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Climate, Santa Ana Winds and Autumn Wildfires in Southern California

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Wildfires periodically burn large areas of chaparral and adjacent woodlands in autumn and winter in southern California. These fires often occur in conjunction with Santa Ana weather events, which combine high winds and low humidity, and tend to follow a wet winter rainy season. Because conditions fostering large fall and winter wildfires in California are the result of large-scale patterns in atmospheric circulation, the same dangerous conditions are likely to occur over a wide area at the same time.

Furthermore, over a century of watershed reserve management and fire suppression have promoted fuel accumulations, helping to shape one of the most conflagration-prone environments in the world [*Pyne*, 1997]. Combined with a complex topography and a large human population, southern Californian ecology and climate pose a considerable physical and societal challenge to fire management.

October 2003 Wildfires

Both antecedent climate and meteorology played important roles in the recent extreme wildfires in southern California. After a multi-year drought contributed to extensive mortality in western forests and chaparral, late winter precipitation and a cool spring and early summer fostered the growth of grasses that were cured out during a hot summer and autumn in 2003, producing an extensive fine fuel coverage. Fanned by moderate Santa Ana winds, 12 major fires started between 21 October and 27 October in southern California and another began on 28 October near Ensenada in Baja California, Mexico (see Figure 1). Together, the fires had burned over 300,000 hectares by November. All of these human-induced fires started in chaparral on or below the western slopes of California's coastal mountain ranges and initially burned toward the Pacific Ocean. Their paths toward the sea were, in many cases, coincident with some of the most densely populated urban areas in the United States.

The Santa Ana winds that fostered the rapid growth of these fires were not in themselves extraordinary, though the hot and dry conditions leading up to the fire events were at record or near-record levels. Large wildfires in chaparral in the autumn and winter months are also not extraordinary events in southern California. They have occurred frequently

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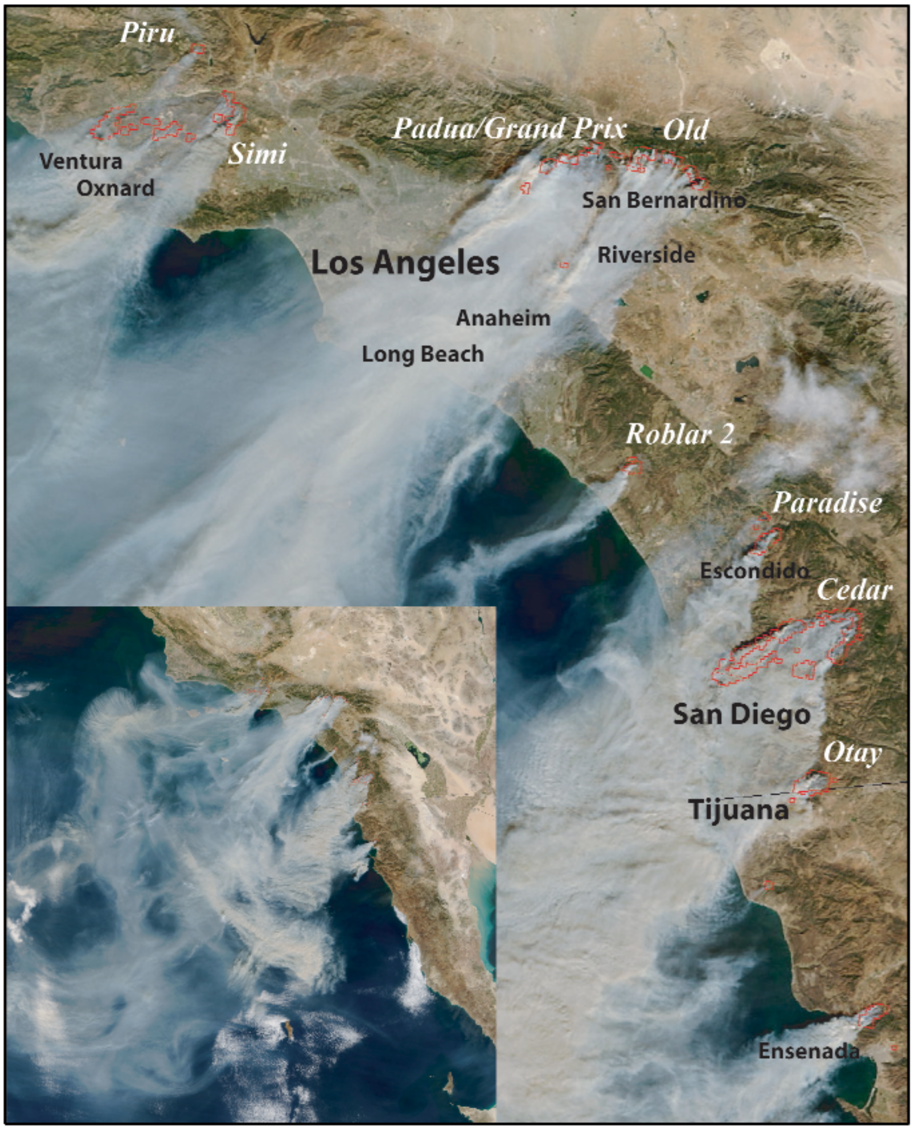

Fig. 1. Smoke from southern California wildfires is shown on 26 October 2003. Active fire perimeters are outlined in red in Ventura, San Bernardino, Los Angeles, and San Diego counties, and in Baja California, Mexico. Selected city names are in black; fire names in white. Source image courtesy of NASA/MODIS Rapid Response Team.

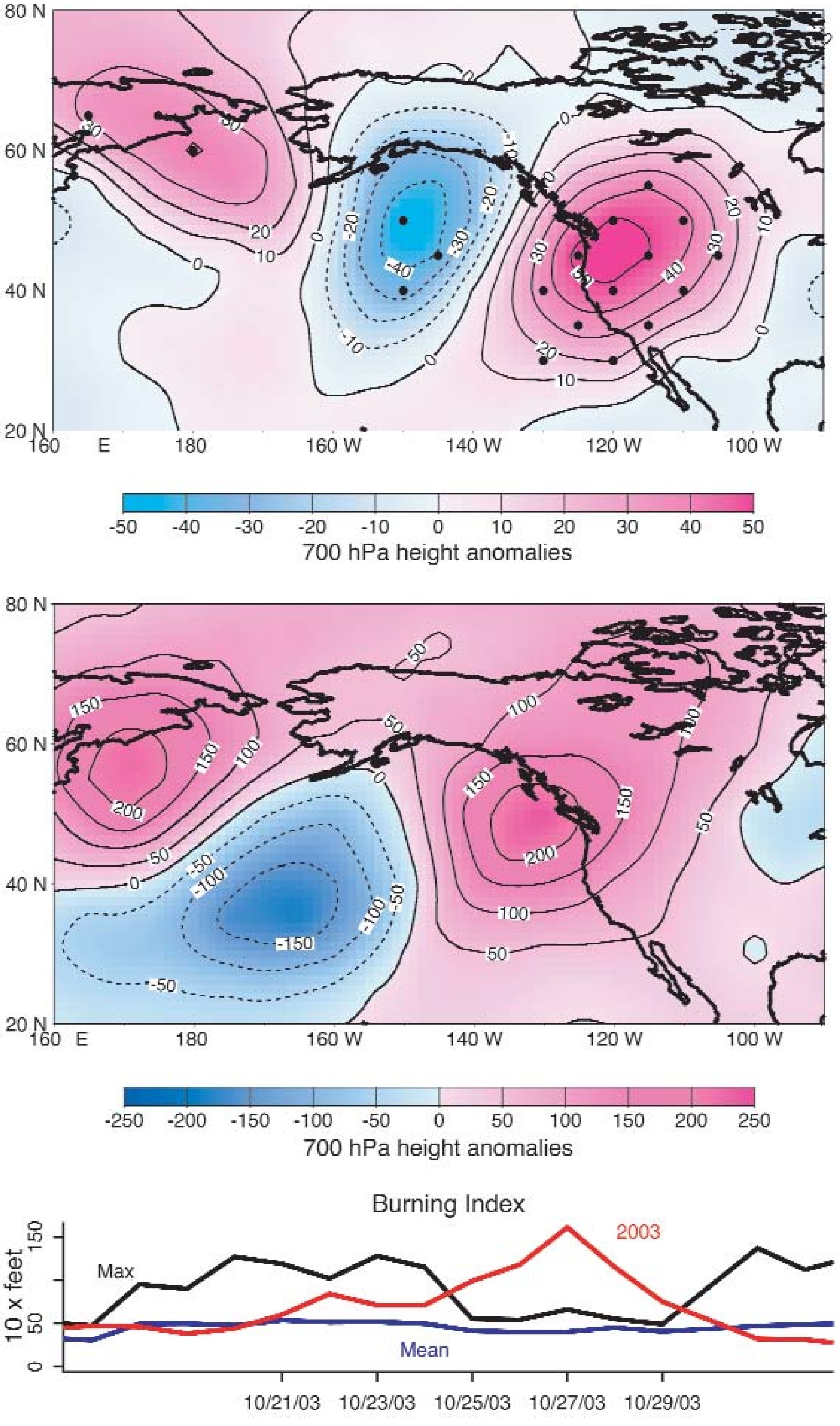

Fig. 2. (top) Composite, 700-hPascal height anomalies are shown for the ignition date for fires burning > 400 hectares (1000 acres) in Cleveland National Forest. Black dots indicate statistically significant anomalies compared to the historical record at the 95% confidence level; (middle) 700-hPascal height anomalies for 25 October 2003, ignition date for Cedar fire. (bottom) daily Burning Index for Cleveland National Forest in October (1992–2000 mean and maximum, and 2003 values).

during the last century. Moreover, charcoal records from Santa Barbara Channel sediments indicate the frequency of wildfires in the region has not changed significantly in the last 500 years [*Mensing et al.*, 1999]. The severity of the immediate human impact of the October 2003 wildfires was exacerbated by the rapid growth of an extensive wildland-urban interface proximate to a population of nearly 20 million in southern California, where the population has more than doubled since 1950.

The intensity of the fires and the severity of their ecological impact on the region's forests were exacerbated by the long-term accumulation of fuels such as snags, logs, and heavy brush due to 20th-century fire suppression policies and watershed preservation efforts since the late 1800s.

Santa Ana Winds

In southern California, Santa Ana winds are a recurrent regional-scale influence in the autumn, winter, and spring months, peaking in December. Dry Santa Ana winds promote the ignition and rapid spread of wildfires by drying fuels and fanning the flames of fires once they are started. Their greatest effect on fire tends to be in autumn, when vegetation has been desiccated after a long dry summer and before the onset of the winter rainy season. Winter rainfall is highly variable in southern California, however, and in some years, large fires have occurred during Santa Ana conditions as late as February.

The Santa Ana is the name given to foehn-like winds in California, which result when a cool, dry air mass flows downslope from high-elevation basins in the western North American interior toward lower atmospheric pressures off the Pacific coast. This flow is funneled toward passes in the southern California coastal ranges by the higher Sierra Nevada range in the west and the Rocky Mountains to the east. As the air sinks, it is compressed, warming it and reducing its relative humidity. Compression of this air mass through mountain passes often produces winds of 40–60 km/hr, and in extreme cases, may yield wind speeds in excess of 100 km/hr. These dry, sometimes hot, winds quickly reduce fuel moistures, greatly enhancing the risk of fire, and fan the flames of any fire once started.

Four national forests in southern California—the main portion of the Los Padres, and the San Bernardino, Angeles, and Cleveland National Forests—cover about 700,000 hectares in a broad arc running along the coastal mountain ranges from about 35.5° to 32.5°N latitude. Digitized fire histories for these forests are available from 1970 and provide a representative sample of large wildland fires in chaparral and forest ecosystems for the region.

Inspection of weather maps associated with large autumn and winter fires reveals that the majority occurred during Santa Ana events. Composites of 700 hPa heights—that is, the average height of a 700 hPa atmospheric pressure—for each forest for the ignition dates of large fires exceeding 400 hectares from September to January (1970–2000) indicate a consistent pattern of anomalous atmospheric circulation in the mid-troposphere. The top panel in Figure 2 is the composite for 29 large fires reported during this period in the Cleveland National Forest near San Diego. This pattern is characteristic of Santa Ana conditions, with an anomalously deep Aleutian low and a high-pressure system centered over the northwest. The anti-cyclonic flow around the high-pressure feature brings dry air from the interior basins toward the southern California coast.

Fire ignitions peaked on 25 October for the October 2003 Santa Ana-driven wildfires; four large fires started that subsequently burned nearly 200,000 hectares, including the largest fire in California history—the Cedar fire in Cleveland National Forest (CNF) that burned

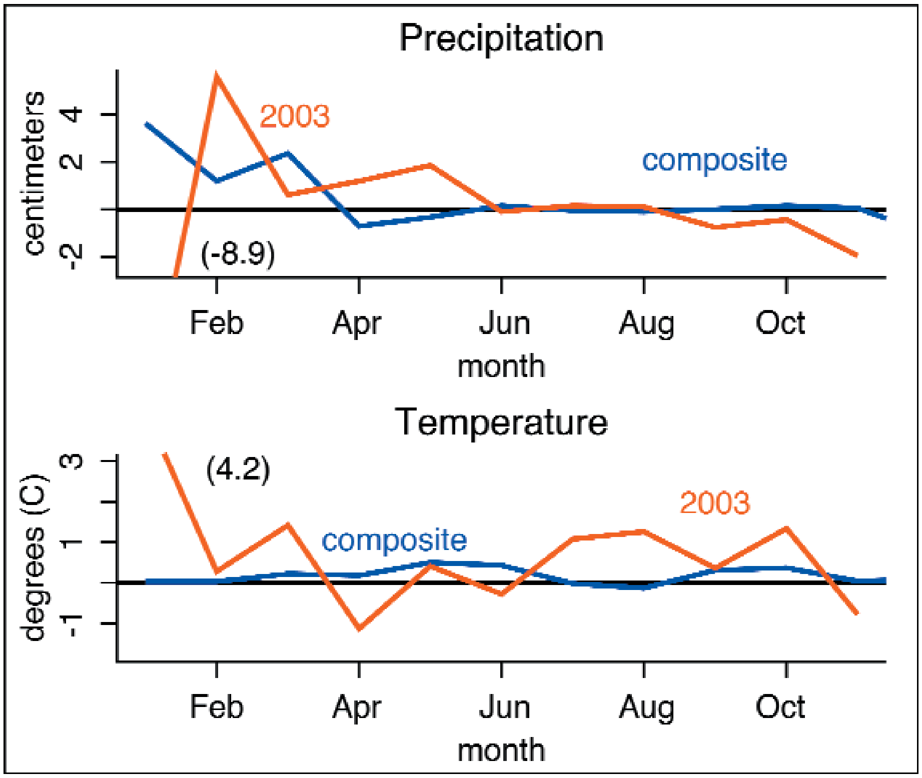

Fig. 3. Monthly precipitation and temperature anomalies are shown for coastal southern California 2003 versus a composite of years, with fires burning more than 400 hectares in Cleveland National Forest in September through January. Data are for the California "South Coast Drainage" Climate Division, from the National Climate Data Center.

over 113,000 hectares. Like 97% of large autumn and winter wildfires in southern California's four national forests since 1970, these ignitions were of human origin. The 700-hPa height map for 25 October (Figure 2, middle panel) shows a pattern similar to that of the large fire composites. Observed wind speeds during the fire period were typically 25–40 km/hr, with gusts of around 65 km/hr. While these winds were not exceptional for a Santa Ana event, they were, in combination with homogenous dry fuel conditions, effective in promoting rapid fire spread. One of the fires—the Cedar fire near San Diego—grew from 200 to 12,500 hectares in 4 hours. The combination of warm temperatures and wind, even though moderate in speed, reduced relative humidity to around 10% during most afternoons during the fires. Humidity recovery overnight was also limited, increasing to only 20–30%. The extended period of low relative humidity was partially responsible for the extreme fire behavior observed during the events.

Fire managers in the United States use fire danger indices from the National Fire Danger Rating System (NFDRS) to support decisions related to fire management. The NFDRS Burning Index (BI) is related to the potential length of flames at the leading edge of a fire and describes the difficulty of controlling a fire under worst-case conditions (see *Schlobohm and Brain* [2002]). The BI responds to changes in wind speed and relative humidity on short time scales of hours to days, and thus, it is sensitive to the onset of Santa Ana conditions.

The BI calculated for CNF in October 2003 was at or below daily means for the previous decade up until 21 October (Figure 2, bottom panel). The period of 25–27 October saw a rapid increase in the index, with the onset of Santa Ana conditions on the night of the 25th. The Cedar fire started the evening of the 25th and grew rapidly overnight and through the morning of the 26th, while the large Paradise and Otay fires started to the north and south of the Cedar fire on the 26th. Fire fighters did not make significant progress in containing the Cedar and Paradise fires until 30 October, when the Santa Ana weakened and relative humidity rose and temperatures fell. The BI for CNF clearly reflects both the onset and progression of Santa Ana conditions, as well as their reversal (Figure 2, bottom panel).

The NFDRS Energy Release Component (ERC) is an indicator of heat energy at the head of the flaming front calculated in units of J/m^2. ERC is also an index of longer-term drought conditions, and thus provides a general state of fuel dryness. All NFDRS stations in the region observed numerous daily record ERC values leading up to and during the main fire period (17–30 October). Many of these extremely high values were also near or exceeded all-time October monthly records.

Antecedent Climate

Large fires in autumn and winter in coastal southern California chaparral appear to be linked to antecedent climate as well as to concurrent meteorology. Precipitation tends to be above normal in the winter or early spring prior to the fire season (Figure 3, top panel), suggesting that large fall and winter fires are preconditioned two or more seasons in advance. Wet winters enhance the growth of grasses and other fine fuels. The 2003 fire season differed somewhat from the composite in that the positive precipitation anomalies in late winter and spring followed an extended 5-year drought. However, this precipitation and subsequent cooler temperatures were sufficient to promote the growth of fine fuels during the winter and spring, increasing the continuity and load of fine fuels across the region [*Predictive Services*, 2003].

Temperatures during years with large autumn and winter fires do not follow a distinct pattern. In composite, monthly mean temperatures are slightly warmer than average in the preceding winter and spring and during the autumn period when large fires occur, but they contain a great deal of variability across large fire events. The year 2003 saw a very warm winter followed by a cool spring and then a very warm summer and autumn (Figure 3). Temperatures during the first week of the fires were record-setting and averaged 10–20°C above normal. This pattern probably accentuated the growth and curing cycle for the grasses and other annual vegetation that burned over much of the area.

Fire Management

Wildfires can become large and costly when antecedent climate and meteorology facilitate their rapid spread. They are also more likely to escape early control under dangerous conditions when there are multiple ignitions that overwhelm locally available suppression resources, and when ignition locations are not easily accessible. Although Santa Ana winds are intensified locally in settings such as mountain passes and canyons, they are driven by regional and larger-scale atmospheric patterns. Consequently, they usually occur over a broad footprint so that the same dangerous conditions are likely to affect the entire 400-km coastal mountain reach of southern California.

This synchrony of risks in inaccessible terrain over a large region poses a serious challenge for wildfire management. Judging from U.S. National Forest Service fire records, the probability of multiple large fires occurring similar to those in 2003 is historically high. In southern California, from 1970 through 2003, whenever one or more large fires (greater than 400 hectares) burned in a national forest in September through January, there was a nearly one in four chance that one or more of the other three forests would also experience a large fire starting within the same 9-day period.

Early control is crucial when conditions favor rapid spread. Not only does the rapid growth of the fire perimeter greatly complicate containment, but the heat of a large fire dries neighboring fuels and generates its own winds, facilitating both the spread of the fire and extreme fire behavior that increases the risk to fire fighters and the public. The 2003 southern California fires behaved unlike any reported before [*Mission-Centered Solutions*, 2003]. The extreme nature and severity of the fire behavior surprised firefighting crews and subsequently caused them to realize that traditional suppression attack tactics were ineffective. Fire whirls were dramatic, as much as 800 m wide, crossing burned areas into unburned areas and causing spot ignitions ahead of the fire by as much as 1200 m. Pilots reported burning debris as high as 450 m above ground. Fire and heat from burning structures and ornamental vegetation were as much of a problem as any of the natural fuels.

Many forested areas that burned in October 2003 probably burned much more completely than they would have in the absence of successful fire suppression over the past century. Dense vegetation fostered the rapid spread of high-intensity fires in the forest canopy. Widespread die-offs of this vegetation may help to reduce the risk of canopy fires in the future. In recent years, large portions of southern California have experienced substantial vegetation mortality resulting from drought, insects, and disease [*Predictive Services*, 2003]. After the fine canopy fuels (needles, leaves, twigs, etc.) fall to the ground, the standing dead trees may be less prone to spreading fires in the canopy (Craig Allen, pers. comm.).

About 80% of the area burned in the October 2003 southern California fire siege, however, was in chaparral or grassland. Whereas healthy forests in southern California can sustain a low-intensity fire regime with regular surface fires in the absence of fire suppression, chaparral always experiences canopy fires that consume much of the vegetation. Not only does chaparral regenerate quickly, but a relatively small proportion of the areas with homes proximate to wildland vegetation actually burned—only about 5% of southern California's wildland-urban interface in total (S. Stewart, pers. comm.). Consequently, the risk of large regional-scale fires remains high.

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Seabed AUV Offers New Platform for High-Resolution Imaging

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A number of marine biological, geological, and archaeological applications share the need for high-resolution optical and acoustic imaging of the sea floor [*Ballard et al.*, 2002; *Greene et al.*, 2000; *Shank et al.*, 2002]. In particular, there is a compelling need to conduct studies in depths beyond those considered reasonable for divers (~50 m) down to depths at the shelf edge and continental slope (~1000–2000 m). Some of the constraints associated with such work include the requirement to work off of small coastal vessels or fishing boats of opportunity, and the requirement for the vehicle components to be air-shippable to enable inexpensive deployments at far-flung oceanographic sites of interest.

Over the last 2 and a half years, the Seabed Autonomous Underwater Vehicle (AUV) has been designed and deployed in support of such tasks off of Puerto Rico, Bermuda, Stellwagen Bank off Massachusetts, and the U.S. Virgin Islands.

Components and Capabilities

In designing the Seabed AUV (see http://www.whoi.edu/DSL/hanu/seabed), a decision was made to incorporate standard oceanographic sensors as far as possible to minimize costs and allow for easy maintenance. It currently supports a 300-kHz side-scan sonar, a 1200-kHz Acoustic Doppler Current Profiler, a Seabird pumped Conductivity, Temperature and Depth sensor, a 675-kHz mechanically scanned pencil beam sonar, and a 12-bit (high dynamic range) camera system. A 2-kWhr lithium-ion battery pack provides an 8-hour endurance for Seabed running at speeds between 0.3 m/s to 1 m/s. Its size—each of its two torpedo-shaped hulls is 1.5 m in length—and weight of 250 kg permit easy deployment off small coastal or fishing vessels of opportunity, and it can be shipped by air at a very reasonable cost to most departure ports.

Optical Imaging and Navigation and Control

Seabed has been designed specifically to further the growing interests in the area of sea floor optical imaging; specifically, high-resolution color imaging and the processes of photomosaicking and three-dimensional image reconstruction. In addition to high-quality sensors, this imposes additional constraints on the ability of the AUV to carry out structured surveys, while closely following the sea floor. The distribution of the four thrusters, coupled with the passive stability inherent in a two-hulled vehicle with a large meta-centric height, allows the Seabed AUV to survey close to the sea floor, even in very rugged terrain.

Figure 1 illustrates vehicle performance in such challenging applications. The vehicle (top left) can follow steep gradients at constant altitudes; in this case, on a coral reef off the U.S. Virgin Islands, and follow a greater than 45° slope at 3 m (top center) while obtaining high-resolution imagery with good color fidelity.

Figure 2 shows an image obtained from the vehicle using its camera and lighting system at night in 65 m depth, in the absence of ambient lighting. The nonlinear preferential attenuation of different parts of the visible spectrum underwater led to images that are not color-balanced. However, the 12 bits of dynamic range provided by the camera allow us to compensate and color balance the imagery as shown in Figure 2 (bottom) by using methods including frame averaging and parametric surface fitting in the homomorphic domain.

To accomplish high-resolution, large-area surveys, the AUV is run under closed loop control [*Whitcomb et al.*, 2000]. Navigation in shallow water (down to a few hundred meters) is accomplished by using a doppler velocity log in combination with Global Positioning System data before and after the dive. Algorithms for bottom-following in rugged terrain also allow the AUV to carry out autonomous surveys in regions of high relief while running precise track lines. The results of such a task are illustrated in Figure 3. Here, the AUV was imaging a boulder pile with a series of closely spaced track lines, while maintaining a constant 3-m altitude off the bottom in an area where the relief was also of that order.

Photomosaicking Underwater Imagery

Photomosaicking underwater is a challenging task [*Pizarro et al.*, 2003]. The nonlinear attenuation of color underwater, the absence of uniform ambient lighting, an unstructured

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