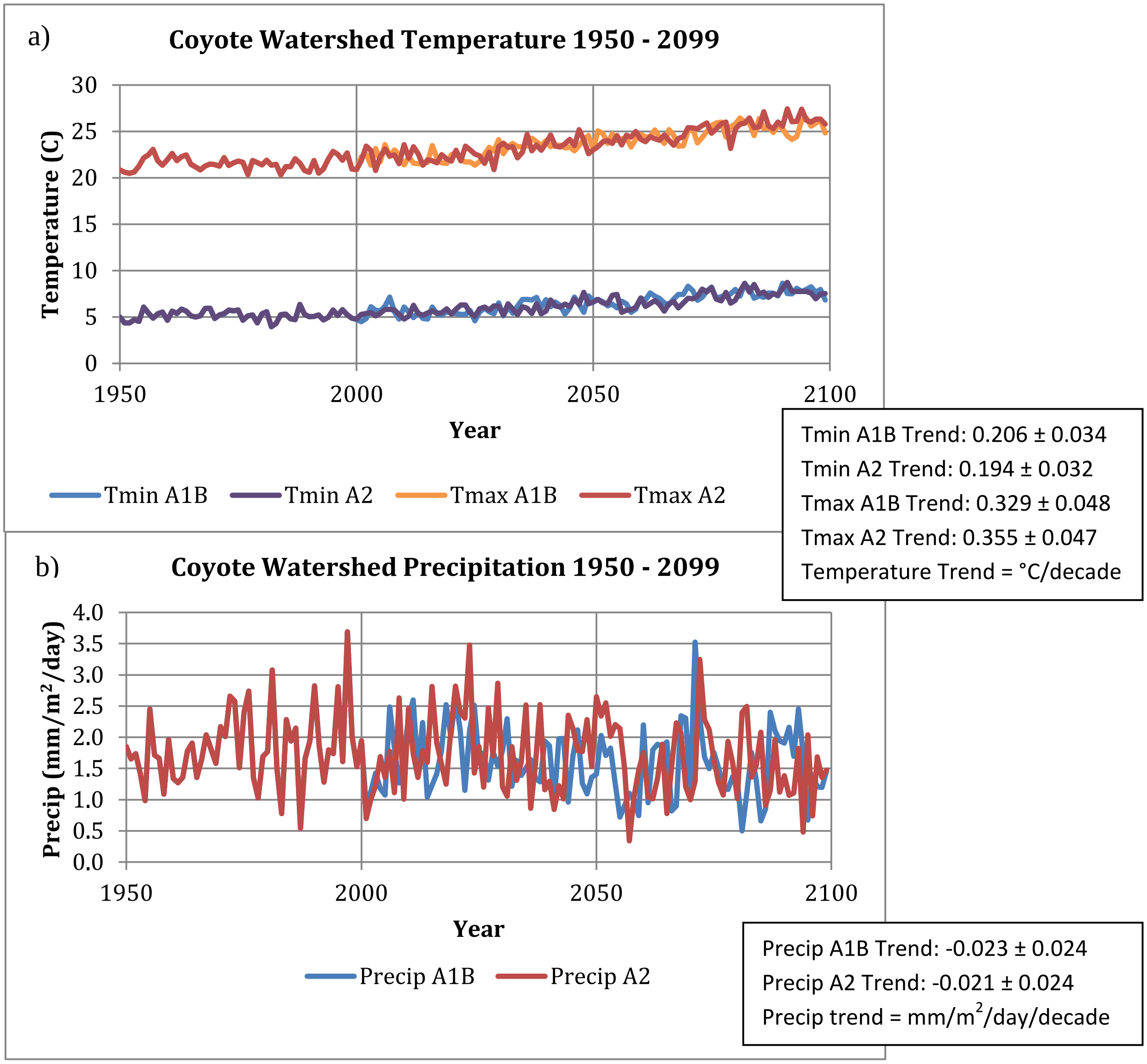

Figure 2. (a) Time series and trends of projected minimum and maximum temperatures, and (b) time series of precipitation in the Coyote Watershed for 1950 – 2099.

GPP in the Coyote Watershed decreases from May to September, as well as in November under A1B, with an increase in April. But, a decrease is expected under the A2 scenario during the whole period from April to December (Figure 4). The decadal differences show similar patterns, though with fewer months of significance.

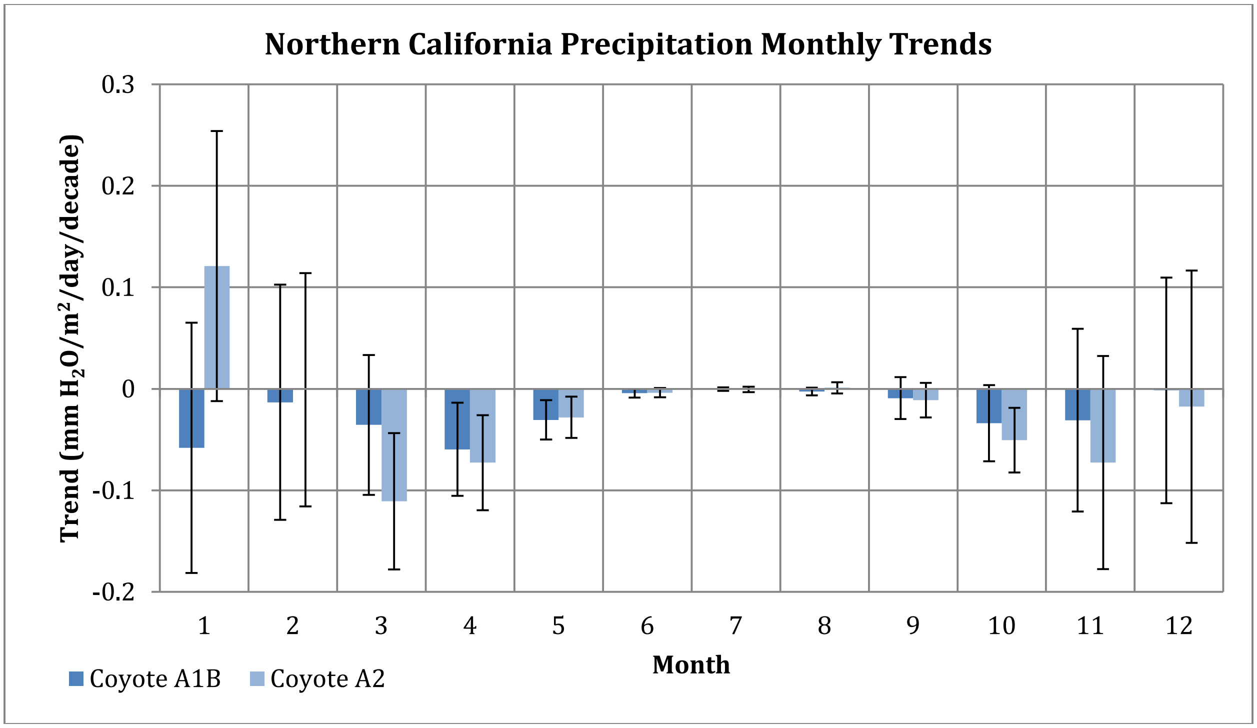

Figure 3. Coyote Watershed monthly precipitation trends for time period 1950-2099.

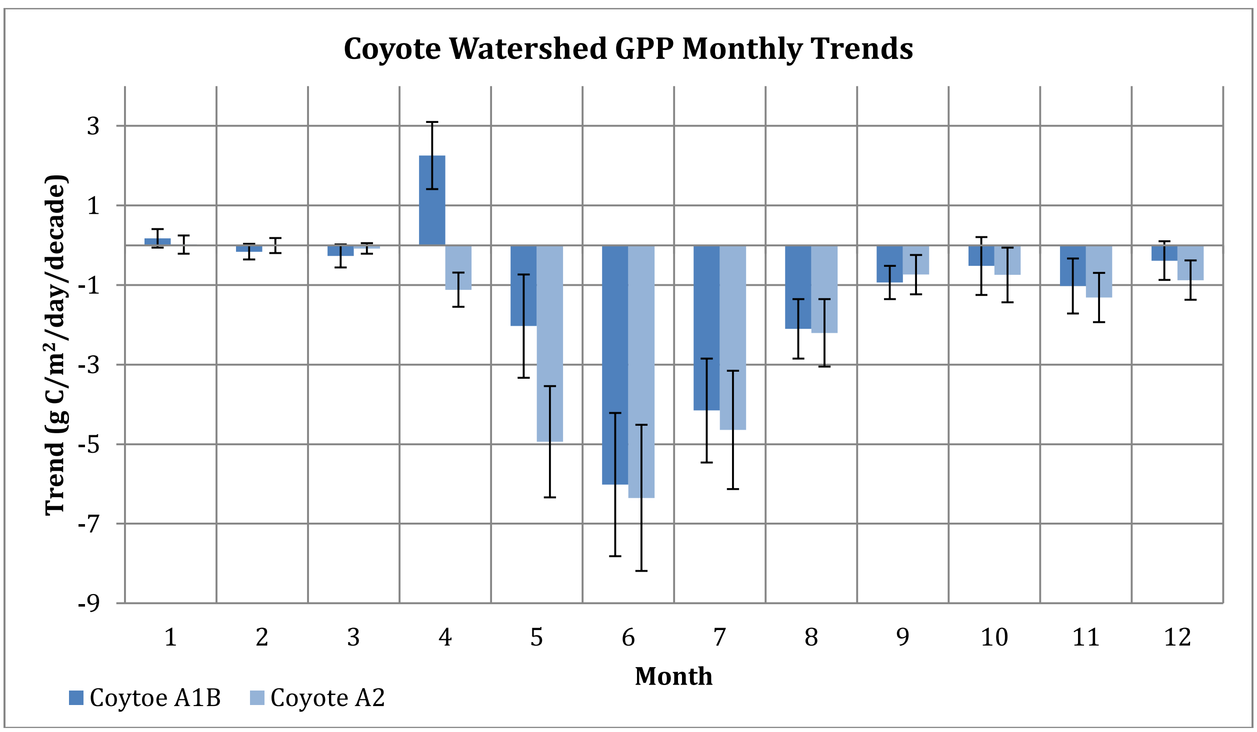

Figure 4. Coyote Watershed monthly GPP trends for time period 1950-2099.

The results for the runoff trends and decadal differences can be seen in Figure 5. The runoff trend only decreases for April and June under the A1B scenario. These two months as well as March have significant decreases in runoff under the A2 scenario. The decadal difference calculations show no months of significant change for A1B, and only March and June as months with a decrease in runoff under the A2 scenario.

ET trends increase for January through April and decrease for June through September under the A1B scenario. The A2 scenario shows the same months with the same changes in addition to decreases in ET in October and November. The decadal differences for the A1B show the same results as the trends. These results are summarized in Figure 6. However, the A2 decadal differences differ from the A2 trends in that none of the months between September and December hold significant changes in ET.

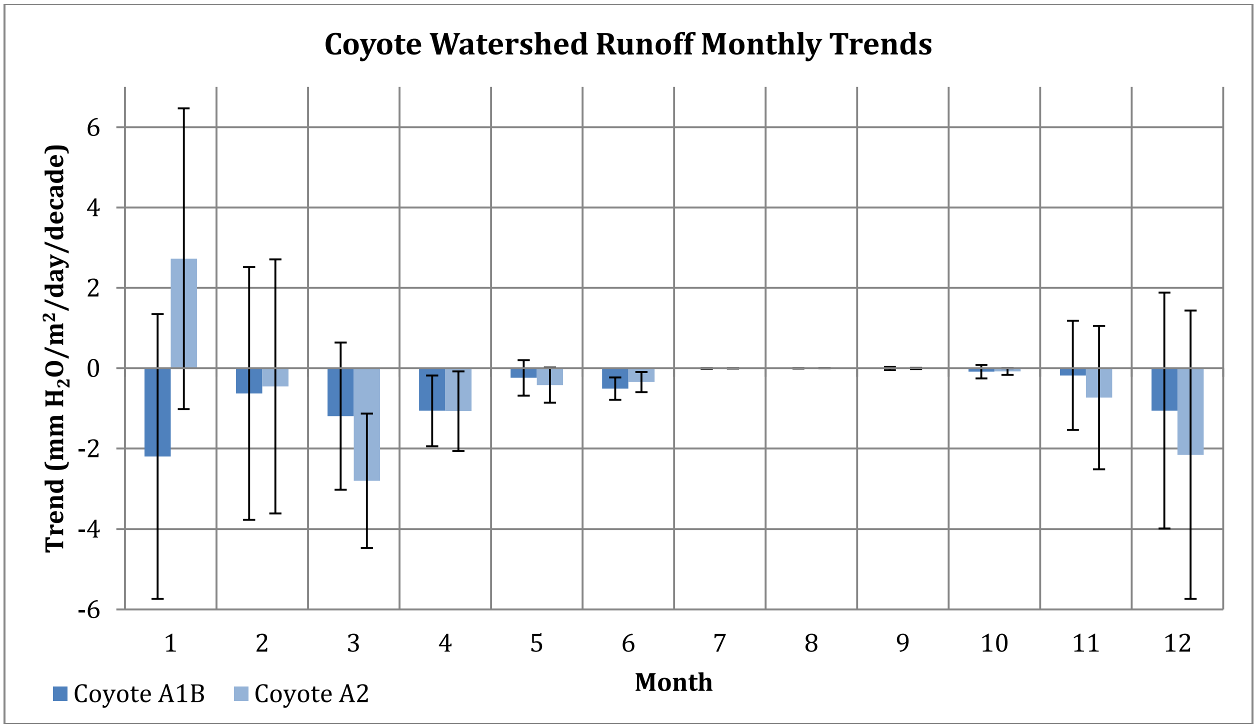

Figure 5. Coyote Watershed monthly runoff trends for time period 1950-2099.

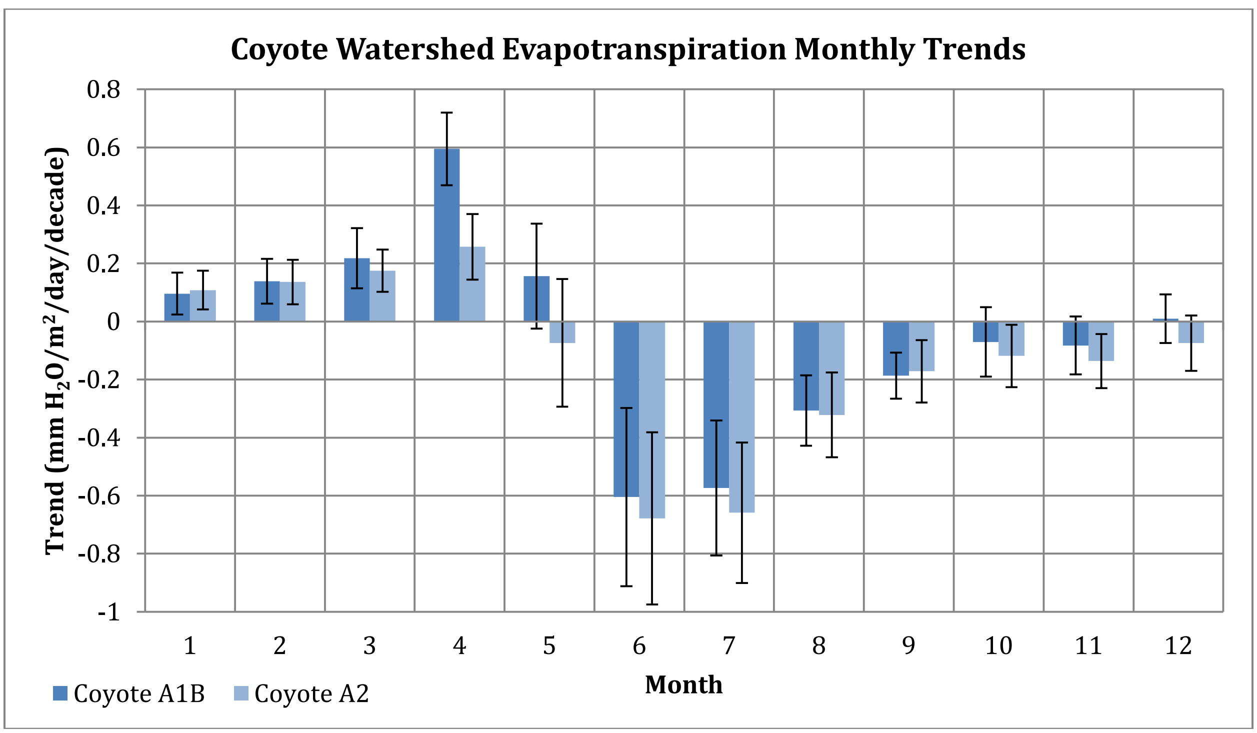

Figure 6. Coyote Watershed monthly evapotranspiration trends for time period 1950-2099.

Monthly averages for GPP are also plotted using the 2000 – 2009 decade and the last projected decade (2090 – 2099) under both scenarios (Figure 7). Figure 7a shows the GPP values under only projected climate changes, while Figure 7b shows both changes in projected climate as well as changes due to projected increases in impervious surfaces. The impervious surfaces within the Coyote Watershed are projected to increase by 9.67% for the A1B scenario, and by 60.57% for the A2 scenario.

In each month of the year, the GPP values for the 2000 – 2009 decade are higher than those for either of the climate projection scenarios. GPP increases until it peaks at 266 g C/m^2/month in May, and then decreases until September where it reaches a minimum of 14 g C/m^2/month. Beyond this point, the values remain nearly the same in the winter season. The A1B 2090 – 2099 projections show that the maximum GPP value (244 g C/m^2/month) occurs in April and the GPP throughout the year is lower than the 2000 – 2009 decade. Under the A2 scenario, the peak GPP (236 g C/m^2/month) also shifts to April, and overall has the lowest GPP values observed.

Figure 7b, which displays GPP under both climate and land use change projections, shows an overall decrease in GPP for the 2090 – 2099 decade. The A1B scenario now peaks at 208 g C/m^2/month in April, and the A2 scenario has GPP peaking at 187 g C/m^2/month in April. Overall, this is a 28% decrease in annual GPP for the A1B scenario, and a 41% decrease in the A2 scenario from the original 2090 – 2099 projections which considered only climate change.

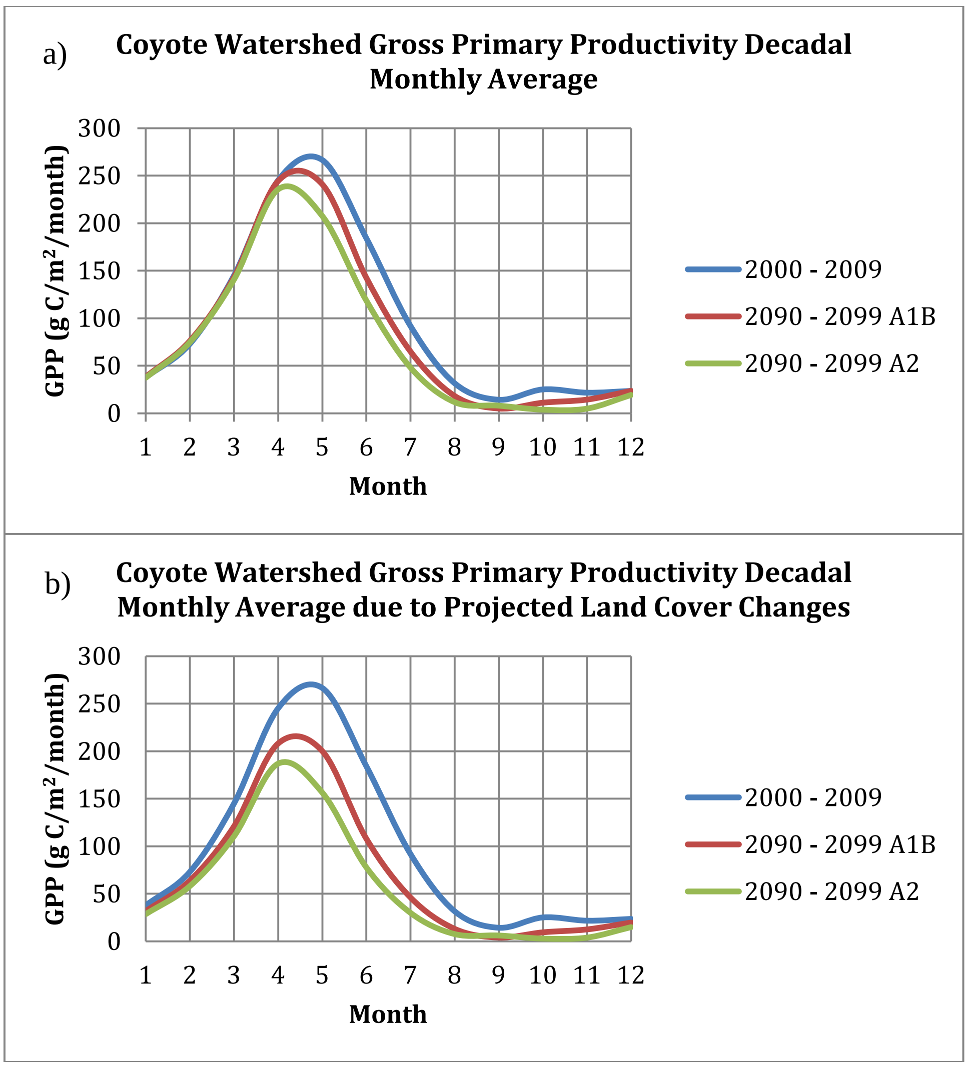

Figure 7. (a) Coyote Watershed GPP decadal monthly average under projected climate change. (b) Coyote Watershed GPP when considering projected increase in impervious surfaces with projected climate.

The same analysis is also done for runoff (Figure 8a). The general pattern is a decrease from the maximum (116 mm/m^2/month) that occurs in January to around June. In the summer months and most fall months, values become very small; however, there is a sharp increase after November. The values for 2000 – 2009 decade generally lie between the A1B and the A2 projected values. However, in November and December, there is only a small increase in runoff for the projections relative to the 2000 – 2009 values. The A1B projected values are higher than the projected A2 values or 2000 – 2009 decade values between January and June. The maximum for the scenario occurs in February, with a value of 92 mm/m^2/month. Note that this runoff peak later in the rainy season may be due to decadal variability. Runoff under the A1B scenario generally starts rising in November, where a sharp increase occurs. From January to May, the A2 scenario projects the lowest values of runoff. In October, the runoff begins to increase from the summer minimum, and in December, the values increase to a maximum of around 104 mm/m^2/month.

Figure 8b shows the runoff after land use has been considered. The most dramatic change is in the A2 winter runoff, where it now peaks at 297 mm/m^2/month. The increase in runoff under the A2 scenario can be partially explained by the 60.57% increase in impervious surface area projected from 2009 to 2099. Overall, runoff increases in the A1B scenario by 35%, and by 72% in the A2 scenario.

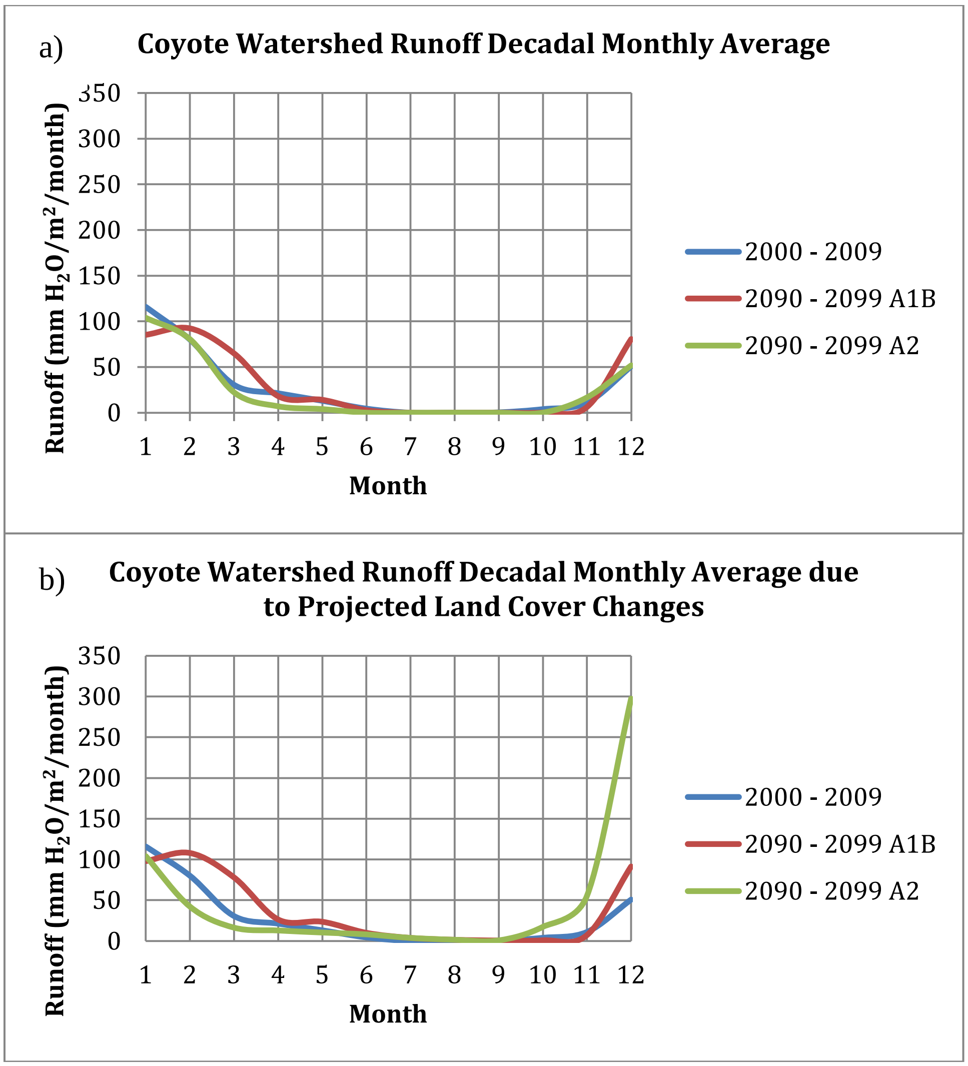

Figure 8. (a) Coyote Watershed runoff decadal monthly average under projected climate change. (b) Coyote Watershed runoff when considering projected increase in impervious surfaces with projected climate change.

Overall, ET averages show the same general pattern for each scenario as well as the 2000 – 2009 decade (Figure 9). In this decade, ET values increase and peak at 41 mm/m^2/month in May, and then decrease until around

September, beyond which the pattern remains relatively flat for the rest of the year at 5 mm/m^2/month. It is also noted that from May to November, the ET values for the 2000 – 2009 decade remain higher than what is projected in the A1B and A2 scenarios. ET values increase starting around January under the A1B scenario, and the maximum occurs in May at 41 mm/m^2/month. The ET value projected for the A1B is greater than the maximum values in the A2 scenario. From May through December, the values decline to approximately 4 mm/m^2/month in a similar manner as the 2000 – 2009 decade. The A2 scenario follows similar increasing and decreasing patterns as mentioned. The peak ET value (38 mm/m^2/month) occurs in May, and is the lowest maximum in the figure. Additionally, the ET values remain the lowest at around 3 mm/m^2/month in nearly all months between September and December. As shown in Figure 6, in both the A1B and A2 scenarios, the February through April ET values are significantly higher than the 2000 – 2009 values, and the June through October values are significantly lower than the 2000 – 2009 values, indicating that ET may start to peak earlier in the season.

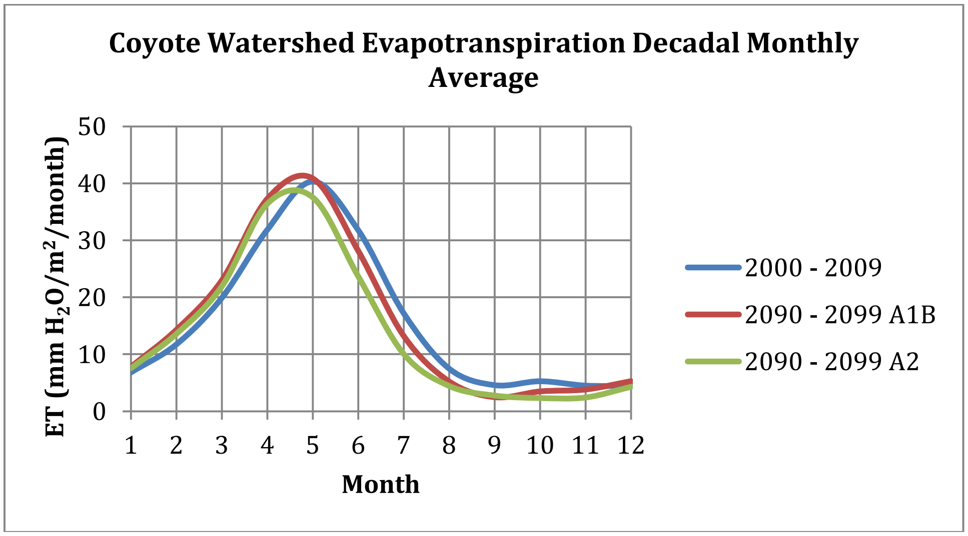

Figure 9. Coyote Watershed ET decadal monthly average under projected climate change.

FIELD WORK

To start identifying options for water conservation, a brief study of the water used for irrigation at NASA Ames was done to determine the areas where over-irrigation was occuring. At NASA Ames there are only two meters that record water used exclusively for irrigation, and are located in the north, and northwest areas of the center. The irrigation systems for these two areas are run by several different timers, and cycle every week.

In the week between July 11 and July 17, 2011, both meters were read daily. The water used for irrigating in the north area of the center was about 63,175 liters (16,689 gallons), and for the northwest area the water used was 469,425 liters (124,009 gallons) during the week of study. ArcGIS was used to find the total areas of the irrigated regions governed by each meter, and the average flow rate was calculated to be 34,191 liters/hectare/day (4,279 gal/acre/day) for the north area, and 55,200 liters/hectare/day (6,885 gal/acre/day) for the northwest area.

The irrigation system does not operate all year, but only runs when regular rainfall is not sufficient to sustain the vegetation. This period varies, but it was assumed for this study that the system operates for roughly 30 weeks between March and October in order to calculate average water consumption per year.

It is estimated that about 41 hectares (102 acres) are irrigated with fresh water at NASA Ames. The flow rates determined from this field work are used as a summer seasonal flow. The fall flow rate is calculated from the fall 2010 readings taken by center personnel, and is about 43% of the summer flow. It is assumed that the spring flow rate is the same as the fall flow rate.

Taking each of these seasonal flow rates and applying that to the irrigated area of the rest of the center, it is calculated that just over 279 million liters (roughly 74 million gallons) of fresh water is used to irrigate NASA Ames during the year. This is about 41% of the 180 million gallons used at NASA Ames for 2010 (Hightower, *Pers. Comm*, 2011).

DISCUSSION AND CONCLUSIONS

The variables that were discussed have some dependence on each other. Daily temperature range and vapor pressure deficit were shown to increase significantly. Also, precipitation is significantly decreased in both scenarios in the spring, as seen in Figure 3, which has an effect on the gross primary productivity, evapotranspiration, and runoff values. The decrease in runoff (Figure 5) is associated with the decrease in precipitation in the area, however this figure does not account for impervious surfaces. Larger areas of impervious surfaces increase runoff, which may partially explain the rapid increase in runoff for the A2 scenario in November and December in Figure 8b.

GPP is projected to decrease significantly in months outside of the rainy season, which means there may be less vegetative growth (Figure 4). While summers are already dry for the region, a further decrease in GPP indicates that summers may become harsher on vegetation in the future. Figure 7 shows how GPP values, as well as how the timing of the maximum values of GPP, change under different scenarios. From this figure it can be seen that the 2000 – 2009 decade GPP values are higher than what is being predicted under either scenario. The peak in GPP can be understood to be the maximum for the growing season, therefore it is seen that with increased emissions come earlier and less productive growing seasons. Additionally, impervious surfaces restrict vegetative growth, and the increase in impervious surfaces also contributes to a decrease in GPP. Overall, the region is projected to become less hospitable toward plant life, though the effects are not as severe under the A1B scenario.

ET is projected to increase in the winter and spring, but decrease in the summer and fall (Figure 6). As temperatures increase, existing vegetation loses more water, resulting in greater ET values in the winter and spring. However, after a few months of elevated temperatures and decreased precipitation, the vegetation dies, and ET values drop, as seen in the summer. This can also be seen in Figure 9 when considering the A2 scenario. Based on the ET trends and projected values for 2090 – 2099 the average yearly peak ET values start to occur earlier in the season. However, these values are generally lower than the 2000 – 2009 decade and the A1B scenario. These projected changes in ET are also evidence of the region becoming less supportive of vegetation.

With the changes discussed in precipitation, temperatures, GPP, and ET, NASA Ames may experience drought conditions more frequently and in greater severity. Additionally, snowpack in the mountainous regions of California are relied upon to produce a continuous supply of water and hydropower as it melts in the summer months. Therefore, droughts may be more intense due to snowpack being reduced and melting earlier in the year in the Sierra Nevada Mountains due to rising temperature. This may impact NASA Ames significantly because the site receives water and hydropower from the Hetch Hetchy reservoir, which is located in these mountains.

These changes to the climate and ecology also have an impact on the frequency and intensity of disasters that can pose a risk to NASA Ames. Longer summers combined with drought conditions created by decreased rainfall and increased temperatures mean that there is the potential for a large amount of fuel to be created from dead vegetation that may increase the duration and intensity of wildfires. While fires are hazardous on their own, they also cause flooding events to be more dangerous as well. Flooding may become more frequent due to the growth in impervious surface areas. A decrease in vegetation due to fires will make floods more dangerous due to the increased risk of mudslides.

Field work was done to provide information about water consumption from irrigation at NASA Ames. It was approximated that just over 279 million liters (roughly 74 million gallons) of fresh water is used for irrigation for the entire center for a year. In 2010, a total of about 674 million liters (178 million gallons) of water was used at the Ames facility. This means that about 41% of all water consumed by NASA Ames is used for irrigation. With a projected longer dry summer season and concern over water availability in the future, NASA Ames could conserve water by implementing new sustainability measures such as using more timers and meters for irrigated areas to better evaluate and control the amount of water used for irrigation.

FUTURE WORK

The results are being shared with Ames Environmental Management Division, Master Planners, and Facilities personnel to provide them with projected climate change effects to the area, and help them meet their goals of better water sustainability for the center. The results will also be available for other federal facilities in California.

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