Influence of the Arabian Sea tropical cyclone and the Western disturbance on the appearance of *Puccinia graminis* f. sp. *tritici* virulence Ug99-TTKSK in Iran in 2007

In Iran wheat was sown over 6.5 million hectares (m ha) in 2012, of which 4.0 m ha has access to irrigation and the rest is rainfed. Irrigated wheat is cultivated under four different environments and the total wheat production of Iran is about 14.6 million tonnes. This includes the long-duration/winter-type durum grown in the western parts for Cus-Cus and bulgur, etc.[1]. Wheat in the plains is sown during November as an irrigated crop and is harvested by early May. Facultative, long-day bread wheat is grown in the middle elevations, whereas at higher elevations where snowfall is common, winter wheat is grown from October to July/August[1]. There is also the much longer duration wheat that is grown in the hills of Iran. Iran cultivates barley (*Hordium vulgare*), bread wheat (*Triticum aestivum*), durum (*T. durum*) and Khapli (*T. dicoccum*)[2] are also cultivated in Iran, which are vulnerable to *Puccinia graminis tritici* (*Pgt*) that causes stem rust on wheat.

In 2007, stem rust samples collected from Broujerd and Hamedan in Iran were of virulence Ug99-TTKSK. It was inferred that the inoculum source was from Africa where Ug99-TTKSK was prevalent[3,4]. Such a spread created fear about stem rust pandemics and associated foodgrain shortages[5]. Locations where Ug99-TTKSK was reported are within the Zagros mountain range system with several snow-clad peaks. This area comes under Zone IV (cold zone) and some locations even record a minimum temperature of –10°C. In this zone cold-tolerant facultative wheat is grown over 0.87 m ha, of which 34% is irrigated and the remaining is rainfed.

The spread of Ug99-TTKSK urediniospores from Africa passing over the great Arabian Desert to Lorestan and Hamadan Province, Iran[3], is not likely to happen due to surface-level winds. Spread of *Pgt* urediniospores over an aerial distance of 1000 km is due to the enabling mid-altitude wind systems (~3000 m height) or by large cyclonic circulations and associated rain that wash-down the spores to crop foliage[6]. Therefore, mid–low-level weather systems of January to June 2007 of this region were examined.

In 2007 winter, Iran experienced 2°C below normal winter mean temperature and the summer mean temperature was 2°C above normal. And nearly half of Iran experienced 25% above normal winter rainfall. Wheat season 2007 was wet, from the time of seeding in November 2006 till harvest in July 2007 (ref. 7). Winter precipitation in Iran is caused by mid–low-level altitude low pressure systems known as the Western Disturbance (WD) that forms periodically in the Black Sea area during the winter months[8]. In 5–7 days period, these low pressure systems gradually drift toward the Himalaya/Indian subcontinent causing snowfall, rain and cold spell. The mid–low-level synoptic weather charts of the Northern Hemisphere for this period showed many low pressure systems of WD drifting eastwards, but the wind generated did not link Iran with Ethiopia, Yemen or Kenya.

The northern part of the Arabian Sea is not the regular area where tropical cyclones occur. But something unusual happened during late May and early June 2007. A tropical cyclone *Gonu* formed 600 km south of Mumbai on 30 May 2007, intensified and moved towards

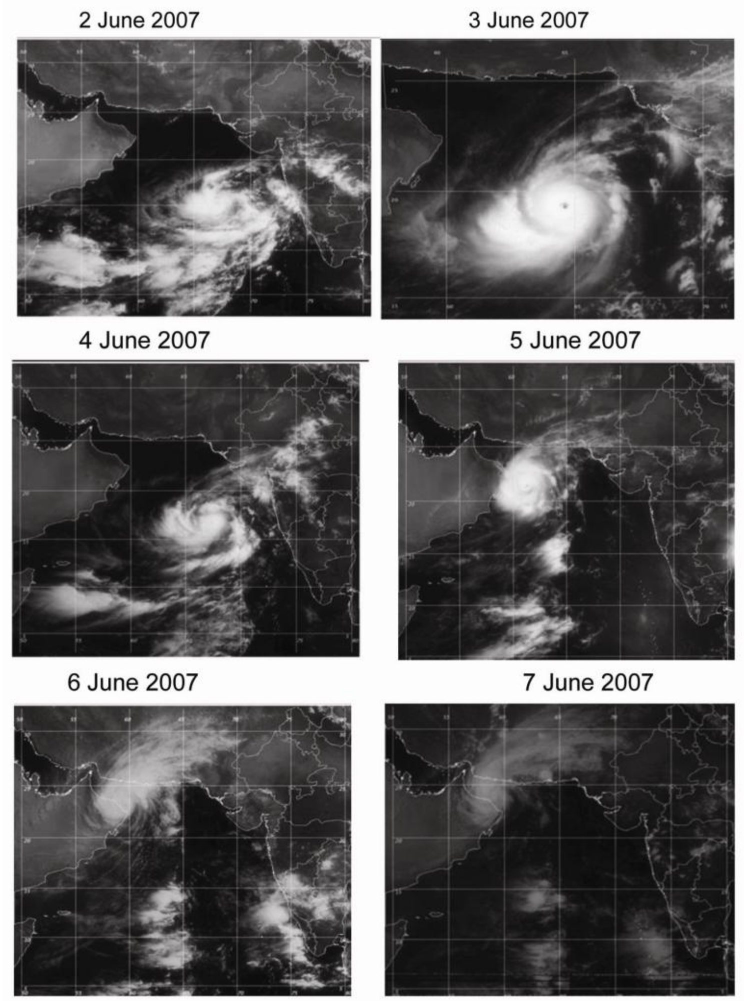

Figure 1. Visible light spectrum scans of tropical cyclone *Gonu* as sensed by the Indian satellite Kalpana. (Courtesy: India Meteorological Department, Government of India.)

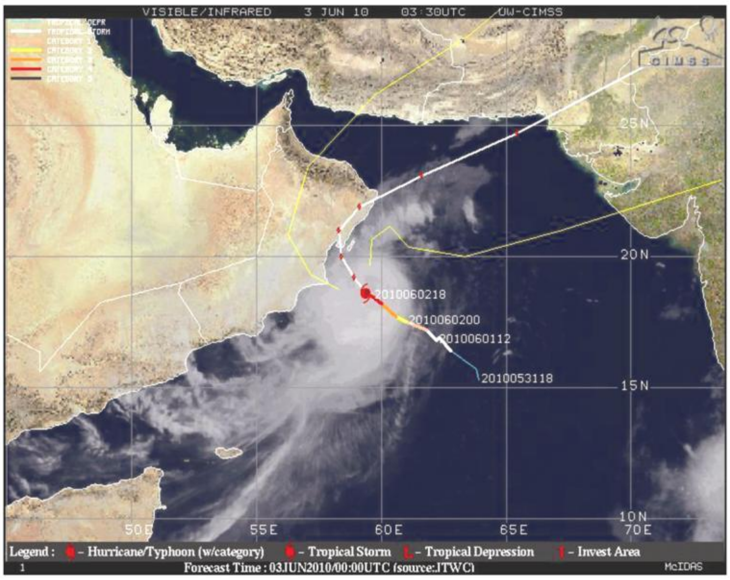

Figure 2. National Oceanic and Atmospheric Administration (NOAA) satellite data-generated position of tropical cyclone *Phet* near Muscat on 2 June 2010. The track route of the cyclone, intensity and position each day are marked till it landfilled in Karachi, Pakistan (courtesy: NOAA, USA).

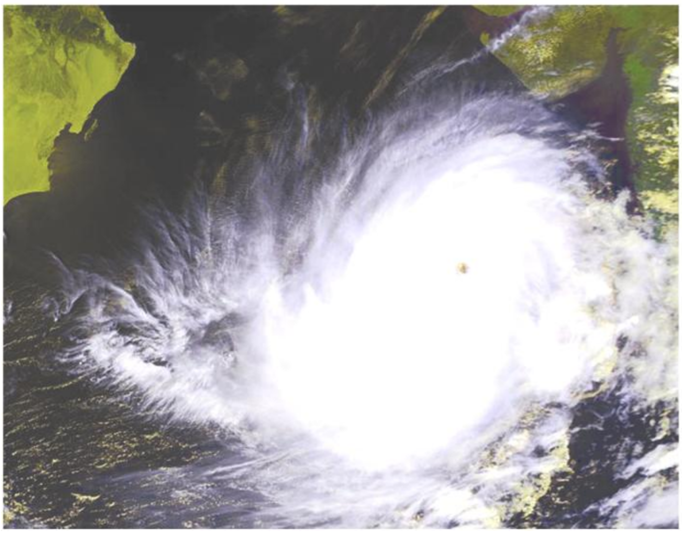

Figure 3. Weather satellite photograph of tropical cyclone 01A as on 24 May 2001, generated by NOAA. The cyclone eventually had landfill over Gujarat, India (courtesy: NOAA, USA).

northern Oman. *Gonu* was periodically tracked by the Indian (meteorological) weather satellite Kalpana (Figure 1). On 4 June 2007, the Kalpana satellite spotted *Gonu* while it was approaching the northeastern shore of Oman. On 4 June 2007, the powerful storm reached a dangerous category and crossed the easternmost tip of Oman on late 5 June 2007. On 6 June, the cyclone turned to the north-northwest and made landfall on the Makran coast of Iran[9]. Long-term climatic data indicate that cyclonic systems like *Gonu* rarely form during the monsoon months (June to September) in the Arabian Sea[10] and seldom move the way it did, causing high-speed wind circulation and heavy rainfall.

The tropical cyclone *Phet* reached its greatest intensity off the coast of Oman on 3 June. After making landfall in Oman, it somewhat weakened but remained organized to move back over the Arabian Sea toward Pakistan (Figure 2). The heaviest rainfall of ~600 mm was recorded off the coast of Oman, where the storm reached its greatest intensity. Following that light rain was recorded along the coasts of Oman, Iran, and Pakistan. Even though Ug99-TTKSK was recorded in Iran in 2007 and *Phet* traversed the area in 2010, this virulence did not spread eastwards to Pakistan[11].

The other storm formed over the Arabian Sea was cyclone 01A, which tracked northwest along the coast of India between 21 and 28 May 2001. Unlike *Gonu*, cyclone 01A never reached ashore[9] and ended in the sea itself (Figure 3). There was another tropical cyclone 01A category system that persisted from 5 to 11 May 2004 formed near the west coast of India in the Arabian Sea and crossed Gujarat/Sindh (Figure 4). These two cyclones did not result in the spread of Ug99 which was already prevalent in Uganda and Kenya[5]. Occurrence of tropical cyclone in the Arabian Sea is very rare; about 1.84 cyclones per year[12].

Aerial transport of fungal pathogen alone is seldom responsible for the introduction of non-indigenous virulence into distant regions. However, the capacity to use the atmospheric pathway for rapid spread in large part determines the invasive potential of organisms once they are introduced[13]. Because physical and biological features of the Earth's surface influence the routes and timing of organisms that use the atmospheric pathway, long-distance movement of *Pgt* is largely regular and thus predictable. The *Puccinia* pathway identified in the Indian subcontinent is a classic example[14]. Hurricanes and tropical storms are known to facilitate the long-distance dispersal of fungal plant pathogen and also when they pass close to the inoculum area of *Pgt* and have landfill at a place ~1000 km away over fields having wheat seedlings. The post-cyclone rainfall and leaf wetness conditions favour rapid stem rust development[6].

Cyclonic systems have also been associated with long-range dissemination and local increase of the bacterium *Xanthomonas axonopodis* pv. *citri* (*Xac*), which causes Asiatic citrus canker (ACC). And when combined with pre-storm introductions to new areas, post-storm spread of *Xac* was rapid and overwhelming. In 2004, three hurricanes (*Charley*, *Frances* and *Jeanne*) and one tropical storm (*Ivan*) crossed the Florida peninsula,

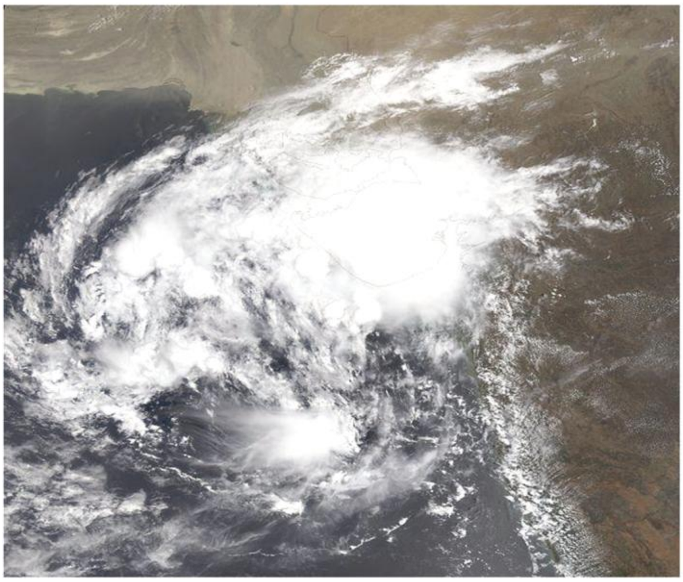

Figure 4. Tropical cyclone 01A swirling in the Arabia Sea as on 10 May 2004. The centre of the storm was close to 250 km south of Veraval in Gujarat and was moving north towards the southern coast of Gujarat with winds of 60–80 km/h (courtesy: NOAA, USA).

USA and exacerbated pre-existing ACC infections and dispersed the pathogen over a wide area[14].

In 2006 and 2007, Admassu *et al.*[15] analysed 152 stem rust samples from Ethiopia and recorded 22 different types of *Pgt* virulence. Ug99-TTKS was present in all the sampled regions, except in northwest Ethiopia. Had *Gonu* enabled the spread of Ug99-TTKSK from Ethiopia to Iran, then the other *Pgt* virulence types recorded by Admassu *et al.*[15] could have also reached Iran where diverse wheat varieties are grown. *Phet* brought strong winds and heavy rains to the Arabian Sea, the Arabian Peninsula and to the coast of Pakistan in late May and early June 2010. The path of *Phet* mapped by the Earth Observatory, National Oceanic and Atmospheric Administration (NOAA), USA is given in Figure 2. At that time even though *Pgt* Ug99-TTKSK was present in Iran, *Phet* did not spread the *Pgt* Ug99-TTSK further either within Iran or to neighbouring Pakistan/India. This isolated report of Ug99-TTKSK from Iran needs an epidemiological examination in the light of India's concerns to increase wheat production further[16]. This study indicates that the North Arabian Sea tropical cyclones and WD are not involved with the appearance of *Pgt* Ug99-TTKSK in Iran in 2007. This further reinforces the earlier results that *Pgt* virulence from East Africa[17,18] does not spread to India[19] under the influence of these macro weather systems.

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