5.10 CLUSTER ANALYSIS OF METEOROLOGICAL STATES TO UNDERSTAND THE WEEKDAY-WEEKEND OZONE RESPONSE IN THE SAN FRANCISCO, CA BAY AREA

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1. INTRODUCTION

This study examines the response of ozone to different emissions inventories occurring on the weekdays and weekends using historical data for the San Francisco, CA Bay Area from the years 1996 to 2003. Because of the strong influence of meteorological factors on the buildup of ozone in urban areas, it is not possible to directly determine the weekend response to ozone by statistical comparison of weekday and weekend ozone levels. First, as recommended by the Environmental Protection Agency (EPA, 1996), meteorological regimes conducive to ozone episodes can be identified from historical wind field data. Then, the ozone levels achieved at various geographical locations can be compared between weekday and weekend days assigned to the same meteorological category.

Clustering algorithms are a class of data-driven methods that allow the statistical identification of similar groups of observations from historical data. In the context of air quality meteorology, they can be used to determine groups of days with similar physical characteristics. The clustering algorithm presented in Beaver and Palazoglu (2005) is used to group days having similar ground-level mesoscale flow patterns. These patterns are taken as surrogates for the prevailing meteorological state. By comparing achieved ozone levels between weekday and weekend days having similar prevailing meteorological conditions, the response of ozone to different emissions inventories can be observed from field data.

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2. STUDY DOMAIN AND DATA

The San Francisco, CA Bay Area (Figure 1) is a densely populated urban area. Mobile internal combustion engines are the largest anthropogenic source of ozone precursors, especially NO_x species. Weekday–weekend traffic patterns cause significant differences in the emissions inventories between weekday and weekend days. As biogenic emissions account for over 40% of the total Bay Area VOC emissions, vehicular NO_x emissions play the dominant role in determining the VOC to NO_x concentration ratio (hence referred to as VOC/NO_x). See Tonnesen and Dennis (2000) for a discussion of ozone sensitivity to precursor emissions and its relation to VOC/NO_x.

Weekdays typically exhibit a strong spike in emissions from 5 to 8 AM local time due to massive amounts of emissions generated during the morning rush hour. High NO_x levels during these hours may push VOC/NO_x down toward the NO_x rich regime (generally taken as VOC/$NO_x < 6$) where radical scavenging limits weekday morning ozone production. These early morning emissions may be subject to dilution and advection from the ground level before the strong, afternoon sunlight is available to generate ozone via NO_2 photolysis. Afternoons may reach the NO_x limited regime (VOC/$NO_x >$ 9), as much of the NO_x from the morning rush hour has been transported and reacted away by this time.

Overall, weekday anthropogenic emissions far exceed that of the weekends. Weekends exhibit much lower NO_x concentrations than weekdays during the early morning hours. Weekend NO_x levels peak from 10 AM until noon, and achieved NO_x concentration maxima are considerably lower than for weekdays. Continued traffic throughout the day produces fresh NO_x during these hours as well. As such, weekend morning hours have moderate VOC/NO_x and are not as prone to radical scavenging as weekdays. Also, the fresh weekend afternoon NO_x (emitted during the period of most intense solar activity) may contribute to local afternoon ozone formation.

The topography of the Bay Area (see Figure 1) has an important influence on the mesoscale flow patterns that affect the transport and dilution of ozone and its precursors. On many summer days, a strong, westerly marine layer flow arrives from the Pacific, advects through the mouth of the Bay, and penetrates into the Central Valley. Sites nearest the mouth of the Bay are generally well ventilated and rarely experience exceedances of the National Ambient Air Quality Standard (NAAQS) for ozone. Stagnant conditions can develop, especially at the more inland locations, when either the marine flow is blocked from reaching the Central Valley or the marine flow arriving from over the Pacific Ocean is weak to begin with. Days with more stagnant conditions are susceptible to higher ozone levels, and the levels on the hottest of these days can violate the NAAQS.

Two monitoring networks operated by the Bay Area Air Quality Management District (BAAQMD) provide hourly historical data for the region. An air quality monitoring network measures compositions for ozone at 22 locations and oxides of nitrogen at a subset of 13 of these stations as well. A separate meteorological monitoring network of 12 stations provides a representative sampling of wind speed, wind direction, and temperature for the Bay Area. The geographic locations for these stations are shown in Figure 1. The legend in the bottom left corner of this figure indicates subregion classifications for the stations. Hourly data was obtained for the dates 1 June through 30 September of the years 1996 to 2003.

3. METHODS

Because of the large dependence of ozone production and buildup processes on meteorological factors, it is not feasible to directly compare observed pollutant compositions for days with vastly different atmospheric conditions. As recommended by the EPA (EPA, 1996), the wind field is the most important consideration, as it affects the transport and dilution of ozone and precursors. The ground-level wind field is largely determined by the prevailing meteorology and offers a means by which the mesoscale state of the mixed layer can be characterized quantitatively. Once meteorological categories are delineated, it will be possible to directly compare the effects of changing emissions on daily maximum ozone composition.

The study described in Beaver and Palazoglu (2005) identifies four dominant, recurring wind field patterns for the Bay Area using a nonhierarchical clustering algorithm based on the Dynamic Principal Components Analysis statistical model (Ku, Storer, and Georgakis, 1995). The clustering algorithm is designed to identify synoptic scale patterns from a spatial field of time series measurements exhibiting a pronounced diurnal cycle. Days of the observation period are then assigned to these four classes, as indicated in Figure 2 showing the results of Beaver and Palazoglu (2005). The time series for cluster membership indicates the evolution of the atmospheric system through a sequence of persistent states in which the clusters are realized for multiple consecutive days. A small fraction of days cannot be assigned with confidence to any cluster, while other transition days are assigned to two clusters. The four clusters respectively comprise 353, 309, 341, and 86 days of the 976 days in the observation period.

Only two of the four clusters represent meteorological conditions conducive to NAAQS exceedances for 8-hr ozone. Clusters #2 and #3 have 2 and 1 exceedances, respectively, and in general have acceptable air quality. Of the 57 Bay Area 8-hr NAAQS exceedances occurring in the observation period, 47 episodes are assigned to cluster #1 while 11 are assigned to #4. (There are several episodes occurring on transition days assigned to both clusters #1 and #4.) Note that meteorological state #4 occurs only about a fourth as frequently as the other clusters, and thereby contains a significant proportion of episode days and is considered conducive to ozone buildup although it has a much smaller number of exceedances than #1. As the large majority of NAAQS ozone exceedances occur in either cluster #1 or #4, these meteorological states represent necessary but insufficient conditions for producing elevated ozone levels. Within these meteorological states, the variability of daily maximum ozone levels can be explained by the weekend effect (as discussed below) and temperature.

Clusters #2 and #3 represent a well-ventilated Bay Area due to a strong, shoreward flow of clean, marine air which prevents ozone from accumulating to harmful levels. Clusters #1 and #4, on the other hand, capture two different mechanisms under which stagnant conditions develop in the Bay Area. Cluster #1 is associated with a strong high pressure center over the Central Valley which blocks the flow of marine air through the Bay Area. This weather pattern is prevalent during the late summer months of August and September, is less active in July, and rarely appears in June. Cluster #4 occurs much less frequently than the other clusters and captures the presence of various offshore weather systems which disrupt the typically strong shoreward marine flow. Cluster #4 appears to have a more shallow mixed layer than the other clusters, as observed precursor levels are considerably higher for this cluster. This weather pattern occurs most frequently in September, occasionally in June, and almost never is realized during the middle summer months. See Beaver and Palazoglu (2005) for a more complete description of the meteorological regimes.

The emissions characteristics of the Bay Area are largely determined by automobile use. Weekdays (Monday – Friday) tend to exhibit similar emissions characteristics as rush hour traffic patterns and commercial transportation contribute to the bulk of driving. The bulk of ozone-producing NO_x emissions are concentrated in the early morning hours, producing a spike in observed NO_x composition. Weekends have significantly reduced total NO_x emissions relative to the weekdays. Also, the weekend emissions of NO_x tend to be spread more evenly throughout the day than the weekdays.

Within a given meteorological regime, the effect of these changing NO_x emissions from the weekdays to the weekends can be gauged simply by comparing the achieved daily maximum 1-hr ozone compositions for weekdays to that of the weekend days. The holidays of Independence Day and Labor Day and their included holiday weekends (e.g. Saturday through Monday for a Monday holiday) are generally associated with increased travel by automobile, and are examined as a third class of days aside from the non-holiday weekends and weekdays. While previous comments were made regarding NAAQS exceedances for 8-hr ozone, the weekday-weekend response of ozone is gauged in terms of achieved 1-hr averaged ozone composition. For clusters #1 and #4 only, the average daily maximum 1-hr ozone composition is calculated for the non-holiday weekdays, non-holiday weekends, and the holidays (including both weekdays and weekends). The results are shown in Figure 3. As there is only a single holiday belonging to the infrequent meteorological class #4, these results are not shown.

The weekdays and weekends produce significantly different levels of ozone concentration in different regions of the study domain. For both clusters, the weekends tend to have higher ozone levels than the weekdays. For cluster #1, this effect is observed only in the Livermore Valley and South Bay stations where ozone composition is about 9 ppb higher on the weekends. (See legend in Figure 1 for subregion classification of the monitoring stations.) For cluster #4, however, the weekends exhibit much more widespread and severe ozone levels than the weekdays. The largest increase in ozone levels from the weekdays to the weekends occurs in the South Bay near the San Jose metropolitan area, where ozone levels are about 16 ppb higher. Cluster #4 additionally has weekend ozone levels about 14 ppb higher in the Extreme South Bay, 10 ppb higher in the Livermore Valley, and 7 ppb higher in the East Bay. Weekend ozone levels are also over 10 ppb higher in the metropolitan areas of San Francisco and Oakland, however ozone concentrations remain well below the exceedance level for this ventilated region nearest the mouth of the Bay.

For cluster #1, the holidays exhibit ozone levels several ppb higher than the weekends throughout the Bay Area. There are insufficient holidays assigned to #4 to determine the nature of the holiday effect for this cluster as well.

4. DISCUSSION

After minimizing the effects of the meteorological state on the ozone production system, it is possible to gauge the effects of changes in the emissions inventory using data obtained from field measurements. The most obvious comparisons can be made between the weekdays and weekends assigned to the same meteorological class. Here, comparisons are only made for the stagnant clusters #1 and #4, which are conducive to elevated ozone levels. In general, precursor concentrations are highest for #4 due to the reduced mixed layer height, resulting in higher observed ozone concentrations than #1. Clusters #2 and #3 are more ventilated and in general have lower precursor concentrations and are therefore not as sensitive to emissions characteristics as the episode prone clusters.

For both clusters #1 and #4, ozone levels are significantly higher on the weekends than the weekdays. For cluster #1, this effect is prevalent throughout the heavily populated South Bay region containing San Jose and its suburbs. Weekday and weekend emissions inventories are considerably different for this urban area due to intense automobile use. Cluster #1 also has a significant weekend effect in the Livermore Valley. This inland valley is less densely populated than much of the Bay Area and ozone buildup processes are often dominated by meteorological conditions affecting local transport. After isolating the days assigned to cluster #1, exhibiting stagnant afternoon meteorological conditions in the Livermore Valley, the weekend effect can clearly be observed for this region.

Cluster #4 exhibits elevated weekend ozone levels in all regions of the study domain. One reason for the much elevated weekend ozone levels for cluster #4 over #1 is the very shallow boundary layer for #4. Because of the reduced volume of mixed air, the same change in emissions from the weekdays to the weekends has a significantly pronounced effect in #4. The same physical mechanism appears responsible for producing the weekend effect observed under both meteorological regimes, however the response of ozone levels to the changing NO_x emissions is stronger for cluster #4 than #1.

Elevated weekend ozone levels are caused by weekday-weekend differences in the diurnal cycle for NO_x emissions. Under stagnant meteorological conditions, weekday mornings become NO_x saturated due to the morning rush hour. Stagnant weekend mornings exhibit more moderate VOC/NO_x than weekday mornings, indicating a regime in which ozone production is not limited by radical scavenging. Also, as weekdays have the bulk of NO_x emissions occurring during the early morning hours, NO_x species are consumed and/or transported from their source or origin such that afternoon NO_x concentrations are low and the photochemistry becomes NO_x limited as the day progresses. Weekend afternoon VOC/NO_x generally favors a NO_x limited regime as well, however fresh NO_x emitted throughout the weekend days results in higher afternoon ozone production rates than for weekdays. It is unclear how the magnitude of each effect contributes to the overall observed weekend ozone response.

The highest ozone levels are observed in the Livermore Valley for the holidays falling in meteorological category #1. In general, the holidays of cluster #1 have higher ozone levels throughout the study region than for the weekdays or weekends of this cluster. Holidays are similar to weekends in their diurnal cycle for vehicular emissions, however more total emissions are generated due to increased holiday travel. Thus, the holidays can be viewed as extreme cases of the weekend effect. There is a significant reduction in total NO_x emissions relative to the weekdays, but holidays have fresh emissions released throughout the day.

Though the most severe ozone levels are observed during the holidays, these days are only a small fraction of the observation period and do not indicate a highly representative set of days for the purposes of air quality planning. It can be noted that the most common type of day with elevated ozone levels occurs for the largest cluster #1 during the weekdays (which by definition occur at a higher frequency than the weekends). This most typical class of days exhibits the least severe ozone levels of either cluster. On the other hand, the most severe ozone levels (aside from the holidays) occur for the infrequent cluster #4 on the weekends. Thus, the most typical conditions for ozone buildup result in moderate ozone levels, while the least typical conditions result in the most severe ozone episodes.

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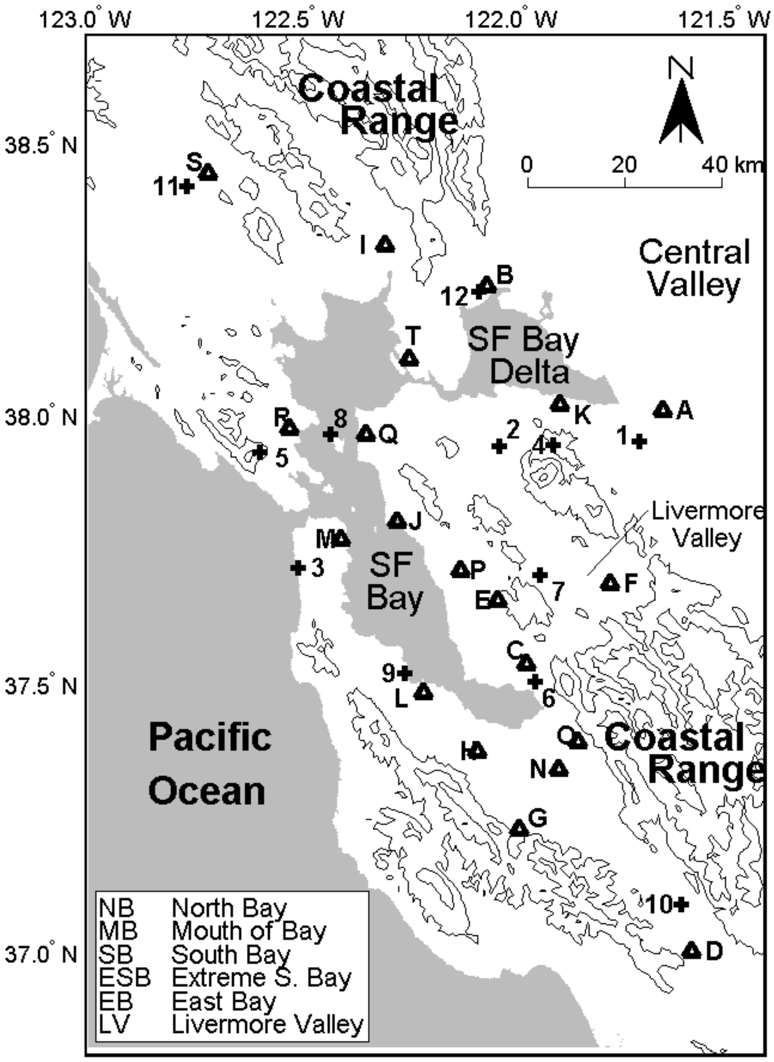

Meteorological Stations (+)

1	Bethel Island	-2 m	EB
2	Concord	24 m	EB
3	Fort Funston	57 m	MB
4	Kregor Peak	577 m	EB
5	Mt. Tamalpais	762 m	MB
6	NUMMI	9 m	SB
7	Pleasanton	99 m	LV
8	Pt. San Pablo	70 m	MB
9	San Carlos	1 m	SB
10	San Martin	85 m	ESB
11	Santa Rosa	29 m	NB
12	Suisun	5 m	EB

Air Quality Stations (Δ or +)

A	Bethel Island*	6 m	EB
2	Concord*	26 m	EB
B	Fairfield	4 m	EB
C	Fremont*	24 m	SB
D	Gilroy	55 m	ESB
E	Hayward	288 m	SB
F	Livermore*	145 m	LV
G	Los Gatos	186 m	SB
H	Mountain View	24 m	SB
I	Napa*	22 m	EB
J	Oakland	7 m	MB
K	Pittsburg*	9 m	EB
L	Redwood City*	9 m	SB
M	San Francisco*	5 m	MB
N	San Jose*	24 m	SB
O	San Jose (East)	63 m	SB
P	San Leandro	36 m	SB
10	San Martin	87 m	ESB
Q	San Pablo*	15 m	MB
R	San Rafael*	11 m	NB
S	Santa Rosa*	49 m	NB
T	Vallejo*	30 m	MB

* Station monitors NO_x

Figure 1: Study region for the cluster analysis showing the locations of meteorological and air quality monitoring stations. Contour lines are at 300, 600 and 900 m. Names and elevations for the stations are given in the legend. Note that the air quality monitoring stations at Concord and San Martin are located in close proximity to corresponding meteorological monitoring stations. These two stations are not shown explicitly but should be referenced under the meteorological monitoring station bearing the same name.

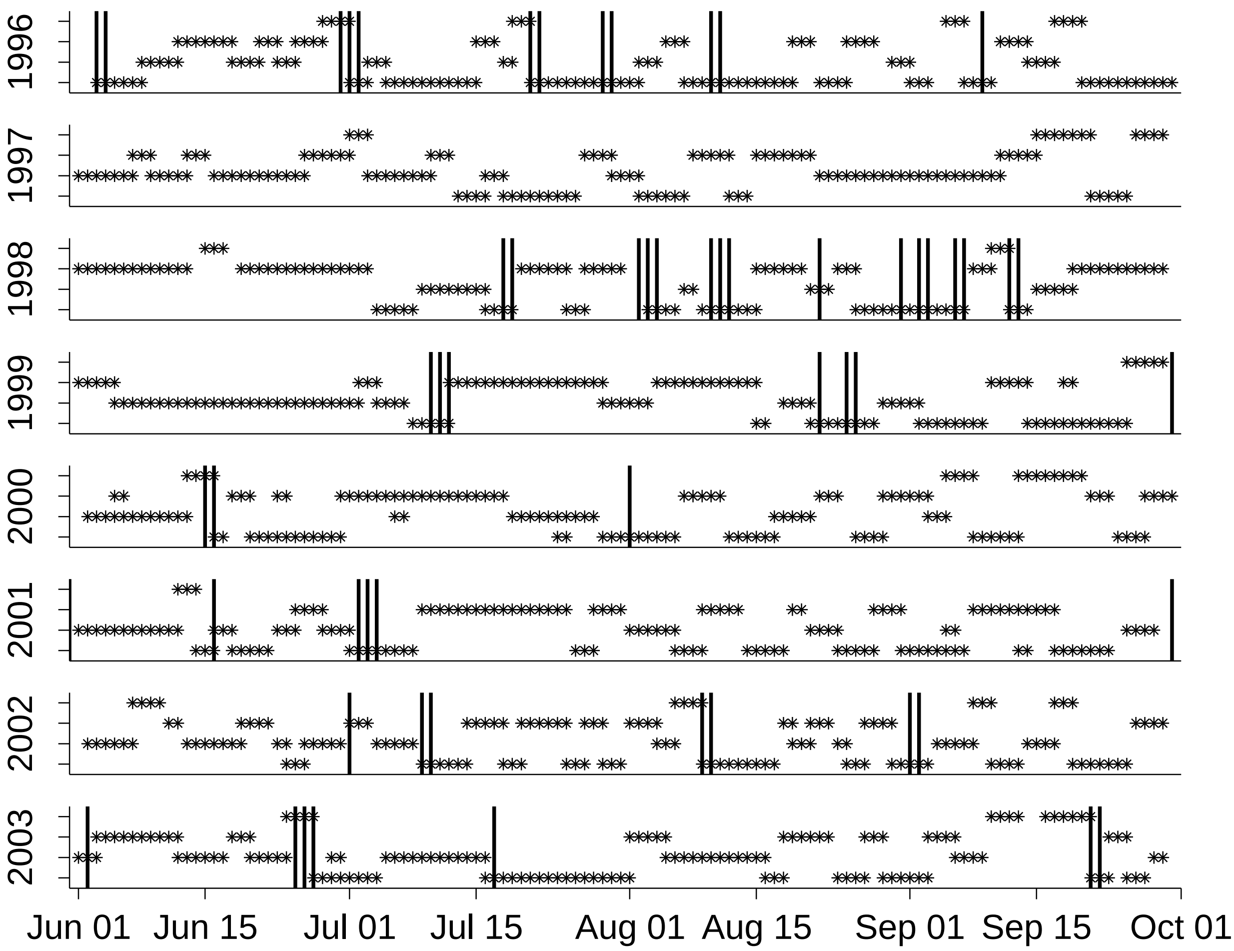

Figure 2: Cluster membership for summer days in 1996 to 2003 observation period. Y-axis position of asterisk indicates cluster membership for each day. Tick marks at 1–4 (from bottom to top) correspond to clusters #1–4, respectively. Vertical lines indicate the days exceeding the NAAQS for 8-hr ozone.

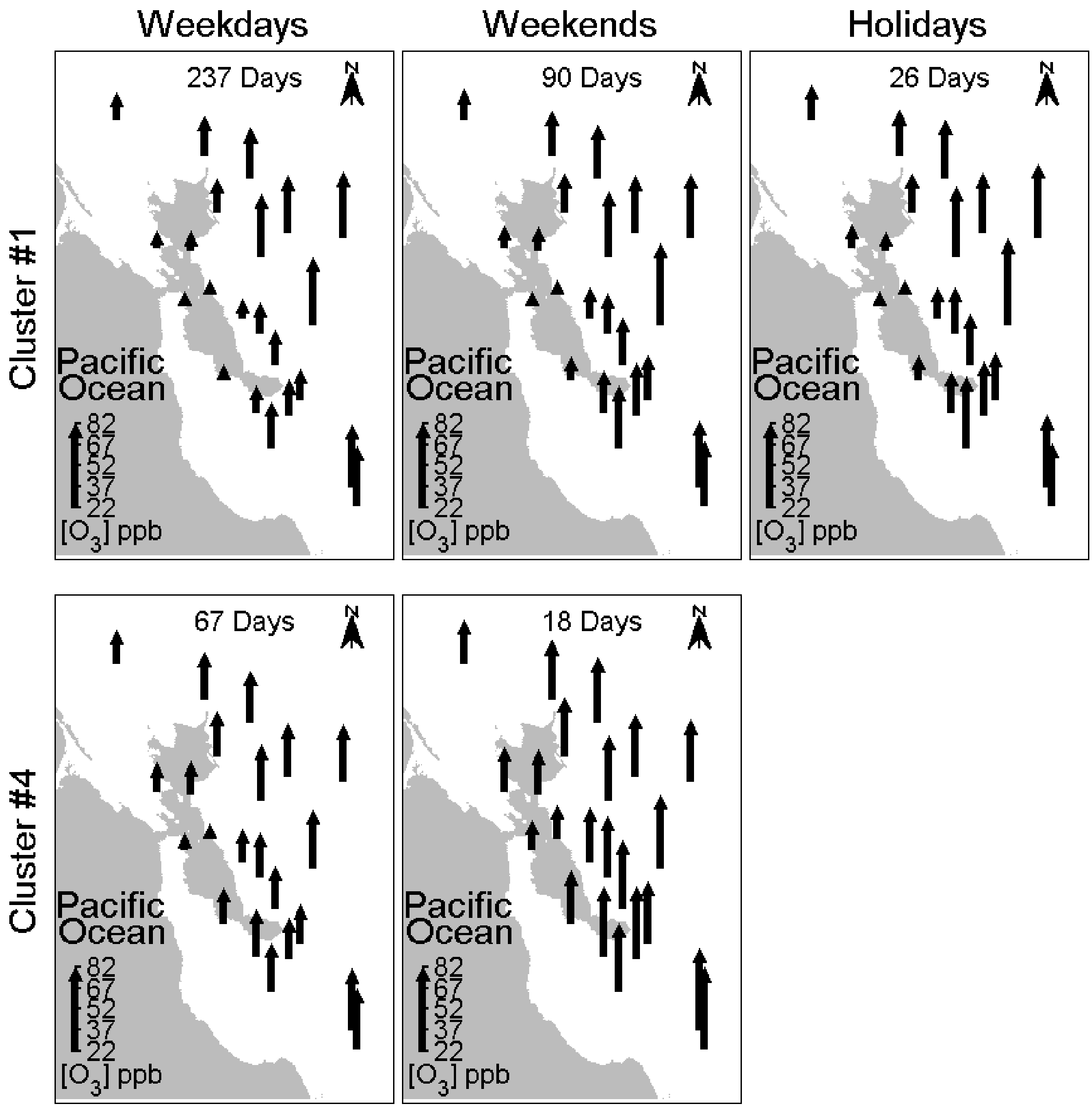

Figure 3: Mean daily maximum 1-hr ozone composition (ppb) at each station for weekdays, weekends, and holidays for two meteorological classes indicated by length of arrow. Sample size for each mean indicated at top of maps.