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A Synoptic Climatology for Forest Fires in the NE US and Future Implications from GCM Simulations

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Abstract. We studied surface-pressure patterns corresponding to reduced precipitation, high evaporation potential, and enhanced forest-fire danger for West Virginia, which experienced extensive forest-fire damage in November 1987. From five years of daily weather maps we identified eight weather patterns that describe distinctive flow situations throughout the year. Map patterns labeled extended-high, back-of-high, and pre-high were the most frequently occurring patterns that accompany forest fires in West Virginia and the nearby four-state region. Of these, back-of-high accounted for a disproportionately large amount of fire-related damage. Examination of evaporation and precipitation data showed that these three patterns and high-to-the-south patterns all led to drying conditions and all other patterns led to moistening conditions. Surface-pressure fields generated by the Canadian Climate Centre global circulation model for simulations of the present ($1xCO_2$) climate and $2xCO_2$ climate were studied to determine whether forest-fire potential would change under increased atmospheric CO_2. The analysis showed a tendency for increased frequency of drying in the NE US, but the results were not statistically significant.

Keywords:

Introduction

Wildfires are known to correlate with climatic events on short time scales of El Niño events (Simard et al 1985) and much longer time scales as determined by charcoal stratigraphic analysis and fire scars (Clark 1990; Meyer et al 1992; Swetnam 1993). The linkage of forest fires to meteorological events includes both likelihood of severe drought conditions due, for instance, to persistent high-pressure conditions (Schroeder et al 1964) and frequency of lightning events (Price and Rind 1993). In fact, a worst-case fire scenario would have an extended drought followed by a synoptic pattern conducive to thunderstorms with minimal precipitation and strong surface winds to propagate new or pre-existing fires. Brotak and Reifsnyder (1977) found that most major wildland fires in the eastern US occurred during surface frontal passage with strong winds and no precipitation. Such events were associated with a specific type of 500-mb trough that was intense but of small latitudinal extent. Whether these larger fires are ignited by lightning or human causes, meteorological conditions play a dominant role in determining the extent of their societal impact. These studies point out the need for examination of the types and sequences of types of synoptic-scale meteorological events that accompany large forest fires.

The goal of our research is to examine the relationship of forest-fire occurrence to weather patterns and sequences of weather patterns. Success in this goal gives a basis for estimating future forest-fire likelihood by using global-climate models that project changes in climate patterns. We examined the relationship between weather patterns and forest fires by analyzing daily surface-pressure maps and precipitation and evaporation data for a subregion of the northeastern US (West Virginia) that experienced extensive forest-fire damage in November 1987. Synoptic weather maps for five years were used to identify distinctive flow situations throughout the year. These patterns served as a basis for categorizing data on evaporation, precipitation, and forest-fire occurrence.

Surface-pressure fields generated by the Canadian Climate Centre global circulation model for a three-year simulation of the present ($1xCO_2$) climate and a three-year simulation of the $2xCO_2$ climate were then studied to determine whether a global climate model can simulate typical surface-pressure patterns common to this region. We compiled statistics on frequency of occurrence of characteristic synoptic patterns in the $1xCO_2$ simulations to determine the model bias for simulating the ensemble of observed surface-pressure fields and their seasonal distribution. This model bias together with pressure-pattern distributions produced by the $2xCO_2$ simulation allow us to speculate on the prospects for forest fires in the northeastern US under a doubled-CO_2 climate.

Forest Fire Data

We examined data on forest-fire occurrence in the northeastern US for the periods 1971-84 and 1987-90 (available from the USDA Forest Service, North Central Forest Experiment Station) that were used in the development of the METAFIRE fire-severity prediction system (Simard and Eenigenburg, 1990). These data give the subarea of a state affected and the number of acres burned for fires that burned more than 500 acres. This database does not include the many small fires during this period but includes those that have major impact on fire suppression activity. We had no accompanying data on ignition agents or fire-suppression activity, so human intervention contributes uncertainty to the fire event data. By limiting our attention to large-scale fires, however, we increase the likelihood that the events considered have a meteorological connection.

Fires recorded in the dataset peaked very strongly in April and November, with approximately one third of occurrences being in each of these two months. The fire damage in West Virginia in 1987 stands out as the most devastating period within the record examined for the NE US region. We used this location and year to examine in detail the synoptic meteorology patterns leading up to and accompanying the fire period. The selection of this particular location means that when we examined and assigned a particular synoptic weather pattern to each day, we looked for the pattern that affected the fire-damaged area of West Virginia. On a particular day, the pattern affecting a nearby state might differ from the pattern assigned to West Virginia.

Synoptic Meteorology Patterns

Schroeder, et al. (1964) presented an extensive analysis of synoptic weather types associated with critical fire weather. They related fire danger to persistent high-pressure centers and pre- and post-frontal areas associated with these centers. In the eastern US, if a high-pressure center moves to the north of a possible fire region, the high fire danger tends to be in the post-frontal area on the leading side of the high; if the center passes south of the location, high fire danger is more likely to be in the pre-frontal area west and north of the center of the high.

Yarnal (1993) extensively analyzed synoptic patterns for the eastern US. He concluded that almost all weather systems affecting this area throughout the year could be divided into eight synoptic patterns. He labeled these patterns as follows:

Rain-Cyclones	Back-of-High
Cold-Frontal-Passage	Pre-High
Extended-Low	High-to-the-North
Extended-High	High-to-the-South

These patterns are shown in Figure 1. Discussion of the weather characteristics accompanying each of these patterns is given in Yarnal (1993). This classification system differs from the scheme of Schroeder et al (1964), for instance, in that Yarnal uses wind speed, wind direction, relative humidity, weather, and other factors as well as the surface weather patterns, whereas Schroeder focuses only on the surface-pressure patterns and upper-air flow fields. Brotak and Reifsnyder (1977) also examined the meteorological patterns accompanying the occurrence of wildland fires, but their analysis was focused on the conditions that transformed small fires into large fires. This focus emphasizes wind conditions that led to spread of fires rather than the series of synoptic conditions that create the environment for fires to begin. More objective computer-based synoptic climatology analyses are possible by use of empirical orthogonal functions, correlation coefficients and other methods (Yarnal, 1993). We chose a more subjective synoptic meteorology pattern approach because it uses realistic patterns that are easily recognized by forest meteorologists. This method also allows us to bridge from observed evaporation and precipitation data to the climate model results without having to use (notoriously poor) representations of precipitation by the climate model.

We classified daily weather maps for five years (NOAA 1979, 1980, 1982, 1983, and 1987) using the Yarnal categories. These years were chosen because for these years we had access to a reasonably complete set of daily weather maps and because the evaporation and precipitation records for four stations in West Virginia for this period do not have major gaps. We forced all maps to fit into one of the eight patterns shown, since only about 3% of the total number of maps were ambiguous.

Yarnal gives plots of the distribution of patterns throughout the year for the Pittsburgh, PA area for the years 1978-87. It would be expected that, on a few days, the dominant pattern would be different for

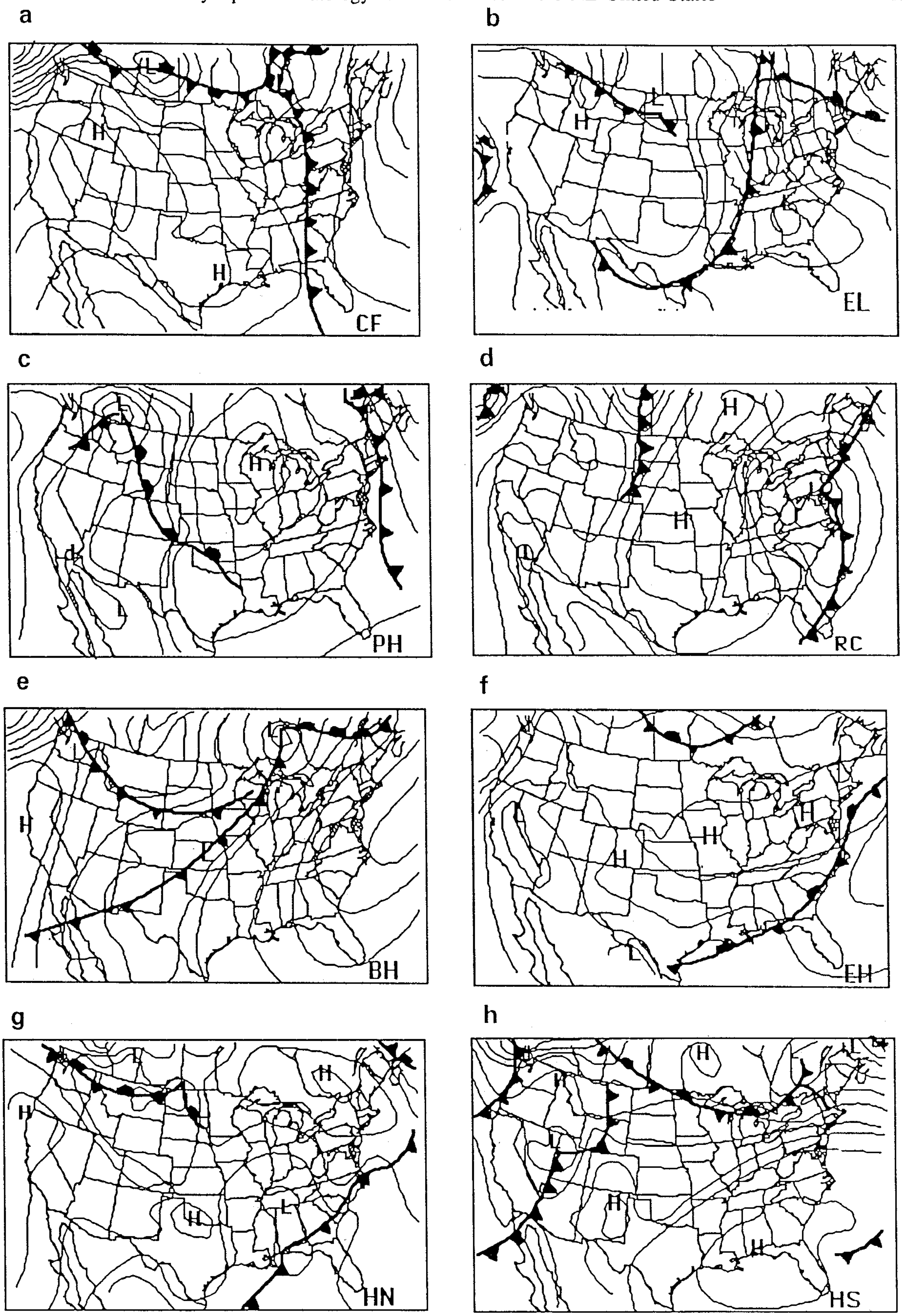

Figure 1. Synoptic meteorology patterns that influence the eastern United States as defined by Yarnal (1993): (a) cold-front, (b) extended-low, (c) pre-high, (d) rain-cyclone, (e) back-of-high, (f) extended-high, (g) high-to the north, and (h) high-to-the-south.

Pittsburgh than for West Virginia. However, our annual distribution of patterns generally agreed with the distributions given for each respective year by Yarnal. Table 1 gives the distribution, in percent of available number of days, of synoptic patterns we found for West Virginia for these five years. Also given is the distribution of patterns Yarnal (1993) reported for ten years of data for Pittsburgh. Our seasonal distribution (not shown) of patterns also is in general agreement with the results of Yarnal.

Relation of Synoptic Patterns to Forest Fires

It is informative to look at the sequence of weather patterns leading up to occurrences of major fires. The PH pattern frequently, although not always, was observed to be a transition pattern to more drier conditions. Several times during the summer of 1987, a PH would become established with a clearing sky, increasing temperature, and decreasing relative humidity. The PH pattern would persist for about a day, in some cases permitting fires to start. However, fires ignited during these conditions were generally small, burning areas of 500 to 2,000 acres.

The PH pattern typically was replaced by an EH pattern, which was accompanied by calm winds, high temperatures, low humidities, and clear skies. This system typically would dominate for about two days. Some EH patterns lingered for as long as five days. This was a common pattern accompanying the onset of large fires with damaged areas between 500 and 4,000 acres, some blackening 15,000 acres.

The largest fires in West Virginia, however, were associated with the next phase (BH) of the movement of the dominating high-pressure system. As the high moved out over the Atlantic Ocean, moist on-shore surface air was orographically lifted, occasionally leading to shower activity on the eastern slopes of the Appalachians. But by the time air parcels arrive in West Virginia, the moisture level was reduced, and a 'chinook' condition developed with one or more of the following conditions existing in West Virginia compared to the eastern side of the mountains: 5°F higher temperature, 5°F lower dew-point temperature, or 5 kt higher windspeed. Not only was the damage area large under these conditions (ranging from 500 to 10,000 acres), but there was a higher incidence of multiple fires. In some cases, fire damage exceeded 30,000 acres. The BH system was by far the most destructive pattern found for West Virginia in 1987.

To increase the number of fire events for comparison with daily weather maps, we also examined the distribution of fire-damaged areas for the four-state region of West Virginia, Ohio, Pennsylvania, and New York over the period for which we have fire-damage data (1971-84 and 1987-90). The synoptic climatology was re-done separately for each state. The results, given in Table 2, add further evidence linking of EH, BH, and PH patterns to major fire damage and the relative absence of fires, particularly large fires, with other patterns. The BH system is comparable to the pre-frontal zone of high fire potential identified by Schroeder et al. (1964) for a high-pressure center passing south of the fire area.

Table 1. Annual distribution (%) of Yarnal classes.

	EH	EL	RC	CF	PH	BH	HS	HN	Missing (%)
1979	18	8	21	11	17	19	3	2	2
1980	25	11	15	10	15	12	7	5	1
1982	22	8	13	10	16	21	5	5	10
1983	25	5	15	8	12	17	11	7	6
1987	34	5	15	13	9	15	3	5	6
MEAN	25	7	16	10	14	17	6	5	5
Yarnal	18	7	24	13	14	16	5	2	1

Evaporation and Precipitation Data

Four stations in West Virginia (Bluestone, Coopers Rock, Kearneysville, and Parsons) report daily pan evaporation and precipitation data during the warm season. The periods of record were not consistent among the four stations in that for some stations in some years, evaporation measurements were reported as early as April whereas for other locations or years measurements started in June. Likewise, the ending date sometimes was in September and sometimes October. For each year studied, we took only the period of record that was common to all four stations and calculated the four-station average for each day. Evaporation measurements can be contaminated by a number of factors and will have a different spatial variability than precipitation measurements. Furthermore, combining daily evaporation values from June with values from October for the same map class surely raises the variance. Despite these acknowledged sources of uncertainty, we have found some consistencies across the data we analyzed. We calculated evaporation minus precipitation (E-P) for each station for 1979, 1980, 1982, 1983, and 1987 for each day of record (676 days were analyzed) and tabulated values for each Yarnal synoptic weather type. The results are shown in Table 3.

Table 2. Number of fire events under various synoptic meteorology patterns for different damage categories (acres) for WV, OH, PA, and NY.

ACRES x 1000	BH	PH	EH	HN	CF	HS	RC	EL
	YARNAL CLASS							
<1	6	5	3	0	2	2	1	0
1-2	5	5	5	1	1	1	0	0
2-5	3	2	2	1	1	0	0	0
5-10	2	2	1	0	0	0	0	0
10-15	2	0	1	0	0	0	0	0
15-20	0	0	1	0	0	0	0	0
>20	3	1	0	0	0	0	0	0

From this table we conclude that:

1) EH and BH patterns consistently lead to drying conditions
2) HN and HS patterns tend to produce drying conditions
3) EL, PH, and CF patterns tend to produce moistening conditions
4) RC patterns consistently lead to moistening conditions.

In decreasing order of drying potential for West Virginia, we rank order the patterns as follows: EH, BH, HN, HS, PH, EL, CF, RC. As previously noted for 1987, PH seemed to be a dry pattern leading the transition to even drier EH and BH patterns. However, this is not always the case, as shown in Table 3, where the PH pattern shows a slight tendency to support moistening conditions.

Global Climate Model Results

Global climate models have been widely used for climate-change impact assessments (Smith and Tirpak, 1989). These studies have used monthly mean values of meteorological variables generated by GCMs as the basis for determining the impact of a doubling of CO_2 on agriculture, forests, sea level, biological diversity, water resources, and electricity demand. Although such studies give a general overall view of impacts of climate change, their use of mean monthly variables, rather than daily means and extremes, may significantly underestimate impacts in some areas such as agriculture. Improved impact assessments are now possible because of the twice-daily values of meteorological variables available from models such as the Canadian Climate Center (CCC) GCM.

The CCC GCM (Canadian Climate Centre, 1990) is a T32L10 model with a transform grid of 3.75° x 3.75° with upgraded physics, including full diurnal and annual cycles. It has a thermodynamic ice model and a slab ocean with transports that permit good simulation of the present ocean-temperature distribution and ice boundaries. Its surface hydrology is an improvement on the standard "bucket" method. The model projects a 3.5°C global warming [which is near the center of the 1.5 to 4.5°C "consensus" range of the Intergovernmental Panel on Climate Change (IPCC, 1992)] and a precipitation increase of 4% (which is drier than most other models) for a doubling of atmospheric carbon dioxide. A description of the second generation of this model (GCMII) and the equilibrium

Table 3. Daily mean values of evaporation minus precipitation (E-P) in units of inches for each Yarnal map classification for five years. Period evaluated each year is given in parentheses. The second line under each year gives the number of occurrences that contributed to the value for each respective category and year.

YEAR	HS	CF	BH	EH	RC	PH	EL	HN
	YARNAL MAP CLASS							
1979 (JUN-SEP)	.18 1	-.10 19	.09 25	.14 24	-.20 25	-.05 15	.03 12	-.11 1
1980 (JUN-OCT)	-.05 14	-.21 21	.13 23	.14 45	-.04 19	.04 11	.04 13	.02 6
1982 (JUN-SEP)	.07 3	-.07 14	.14 16	.13 30	-.24 13	-.01 19	-.04 13	-.05 6
1983 (JUN-OCT)	.03 12	-.05 16	.12 25	.13 56	-.05 11	-.03 15	-.32 4	.01 14
1987 (MAY-SEP)	.21 3	.01 19	.07 23	.15 56	-.13 15	.00 8	-.15 5	.21 6
MEAN TOTAL DAYS	.02 33	-.09 89	.11 112	.14 211	-.14 83	-.01 68	-.04 47	.03 33

climate it produces are given by McFarlane et al (1992), and the greenhouse-gas induced climate changes simulated by the model are given by Boer et al (1992). The North American grid for this model is shown in Figure 2.

We analyzed three years of daily data for each of the $1xCO_2$ and $2xCO_2$ simulations produced by GCMII. Surface-pressure values produced by the model are reduced to sea level by the hydrostatic method used by the National Meteorological Center for the NGM and Eta models (Russ Treadon, private communication). Sea-level pressure maps were plotted for the 12 UTC (5 AM EST) model data, since this time was reasonably close to the times of the daily weather maps (6 AM EST). Fronts were not analyzed on the maps from the climate model, so the CF designation was assigned to events having a pressure trough with northwest winds to the west and southwest winds to the east of West Virginia.

Model sea-level pressure maps resemble observed surface maps except for an anomalous and persistent high-pressure value at one grid point in the Gulf of Mexico and one in the Atlantic Ocean. These values were excised and replaced by the mean of their four nearest neighbors to eliminate distortion of the isobars. A sample sea-level pressure map is shown in Figure 3. Results of our preliminary analysis of three years (except for three days that were lost in data transmission) of the model data for $1xCO_2$ and $2xCO_2$ are shown in Table 4.

Although the maps derived from the climate model look similar to daily weather maps, fronts are not plotted and details characteristic of the daily weather maps are missing, so there may be some human bias in assigning a Yarnal pattern to each map. This could be particularly problematic for EL and CF patterns. For this reason, even though we make qualitative comparisons, we caution against making definitive statements on the comparisons between the model results and the observed maps. Comparison between model results for $1xCO_2$ and $2xCO_2$ minimizes this bias, however, and provides some interesting observations.

Compared to the observed patterns, the CCC model for $1xCO_2$ produces too many HS, too few CF and EH, with about the right number of HN, BH, RC, PH, and EL. In the model, high-pressure systems to the west of the West Virginia area slide south and southeast too frequently and too infrequently move to the northeast or elongate on a NE-SW axis over the Ohio valley. Comparison of these biases with the evaporation potential of each category shows some tendency for off-

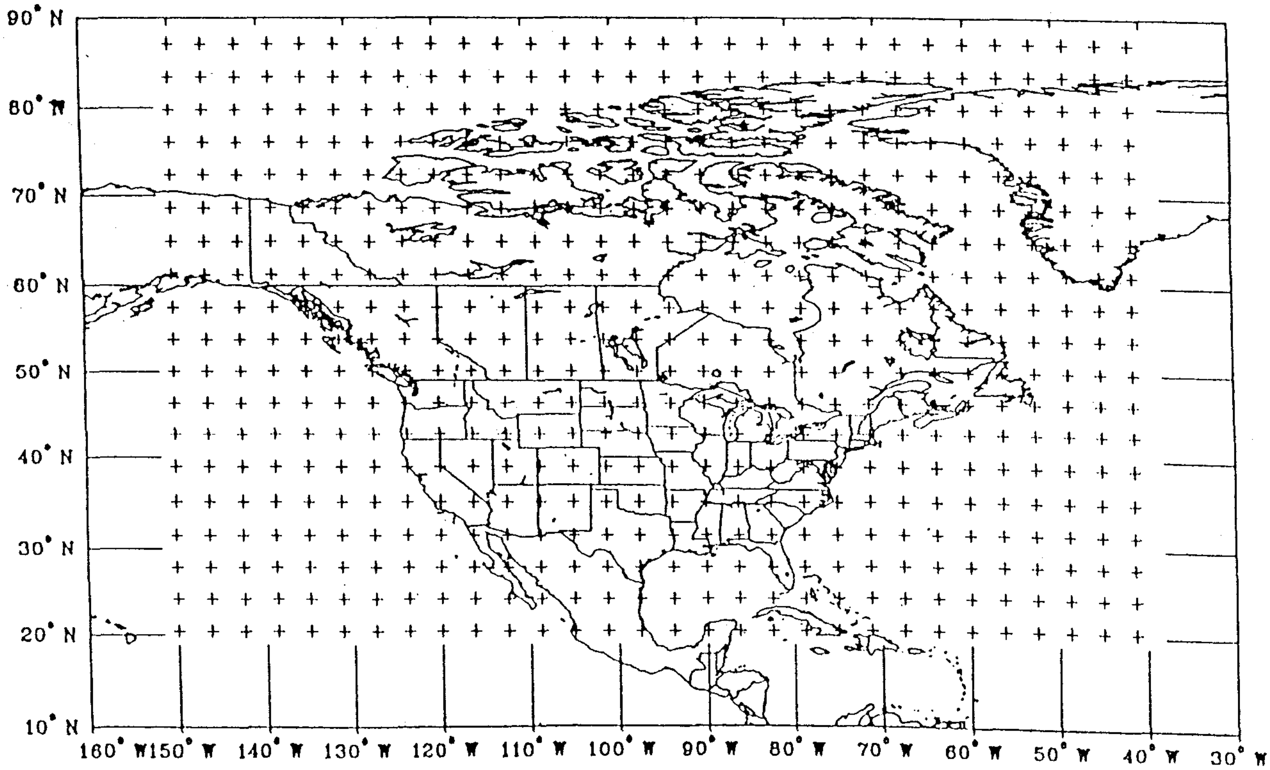

Figure 2. Grid used for the Canadian Climate Centre Global Circulation Model.

Table 4. Annual distribution (%, within roundoff error) of Yarnal classes from observed data and a global climate model for West Virginia.

	Drying				Moistening				
	EH	BH	HN	HS	RC	CF	EL	PH	Missing
					Observed				
5-yr	25	17	5	6	16	10	7	14	5
					Climate Model 1XCO2				
YR 01	8	22	2	20	20	7	11	10	0
YR 02	17	14	3	17	19	1	7	21	1
YR 03	7	24	4	27	12	3	10	14	0
3-yr Mean	11	20	3	21	17	4	9	15	0
					Climate Model 2XCO2				
YR 01	8	22	3	24	19	7	9	8	0
YR 02	7	28	2	34	12	2	3	12	0
YR 03	8	19	8	26	11	6	8	14	0
3-yr Mean	8	23	4	28	14	5	7	11	0

setting effects within generally drying or generally moistening patterns.

The model results for $2xCO_2$ (Table 4) show decreased occurrences of EH, EL, RC, and PH, but increased occurrence of BH and HS. These data also show some degree of compensation, but a general increase in the evaporation potential. If we qualitatively consider EH, BH, HN, and HS to be drying patterns and RC, CF, EL, and PH to be moistening patterns, then the results of Table 5 show that the observed data have about equal divisions of drying and moistening patterns and that the $1xCO_2$ results have

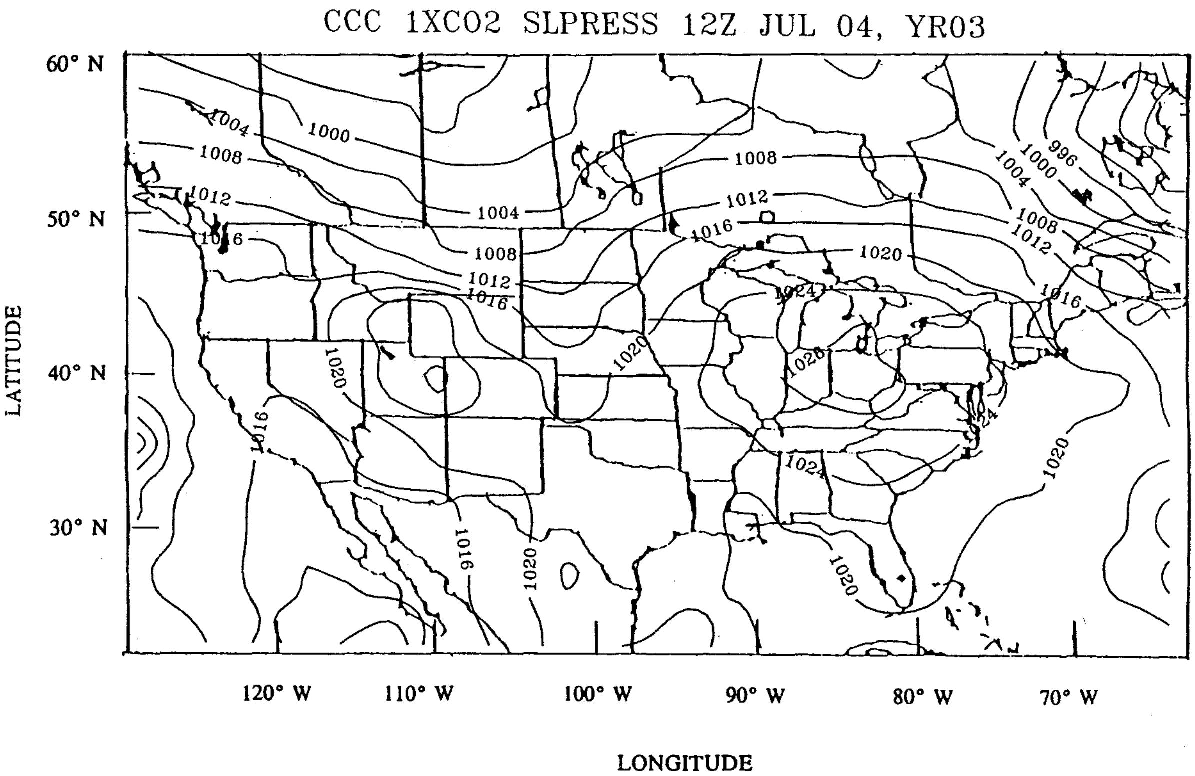

Figure 3. Typical sea-level pressure map produced from the CCC model surface pressure fields.

Table 5. Comparison of drying patterns and moistening patterns (% of available days) for the daily weather maps (DWM), $1xCO_2$ simulation, and $2xCO_2$ simulation of the CCC model.

Map Pattern		DWM	$1xCO_2$	$2xCO_2$
Drying:	EH+BH+HN+HS	53	55	63
Moistening:	RC+CF+EL+PH	47	45	37

essentially the same distribution. The $2xCO_2$ results show a higher tendency for drier conditions compared to the $1xCO_2$ results, but when the results are subjected to a Tukey test for significance, the difference was not significant at the 95% level.

Summary

Analysis of surface daily weather maps for West Virginia indicate that map patterns defined by Yarnal (1993) as EH, BH, and PH are the most frequently occurring patterns that accompany forest fires in West Virginia and the nearby four-state region. Of these, BH accounted for the most fire-related damage. A tabulation of daily evaporation and precipitation by map pattern for the warm season for four stations in West Virginia revealed that EH, BH, HN, and HS patterns are associated with drying conditions, and RC, CF, EL, and PH patterns are associated with moistening conditions.

Analysis of results from a global climate model show that the model produces too many HS patterns and too few CF and EH patterns. High-pressure systems west of West Virginia tend to slide too far to the south and east and too rarely move north of West Virginia. Movement of these high-pressure systems is very important for fire-weather potential in the NE US, so inability of the GCM to capture this movement may limit its usefulness for projecting impacts of doubling CO_2. Nevertheless, we have analyzed data for three years from the global model output for $1xCO_2$ and $2xCO_2$, and we find that doubling CO_2 gives a tendency for an increase in drying patterns and a decrease in moistening patterns. Additional data from the climate model are needed to compare the interannual variability of the model with observed data and to increase the sample size for testing statistical significance.

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References

Brotak, E. A., and W. E. Reifsnyder, 1977: An investigation of the synoptic situations associated with major wildland fires. Journal of Applied Meteorology, 16, 867-870.

Boer, G. J., N. A. McFarlane and M. Lazare. 1992. Greenhouse gas-induced climate change simulated with the CCC second-generation general circulation model. Journal of Climate, 5, 1045-1077.

Canadian Climate Centre. 1990. Application of the Canadian Climate Centre General Circulation Model output for regional climate impact studies - Guideline for users. Atmospheric Environment Centre, Downsview, Ontario, Canada. 24 pp.

Clark, James S. 1990. Fire and climate change during the last 750 yr in northwestern Minnesota. Ecological Monographs, 60, 135-159.

Intergovernmental Panel on Climate Change (IPCC). 1992. Climate change 1992: The supplement report to the IPCC Scientific Assessment. J. T. Houghton, B. A. Callander, and S. K. Varney, Editors. Cambridge University Press, Cambridge, UK. 200 pp.

Meyer, G. A., S. G. Wells, R. C. Balling, Jr., and A. J. T. Jull. 1992. Response of alluvial systems to fire and climate change in Yellowstone National Park. Nature, 357, 147-150.

McFarlane, N. A., G. J. Boer, J.-P. Blanchet and M. Lazare. 1992. The Canadian Climate Centre second-generation general circulation model and its equilibrium climate. Journal of Climate, 5, 1013-1044.

National Oceanic and Atmospheric Administration. 1979, 1980, 1982, 1983, and 1987: Daily Weather Maps, Weekly Series. Climate Analysis Center. Washington DC.

Price, C., and D. Rind. 1993. Lightning and forest fires in a changing climate. In The World at Risk: Natural Hazards and Climate Change, Rafael Bras, Editor. AIP Conference Proceedings 277. American Institute of Physics. 352 pp.

Schroeder, M. J., M. Glovinsky, V. F. Hendricks, F. C. Hood, M. K. Hull, H. L. Jacobson, R. Kirkpatrick, D. W. Krueger, L. P. Mallory, A. G. Oertel, R. H. Reese, L. A. Sergius, and C. E. Syverson. 1964. Synoptic Weather Types Associated with Critical Fire Weather. Pacific Southwest Forest and Range Experiment Station, Berkeley CA. 281 pp.

Simard, A. J., D. A. Haines, and W. A. Main. 1985. Relations between El Nino/Southern Oscillation anomalies and wildfire activity in the United States. Agricultural and Forest Meteorology, 36, 93-104.

Simard, A. J. nd J. E. Eenigenburg. 1990. METAFIRE: A system to support high-level fire management decisions. Fire Management Notes, 51, 10-17.

Smith, J. B., and D. A. Tirpak (editors). 1989. The Potential Effects of Global Climate Change on the United States, US Environmental Protection Agency, Washington, DC.

Swetnam, Thomas W. 1993. Fire history and climate change in giant Sequoia groves. Science, 262, 885-889.

Yarnal, B. 1993. Synoptic Climatology in Environmental Analysis: A Primer. Belhaven Press. London. 195 pp.