PREDICTING THE IMPACTS OF GLOBAL WARMING ON WILDLAND FIRE

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Abstract. Simulations of impacts of a double-CO_2 climate with the Changed Climate Fire Modeling System in Northern California consistently projected increases in area burned and in the frequency of escaped fires compared with simulations of the present climate. However, the magnitude of those increases was strongly influenced by vegetation type, choice of atmospheric general circulation model (GCM) scenario, and choice of climatic forcing variables. The greatest projected increase in fire severity occurred in grasslands, using the Princeton Geophysical Fluid Dynamics Laboratory GCM, with wind speed, temperature, humidity and precipitation as driving variables.

Introduction

Although paleontological evidence (Clark, 1988, 1990) and correlations of data from this century (Beer *et al.*, 1988; Simard and Main, 1987) suggest that the changes in climate predicted to occur in the next century will be accompanied by changes in regional fire regimes, there has been virtually no analysis of how climate warming would affect fire danger, let alone quantitative estimates of changes in the area burned by wildfire. Attempts at such predictions are hindered by the disparity in spatial and temporal scales between models of climate and those of fire behavior (Fried and Torn, 1990) and complicated by the practice of fire suppression. In addition, readily available general circulation model (GCM) output is typically summarized in a form that is better suited to atmospheric research than to ecological applications. Previous treatments of climatic change and fire consisted of sensitivity analyses based on historical weather records and potential climate scenarios generated by either *a priori* adjustment of historical weather parameters (Beer *et al.*, 1988) or adjustment of seasonal averages of weather variables using GCM output (Simard and Main, 1987). Because these studies rely on correlations of annual averages of fire and weather data, they provide little insight into the potential for changes in the frequency of extreme fire events and fail to consider interactive effects of changes in multiple weather variables.

That most of the impacts of wildfires result from extreme, rather than average, events motivated a departure from these statistical approaches in the development of the Changed Climate Fire Modeling System (CCFMS, Fried and Torn, 1990). In this system, GCM data are combined with daily weather records and mechanistic models of fire behavior and fire suppression to simulate a range of fires, including

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relatively infrequent, fast-spreading fires. Climate scenarios in which as many as four climate variables are modified further differentiates this approach from previous analyses of fire and global warming.

CCFMS was designed to estimate the changes in fire behavior and fire outcomes that would result from projected climatic change. Its behavior and sensitivity was explored with three sets of simulations. The response of wildland fire to climatic change was compared for three different GCMs in a grass-fuel analysis zone. The relative sensitivity of CCFMS to each of four climate variables (temperature, precipitation, humidity, and wind speed) was evaluated for grass and redwood analysis zones. The wildland fire response to climatic change in four different fuel types was assessed using a scenario generated from the GISS GCM with all four climate variables modified (All Changed).

Methods

The Changed Climate Fire Modeling System consists of software and protocols for linking GCM output with the California Department of Forestry and Fire Protection's (CDF) Fire Protection Planning System (Fried *et al.*, 1987; Fried and Gilless, 1988), a collection of micro-computer based, deterministic, and largely mechanistic computer models of fire behavior and fire suppression (Figure 1). CCFMS produces comparative analyses of fire behavior and fire size under different climate and fire-management scenarios. The impact of climatic change is assessed for representative fires in analysis zones that are relatively homogeneous with respect to fuels, topography, and population density. The number of fires, as well as their dates and locations, is exactly the same for each set of simulations. What differs is the climate scenario, which affects fire behavior, dispatch level, and area burned.

For each climate scenario, the fire behavior module, FBDMOD (Andrews and Chase, 1989) in Figure 1, combines daily weather records with site descriptions (vegetation and slope class) to estimate fire intensity and rate of spread for any fires that occur. Each fire ignition in the historical record is matched to the rate of spread and fire intensity modeled for its date, time, and location (MERGE), and assigned a dispatch level (FPPSTATS) (which determines the kinds and amounts of fire-fighting equipment sent to a fire) based on fire intensity. The result is a distribution of rates of spread for each of three dispatch levels for each analysis zone. The California Fire Economics Simulator (CFES, Fried and Gilless, 1988) simulates fire growth and initial fire suppression activities on representative fires with spread rates selected from these distributions. For each simulated fire, initial attack forces are dispatched to build a containment line until the fire is either contained or exceeds specified size or time limits. The simulation limits used by the CDF range from 100 acres and two hours for low population density grassland to 25 acres and 1 h for high population density redwood forest. If a limit is exceeded, the fire is classified as an escape; otherwise, the contained fire's final size is recorded. The size and time limits are specified by the CDF to represent the threshold beyond

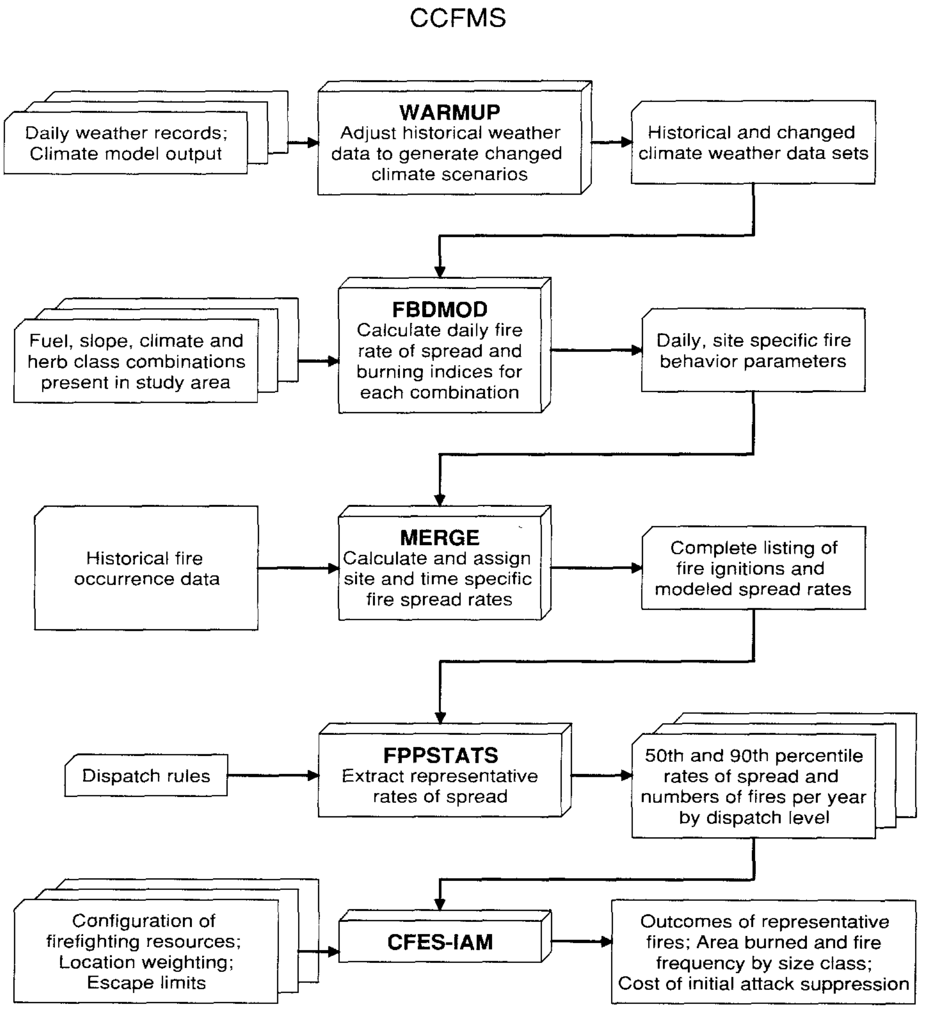

Fig. 1. Data-flow diagram for the Changed Climate Fire Modeling System. Micro-computer programs are indicated in bold face.

which supplementary (as opposed to initial attack) fire-fighting forces would be dispatched and beyond which the simulator's simplifying assumptions regarding fire behavior and suppression tactics would no longer be valid.

While most fires in California are contained quickly and burn only a fraction of an acre, large escape fires account for nearly all of the area burned (Strauss *et al.*, 1989). It is extremely difficult to simulate the area burned by escapes, because large fires may become non-homogeneous in behavior, slope, aspect, wind, and vegetation.

The primary outputs of CCFMS are expected annual frequency of escapes, number of contained fires by size class, and distributions of fire rate of spread.

While annual escape frequencies and area burned in contained fires are comprehensive measures of wildfire outcomes in regions that practice fire suppression, the complexity of fire suppression precludes generalization from these results to changes in fire behavior. For example, since population density affects the dispatch of fire-fighting resources, a fire in a densely populated analysis zone may result in a smaller burned area than an identical fire burning in a sparsely populated zone. Comparing rate of spread distributions under different climate scenarios provides insight into the effects of climatic change on fire behavior. For regions possessing little or no fire protection infrastructure (e.g., Baja California), potential rate of spread simulations constitute the limit of current analytic capability. Such simulations require only daily weather observations and fuel/slope descriptions.

Fire behavior models require data of fine resolution, such as the minimum and maximum daily temperature in the vicinity of a fire. In contrast, readily available climate predictions are of relatively low temporal and spatial resolution. In CCFMS, this disparity is addressed with the use of monthly scaling factors for temperature, precipitation, humidity, and wind speed. Monthly scaling factors are calculated as the ratios of monthly mean values from a double-CO_2 GCM simulation to means from a present climate GCM simulation (Fried and Torn, 1990). Climate change weather series are generated by multiplying historical, daily, local weather observations by these scaling factors.

Theoretically, applying a multiplicative scaling factor to historical weather data modifies the variance of the climatic change weather series, as well as altering the daily values. If α represents the multiplicative scaling factor, X represents historical weather, and Y represents climatic change weather, then $Y = \alpha X$, and $\mathrm{var}[Y] = \alpha^2 \mathrm{var}[X]$. Hence, if $|\alpha| > 1$, the variance of the climatic change weather series is increased, and if $|\alpha| < 1$, the variance is decreased. Application of an additive scaling factor (where $Y = \alpha + X$) does not affect the variance. However, comparison of CCFMS simulation output derived from a weather series scaled with additive factors with one generated using multiplicative factors revealed negligible differences (Fried and Torn, 1990). In this analysis, the model was insensitive to the changes in variance associated with the multiplicative method.

Daily weather records (Figure 2) from 1980–1985 for four weather stations form the basis of all climate scenarios.[1] The Present Climate analysis uses these six years of historical weather data without modification. Climate change weather data sets were produced by multiplying historical weather observations with scaling factors computed using output for the closest surface grid point available from each of three GCMs: NASA Goddard Institute for Space Studies (GISS, Hansen *et al.*, 1988), Princeton Geophysical Fluid Dynamics Laboratory (GFDL, Manabe and

[1] Weather Station data were retrieved from the National Fire Weather Data Library via the Administrative Forest Fire Information and Retrieval Management System (AFFIRMS, Furman and Brink, 1975).

Wetherald, 1980), and the United Kingdom Meteorological Organization (UKMO, Wilson and Mitchell, 1987).[2] These scaling factors are shown in Table I.

An All Changed climate scenario was analyzed for each of the three GCMs in a grass analysis zone. The All Changed GISS scenario was also used with three additional fuel types. Four scenarios were developed by modifying weather data using only the scaling factor (derived from GISS output) for temperature, precipitation, humidity *or* wind speed, to test the importance of each variable.

The wind speed in these simulations was calculated from the monthly mean wind vectors. A second set of wind-only and all-variables changed simulations was carried out in which monthly mean wind speed was calculated in a manner that approximates a mean of scalars.[3]

The effects of climatic change on wildfire severity were analyzed for the CDF's Santa Clara ranger unit, a 560-thousand hectare region located 100 km south of San Francisco, California.[4] The region's climate is moderated by its proximity to the ocean, but during the fire season high temperatures (24–35 °C) are common and precipitation is extremely rare. The dominant vegetation communities are summarized by the fuel types chosen to represent fire behavior: grassland with sparsely distributed oak trees, two types of chaparral, and redwood forest. These fuel types correspond to National Fire Danger Rating System (Bradshaw *et al.*, 1983) fuel models A, B, F, and G, respectively. The region is divided into six analysis zones, from 12 000 to 190 000 hectares each, that are relatively homogeneous with respect to fuels, topography, and population density. Landholdings in the region are quite diverse in both size and utilization, and much of the area is undergoing suburban encroachment.

[2] Output from all general circulation models was obtained from the National Center for Atmospheric Research, Boulder, CO.

[3] GCMs generate vectors representing wind speed and direction at time intervals on the order of 90 min. Monthly mean wind speed can be computed by calculating the wind speed at each time step and averaging these scalars over the month, or it can be calculated by computing an average monthly wind vector and calculating the magnitude of this vector. As with most GCMs, the latter method is used at GISS. GISS also calculates the wind drag and the magnitude (scalar) of wind drag at each time step. Shifts in wind direction over the month result in vector-derived monthly wind speeds that are less than averages of the scalars, resulting in possible underestimates of processes that depend on wind speed throughout the month. To compensate for this problem, GISS recommends calculating monthly wind speed scaling factors using the following combination of wind and wind drag output:

$$\text{Scaling Factor} = \frac{\left(W \times \dfrac{(\text{monthly mean magnitude of wind drag})}{\sqrt{U_d^2 + V_d^2}} \right)_{2 \times CO_2}}{\left(W \times \dfrac{(\text{monthly mean magnitude of wind drag})}{\sqrt{U_d^2 + V_d^2}} \right)_{1 \times CO_2}}$$

where $W = \sqrt{(U^2 + V^2)}$; U and V are mean monthly east and north wind components; U_d and V_d are mean monthly east and north components of wind drag.

[4] All data on historical weather, fire activity, site description and suppression practices were supplied by CDF's Fire Protection Planning staff and field personnel. These data are now on file at CDF's headquarters in Sacramento, where records of all fire incidents since 1980 are archived.

TABLE I: Monthly percent change predicted by the GISS, GFDL and UKMO climate models, and 1980–1985 monthly means, for wind speed, humidity, temperature and precipitation for the Santa Clara ranger unit

Month	Wind speed: Historical, 2 pm 6 year mean (mph)	% change: GISS vector	% change: GISS scalar	% change: GFDL	% change: UKMO
Jan	N/A	84	−35	−10	−2
Feb	N/A	25	−19	−12	−7
Mar	5.9	35	−6	220	−1
Apr	8.3	−12	−24	151	−2
May	6.4	18	45	58	−7
Jun	6.3	22	19	39	−4
Jul	6.4	−5	1	41	−3
Aug	6.4	43	32	13	0
Sep	5.9	12	26	39	−7
Oct	5.2	−19	−28	−39	−15
Nov	N/A	16	−67	3	−11
Dec	N/A	31	−75	−21	−5

Month	Humidity: Historical, 2 pm 6 year mean rel. humidity	% change in specific humidity: GISS	GFDL	UKMO
Jan	N/A	36.5	23.2	50.6
Feb	N/A	33.8	30.0	46.1
Mar	21.4	21.6	37.5	36.4
Apr	21.8	33.1	16.8	27.1
May	40.4	17.3	20.1	17.2
Jun	39.3	16.2	12.5	26.7
Jul	35.0	32.2	7.7	86.9
Aug	37.5	39.7	12.4	54.2
Sep	35.2	26.2	14.5	19.1
Oct	41.2	32.0	32.5	4.6
Nov	N/A	28.0	35.0	55.6
Dec	N/A	44.5	28.6	61.8

Month	Temperature: Historical, 2 pm 6 year mean (°F)	% change in °K: GISS	GFDL	UKMO
Jan	N/A	1.38	0.87	2.23
Feb	N/A	1.52	1.20	2.11
Mar	63.9	0.73	1.63	1.37
Apr	61.6	1.85	0.89	1.76
May	74.5	0.41	1.23	1.99
Jun	78.9	1.11	1.96	1.92
Jul	84.7	1.59	1.45	3.57
Aug	82.8	1.67	1.49	2.69
Sep	82.5	1.25	1.58	2.53
Oct	75.4	1.64	1.69	2.45
Nov	N/A	1.41	1.55	2.19
Dec	N/A	2.00	1.38	2.41

Month	Precipitation: Historical, daily 6 year mean ppt. inches	% change in monthly ppt.: GISS	GFDL	UKMO
Jan	N/A	19.5	14.4	29.3
Feb	N/A	−2.6	30.6	12.8
Mar	0.072	112.7	39.8	38.7
Apr	0.041	−42.0	−14.3	7.7
May	0.007	51.0	−47.1	17.4
Jun	0.000	−77.2	−25.0	0.0
Jul	0.001	0.0	−50.0	−26.7
Aug	0.000	0.0	0.0	0.0
Sep	0.005	75.0	−50.0	0.0
Oct	0.028	−15.0	40.0	−37.5
Nov	N/A	27.0	26.3	−5.6
Dec	N/A	43.0	−32.3	25.5

Weather station data	
Date	
Temperature* (2 pm)	(°F)
Temperature* (24 hour max)	(°F)
Temperature* (24 hour min)	(°F)
Relative humidity* (2 pm)	(%)
Relative humidity* (24 hour max)	(%)
Relative humidity* (24 hour min)	(%)
Wind speed* (2 pm)	(mph)
Wind direction (2 pm)	(1-8)
Precipitation amount*	(inches)
Precipitation duration	(hours)
Source: California Dept. of Forestry and Fire Protection	

* variable was modified by scaling factors to form climate change scenarios.

Fig. 2. List of variables included in historical weather observations.

Results

Sensitivity to Choice of General Circulation Model

Compared with the Present Climate scenario, the GISS, GFDL, and UKMO All Changed climatic change simulations project an increase in both the frequency of escapes and area burned by contained fires in the grass analysis zone (Figure 3). Fire danger, as represented by potential rate of spread, is greater in every month of the fire season (the period from May through September, when seasonal fire engines are staffed) (Figure 4). There is a pronounced shift in the rate of spread frequency distributions with a considerable increase in the number of days with potential spread rates faster than 27 m/min (1.6 km per h) (Figure 5). While the different GCM simulations of the greenhouse effect consistently predict an increase in fire severity, the GFDL model results in the most change in wildfire statistics while the UKMO model results in the least change. The GISS model was selected for the vegetation and climate-variable analyses because it resulted in intermediate changes in fire behavior.

Sensitivity to Climate Variables

Global climate models predict that surface air temperatures will increase throughout the year in California. Higher temperatures are typically associated with heightened fire danger, and indeed, CCFMS predicts higher rates of spread as a result of elevated temperatures (Figure 6). However, under a climate warming, temperature-only scenario, CCFMS shows a reduction in area burned in the redwood

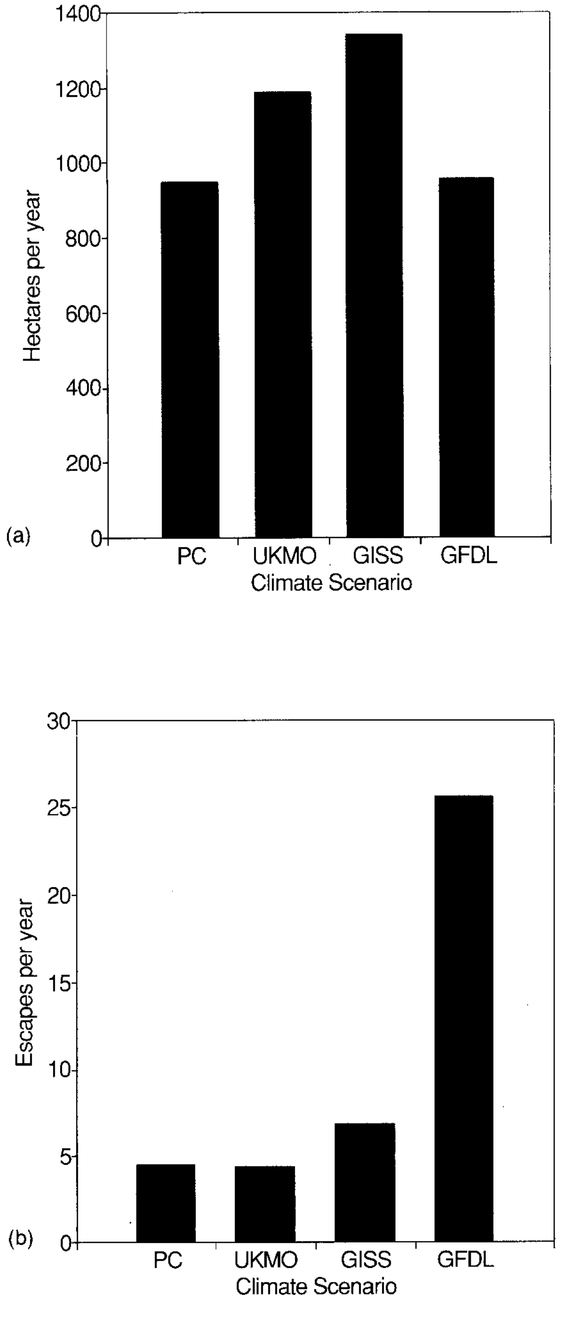

Fig. 3. (a) Area burned by contained fires and (b) frequency of escapes for the Present Climate (PC), and the GFDL, GISS, and UKMO climate warming scenarios in the grass fuel analysis zone, Santa Clara ranger unit.

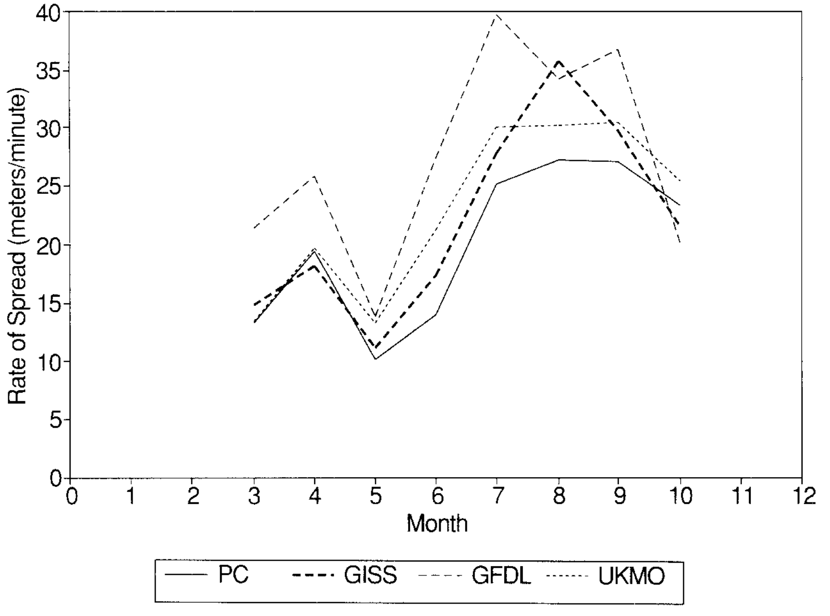

Fig. 4. Monthly average, 2PM rates of spread, modeled for 1980–1985 for the Present Climate (PC) and the GFDL, GISS, and UKMO climate warming scenarios on steep (48% slope) grass in the Santa Clara ranger unit.

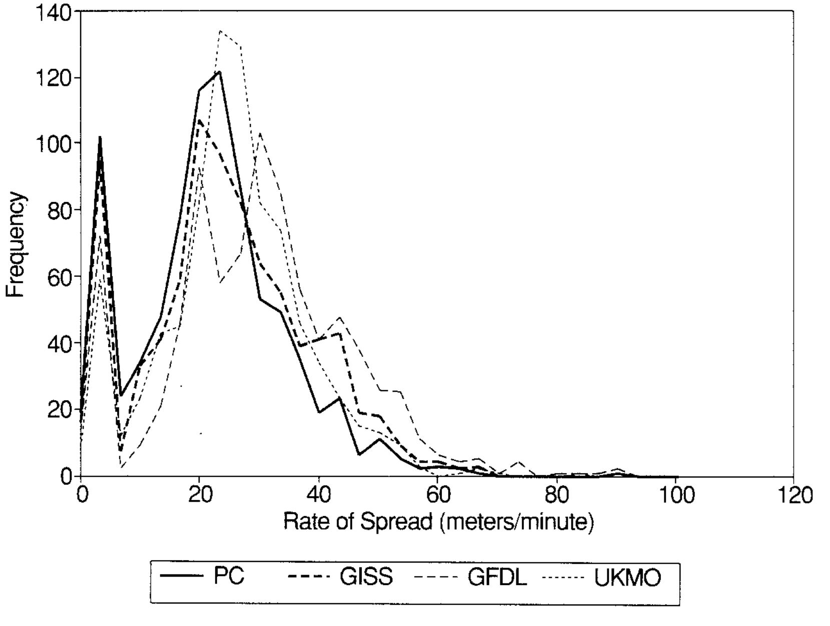

Fig. 5. Frequency of 2PM rates of spread, modeled for 1980–1985 for the Present Climate (PC), and the GFDL, GISS, and UKMO climate warming scenarios on steep (48% slope) grass in the Santa Clara ranger unit.

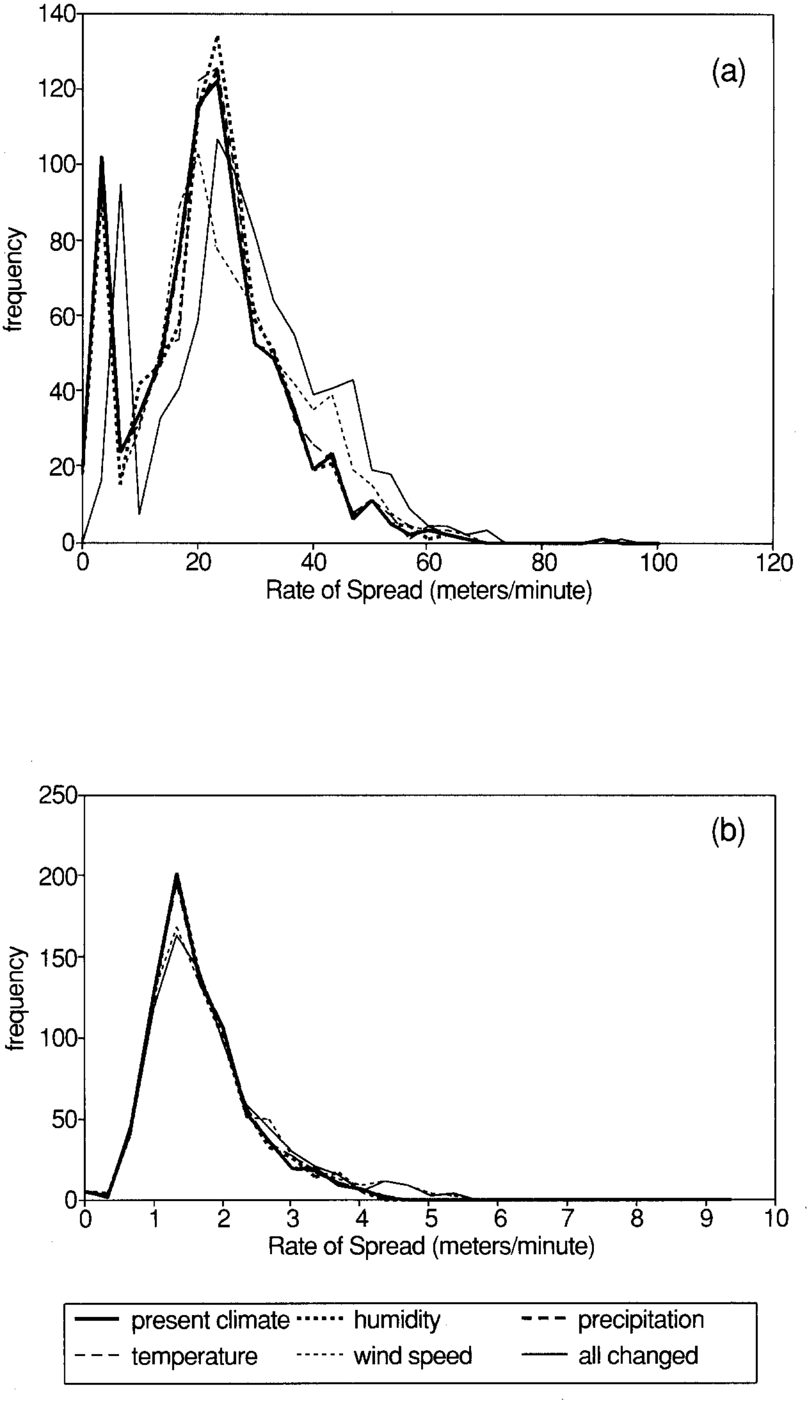

Fig. 6. Frequency of 2PM rates of spread, modeled for 1980–1985 for the Present Climate, GISS All Changed, and GISS wind-, temperature-, humidity- and precipitation-only climate warming scenarios on (a) steep (48% slope) grass and (b) flat redwood in the Santa Clara ranger unit.

fuel zone (Figure 8). This apparent paradox reflects enhanced fire suppression activity rather than diminished fire danger. Final results from CCFMS incorporate both fire behavior *and* fire suppression. Elevated temperatures increase fire inten-

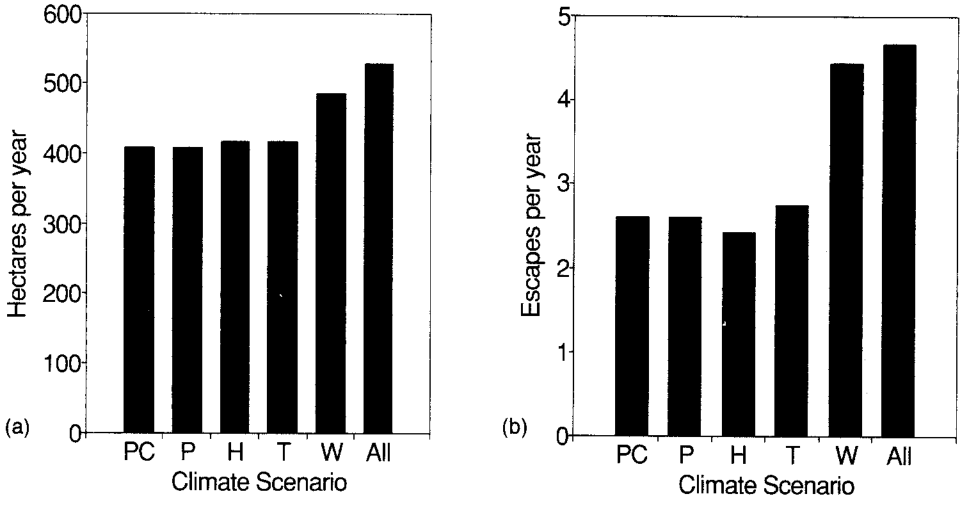

Fig. 7. (a) Area burned by contained fires and (b) frequency of escapes for the Present Climate (PC), the GISS All Changed (ALL), and the GISS wind – (W), temperature – (T), humidity – (H) and precipitation – (P) only climate warming scenarios in the grass fuel, low population density analysis zone, Santa Clara ranger unit.

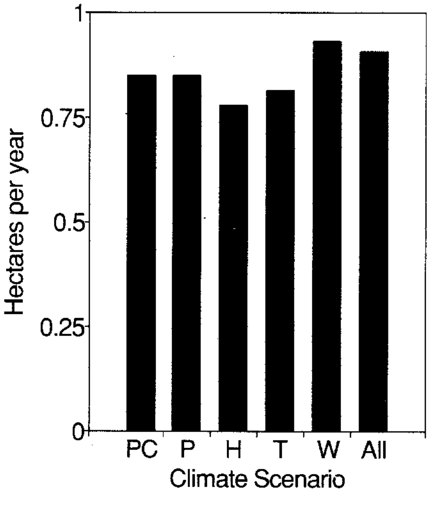

Fig. 8. Area burned by contained fires for the Present Climate (PC), the GISS All Changed (ALL), and the GISS wind – (W), temperature – (T), humidity – (H) and precipitation – (P) only climate warming scenarios in the redwood fuel, medium population density analysis zone, Santa Clara ranger unit. There were no escapes in any redwood fuel scenario.

sity, the parameter on which the dispatch of firefighting resources is based; thus, climate warming results in more fires at high dispatch level. At high dispatch level, CFES dispatches additional fire-fighting resources, such as air tankers (at $2000 per mission). These compensate for the increase in rate of spread caused by higher temperatures, but also increase fire protection expenditures.

Climate warming is expected to increase global precipitation (Hansen *et al.*, 1983). Nevertheless, GCM simulations of climate warming show that some months in California will be wetter and others drier than they are today. For the Santa Clara ranger unit, CCFMS projected no discernable wildfire response to predicted changes in precipitation (Figures 7 and 8). Such results are not surprising given the region's Mediterranean climate, in which the fire season and rainy season have virtually no overlap. For example, even if GCMs predict a reduction in rainfall in February, there would be no change in simulated fire statistics since there are no February fire occurrences in the historical record used in this analysis. In reality, a drier February would likely lead to more fire ignitions. Because there is no August precipitation in the local historical record (and, therefore, no precipitation events to permit scaling), a GCM prediction of precipitation-doubling in August would likewise have no effect on simulated fire behavior.

These GCM warming simulations predict an increase in absolute humidity, probably due to increased evaporation. However, relative humidity decreased due to warmer air temperatures. Both fire danger and fire suppression intensity increased, resulting in a net decrease in the frequency of escapes in grass fuel and area burned in redwood fuel (Figures 7 and 8).

GCM simulations project an increase in wind speeds during most of the year, as the Pacific high pressure cell is strengthened relative to lower surface pressure in California's Central Valley. Of the four climatic forcing variables tested, wind speed resulted in the greatest increase in rate of spread, area burned by contained fires, and frequency of escaped fires (Figures 6–8). The climate change wind-only scenario generated with winds that were averaged to approximate scalar means resulted in even greater fire severity than did the vector-averaged, wind-only scenario (Figure 9).

Response of Vegetation Types

The four fuel types exhibited a differential response to climate warming, with grass fuel most sensitive, brush fuels intermediate, and redwood forest relatively insensitive (Table II). The micro-climates of these vegetation communities suggest one explanation for the response gradient. The open, unprotected structure of grasslands make them particularly responsive to increases in wind speed; the still, humid air layer under a forest canopy can substantially mitigate synoptic weather changes. The variation in moisture retention among vegetation types may also contribute to the differential response. During the fire season, much of the flammable material in grasslands exhibits little, if any, lag in reaching a moisture equilibrium. Any increase

TABLE II: Area burned by contained fires and frequency of escapes for grass, short brush, tall brush and redwood fuel analysis zones under Present Climate and GISS Warming scenarios, Santa Clara ranger unit

Fuel	Present climate	GISS warming
	Hectares burned	
Grass	946.8	1339.2
Short brush	4.0	5.4
Tall brush	0.8	1.7
Redwood	0.8	0.9
	Escapes	
Grass	4.5	6.9
Short brush	0.3	0.4
Tall brush	0.0	0.0
Redwood	0.0	0.0

in temperature or decrease in humidity would quickly affect its combustibility. By contrast, the large, woody debris comprising redwood-forest litter can take as long as 40 days to equilibrate after a change in humidity, effectively buffering the effects of any short periods of hot, dry, or windy conditions. In addition, slope and aspect, which are correlated with vegetation type, may also contribute to the differing sensitivity of fuel types to climatic change. For more on the underlying mechanisms of fire behavior, see, for example, Rothermal (1983) and Albini (1976).

Discussion

Wildfire severity, as measured by fire behavior or outcomes, was greater in every climate warming scenario than it was in the Present Climate scenario. However, the magnitude of the increase does depend on the choice of GCM (Figures 3–5). Given the reliance of past research on temperature changes as proxies for climatic change, one surprising finding of this analysis is the evidence that temperature changes may not be the most important measure of climatic change for predicting the response of wildland fire. Indeed, projected changes in wind speed had considerably more influence than did temperature on wildfire severity in Santa Clara. Furthermore, for both grass and redwood fuels, changing all four climate variables had a greater than additive effect on fire severity (Figures 6–8). Non-linear, interactive terms in the fire behavior models may account for this apparently synergistic phenomenon.

Currently, the quality of wind predictions is probably the most limiting factor in simulating climatic change impacts on wildland fire in California. The sensitivity of the wildland fire system to wind speed makes validation of GCM surface wind output for California highly desirable. Climate modelers express relatively greater confidence in GCM predictions of high-altitude mass air flow than in GCM estimates

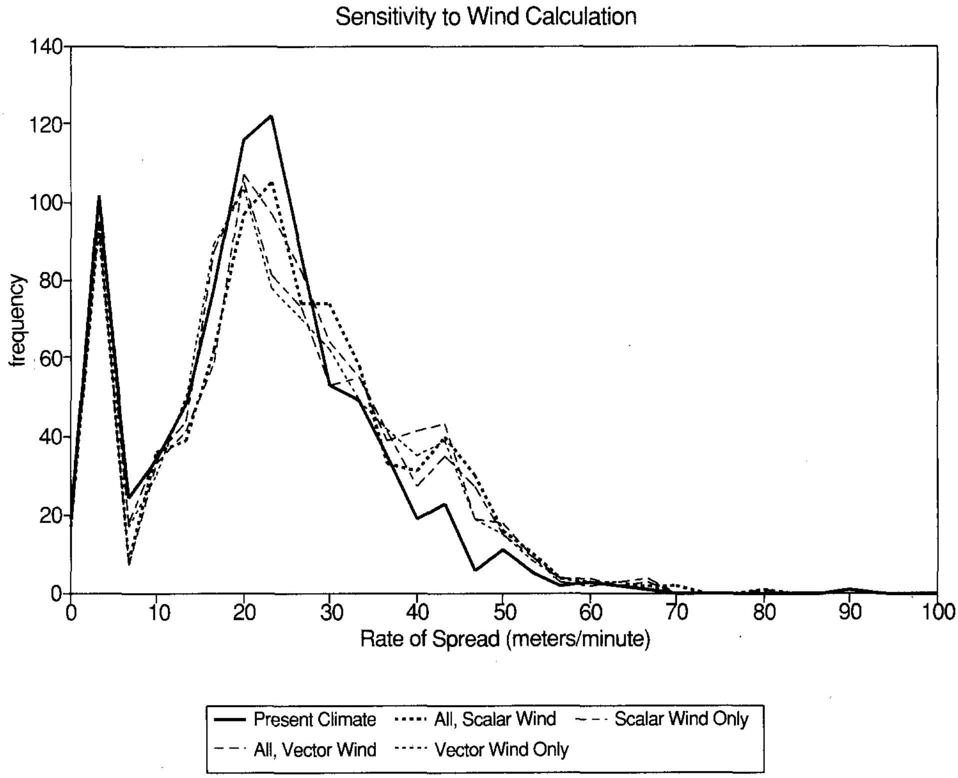

Fig. 9. Frequency of 2PM rates of spread, modeled for 1980–1985 for the Present Climate, GISS scalar method wind-only and GISS vector method wind-only climate warming scenarios on steep (48% slope) grass in the Santa Clara ranger unit.

of surface wind speeds, which are derived from high altitude winds and topographic and surface roughness parameters. A single value represents surface roughness of an entire grid cell, which in California may span from open ocean surface to the Sierra foothills. The resulting grid-average surface wind speed is unlikely to be representative of the area for which fires are being modeled, although the direction of this error has not been determined. However, the *change* in wind speed between GCM warming and present climate simulations may be more robust.

In addition, the effect of GCM output-averaging on climate scenarios, and thus on estimates of fire behavior, is poorly understood. GCMs generate vectors representing wind speed and direction at time intervals on the order of 90 min. In most cases (e.g., GFDL and GISS), these vectors are averaged to obtain monthly wind vectors from which scalar wind speed can be computed. Shifts in wind direction over the averaging period result in vector-derived average wind speeds that are less than averages of the scalars. For example, if the wind blows at five km/h from the east for half of the month, and from the west the other half, then the scalar-averaged monthly-mean wind-speed is five km/h but the vector average is zero. Thus, wind speeds derived from averages of vectors under-estimate fire danger relative to scalar-averaged output from the same GCM simulation. We cannot conclude, however, that the *ratio* of global warming simulation to present climate simulation would be systematically lower for vector- than for scalar-averaged wind speed output (Table I). The practice of UKMO is to compute scalar wind speed for each modeled time interval, then average these scalars to obtain monthly wind speeds. The scalar-averaged, UKMO GCM output led to the smallest change in wildfire behavior of the three models, which may indicate that the differences among GCMs are more important than the influence of output averaging.

To improve GCM-based wind predictions for use in fire models and other fine-scale ecological models, wider availability of scalar-averaged wind speeds and daily or weekly averaging of 90-min time-step output (rather than monthly averages) of climate variables would be highly desirable (Fried and Torn, 1990). Site-specificity of wind predictions might be enhanced by correlating local surface wind speed observations with high-altitude wind or pressure data. These correlations could then be applied to GCM high-altitude wind output to generate scaling factors for surface winds.

While fire statistics modeled for Mediterranean California are not sensitive to changes in precipitation, GCM handling of precipitation could be an important limitation to modeling wildfire in areas where the wet season and the fire season are less distinct. Furthermore, since GCMs vary considerably in their predictions of precipitation patterns in a double-CO_2 climate, the effect of GCM choice might be more pronounced in an analysis of the southeast United States or other areas with a direct link between rainfall and fire severity.

For many ecological processes, GCMs cannot predict precipitation with the accuracy or resolution needed to predict changes in those processes rigorously (Harte *et al.*, 1991). In addition, monthly-averages of precipitation output give no information on changes in precipitation patterns, such as changes in the frequency or duration of storm events. Figure 10 shows how two legitimate methods of apportioning a 15% increase in precipitation could have very different impacts on fuel moisture content.

Precipitation and soil moisture are determinants of vegetation type and fuel accumulation in unmanaged ecosystems. Novel patterns of precipitation, such as occur during El Niño or may occur with climatic change, will likely alter wildfire regimes in California through effects on vegetation. The potential impacts on wildfire of long-term changes in precipitation and soil moisture, as predicted by GCMs, could be modeled by re-mapping the distribution of vegetation communities to reflect these new moisture regimes. The differential response of grass, chaparral, and redwood fuel analysis zones to the same climatic change scenario suggests that vegetation communities influence response to climate warming.

In Santa Clara, fire showed a much greater response to climate warming in steep, south-facing grasslands than in redwood forest (Table II). Thus, the greatest increase in fire severity can be expected in areas vegetated with grass and brush

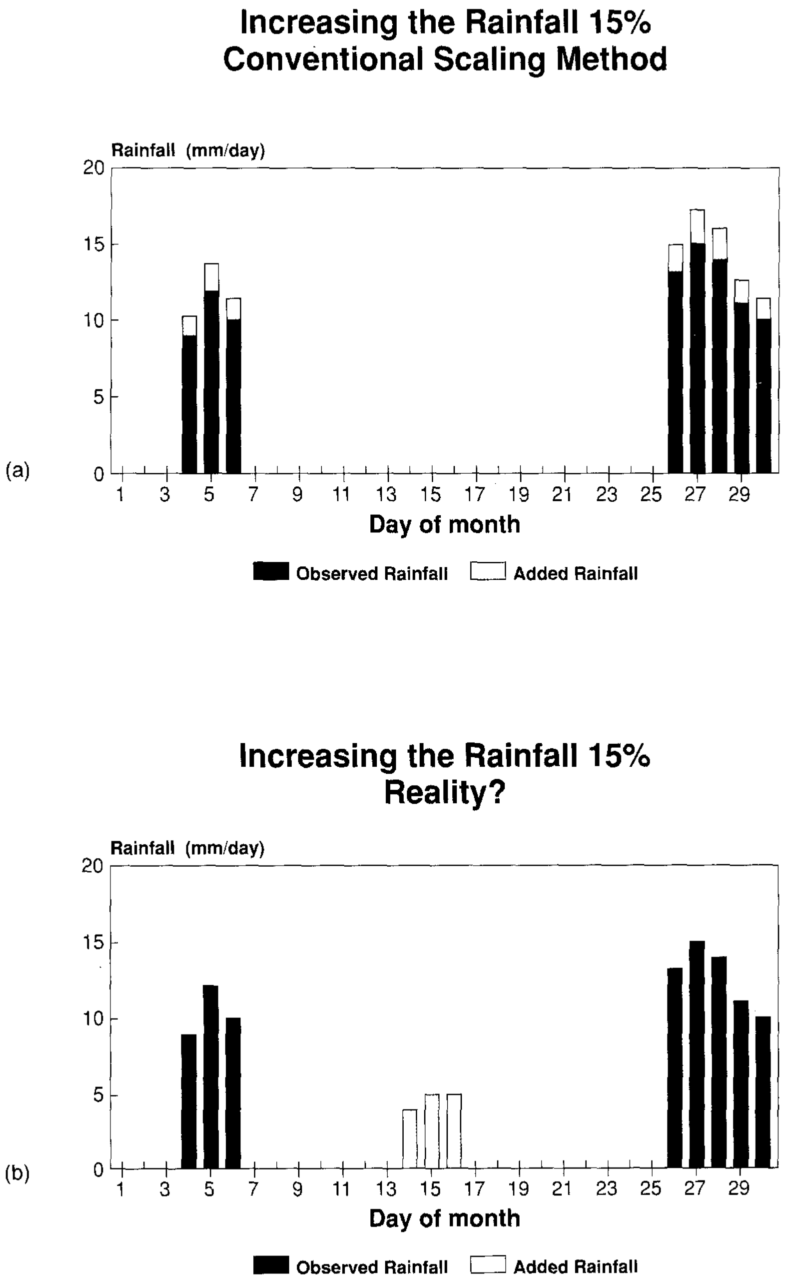

Fig. 10. Two ways in which a 15% increase in monthly rainfall might be distributed over time: (a) the conventional assumption, used by the U.S. EPA and in CCFMS, in which additional rainfall is distributed in proportion to existing rainfall; (b) an alternative assumption, in which the number of rainy days increases.

(which experience the greatest fire severity now). This suggests negligible changes in the loss of forest resources to fire, but it bodes ill for the hundreds of thousands of people living in California's brush- and grass-covered foothills. Ecologically, the predicted changes in fire severity would certainly have complex impacts on vegetation and wildlife, affecting, for example, plant succession, wildlife habitats, and forage production (e.g., Westman and Malanson, 1992).

In wildland fire systems, like the one modeled here, fire behavior is the driving variable in determining containment success, area burned and fire suppression costs (Dimitrakopoulos, 1985). Fire behavior in CCFMS is mechanistically determined by local, daily weather data, fuel, slope, and herb type. In California, fire spread rates are most sensitive to fuel type, followed (in rough order) by wind speed, temperature, humidity, and precipitation. Thus, although the CDF's Fire Protection Planning System (FPPS) was developed to conduct economic analyses of initial attack effectiveness, its adaptation in CCFMS yields an excellent tool for assessing the likely effects of climatic change on the wildland fire system.

FPPS was designed to be valid for comparing alternative fire protection configurations and strategies. Users of CCFMS can have confidence in *comparisons* of projections based on alternative climate scenarios, even if the projections from any one scenario only provide order of magnitude estimates of fire statistics. CCFMS contains the assumption that all fires burn in pure, homogeneous fuels, on a constant slope and with a constant wind speed. Real fires burn in heterogeneous fuels, under shifting winds and uneven topography, and are impeded by natural barriers, such as rock outcrops and roads. Despite these simplifying assumptions, distributions of fires by size class generated with the Present Climate scenario corresponded well with historical distributions (Mitchell and Spero, 1991). Spread rates predicted by the fire behavior model (FBDMOD) were shown to closely match actual spread rates during controlled burns (Sneeuwjagt and Frandsen, 1977).

It should be noted that the results for the Santa Clara ranger unit represent a partial analysis of future wildfire severity in that they ignore probable changes in non-climate factors such as the frequency of fires started by human activities.

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