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Using NDVI to define thermal south in several mountainous landscapes of California

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ABSTRACT

We combined normalized difference vegetation index (NDVI) and digital terrain analysis to detect thermal south (defined in this paper as the warmest slope azimuth, especially for plant growth) in three mountainous landscapes of California. Two methods, respectively, defined topography-controlled thermal south as corresponding to (1) the maximum NDVI contrast between opposite topographic aspects or (2) the maximum covariance between NDVI and deviated southness. Southness was obtained from aspect (slope azimuth in degrees) by taking its negative cosine value. A multi-scale approach using multi-seasonal NDVI images of the three study areas defined that thermal south would vary with seasons, spatial scales, and study areas, but it deviated from 0° to 180° azimuth line towards southwest in all cases. A deviation angle should thereby be applied when aspect is used as a topographic proxy indicating local thermal conditions. However, the angle must be defined in a way specific to the landscape, scale, and season that are under investigation, hence requiring rapid, easy-to-use tools. The two methods, suggested in this paper, reported comparable thermal south and, together with resultant findings, they may contribute to the study of mountain landscapes, since direct meteorological observations are usually sparse or non-existent in mountains.

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1. Introduction

Slope azimuth, or aspect, is often used as a proxy (or part of other simple proxies) to explicitly or implicitly represent local insolation and temperature variability, as it has strong influence on such variability (Geiger, 1965; Rouse and Wilson, 1969). Numerous more complex indices or equations have also been proposed, often in a Geographic Information System (GIS) environment, to map insolation or temperature based on terrain analysis, and aspect is usually a key input variable (Dubayah and Rich, 1995; Lookingbill and Urban, 2003; McCune and Keon, 2002; McKenney et al., 1999; Moore, 1992; Nikolov and Zeller, 1992; Pierce et al., 2005; Wilson and Gallant, 2000). These proxies, indices, and equations—and corresponding uses of aspect—are necessary, because the spatial variability of insolation and temperature is highly heterogeneous in mountains as an effect of topographic differentiation (Geiger, 1965), but its direct observation is usually sparse (Running et al., 1987).

With the absence or shortage of climatic data, many research efforts have been invested to directly examine the role of aspect in differentiating local biophysical environment, especially plant species and composition (e.g. Badano et al., 2005; Dargie, 1984, 1987; Elliott et al., 1999; Holland and Steyn, 1975; Kirkpatrick and Nunez, 1980; Lakhani and Davis, 1982; McCay et al., 1997; McDonald et al., 1996; Perring, 1959). Aspect is also used

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to explain potential evapotranspiration (Shevenell, 1999), plant radial growth (Fekedulegn et al., 2003), historical vegetation change (Bennie et al., 2006), treeline locations and shifting (Dalen and Hofgaard, 2005; Danby and Hik, 2007a), global warming effects on plants (Danby and Hik, 2007b), butterfly phenology (Weiss et al., 1988), soil properties (Kang et al., 2006), rock weathering rates (Hall et al., 2005), and snow accumulation (Goodwin, 1990). The assistance of GIS tools and digital elevation models (DEMs) makes it computationally very convenient to calculate and integrate aspect in environmental analysis (Horn, 1981; Skidmore, 1989).

Most of the above-mentioned uses of aspect have to face a challenge: "…though the southern slopes received more insolation than northern ones, it was the aspect between south and south–west which was the warmest" (Perring, 1959). This phenomenon has been explained by the stronger heating effect of the afternoon insolation as well as factors such as morning fog, evaporation of overnight condensation, etc. (Geiger, 1965; Weiss et al., 1988). A deviation angle may, therefore, exist between the insolation (e.g. geographic) south and the thermal south—the warmest slope azimuth, and this angle should be identified and applied to adjust the calculated aspect values, so that their thermal meanings can be more accurately captured. This is the goal of this paper.

Some researchers have attempted to identify the deviation angle of thermal south from the 0° to 180° azimuth line, mostly targeting better description of vegetation, but there is no agreement regarding either the angle itself or the methodology for the detection of this angle. Lakhani and Davis (1982), for example, compared multiple regression models between species distribution and topography and demonstrated that thermal south was at the aspect of 188° rather than 180°, a conclusion obtained in the undulating, low-relief topography of England with a marine climate. Dargie (1987) argued that the 8° deviation angle of Lakhani and Davis (1982) was too small and 14–19°, depending on the study area and the slope orientation where plant samples were taken, could explain vegetation patterns better. This observation was obtained after a series of ordination analyses in dry hills (annual precipitation <350 mm) of south-eastern Spain, characterizing an arid Mediterranean climate and hilly topography (relief <400 m).

Dargie (1987) further indicated that thermal south for one species could be expanded for local flora, representing an axis of thermal aspect symmetry that deviated from 0° to 180° azimuth line. An underlying assumption supports both these statements and the efforts of identifying thermal south by examining vegetation–aspect relationships. That is: in mountains, the vegetation pattern may be treated as an indicator of local, aspect-driven variability of thermal conditions that helped the formation of the vegetation pattern.

In other studies, thermal deviation was qualitatively evaluated (Kirkpatrick and Nunez, 1980; Perring, 1959; Weiss et al., 1988) or various deviation angles (e.g. 15°, 40°, or 45°) were assigned based on expert knowledge (e.g. Holland and Steyn, 1975; McCune and Keon, 2002; Shevenell, 1999). For example, Elliott et al. (1999) used a deviation angle of 40° to reclassify the aspect in their observation of vegetation–site relationships in a southern Appalachian forest, and McCay et al. (1997) specified the 45–225° line as the thermal axis in a gradient analysis of West Virginia forests. Most of the above studies focused on (stable) vegetation composition and species distribution, correspondingly treating the thermal deviation as an issue of determining an optimal, possibly universal, angle. An even more common way to use the aspect is without applying a deviation angle (e.g. Badano et al., 2005; Bennie et al., 2006; Dalen and Hofgaard, 2005; Hall et al., 2005; Lookingbill and Urban, 2003; McDonald et al., 1996).

A major difficulty in these applications is that while the aspect is a spatially and quantitatively continuous variable that can be easily extracted from DEM-based terrain analysis, it is difficult to collect continuous vegetation data for the analysis of aspect–vegetation relationships, with sufficient spatial resolution and/or extent. The same reason may explain the common practice of categorizing or aggregating aspect in various applications (e.g. Dalen and Hofgaard, 2005; Hall et al., 2005; Kang et al., 2006; Wilkinson and Humphreys, 2006), before linking it to environmental observations, which are often obtained for transects or sampling plots/points and do not provide complete spatial coverage (e.g. Badano et al., 2005; Bennie et al., 2006; Hall et al., 2005; Kang et al., 2006). This situation would inevitably influence the chance of precisely defining a deviation angle for thermal aspect, and it may be improved with the introduction of remote sensing data that have expansive spatial coverage and high spatial resolutions. In this context, this paper introduced seasonal normalized difference vegetation index (NDVI, see Rouse et al., 1973) images of three mountainous areas of southern California to develop methods of defining thermal south and to answer the following question: "Does (or how does) thermal south vary with seasons, landscapes, and spatial scales?"

2. Study area and data

A 160 km^2 (west) section of the Santa Monica Mountains (SMM in Fig. 1 and hereafter), California, was used to test methods of detecting thermal south. The mountains in this area have an east–west trend along the Pacific coast that present an obvious central ridgeline, and are characterized by medium to steep slopes (mean slope is 46% based on 10 m USGS–United States Geological Survey–DEMs, downloaded from the GeoCommunity at http://data.geocomm.com/dem/, last visited March, 2008), as well as a steep elevation transition from 0 to 948 m within short distances (e.g. <5 km). Mediterranean-type climates and landscapes are dominant in this region: most of the annual precipitation is concentrated in November to April with a very dry summer from May to October, when the average monthly temperature is close to, or above, 20 °C (Jackson and Gough, 2001; Loeher, 1983; Raven et al., 1986). The natural vegetation in the mountains is mainly chaparral of various types (69.5% of

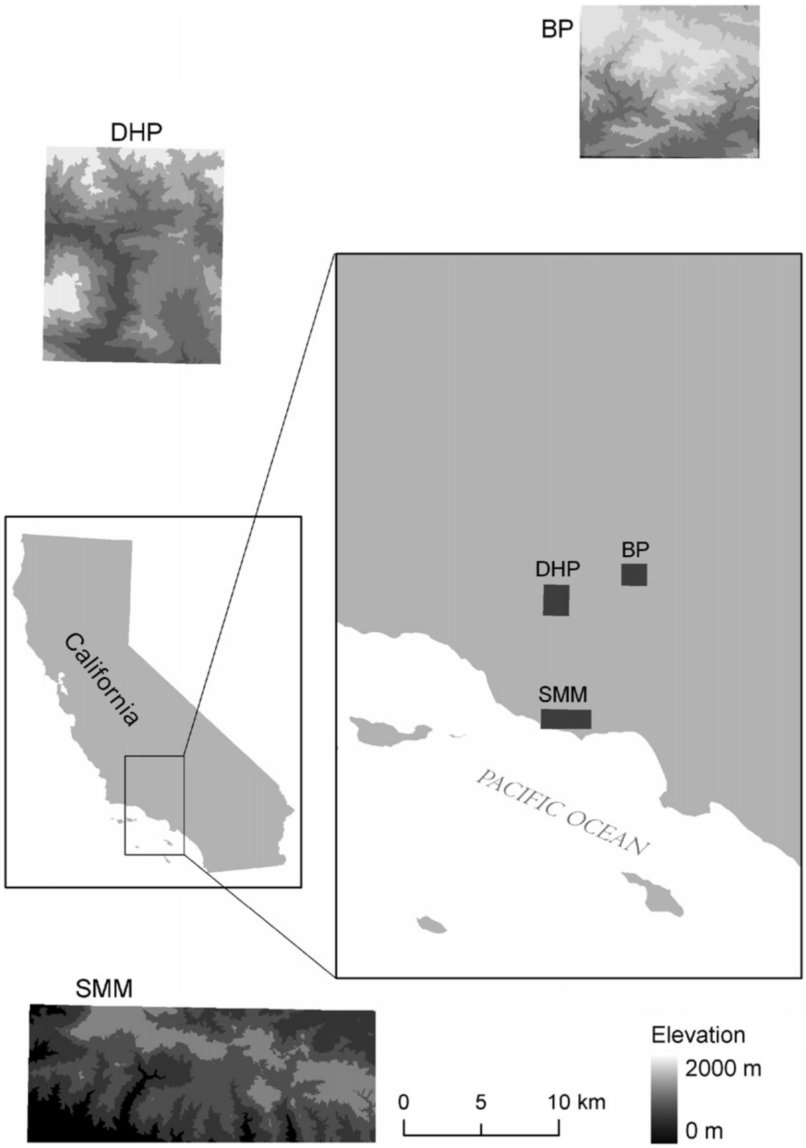


Fig. 1. Locations and DEMs of three study areas. They include Santa Monica Mountains (SMM), Burnt Peak Quadrangle (BP), and Devils Heart Peak Quadrangle (DHP).

the natural landscape) and coastal (short) sage scrub (19.2%), intermingled with occasional grasslands, oak woodlands, and riparian woodlands (11.3%) in flatter places such as valley bottoms (according to the Multi-source Land Cover Data of California Spatial Information Library, see http://gis.ca.gov/meta.epl?oid=5291, last visited March, 2008).

SMM was then compared with two USGS quadrangles of California—the Devils Heart Peak Quadrangle (DHP) of the Ventura County and the mountainous part of the Burnt Peak Quadrangle (BP) of the Los Angeles County (Fig. 1)—to evaluate whether (and how) thermal south would vary with landscapes. The two quadrangles are located about 50–70 km north (inland) of SMM and are also characterized by a Mediterranean-type climate and landscape, dominantly covered with mixed chaparral (>60%, according to California Spatial Information Library). The topography is steep (slope gradient 47–57%) with an elevation range of 396–2000 m.

Urban development has sprawled to mountain rims and even interiors, even though the landscape is generally well preserved in the three study areas, especially in comparison with the eastern and central sections of SMM where urban development has been substantial. The urban and agricultural areas were masked out from the analysis based on the 100 m resolution Multi-source Land Cover Data (2002 v1) of California Spatial Information Library (see http://gis.ca.gov/meta.epl?oid=5291, last visited March, 2008) to highlight topography. Flat areas were also masked out using a slope threshold of 10° (based on the 10 m USGS DEM), since the thermal differentiation induced by aspect is minimal in gentle-slope locations.

USGS 10 m DEMs downloaded from the GeoCommunity (see http://data.geocomm.com/dem/, last visited March, 2008) were used as the source data of all three study areas for multi-scale aspect calculations. Three 30 m NDVI layers of the study areas, of 1st May, 20th July, and 17th September 2000, respectively, were used. They were retrieved from Landsat Enhanced Thematic Mapper Plus (ETM+) cloud-free images of the corresponding dates using scaled band 4 (NIR, 0.76–0.90 μm) and 3 (red, 0.63–0.69 μm) reflectances. The radiance conversion was performed using the coefficients from the header files accompanying the ETM+ data (Markham et al., 1997). A simple topographic illumination normalization method, cosine correction (Teillet et al., 1982), was applied to the derived radiance data. The atmospheric path radiance was estimated from dark objects (e.g. deep water), and the atmospheric transmissivity was regarded as a function of cosine zenith angle (Chavez, 1996). Reflectance retrieval was carried out following the procedure proposed by Chuvieco et al. (2002). NDVI is closely linked to chlorophyll activity and leaf area index (Rouse et al., 1973; Tucker, 1979), hence it is a widely used indicator of vegetation greenness. The three dates represent three seasons in the Mediterranean-type climate of southern California: 1 May is in the later spring signifying the end of the wet, plant-growing season, 20th July is in the dry mid-summer—the midst of vegetation senescence, and 17th September is near the end of the summer, when vegetation senescence has nearly completed (Loeher, 1983; Raven et al., 1986). These three layers were used separately to help identify thermal south, the result of which may indicate whether thermal south shifted between these seasons.

3. Methods

3.1. Transformation and deviation of aspect

Aspect has a circular value ranging clockwise from 0°/360° (north), 90° (east), 180° (south), 270° (west), and back to 0°/360° (Horn, 1981). The negative cosine of aspect, termed "southness" in this paper, reaches the maximum ($=1$) at south, 0 at east/west, and minimum ($=-1$) at north, and is, therefore, a good indicator of topographic south- or north-facing (but not east- or west-facing). When thermal south does not correspond to the 0–180° azimuth line, southness needs to be adjusted by applying a deviation angle d to all aspect values, so as to be a better indicator of the thermal condition variability.

3.2. NDVI-southness association and methods of detecting thermal south

To examine the relationship between aspect and NDVI, NDVI contrasts between opposite aspects were evaluated using an average percentage difference: subtracting south-facing cell NDVI from north-facing-cell NDVI and then dividing the result with the mean NDVI of both aspects. This method was tested in SMM. To observe the general trend of NDVI change with aspect, NDVI values were averaged within aspect groups of 5°, and NDVI of each aspect group was compared with NDVI of the opposite group, starting from the 1° aspect. 72 aspect groups were compared, forming 36 comparison pairs from aspect 1° to 360°. For a more precise evaluation of NDVI variation, a degree-by-degree comparison was also conducted in an aspect range 170–225°. NDVI differences of opposite aspects were then plotted against the turning azimuth line and a trendline was fitted to observe the general trend of change. Thermal south was identified as the one corresponding to the largest NDVI difference between the opposite aspects (or groups of aspects).

The rationale of using NDVI to detect thermal south is that thermal south corresponds to the poorest (e.g. warmest and driest) aspect conditions for plant growth in the Mediterranean-type landscape, poorer than the geographic south. As a result, the lowest NDVI values, on average, should be observed along the thermal south when other vegetation formation conditions are the same; and vice versa for thermal and geographic north.

The above rationale is consistent with the observations of Perring (1959) and Dargie (1987), and it supports another method suggested in this paper: detecting thermal south using NDVI-southness covariance. Particularly, NDVI-southness covariance was compared after adjusting southness with various deviation angles d, to identify the thermal north–south line as the one corresponding to the maximum absolute covariance (Blalock, 1972, pp. 372–378) between deviated southness and NDVI. The objective of this method is thereby to identify d that can maximize the absolute value of COV_d in the following equation:

$$COV_d = \frac{\sum_{i=1}^{N}\{(NDVI_i - \mu_{NDVI})[-\cos(\alpha_i + d) - \mu_{-\cos(\alpha+d)}]\}}{N-1} \tag{1}$$

where N is the number of samples (cells) used in the analysis, μ denotes mean, and α is aspect. To identify d that corresponds to thermal south, various negative d values (which turns thermal south to geographic southwest) were tested by subtracting 1–45° (or 55°, with a 1° interval) from the aspect when calculating southness, as well as positive d values by adding 1–15°. In this way, thermal south was detected within an aspect range of 165–225° (or 235°).

Hence, two methods were used in detecting thermal south, evaluating NDVI difference directly and evaluating NDVI-southness covariance. The two methods were compared in SMM, and the covariance method was used (1) at various spatial scales, (2) for NDVI of different seasons, and (3) in all three study areas to identify whether and how thermal south may shift with scale, season, and landscape.

3.3. Multi-scale analysis

Both NDVI and aspect are scale-dependent variables (Aman et al., 1992; Deng et al., 2007a): NDVI reports the average vegetation greenness of each cell whose value is a function of the cell size; the topographic meaning of aspect varies with the DEM resolution so that it can represent the hillside orientation at a fine (e.g. 10 m) resolution, as well as the mountainside orientation at a coarse (e.g. >500 m) resolution (Deng et al., 2007a). As a result, both the thermal meanings of aspect and its relationship with NDVI may change with spatial scale.

To determine thermal south at different scales, NDVI was calculated at 30 m as well as various coarser resolutions (see the list below), respectively, after aggregating reflectances to these resolutions. DEM data were resampled, or coarsened, to corresponding resolutions using the nearest-neighbour resampling method. Aspect (and southness) was then calculated from the DEMs of these resolutions, and NDVI-southness covariance evaluated. The following resolutions (resolution is also referred as "scale" hereafter) were tested for SMM: 30, 60, 90, 120, 150, 180, 210, 270, 330, 390, 450, and 510 m. The following were tested for DHP and BP for comparison purposes: 30, 210, and 450 m. The comparison of these resolutions may help identify whether (and how) thermal south for "hill" and for "mountain" would vary.

4. Results and discussions

4.1. Change of NDVI with aspect

According to findings in SMM, Fig. 2 shows change of mean NDVI differences of opposite aspects along various azimuth lines at 30 m, after aspects were aggregated into 5° groups. North-facing cells on average had higher NDVI values, and the maximum (aggregated) NDVI contrast obtained in SMM was 13.5% in May, 17.8% in July, and 19.5% in September. This result indicates the existence—in SMM—of cooler and moister conditions on north-facing slopes for plant growth and an increased contrast between south- and north-facing slopes with the extension of the dry season, especially when it was close to the end of the dry season and the vegetation senescence had nearly completed.

The three seasons seemed to share a wide "peak" region of azimuth lines where the largest north–south NDVI contrasts occurred (Fig. 2), but no individual peak was prominent among the region even though small peaks were observable. This peak region fell in an aspect range 175–220°, and its central part clearly deviated to 190–210° rather than following the 0–180° azimuth line. The largest north–south contrast was identified to be at 205° and 235° in May, 220° in July, and 190 and 200° in September. These findings in SMM all indicate the existence of thermal south that has deviated to southwest to variable degrees in all three seasons, conforming to previous observations in the literature.

The above conclusion was supported by other evidence in Fig. 2 as well. For example, east-facing slopes (aspect = 90°) had higher NDVI than west-facing slopes (aspect = 270°) in all three seasons, characterizing a consistently cooler and moister landscape. This was especially true in July when east-facing slopes had a 13.4% higher NDVI than west-facing slopes. Mean NDVI values reached equality not between aspects 90° and 270° but between 125° and 305° in May, 140° and 320° in July, and 120° and 300° in September, respectively.

It should be noted, however, that the thermal deviation identified here may also include the effect of other environmental factors. These may include (1) rainfall difference on east-facing and west-facing slopes, even though May to September signifies a consistently dry season in SMM, BP, and DHP (Jackson and Gough, 2001; Loeher, 1983; Raven et al., 1986), and (2) soil property variability (e.g. depth and texture for water-holding capacity) between different aspects. The possible impact of rainfall and soil properties was not considered separately in this paper.

4.2. Thermal south identified with NDVI-southness covariance

Fig. 3 (*a, b, c*) shows change of NDVI-southness covariance at 30 m in SMM with degree-by-degree adjustment of *d* in Eq. (1). In all the seasons, the covariance had consistent change with *d* producing a stable peak in each case. This peak appeared at an aspect

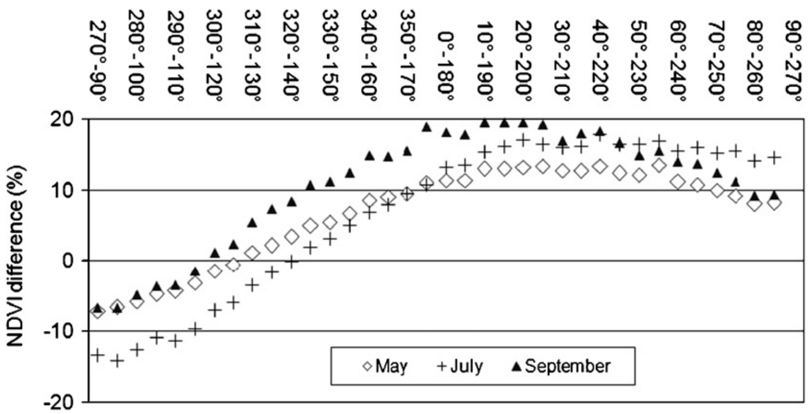


Fig. 2. Mean NDVI differences of opposite aspects along various azimuth lines in SMM. "0–180°" on *x*-axis signifies results of subtracting mean NDVI in aspect range of 181–185° from mean NDVI of 1–5° aspect range, while *y*-axis presents percentage of this subtraction result in average value of above two NDVI means.

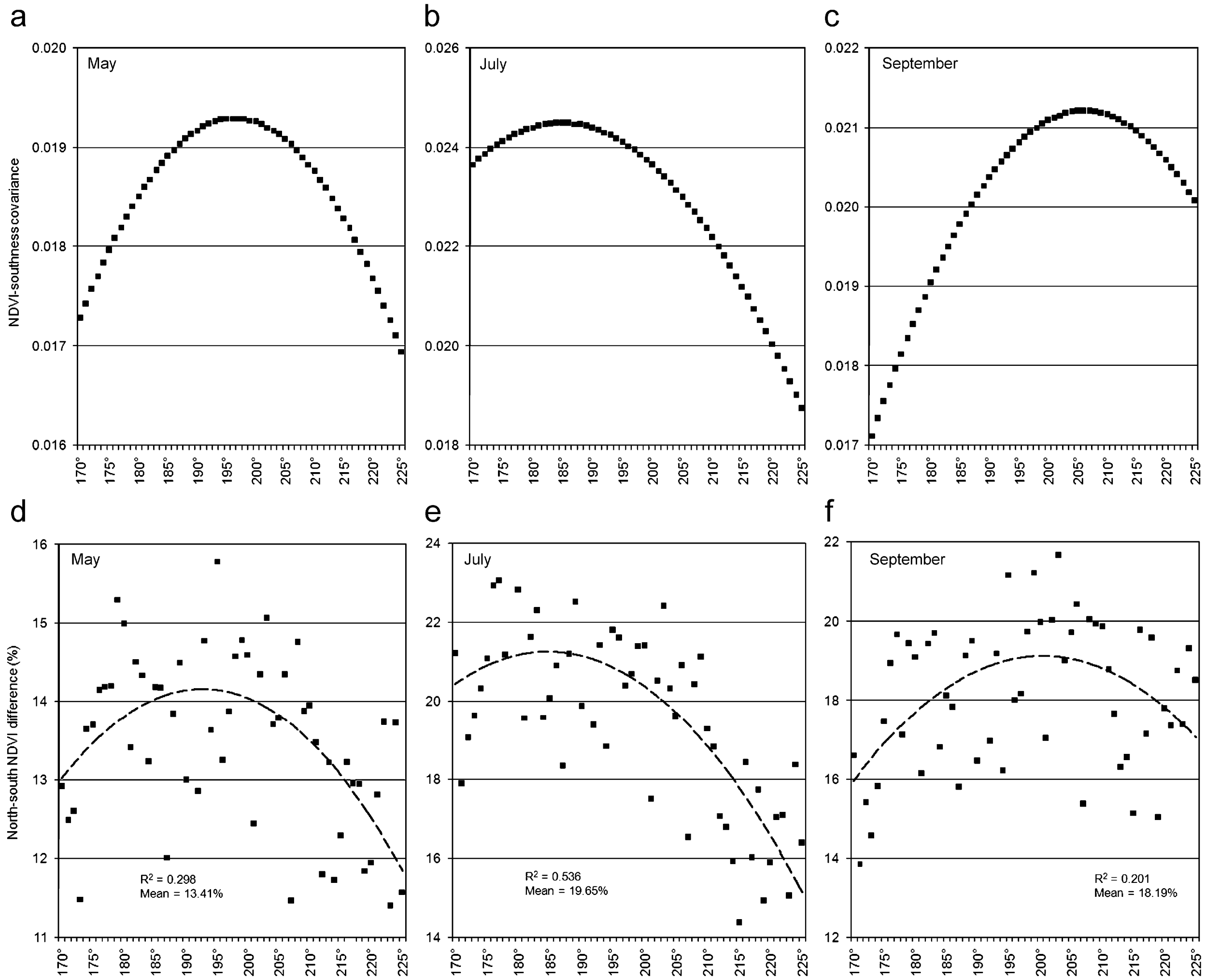


Fig. 3. Variable NDVI–aspect relationships in SMM in 165–225° azimuth zone. They are shown as change of NDVI-southness covariance with deviation of aspect (*a*, *b*, *c*), and change of percentage differences of NDVI between opposite aspects with trendlines fitted (*d*, *e*, *f*). Both changes are presented for May, July, and September at 30 m resolution.

of 196–197° in May, 185° in July, and 206° in September. They are all larger than 180°, indicating the deviation of azimuth lines towards southwest along which the NDVI-southness covariance would reach the maximum. This observation is consistent with other conclusions in the literature (e.g. Dargie, 1987; Lakhani and Davis, 1982; Perring, 1959), but still needs to be confirmed at different scales and in different study areas.

The NDVI-southness covariance method and the 5° NDVI contrast method both reported southwest deviation of thermal south for all three seasons, suggesting that the two methods are comparable in detecting thermal south. The unique peak produced by the covariance method made its results easy to interpret, but little information was given regarding the degree of difference between the thermal south and other aspects. The NDVI contrast method identified multiple peak aspects and an aspect plateau where the north–south contrasts were the strongest, and information was given regarding how the NDVI contrasts would vary from one aspect to another. The success of the NDVI contrast method was nonetheless accompanied by low precision in reporting thermal south (e.g. $>5°$), because aspects were aggregated into 5° groups and the detected peak region was wide.

To evaluate the covariance method, a degree-by-degree calculation of north–south NDVI contrasts in the aspect range of 170–225° was conducted in SMM at the 30 m resolution. A rather scattered, irregular pattern of change was produced (Fig. 3(d)–(f)), reflecting the fact that NDVI was only weakly correlated to southness in this landscape (Deng et al., 2007b). When polynomial trendlines were fitted to the data, the correlations were low (Fig. 3(d)–(f)), but the general trend was that large north–south NDVI differences tended to appear at aspect ranges of 185–200° in May, 180–190° in July, and 195–210° in September, similar to the result obtained from the covariance method (Fig. 3(a)–(c)). In all, the covariance method seemed to have the advantages of simplicity, precision, and consistency in reporting thermal south.

4.3. Change of thermal south with season and scale

The covariance method was used for this part of the analysis, and peak covariance between NDVI and adjusted southness was observed at all the tested scales (30–510 m) and in all seasons (Fig. 4). Fig. 5 summarizes the variation of thermal south identified in SMM. The multi-scale analysis in SMM confirmed the finding at 30 m that thermal south deviated towards southwest in all seasons but the deviation was non-uniform between seasons and scales. September had the largest deviation (25–53°) at all scales in SMM. This result may be associated with the

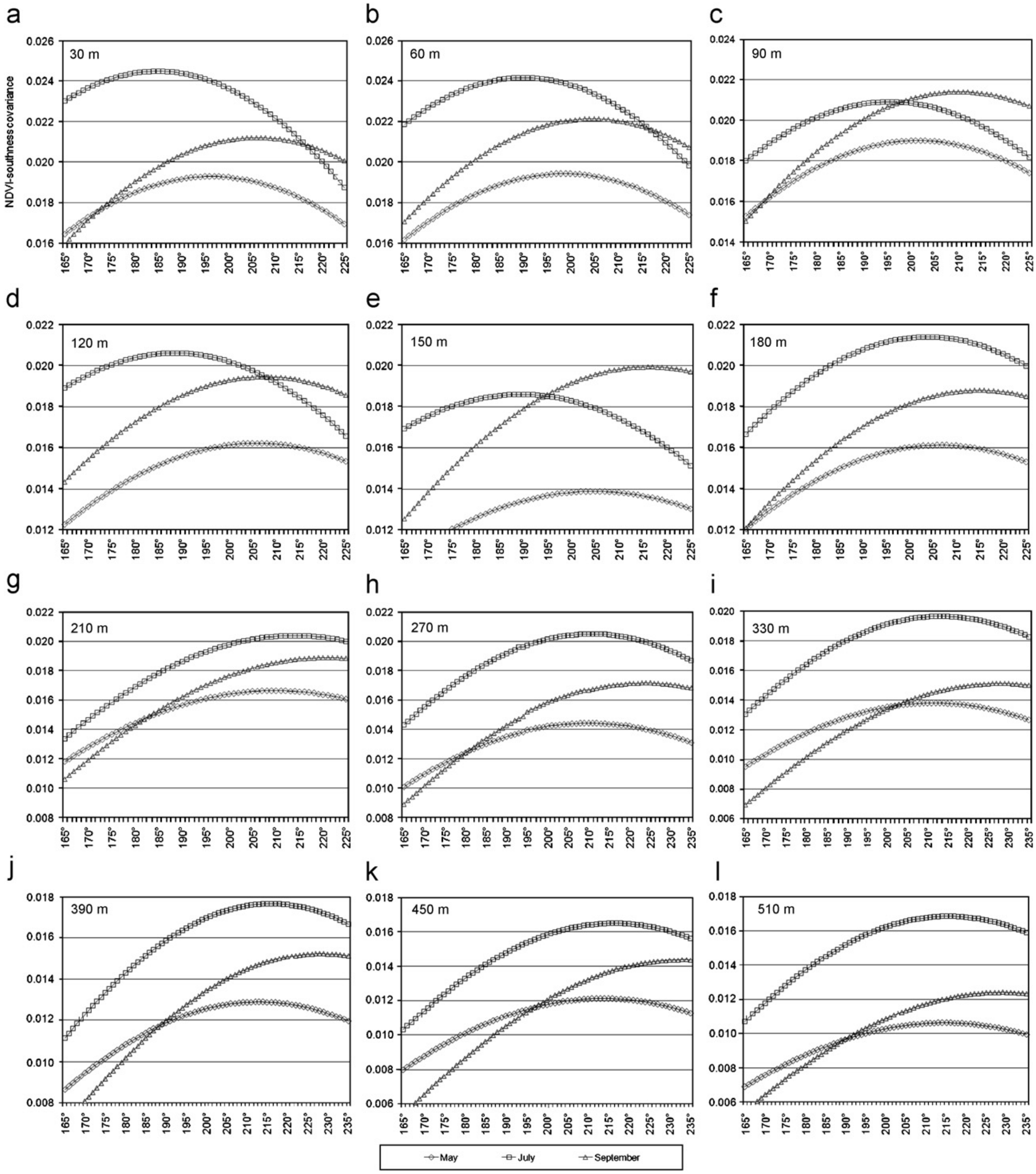
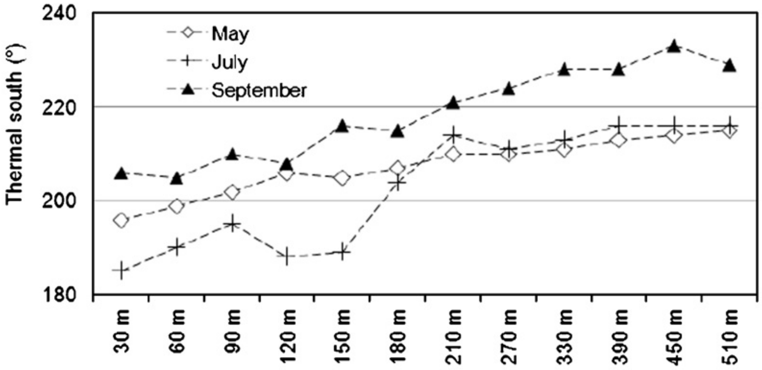


Fig. 4. Multi-scale NDVI-southness covariance in SMM and its variability with southness deviation. Southness of 20 spatial scales (30–510 m) was deviated in an aspect range 165–225° (or 235°) before being linked to NDVI of corresponding spatial scales in different seasons (May, July, and September).



May	196°	199°	202°	206°	205°	207°	210°	210°	211°	213°	214°	215°
July	185°	190°	195°	188°	189°	204°	214°	211°	213°	216°	216°	216°
September	206°	205°	210°	208°	216°	215°	221°	224°	228°	228°	233°	229°

Fig. 5. Thermal south in SMM. They are reported as variable aspect values identified using covariance method in different seasons at various spatial scales.

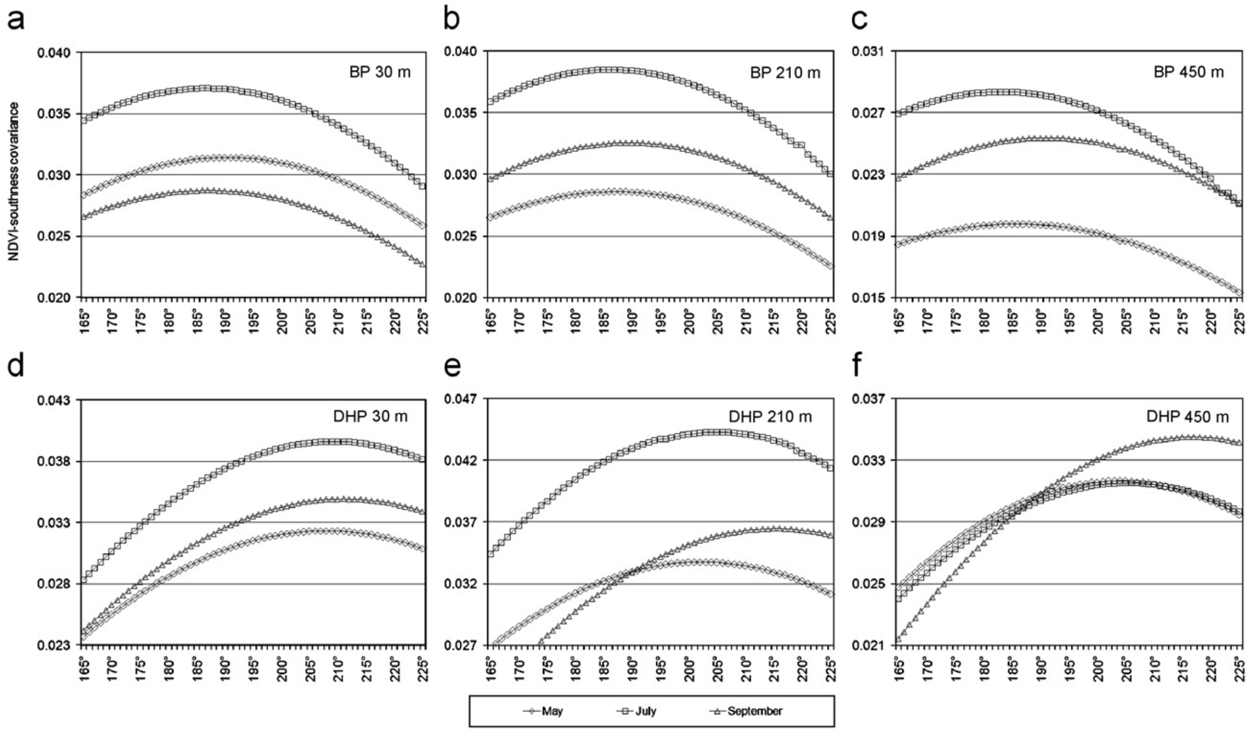


Fig. 6. Multi-scale NDVI-southness covariance in BP and DHP and its variability with southness deviation. Southness of three spatial scales (30, 210, and 450 m) was deviated in an aspect range 165–225° before being linked to NDVI of corresponding spatial scales in different seasons (May, July, and September).

Mediterranean-type climate of SMM: while southwest slopes are warmer than symmetrical southeast ones in all seasons, the uniformly dry landscape of September (Deng et al., 2007b) made this effect more dramatic than in moister May and July. In all three seasons, there seemed to be an overall increasing trend of thermal deviation with the coarsening spatial scale in SMM, except in July at 120 and 150 m scales (Fig. 5). With changing scale, the range of variability of thermal deviation for each season was 19° (May) to 31° (July and September).

4.4. Change of thermal south with study area

Fig. 6 shows the results of thermal south detection in BP and DHP using the covariance method at three spatial scales (30, 210, and 450 m). The defined thermal south

Table 1
Thermal south differences of three study areas (SMM, BP, and DHP) across three seasons (May, July, and September) and three spatial scales (30, 210, and 450 m).

	30 m			210 m			450 m		
	SMM (°)	BP (°)	DHP (°)	SMM (°)	BP (°)	DHP (°)	SMM (°)	BP (°)	DHP (°)
May	196	189	208	210	187	202	214	186	203
July	185	187	209	214	186	205	216	183	205
September	206	187	211	221	189	215	233	191	217

differed consistently between the study areas, but it deviated towards southwest–more or less–in all cases (also see Table 1). BP seemed to have the least deviation, consistently much less than DHP (for about 20°) in all seasons and scales even though the two study areas are only 20–30 km apart. This may be related to the fact that BP is located more inland (northeast) than DHP (Fig. 1). Both BP and DHP had a much smaller seasonal and scale-to-scale variability of thermal south than SMM (Table 1). All these indicate that the thermal deviation is highly variable between landscapes. It is hard to interpret why SMM, BP, and DHP had thermal deviations in particular ways, but their difference may be related to the fact that: (1) the distances of the three areas to the ocean (and accordingly their climates) are different, SMM being the closest and BP the farthest, and (2) the elevations are much higher in BP and DHP.

5. Conclusions

Two methods were proposed to define topography-controlled thermal south as corresponding to (1) the maximum NDVI contrasts between opposite aspects and/or (2) the maximum covariance between NDVI and (deviated) southness. The two methods tend to identify similar thermal south but they also produce different outputs. The NDVI contrast method can identify both the peak region and the extent of the NDVI contrast, whilst the covariance method can produce unique and easy-to-interpret covariance peaks. The results obtained in three mountainous areas of California, SMM, BP, and DHP, indicate that thermal south tends to deviate to southwest from 0° to 180° azimuth line, and a deviation as large as 53° may occur. Thermal south may not be static across seasons: a consistently larger deviation in September was observed in SMM—but not in BP and DHP. It may not be static across scales either: with coarsening spatial scale, a trend of increasing deviation was observed in SMM (but not in BP and DHP).

The three study areas produced very different observations of the thermal south. The largest westward deviation and the most apparent seasonal and scale-to-scale shift of thermal south were both observed in SMM. Even though they are located close to each other, BP and DHP also showed large differences in the extent of deviation (but not in seasonal and scale-to-scale change). The above differences may be explained by the distance to the ocean (BP being the farthest) and elevation differences (SMM being the lowest). The conclusions obtained in the three study areas regarding thermal south, however, may not be applicable to other areas, whose thermal south may need to be defined independently using the suggested methods. In the mean time, the complex combination of temperature and precipitation (and possibly soil) need to be considered in future efforts of defining thermal south, especially for areas and seasons where aspect–precipitation and aspect–soil linkages are strong.

In all, the definition of thermal south may need to be specific to the season, study area, and possibly spatial scale. This finding, together with the suggested methods reaching the finding, may help defining the role of aspect in mountain environments, especially in the formation of vegetation patterns. Such an option is important, because direct meteorological and vegetation observations are usually unavailable or non-existent with sufficient spatial resolutions.

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