Environmental impacts of the Persian Gulf oil spill and oil-fire smoke

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Using satellite imagery from INSAT-1B, NOAA-11 and IRS-1A we have continuously monitored the recent Persian Gulf oil slick and the fire-smoke from the burning oil wells. From the areal confinement of the slick, we conclude that the large-area effect of the slick will not be very significant and only local areas will suffer environmental hazards. Smoke-induced cooling of key thermal subsystems of the monsoon over the Indian subcontinent is estimated to be about 1 K, which may result in a slight delay in the onset of monsoon in 1991, as well as some weakening of it. The local-area cooling, estimated to be 9 K, matches the reported drop of 8 K.

THE potential of satellite remote sensing, particularly when concurrent and synoptic imagery in the visible, middle-infrared and thermal-infrared are combined, for monitoring the extent and dynamics of oil slicks as well as smoke from burning oil wells, is well established[1–4]. Extensive studies carried out using LANDSAT Thematic Mapper data[5] of the Alaskan oil slick of March 1989 where about 300,000 barrels of crude oil were accidentally spilled into the waters of Prince William Sound, have not only enabled users of remote-sensing data to obtain a calibrating benchmark for such studies but also provided a clear understanding of the dynamics and temporal behaviour of such oil slicks as well as their effect on marine biota. The temporal dynamics of oil slicks has been studied by Clark *et al.*[6], from the results of which one can conclude that heavy concentration of oil is generally found towards the downwind edge of the slick. These studies have shown that, as the oil spreads, the volatile component of the oil, which accounts for almost 40%, evaporates within 24 h, the heavier hydrocarbons sink to the bottom of the ocean, while the medium-density compounds form oil emulsions with water, called mousse. Over a period of 10–15 days the wind and the sea waves break the mousse into small tar balls, which may wash ashore or drift away in the ocean. Detailed studies carried out by Hoult[7], involving both experimental observations and theoretical models, have demonstrated that the spread of the oil slick ceases after some time, depending on the volume of oil spill, when the surface-tension effects become dominant compared to wind, tidal, gravity and viscous forces. While the time for maximum spread depends on the temperature and salinity of sea water, and volatility and solubility of oil and its biological properties, surface-tension effects become dominant when the thickness of oil is reduced to about 25 μm, after which further spread does not take place.

The efficiency of various spectral bands in the ranges 0.38 to 1.1 μm and 8.5 to 12.5 μm for oil detection was investigated in detail by Neville *et al.*[1] The study showed that the thermal-infrared channel had the highest contrast for detecting oil slicks and the area of the slick could be computed with reasonable accuracy from imagery in the 0.70–0.79-μm and 8.5–12.5-μm bands. Studies by Brussieux *et al.*[2] indicated that (i) the thermal-infrared radiometer shows hydrocarbons to be 'cooler' than the sea temperature, (ii) a large quantity of concentrated oil slick appears as a 'hot' area, (iii) infrared radiometry can detect an oil slick of thickness as low as 25 to 50 μm, and (iv) principal component analysis can be effectively used to separate thick and thin oil layers.

In this paper we describe the nature and temporal variation of the oil slick as well as of the smoke from burning oil wells in the Persian Gulf area that resulted from the recent Gulf war. The slick and smoke were continuously monitored using five-channel imagery from the Advanced Very-High-Resolution Radiometer (AVHRR) instrument on the NOAA-11 satellite and two-channel imagery from the INSAT-1B geo-stationary satellite during 17 January to 11 March 1991, supplemented by high-resolution four-band imagery (resolution of 36 and 72 m) from the Indian Remote Sensing Satellite IRS-1A. Table 1 gives the data set used for the present study. We also present some conclusions on the environmental impact of the oil

Table 1. Data set of satellite observations of the Gulf oil spill and oil-fire smoke.

NOAA-11 (AVHRR)	17, 26 January 3, 4, 5, 10, 12, 13, 14, 15, 20, 21, 22, 23 February 2, 11 March
INSAT-1B (VHRR)	From 26 January, data were collected every six minutes, in the sector-scan mode in the initial period; subsequently daily observations were made at 1100 h local time.
IRS-1A	6, 28 February

slick, and smoke in particular, based on extensive calculations.

Methodology

Temperature anomalies in the ocean were inferred by thresholding and band slicing of channel-4 data (10.5–11.5 μm) from NOAA-11. The analysis of smoke plumes was carried out using the visible channel (0.58 to 0.68 μm). The data from all five channels of NOAA-11 AVHRR were used in various combinations to generate false colour composites (FCC), and linear and nonlinear stretching was performed to find out the optimal enhancement in the colour-composited images to delineate the oil slick. Linear contrast stretch on the FCC of channels 3, 4 and 5 produced consistently good results for deriving the temporal evolution of the oil slick. Principal component analysis (PCA) was carried out using data from all the five channels. Hue, saturation and intensity (HSI) transformation was performed using data from channels 3, 4 and 5, followed by histogram equalization. These enhancements provided a better delineation between thick and thin oil slicks.

The high-resolution 4-band data from IRS-1A were used for confirmatory checks. IRS-1A images of 6 and 28 February 1991 over Ras-Al-Ghar and Al-Jubayl areas were subjected to principal component analysis in all the four stretched bands (0.45–0.52, 0.52–0.59, 0.62–0.68, 0.70–0.86 μm), apart from generating FCCs, and these were analysed to cross-check the results obtained from INSAT and NOAA-11 imagery.

The multi-band sea-surface temperature derived from the imagery of 26 January and 3, 4, 12 and 15 February using the MCSST algorithm developed by McClain *et al.*[8] showed that thick oil zones had higher temperature compared to the surrounding water. The multitemporal analysis of sea-surface temperature, presented in Table 2, shows that, during 26 January to 3 February, the temperature difference between thick oil and neighbouring water was about 4 K due to intense solar heating of the oil layer. By 12 February, the difference between the temperature of the thicker layer and water had come down to about 2 K, clearly indicating the thinning down and spreading of the oil, which was corroborated from the FCC/PC/HSI combinations. By 15 February the water temperature was higher than the oil temperature, probably because of an emissivity effect combined with further thinning.

Table 2. Multitemporal analysis of sea-surface temperature.

		T (K)	
Date		Input DN	K
26.01.1991	Thick oil	205	293.62
	Thin oil	190	290.59
	Water	185	289.58
03.02.1991	Thick oil	207	295.83
	Thin oil	197	292.68
	Water	192	291.10
12.02.1991	Thick oil	190	292.08
	Thin oil	176	286.52
	Water	173	288.98
15.02.1991	Thick oil	202	289.90
	Thin oil	183	284.32
	Water	208	291.66

Progress of the oil slick

Figure 1,*a* shows the FCC image of 26 January 1991 from NOAA-11 over the Gulf region. The figure clearly shows that, as of 26 January, i.e. two days after the reported oil spill, the oil slick formed large, thick globules, spreading over an area extending 10 km east–west and 60 km north–south, from Mina Saud off the Kuwait coast to Ras-Al-Khafji. The quantity of oil spill, estimated using the exponential thickness profile in conjunction with areas of different thickness zones derived from radiance measurements in band 5 of NOAA-11, till then was about 10 million barrels (Figure 1,*b*,*c*).

The enhanced NOAA-11 image of 12 February (Figure 2,*a*,*b*) shows that, by that day, the oil spill had spread considerably, extending about 60 km in the east–west and almost 300 km in the north–south direction. By then the oil slick had thinned down considerably owing to spreading, ocean dynamics and evaporation of volatile hydrocarbons. A comparatively thicker layer was observed to be extending 30 km east–west and 200 km north–south from Mina Saud to Abu Ali along the Saudi coast and it was 30 km away from the desalination plant at Al-Jubayl. Further, a smaller oil spread was also observed 35 km to the south of Khor-Al-Amaya oil terminal. The images taken after 12 February have not shown any further spreading, particularly of the thicker oil slick. The IRS-1A image of 28 February (Figure 3) indicated the presence of only thin oil near the desalination plant near Al-Jubayl—consistent with Hoult's[7] results—indicating that the thickness of the oil in the expanded area might have become less than 25 μm, taking it to the surface-tension-effect regime.

Smoke from burning oil

The NOAA-11 image of 26 January (Figure 1) clearly shows considerable fire and smoke emissions near Basra, close to the Rumaila oil field, near Jaz Babiyan island at Khor-Al-Amaya oil terminal, and at Al-Ahmadi in Kuwait. The wind pattern was such that the smoke was essentially blowing south-east on this day at lower altitudes. By 12 February (Figure 2,*b*) the smoke

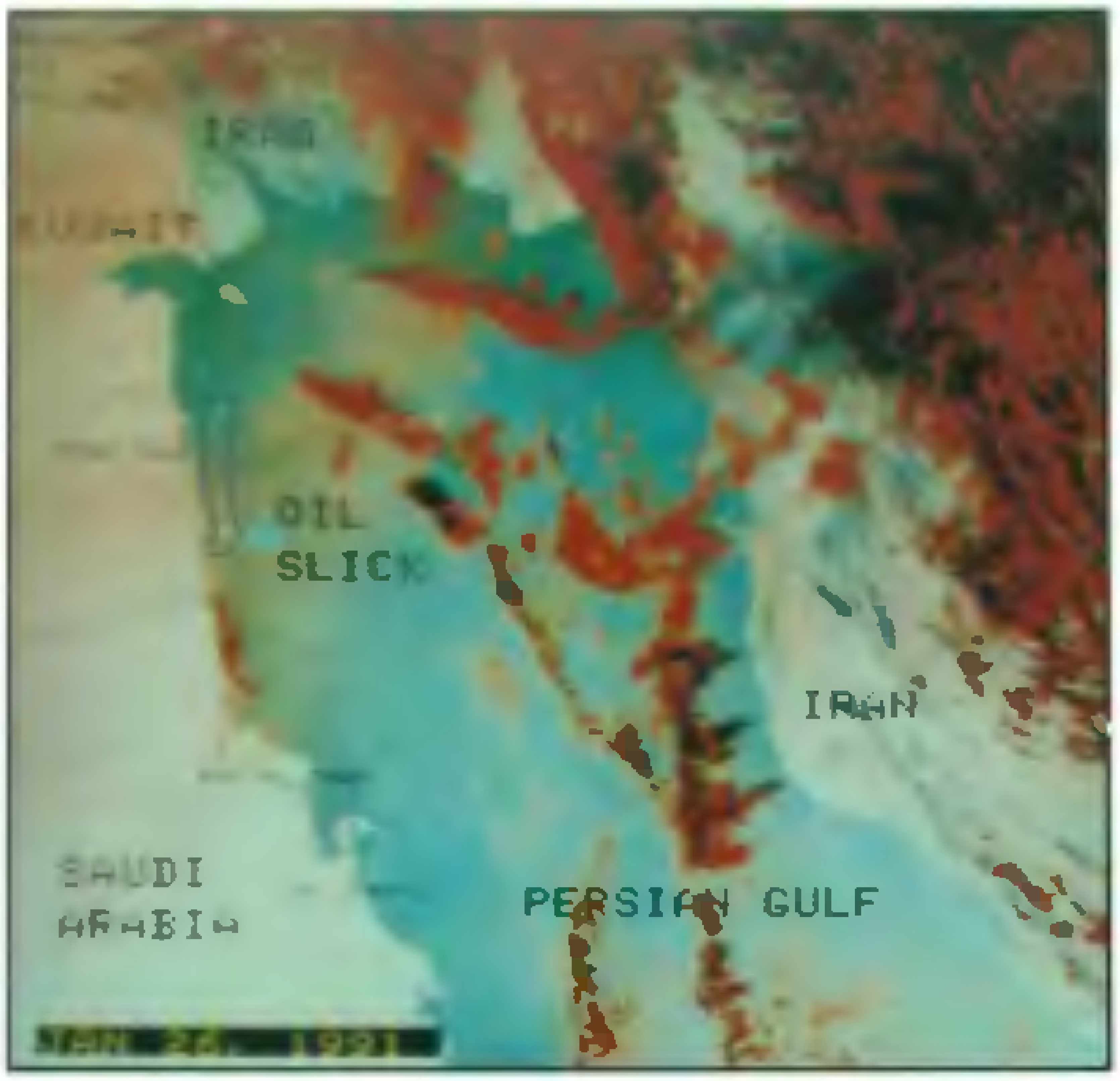

Figure 1,a. Enhanced FCC image of 26 January 1991.

Figure 3. IRS-1A image of Al-Jubayl area of 28 February 1991.

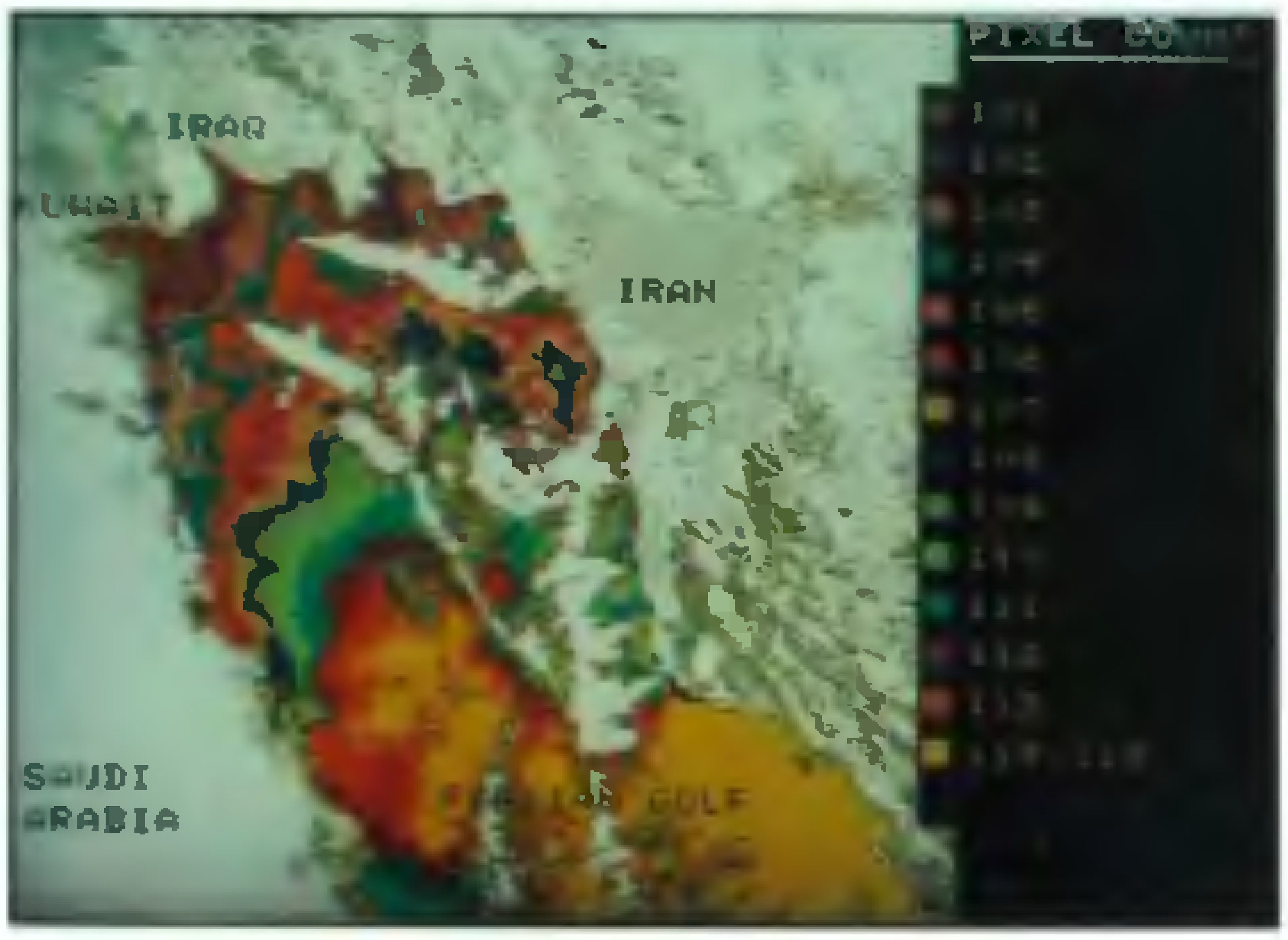

Figure 1,b. Density sliced image of band 5 of 26 January 1991.

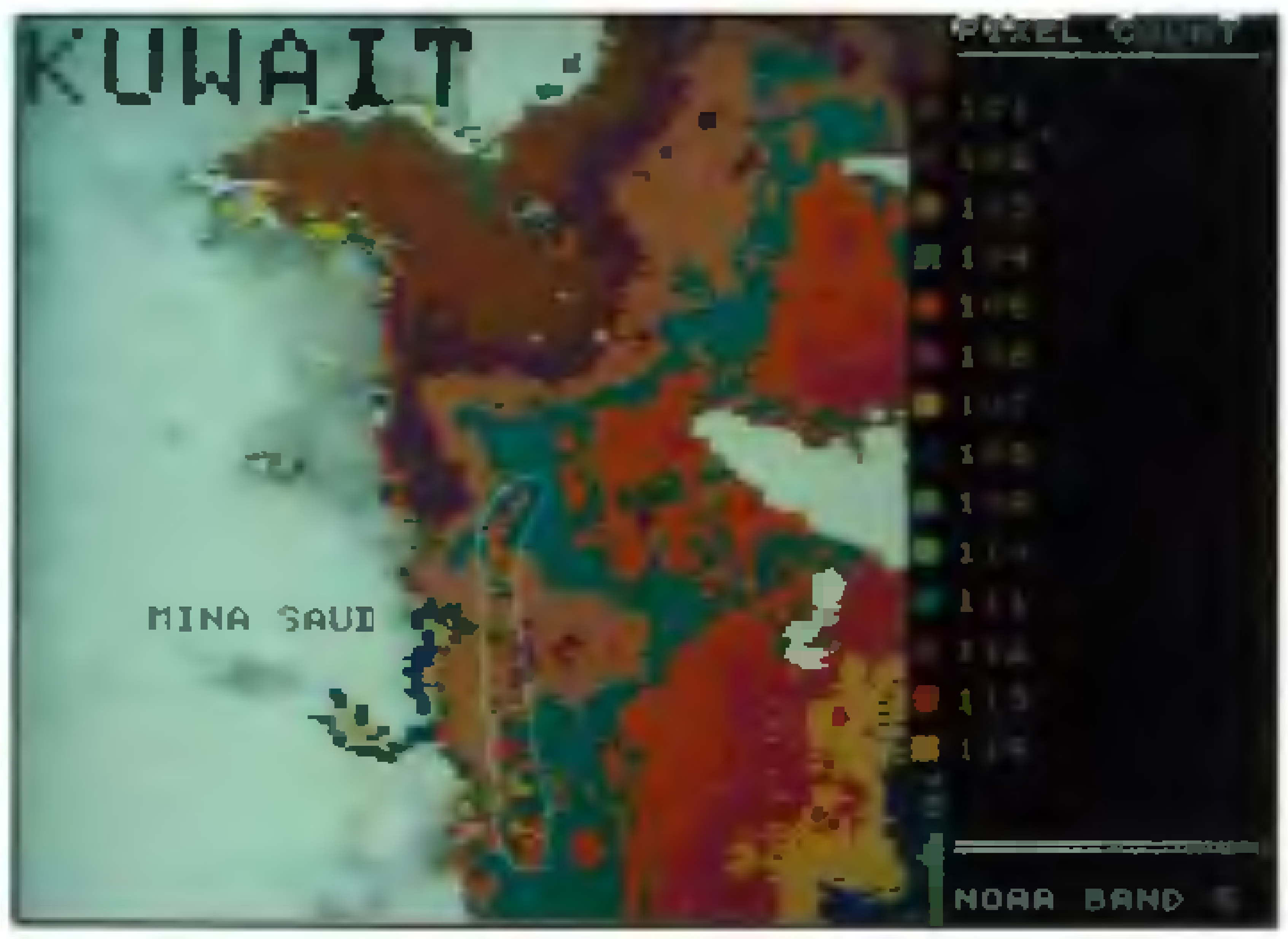

Figure 1,c. 3 × enlarged image showing the oil slick area of 26 January 1991.

trail was directed towards the south and the thin smoke was spreading across a considerable part of Saudi Arabia.

The image of 21 February (Figure 4), however, dramatically revealed the presence of a thick, large smoke plume from a large number of burning oil wells around Al-Ahmadi and Wafra oil terminals. The new dense smoke covered about 800 km^2 of area, extending 45 km in the east–west and 20 km in the north–south direction. Part of the smoke was clearly seen above the cloud level, indicating that it had reached the upper atmosphere. The eastward spreading of the thick smoke plume, where winds were westerly, also confirmed its good height. The analysis of 'smoke-top temperature' from channel 4 of NOAA-11 indicated a minimum height of 3 km. This may be an underestimate owing to solar warming relative to environment.

The image of 23 February (Figure 5) shows a significant expansion of the dense black smoke, spreading all the way to Ras-Al-Ghar, almost 250 km southward of its source. The thinner smoke, seen in red in Figure 5 surrounding the thick smoke, had spread beyond Al-Jubayl by 23 February. Subsequent images taken from 24 February to 11 March showed further spread in the smoke to the entire Gulf area.

While it is not possible to estimate, from the satellite imagery, the number of burning oil wells and quantity of oil being burnt continuously, we make certain observations on the regional effect of the smoke, particularly on the monsoon, in the following sections. Our observations are based on the reported number of 600 burning oil wells and on detailed theoretical models.

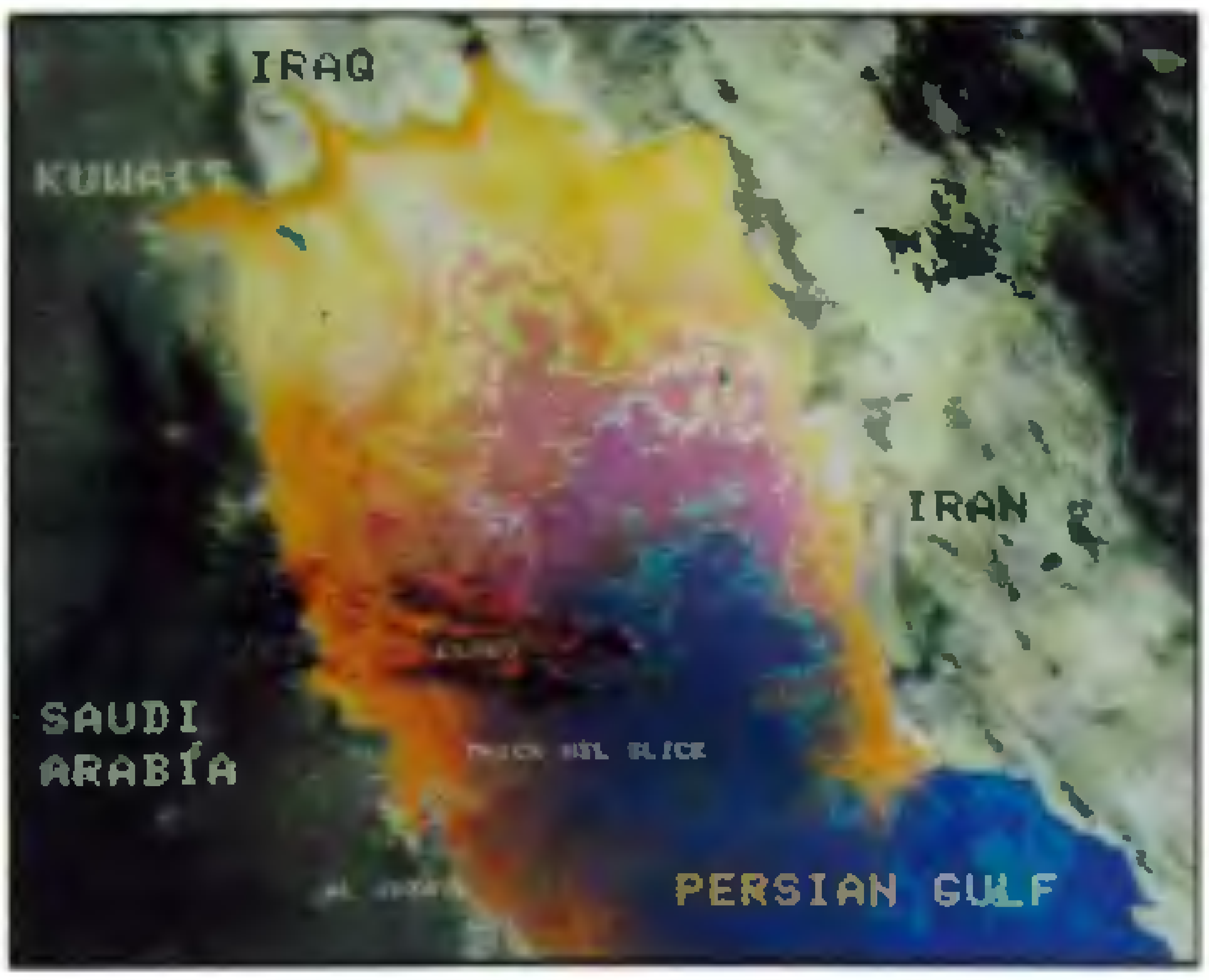

Figure 2,a. Colour composite of principal component analysis of 12 February 1991.

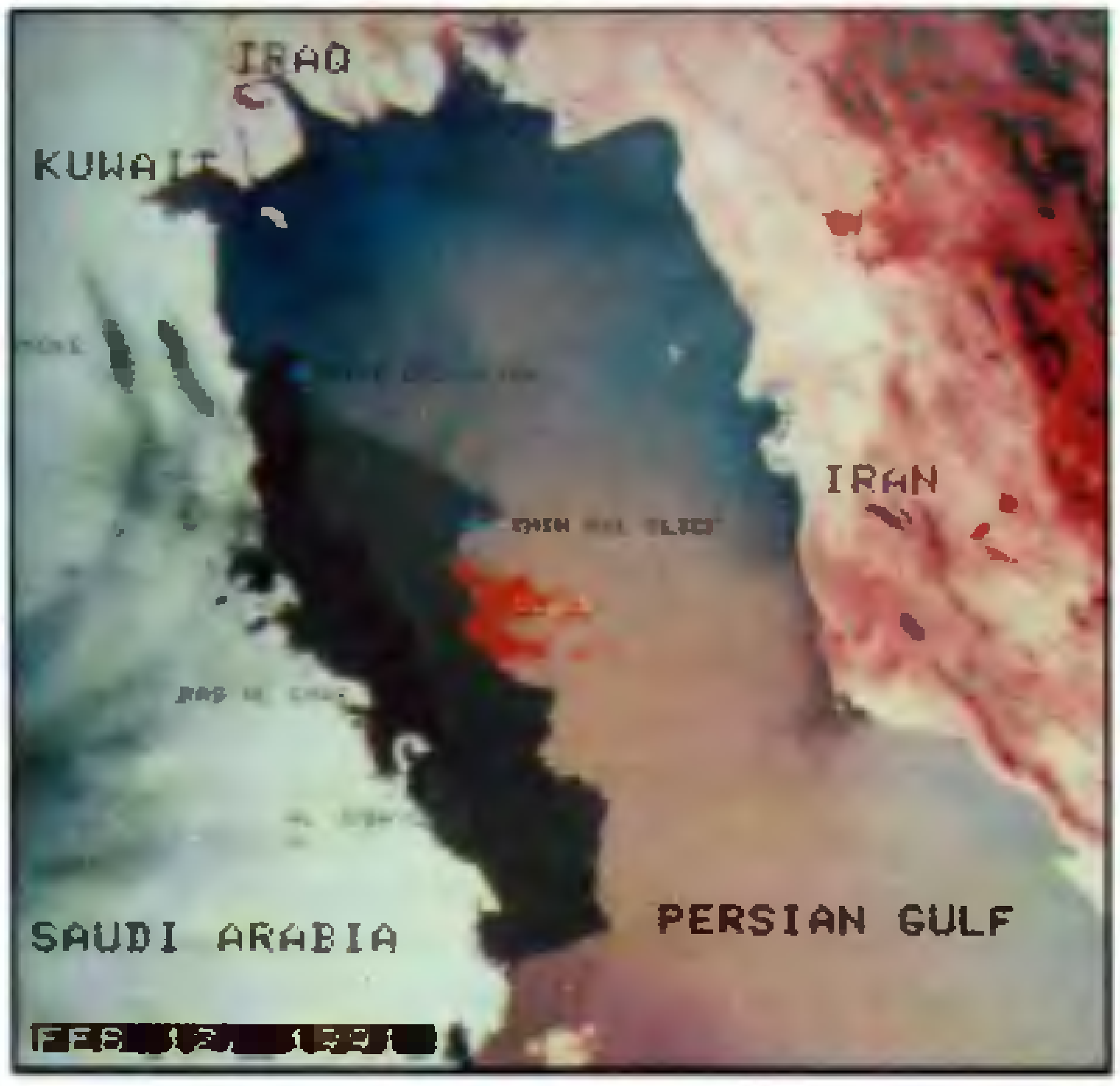

Figure 2,b. Enhanced FCC image of 12 February 1991.

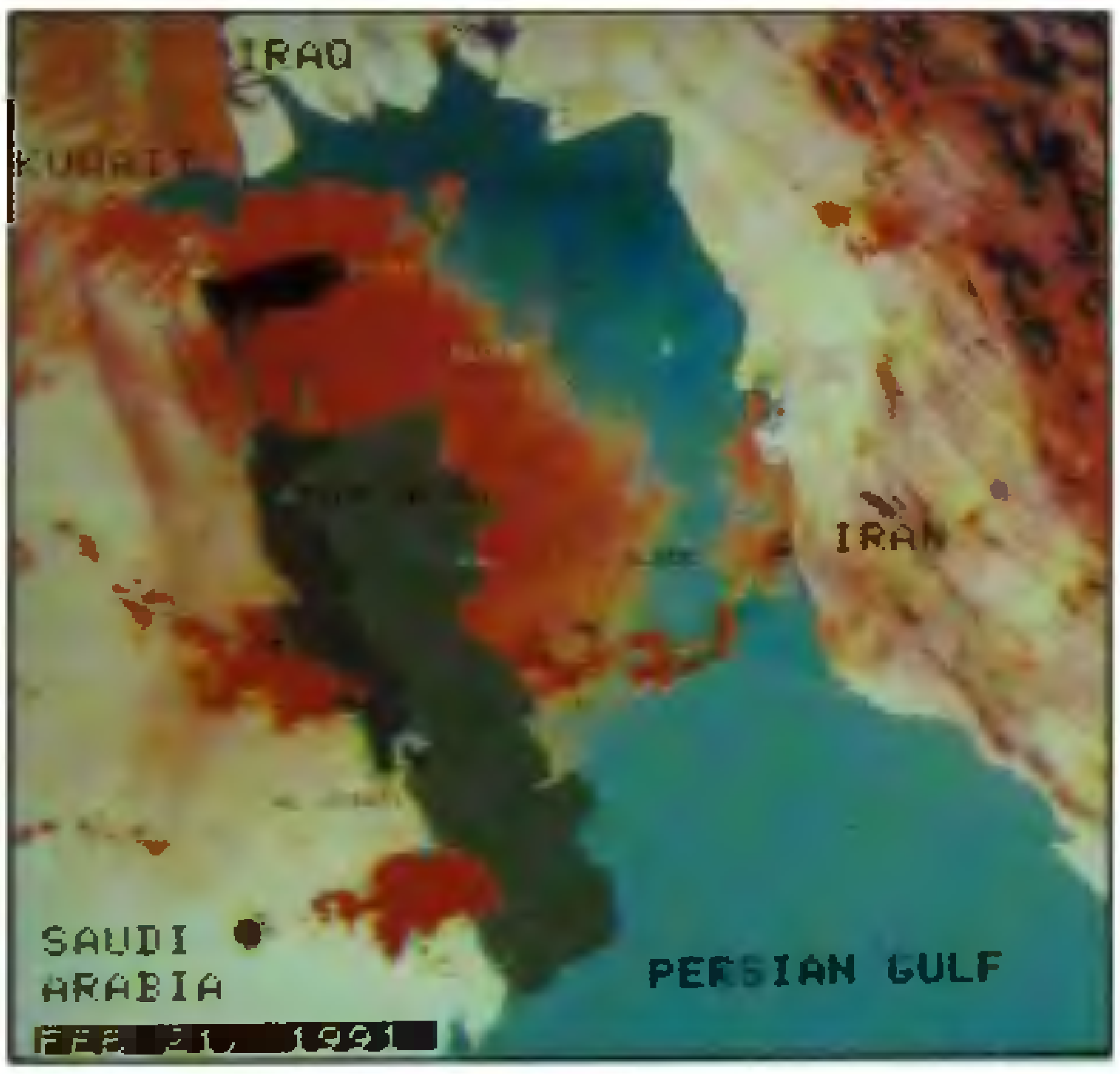

Figure 4. Enhanced FCC image of 21 February 1991.

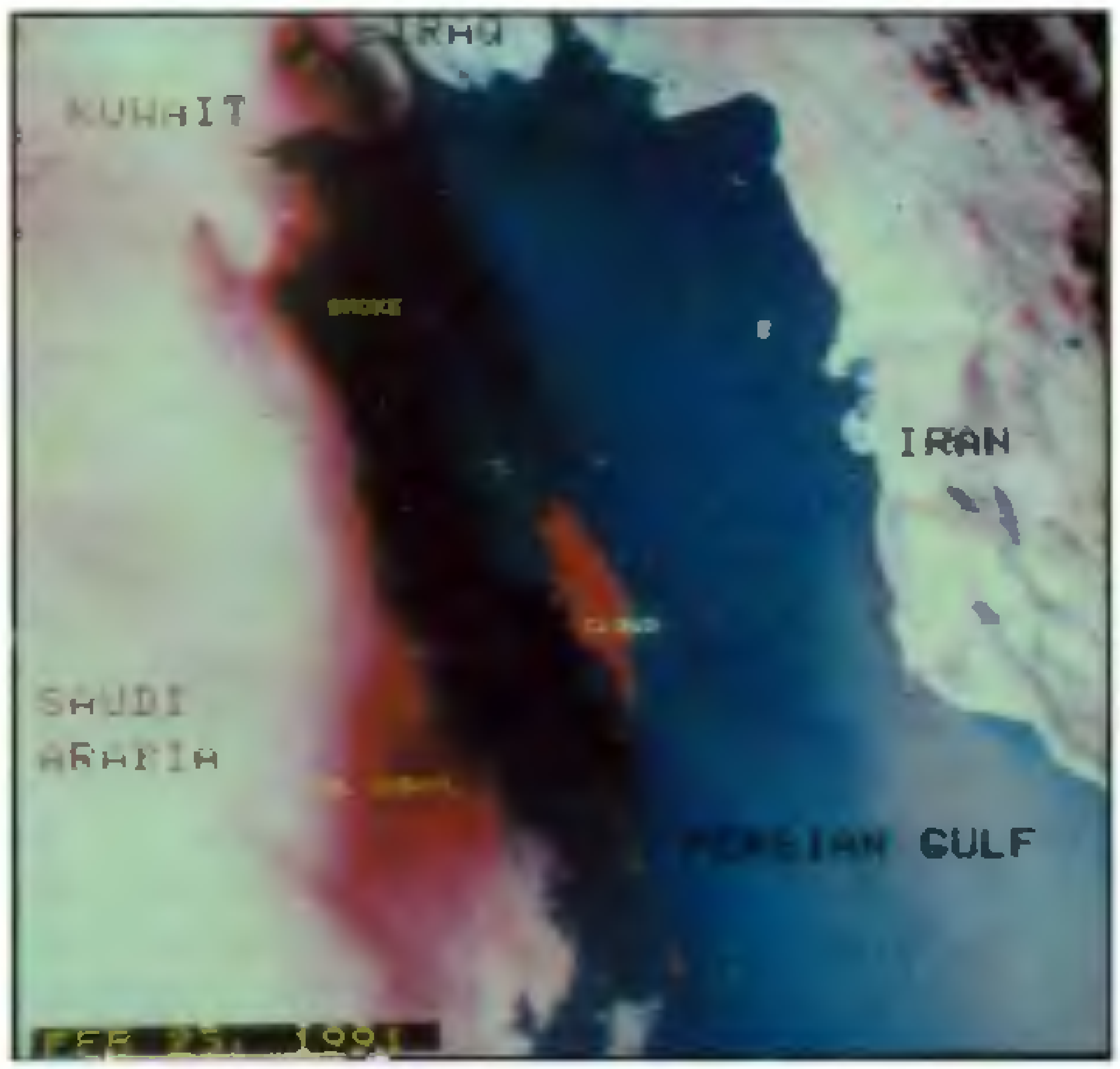

Figure 5. Enhanced FCC image of 23 February 1991.

Environmental effects of the oil slick

Since the oil slick was maintained within the early estimate of 10 million barrels of oil, as evidenced by subsequent imagery, it is inferred that the detrimental effect of the oil slick alone, in spite of its being about 30 times more than the accidental Alaskan oil spill, is likely to be limited. This is in spite of the fact that the depletion rate of the oil slick is in fact likely to be even slower, compared to the Alaskan case[6], because of the sandy beach in the area. While, as reported, there were casualty initially of a large number of diving sea birds, the long-term effect of the oil slick is not likely to be very significant. Again, based on Alaskan studies[6], it is concluded that traces of the oil slick that form the heavier component which sinks to the bottom of the ocean would remain for a period of at least two years, but its effect on the biota over a large area is not likely to be significant. The small amount of 'leakage', from the Gulf to the Arabian Sea, of the intermediate-density component at intermediate ($\simeq 300$ m) depth via under-currents is also not likely to pose any threat.

Smoke-induced cooling

The global effect of smoke coming out of the reported 600 burning wells, amounting to over 2.5 million barrels of oil burning each day, is, however, of great concern and must be carefully analysed. Since about 5% of this oil is converted into smoke, over 20,000 tons of smoke each day, or 600,000 tons of smoke per month, would be injected into the atmosphere. It may be noted that, if the smoke emission continues for a long period, it would amount to over a thirtieth of the global smoke emission from normal fuel burning and industrialization, which is estimated at 200 million tons per year. The continuous burning of oil wells will keep on replenishing the smoke content of the atmosphere, against gravitational settling, wide dispersal and precipitative scavenging, notwithstanding a slight reduction in the injection rate of the smoke into the upper atmosphere due to a saturation effect after the initial 15 days, which is the lower tropospheric residence time over the desert. Account should be also taken of the lofting of smoke by solar warming, and of the forceful ejection of smoke. Extensive calculations were carried out for the long-term effect on global temperature, assuming an initial upper-tropospheric injection rate of 5% and a stabilized injection rate of 3% after 15 days, and assuming different scenarios for the capping of the oil wells, commencing on various dates (from 10 March to 19 April) and with different numbers of wells capped per day (from 2 to 12).

The initial latitude and longitude spread of the smoke, as seen from the satellite imagery, is about 3 and 1° respectively. To compute the long-term effect, the diffusion of smoke in latitude and advection in longitude have been taken from climatology as 0.1 degree and 10 degrees per day respectively. The former is based on Sr-90 data[9] and the latter on the climatic wind. On the basis of extensive studies on the characteristics of the smoke[10], we have used 20% smoke content as a reasonable number for estimating the carbon content that is injected into the atmosphere, even though this might be a slight underestimate for the hydrocarbon source of smoke, especially when some oxygen starvation at the centre of a large fire is considered. The effective optical depth for the smoke emission was calculated[11] using the equation

$$\tau(\text{eff}) = 1.7\,[\tau(\text{absorption}) + 0.15\,\tau(\text{scattering})].$$

Absorption and scattering optical depths are estimated from the specific absorption and scattering coefficients and the column density of smoke. The estimation of 'local' surface cooling gives a drop of 9 K, which closely matches the reported drop over Kuwait of 8 K on 12 March. The fall in temperature as a function of time, as the number of wells burning is progressively reduced at the rate of three per day beginning 30 March (the reasonable scenario based on reported plans), for three locations, namely 30° N and 70°, 90°, 80° E, i.e. Pakistan, the Tibetan Plateau and Delhi, was calculated, the first two being critical synoptic systems for 'driving' the monsoon. Figure 6 shows the results of the calculations for the adopted scenario which indicate that a cooling of over 1 K can be expected during late spring and early summer over all these regions. Figures 7 and 8 show the results of similar calculations with different scenarios for control of the oil-well fires, i.e. capping at the rate of two and six wells per day starting from 10 March and 19 April respectively. Here it is noticed that the capping rate is more important than the start day for efficient reduction of the smoke-induced cooling effect in the pre-monsoon period.

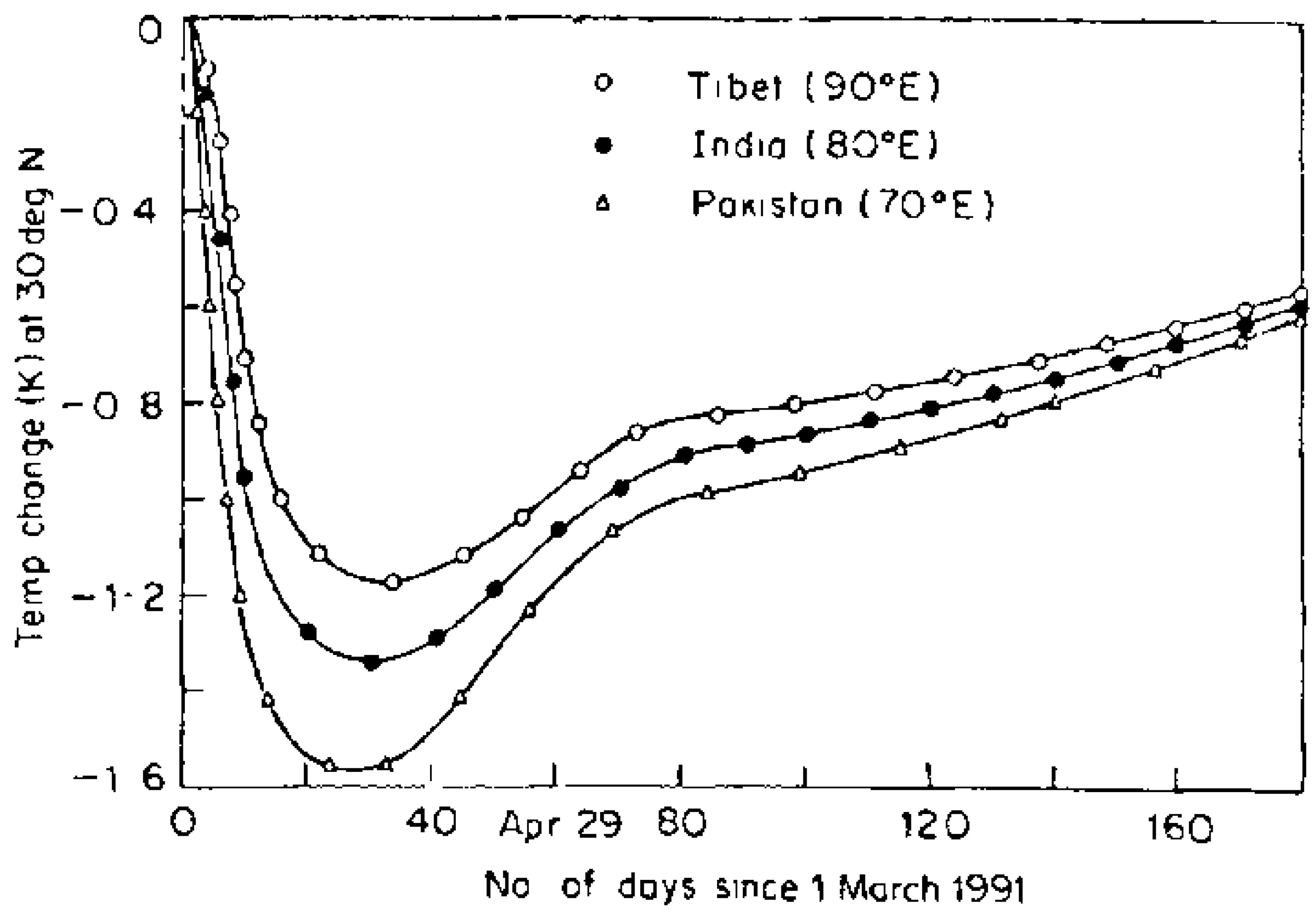

Figure 6. Surface cooling over Pakistan, India and Tibet (for capping three wells per day starting from 30 March 1991)

Impact of cooling on monsoon

The regional cooling over a relatively narrow belt

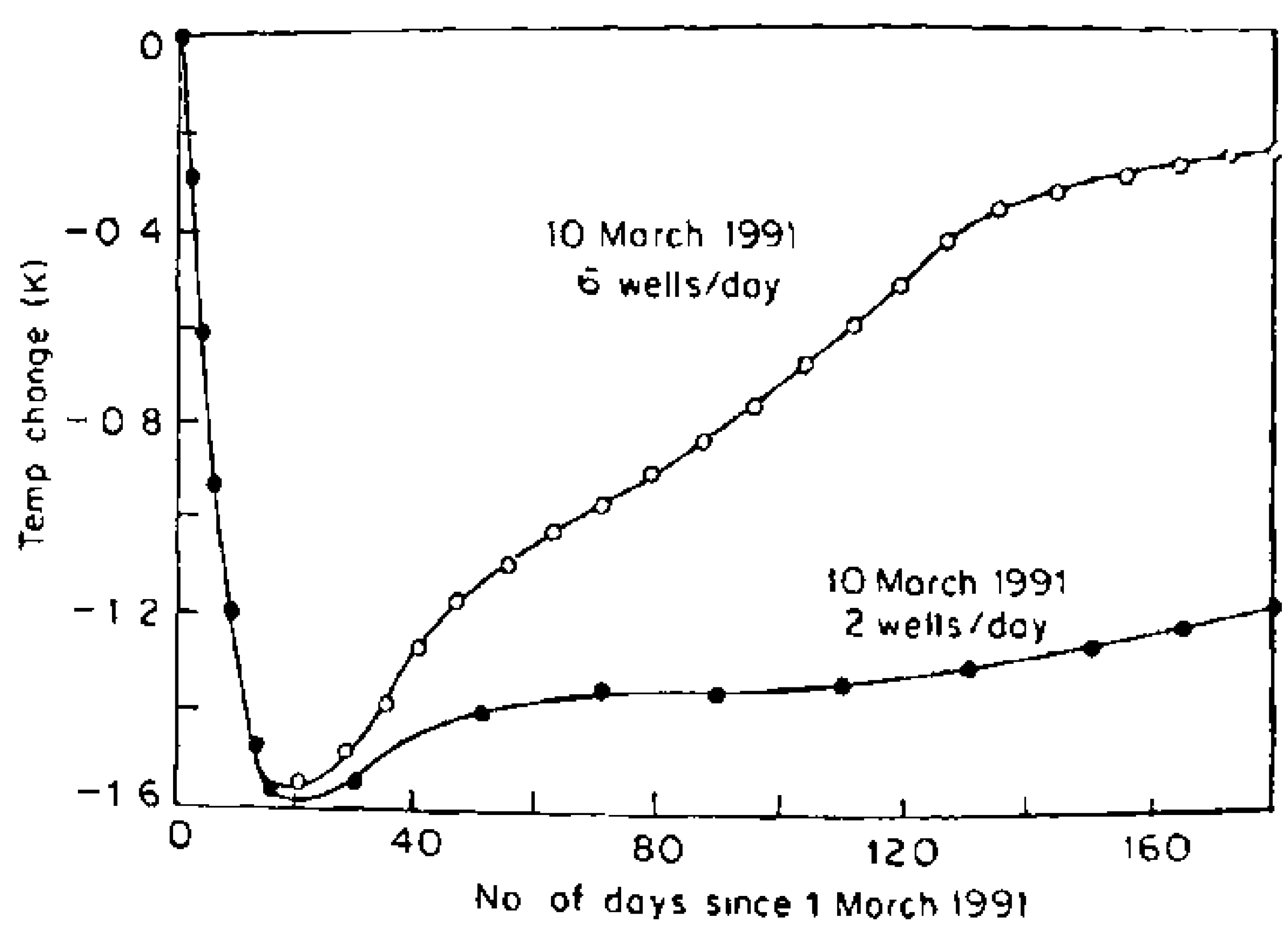

Figure 7. Surface cooling over Pakistan (for capping two and six wells per day starting from 10 March).

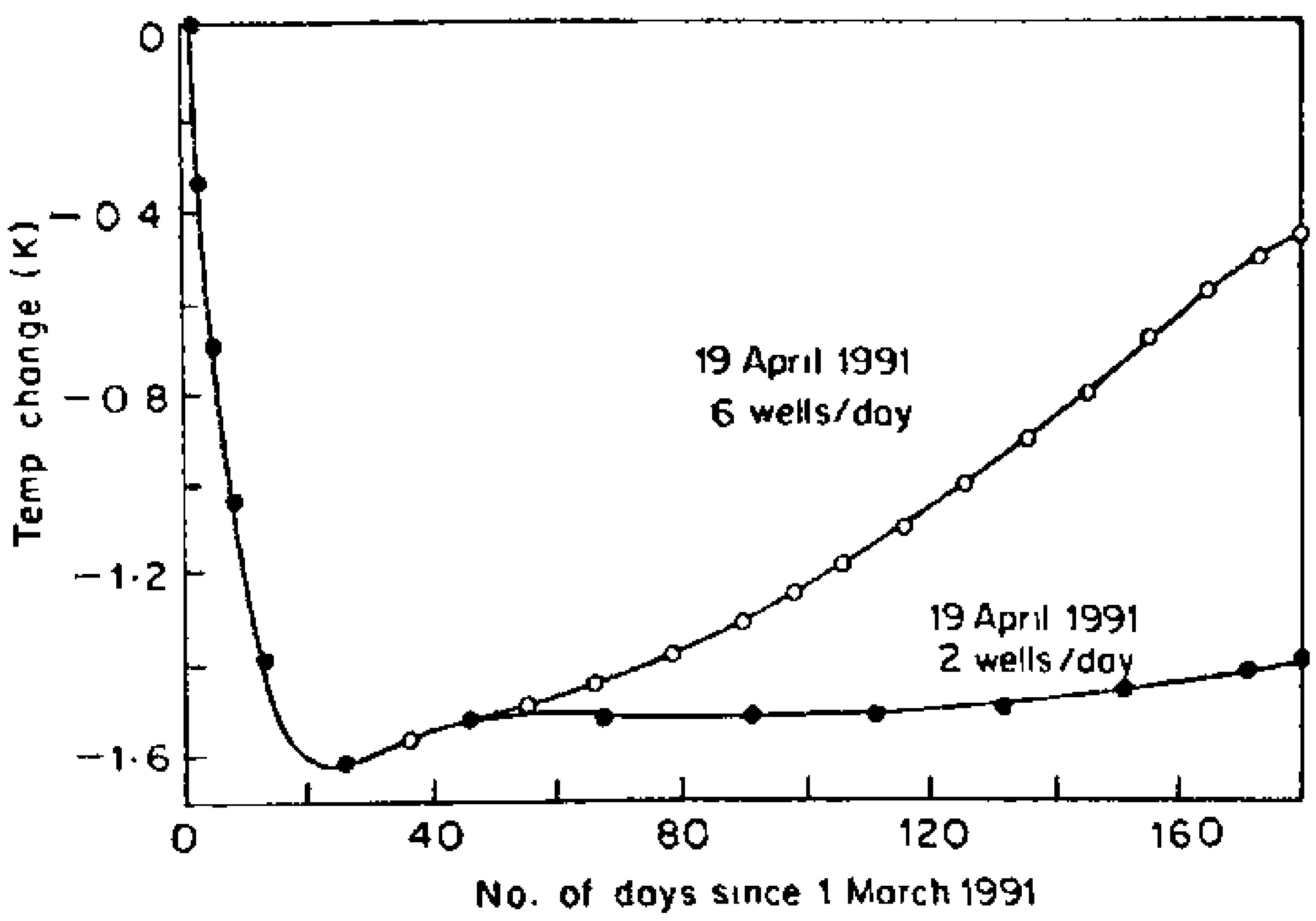

Figure 8. Surface cooling over Pakistan (for capping two and six wells per day starting from 19 April)

(about 8 degrees in latitude, centred at 30° N) over the Indian subcontinent (and further west up to Kuwait) in the pre-monsoon months is unprecedented and hence its probable impact on the monsoon has to be only estimated based on model calculations. By considering the 'thermal' cause of the monsoon, analysis of the impact of volcanoes and results of studies of the roles of the 'Tibetan High' and 'Heat Low' in the monsoon, we present a few conclusions on the likely effect of the regional cooling on the forthcoming monsoon.

The basic radiative forcing and condensational feedback mechanisms of the monsoon are well accepted, and in a broad sense it may be considered a large-scale 'sea breeze' generated by the land–sea heating contrast, sustained by latent-heat feedback. Any reduction in the overall solar radiation should tend to reduce this contrast (land being much more responsive than ocean to heat changes) and hence weaken the monsoon. This is confirmed from palaeoclimatic analysis as well as modelling studies[12]. When the solar radiation is differentially attenuated between different latitude zones, as in the case of volcanic dust-veil injection into the stratosphere, interesting variants of the above basic result occur. Low-latitude volcano explosions tend to weaken the monsoon whereas high-latitude explosions slightly improve monsoon performance[13]. These observations are explained in terms of decrease in land–sea heating contrast and increase in equator-to-pole temperature gradient respectively. It is to be noted that volcanic eruptions with higher sulphur content have greater atmospheric effect, as the stratospheric sulphuric acid is very effective in attenuating solar radiation[14], which also points to the volcano radiation monsoon link suggested earlier. In the present case of oil fire also, sulphur content is expected to be high; from the above observation, this may further aggravate the situation in terms of enhanced attenuation.

The tropical stratospheric aerosol will of course cool all tropical land regions and not just a limited region as in the present situation. Still, if the cause of its impact on the monsoon has been correctly identified as the regional land–sea thermal contrast, the oil-fire and volcano situations should have similar impact, except, possibly, the difference due to Indonesia being not affected here unlike in the volcano case. The surface cooling associated with volcanic dust-veils is of the order of a few tenths of a degree lasting a few months[15]. Further, a study of the record of northern hemisphere surface temperatures (NHST)[16] over the past 100 years also shows that decades of good-monsoon years and those with frequent droughts differ by only 0.5 K in NHST. Thus the 'threshold' of significance for surface-temperature perturbation to affect monsoon may be placed at 0.5 K (especially when it occurs over thermally relevant systems such as the 'Pakistan Heat Low' and the 'Tibetan High/anticyclone'), which is less than half the estimated regional cooling, which is expected to last several months.

The major low-level manifestation of the monsoon circulation is the Somali Jet over the western Arabian Sea. A model of its development and fluctuation[17] indicates that it responds to both the Mascarene high-pressure 'source' region and the heat-low 'sink' region. The latter broadly ranges from the Saudi Arabian desert to the monsoon trough over the Indian Gangetic Plain, but is most marked over the Jacobabad and surrounding area in Pakistan.

Any insufficiency in the late-spring/early-summer development of the Heat Low will weaken one of the two driving terms for the Somali Jet, which brings much moisture to India through evaporation over both the Indian Ocean and the Arabian Sea. The Heat Low is primarily caused by the intense solar heating coupled with upper-level subsidence, the latter partly attributed to atmospheric dust-induced cooling[18]. The soot-induced surface cooling as well as upper-level warming (by solar-radiation attenuation and absorption respectively) will reduce the above two effects; this is detrimental to the full development of the Heat Low. Observation of weaker Heat Low (negative temperature anomaly or positive pressure anomaly) in the years of poor monsoon, e.g. 1987, corroborates this hypothesis.

The second important thermal synoptic subsystem of the monsoon, which is also affected in the present scenario, is the Tibetan High (upper anticyclone). Here the situation is a little more complex. The correct positioning and strength of this system are important for the timely onset and normal performance of the monsoon; years in which the anticyclone remained east of its normal position had delayed onset, which also resulted in drought-like conditions, especially over north west India, possibly due to the positioning of the descending branch of the east west overturning over that region in those years. The anticyclone is to the east–southeast of Tibet in the pre-monsoon months; its northwestward shift and positioning over Tibet are important for 'triggering' onset of the monsoon, as shown by both modelling study[19] and observations[20]. However, after the initial shift owing mainly to direct solar heating of the Tibetan Plateau, the subsequent sustainment of the anticyclone is fed by condensational heating due to strong convective activity along the Himalayan eastern foothills[19], as seen by satellite estimates of heating rates[21]. Thus the cooling due to solar attenuation may only perturb the initial placement of the anticyclone but not necessarily its subsequent development (sustainment), unless the soot particles act to overseed the northeast-Indian cloud systems. Further, satellite observations indicate that the 100-mb level undergoes an appreciable cooling of about 10 K, accompanied by a warming by a similar amount at 200 mb, over a period of about a month, centred at the onset of monsoon, over the eastern Tibetan Plateau[22], and the presence of soot in the stratosphere can hinder both these processes. Pant[23] has made an analysis of 500-mb temperature anomalies observed over a few stations in the Tibetan Plateau and their association with different phases of the monsoon. The lowering of temperature was seen to be associated with the beginning of the break phase of the monsoon, and vice versa. Changes of the order of 10°C at the 500-mb level were observed between active and break cycles, with a change of roughly 1°C/day near the ground. MONEX results also revealed[24] that the seasonal warming of the Tibetan Plateau in 1979 was weak, coincident with subdued activity of overall monsoon activity in that year. Murakami and Ding[25] studied wind and temperature changes over Eurasia prior to onset of monsoon. They concluded that the increase in upper-tropospheric temperature and heating over the mid-latitude regions over the Indian longitudes could be prerequisites to establishment of the summer monsoon over India. Kuma[26] made an extensive model computation to understand the conditions for the onset of monsoon. He found that formation of the Tibetan anticyclone is necessary for monsoon onset. Moreover, for formation of the anticyclone, heating over the Tibetan Plateau was found to be important (as a general background condition), besides the specific triggering action caused by the southeast-Asian monsoon. These perturbations can be reasonably expected to result in a delay in the onset of monsoon, while the heat-low effect will cause overall weakening of the monsoon.

Conclusion

The smoke-induced surface cooling (and slight upper-level warming) by itself should result in a delay in the onset of monsoon in 1991 as well as some weakening of it, and even monsoon 1992 might be similarly affected unless the Gulf oil-well fires are controlled by next spring. Since the monsoon is governed by a number of global factors, we have not attempted to predict the overall status of it in this paper, but only wish to draw attention to the relative weakening and delay in the monsoon resulting from the prolonged burning of oil wells in the Persian Gulf area.

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