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Atmospheric and fuel conditions related to the Puerto Madryn Fire of 21 January, 1994

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The atmospheric and fuel conditions that led to the case of extreme fire behaviour registered in Puerto Madryn in north-eastern Patagonia, Argentina, on 21 January 1994 were analysed in this study. The analyses included surface and upper-air meteorological conditions, fuel composition and load, and morphometry of the burnt area. When the fire occurred the total fuel load was 16 688 ± 2 611 kg of dry matter per hectare, with fine fuel representing 66% of the total fuel load. At the time of the major fire run, the air temperature reached 32 °C and relative humidity decreased to 13%. The fuel load and its high proportion of fine fuels, the extreme temperatures, the low relative humidity, and the changes in wind directions which resulted from the conjunction of synoptic and local-scale phenomena, enhanced the development of a large convection column which favoured the interaction of surface and upper-air winds. As in similar cases reported for other ecosystems, the combination of these phenomena led to this case of extreme fire behaviour. It is intended that this analysis will contribute to the future development of fire alert systems for the region and to the worldwide knowledge of extreme fire behaviour in different scenarios.

1. Introduction

The coastal rangeland area of north-eastern Patagonia in Argentina is a shrubby steppe characterised by its high winds and low and irregular precipitation (Soriano, 1983; Ares *et al.*, 1990). This area is prone to wildfires during late spring and summer, when high temperatures are coupled with low relative humidity. Lightning, careless campers, hunters and sometimes ranchers are responsible for igniting most of these fires which, in general, are small and easy to control because they occur in heavily grazed areas, where fuel load lacks horizontal continuity.

In some areas, however, and especially around Patagonian coastal cities, many ranches have been abandoned for various reasons. The lack of grazing has allowed the recovery of vegetation, increasing the shrub and grass components. In these particular areas, the rate of decomposition of standing dead material to litter and then to organic matter is very slow, and this accumulation of fine and medium-sized dead fuels notably increases the fire hazard.

On 21 January 1994, at about 1430 (local time), a wildfire was detected in a rangeland area 10 km west of Puerto Madryn in north-eastern Patagonia. Three crews with a total of 25 people were dispatched from the Puerto Madryn Volunteer Fire-Fighters Department to suppress what at the beginning was thought to be a small, easy to control, rangeland fire. At about 1730, the fire activity increased remarkably; a change in wind direction transformed the south flank of the fire in its head, and in a few minutes the fire was out of control. The radio contact with the fire foreman was lost and the rapid spread of the fire overran the 25 fire-fighters; no one survived.

This case study, aimed at determining the atmospheric and fuel conditions that led to the worst disaster in the wildland fire-fighting history of Argentina, has the following specific objectives:

(a) to determine the fuel load and vegetational characteristics of the burned area;
(b) to describe fire behaviour characteristics; and
(c) to describe the interaction of the synoptic weather pattern, the local atmospheric conditions, and the fire behaviour.

The analysis of this case is a contribution to the worldwide knowledge of extreme fire behaviour in different scenarios. Though each fire is only a single observation of a complex process, the analysis of each fire event can provide insights into the physical processes that control large fire behaviour (Simard *et al.*, 1983).

2. Methods

2.1. Site description

The fire occurred in the north-eastern part of the province of Chubut in Patagonia, Argentina (42° 48′ S, 65° 08′ W), on a plateau 110 to 130 m a.s.l. about 10 km west of the city of Puerto Madryn (Figure 1). It took place in a paddock that, having not been grazed for at least 20 years, had accumulated a considerable amount of fine and medium-sized fuels.

Phytogeographically, this area belongs to the southernmost portion of the Monte Phytogeographic Region of Argentina (Soriano, 1956; Cabrera, 1976). It is physiognomically similar to the Sonoran Desert of the southern United States, where the genus *Larrea* (creosotebush) is dominant, and also to some shrubland regions of Australia. The vegetation of the area (Figure 2) presents an upper shrub layer (1.5 to 2 m tall) composed of *Larrea divaricata, Condalia microphylla, Schinus johnstonii, Chuquiraga hystrix* and *Lycium chilense,* an intermediate shrubby layer (0.5 to 0.8 m tall) dominated by *Chuquiraga avellanedae*, and a grass layer (0 to 0.5 m) composed of the grasses *Stipa speciosa, Stipa tenuis,* and *Poa ligularis* (Bertiller *et al.*, 1991). This vegetation shows arido-passive growing strategies, i.e. that growth and phenological development is interrupted during the summer drought, when plants become completely dry (Fischer & Turner, 1978). The exceptions are *Larrea divaricata* and *Chuquiraga avellanedae,* species with arido-active phenological strategies, which show activity and complete their phenological development during the dry period (Bertiller *et al.*, 1991). This is so because they tap water from deep soil horizons due to their well-developed root systems.

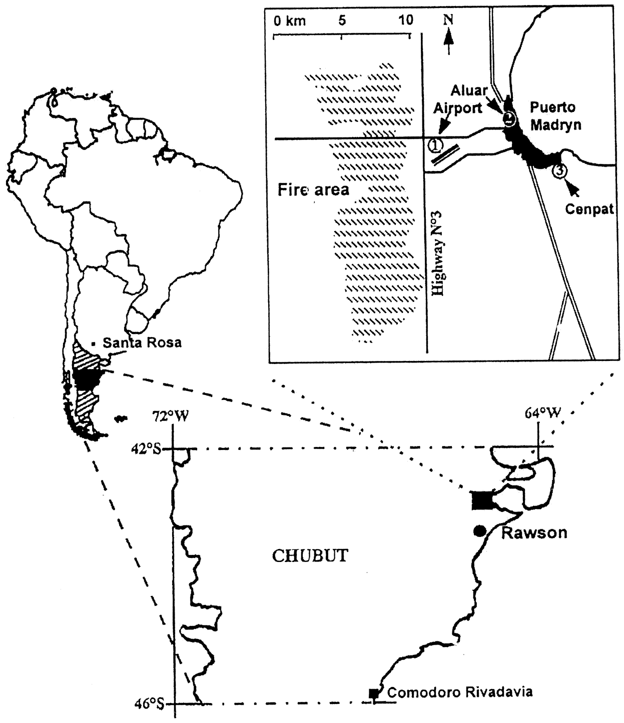

Figure 1. *The Province of Chubut in the Patagonian region (dashed area) of Argentina. In the right corner (enlarged) the Puerto Madryn area where the fire occurred. The numbers 1 (Airport, 110 m a.s.l), 2 (Aluar, 25 m a.s.l.), and 3 (Cenpat, 7 m a.s.l.) represent the location of the nearby meteorological stations. Note that Airport is located on the plateau were the fire occurred. The principal access roads to the city are also shown.*

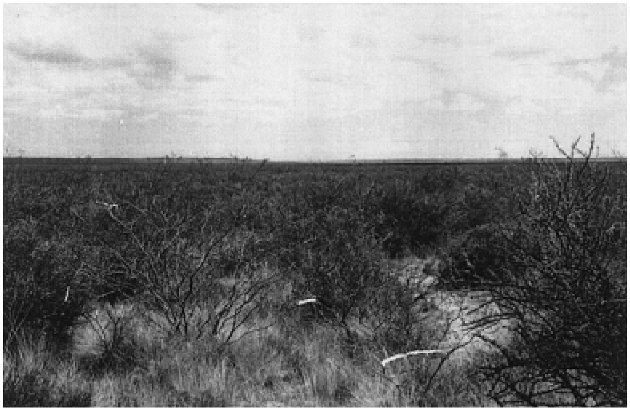

Figure 2. *Vegetational characteristics of the area in which the fire occurred. This vegetation is composed of an upper stratum (1.5 to 2 m tall) dominated by species of the genus* Larrea *(creosotebush); an intermediate stratum (0.5 to 0.8 m tall) composed of* Chuquiraga avellanedae, *and a lower grass stratum (0 to 0.5 m tall) of* Stipa speciosa, Stipa tenuis *and* Poa ligularis. *Litter and standing dead grasses represented 36% of the total fuel load.*

The climate of the area is semi-arid with water deficit throughout most of the year, briefly interrupted from May to June (Figure 3).

(a) Annual mean precipitation is 182 mm, presenting high interannual variation (Barros & Rivero, 1982).
(b) Annual mean temperature is 13.6 °C, with monthly means ranging from 7.3 °C in July to 19.9 °C in January.
(c) Annual mean maximum temperature is 20.2 °C, with monthly means ranging from 12.8 °C in July to 27.4 °C in January.
(d) Annual mean relative humidity is 57%, with monthly means ranging from 48% in December and a maximum of 66% in June.
(e) Annual mean wind speed is 4.6 m s^{-1}, with monthly means ranging from 5.0 m s^{-1} in December and January to 3.6 m s^{-1} in April and May.

Because of its proximity to the sea, this area is often affected by sea breezes from late spring to early fall. The characteristics of this phenomenon were analysed for the periods of September 1974 to March 1975

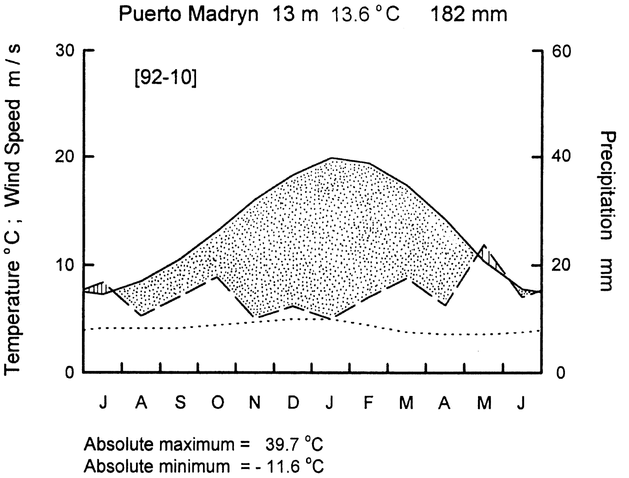

Figure 3. *Climatic diagram (following Walter & Lieth, 1960) for Puerto Madryn. The abscissa represents the 12 months of the year starting in July. Each ordinate division represents either 10 °C, 10 m s^{-1} for wind speed, or 20 mm precipitation. The solid line represents the monthly mean temperature, the broken line represents the monthly mean precipitation and the dotted line represents monthly mean wind speed. The stippled area below the temperature curve represents a period of drought, whereas the hatched areas indicate periods of water excess. Numbers in brackets represent years of observation for precipitation (left) and temperature (right).*

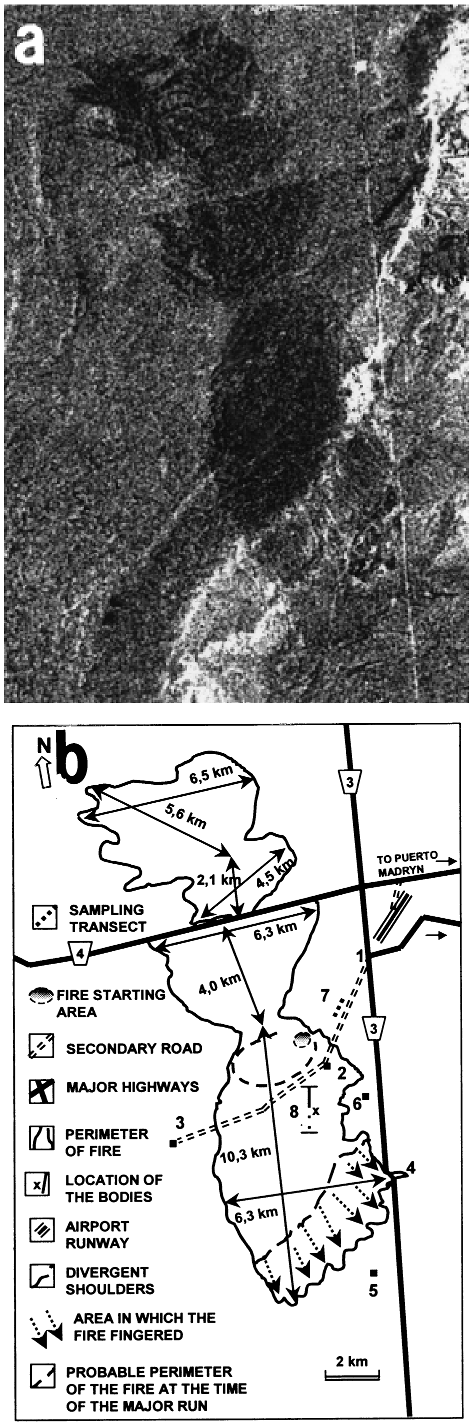

Figure 4. *(a) Multi-temporal image (ERS-1 SAR with enhancement process) of the burned area. This image was composed from data taken before (19 January 1994) and after (8 February 1995) the fire occurred. (b) Morphometric characteristics of the burned area and location of reference points. Numbers 2, 3, 5 and 6 represent abandoned ranch dwells. Number 1 is the secondary road entrance, number 4 is the place where the fire crossed Highway 3, number 7 is the sampling transect, and number 8 is the transect along which the bodies were found.*

(Rivero & Barros, 1975), and from October 1975 to March 1976 (Scian, 1976). According to Rivero & Barros (1975), the most frequent starting time for the breeze was at noon, with the effect lasting for 7 or 8 hours. The average wind speed for the breeze was of the order of 4.2 m s^{-1}, with some cases in which wind speeds exceeded 8.3 m s^{-1} (Rivero & Barros, 1975). In most cases, sea breeze penetration was confined to a 5 km coastal strip, although it has been observed to penetrate up to 17 km inland. The meridional component of the wind was always higher after than before the onset of the breeze phenomenon (Scian, 1976). The geostrophic effect upon the sea breeze accounts for the frequent northerly component of the observed wind.

2.2. Fuel determinations and fire morphometry

The fuel load was determined after the fire on a nearby unburned area. The selection of the area was based on the assumption that the nearby unburned area had the same fuel load and composition as the burned area. This assumption was validated by combining and interpreting ERS-1 satellite imagery, taken the day before the fire occurred, with Landsat-TMS imagery of the burned and unburned areas. The Landsat-TMS image was subjected to a maximum likelihood supervised classification (ERDAS, 1991). Vegetation was sampled in ten 1 m × 2 m quadrats set every 100 m on a 1 000 m transect near the burned area (Figure 4). The transect was located to cover as much heterogeneity as possible. The biomass inside each quadrat was harvested to ground level and litter collected. Samples were taken to the laboratory, separated into 1, 10, and 100 hour fuel classes according to the time required to respond to changes in the environment (Fosberg & Deeming, 1971), oven-dried to constant weight, and weighed. Since dead fuel moisture in recently sampled vegetation never exceeded 30%, all fuels were then treated as dead

(Rothermel, 1983). Because of the structure of the vegetation in the area, litter and dry grasses were weighed separately, since they were the components that gave the horizontal continuity to the fuels.

The morphometric characteristics of the area affected by the fire (area burned, perimeter and length) were determined using ERS-1 images. The total area burned was divided into four well-differentiated sectors. Perimeter and longitudinal axes were measured for each sector. Axes were taken following the criteria of maximum width and length.

2.3. Analyses of meteorological data

Series from three meteorological stations, referred to hereafter as Cenpat, Aluar and Airport (see Figure 1), were used for these meteorological analyses. Airport is located on the plateau while the other two stations are almost at sea level. Therefore, records from Airport were considered to be the most representative because of the proximity of the station to the place of the incident (about 3 000 m), though in many cases it was necessary to complement and/or compare them with data from the other two stations.

Since arido-active plants maintain green tissues during the entire year by their ability to make use of water stored in deep soil horizons, precipitation in the year prior to the fire was compared to climatic values. It was considered not relevant to analyse meteorological factors during the growing season since the annual biomass productivity in the area is not significant compared to the total fuel load accumulated.

The evolution of the synoptic-scale weather situation that existed over the area from 20 to 22 January was described. As synoptic maps correspond to the 0900 analysis, it was considered important to complement the analysis with surface and upper-air observations to make inferences on the displacement of the weather systems. Atmospheric stability for the 950–850 hPa layer was determined and wind profiles were compared to those considered critical for fire behaviour according to Byram (1954). The upper-air records correspond to the soundings from Santa Rosa, 700 km north of Puerto Madryn, and Comodoro Rivadavia, 400 km south of Puerto Madryn (see Figure 1), and were used because of the lack of upper-air measurements in the proximity of the fire. It is important to note that the area that extends from Santa Rosa to Comodoro Rivadavia is a flat plain which does not present topographic barriers.

Video tapes and photographs from the fire, maps and radar images of the area, and relevant documents of the incident were used to analyse characteristics of the fire along with the evolution of the meteorological situation. Members of the Puerto Madryn Volunteer Fire-Fighters Department that worked in logistics during the incident were interviewed. However, it is important to mention that since the personnel present at the time of the fire were concerned with fire control and not with documenting observations, their description of the sequence of events could lack accuracy.

3. Results

3.1. Fuel load and fire morphometry

The total fuel load was 16 688 ± 2 611 kg ha^{-1} of dry matter, with 1 hour fuels representing 66% of the total, 10 hour fuels representing 31%, and the remaining 3% 100 hour fuels. Of the total fuel load, 16% corresponded to litter and 20% to standing dead grasses. Field observations in the nearby unburned area showed that the presence of litter and standing dead grasses gave horizontal continuity to the fuels.

In its two-day run, the fire burned an area of 12 722 ha and had a final perimeter of 86.6 km (del Valle *et al.*, 1997). Observations of the shape of the burned area (Figure 4(*a*)) allowed the authors to identify four distinct sectors resulting from changes in wind direction (Figure 4(*b*)). Perimeters of each sector, from north to south, were 23.9 km, 12.4 km, 18.6 km, and 31.7 km, respectively. Longitudinal axes for each sector are shown in Figure 4(*b*).

3.2. Description of the synoptic pattern

The 0900 synoptic maps for 20 January show a trough over the Atlantic Ocean, east of the coast of Patagonia, Argentina (Figures 5(*a*) and 5(*b*)). A minimum in surface pressure records indicate that the trough axis had passed over northern Patagonia on 19 January at 2000. The easterly component of the wind observed late in the afternoon of 19 January (Figure 6) shows the development of the sea breeze. The 1000 hPa map for 0900 on 20 January (Figure 5(*a*)) also shows a second trough starting to form in the southern Pacific, just perceptible in the 850 hPa analysis (see Figure 5(*b*)). A steady increase in pressure was recorded at Cenpat during 20 January, reaching its maximum by midnight. The 0900 analysis of 21 January (Figures 5(*c*) and 5(*d*)) shows a well-developed post-frontal high pressure system over central Argentina with its southernmost part affecting the area of the incident. The Santa Rosa 0900 sounding (Figure 7(*a*)) indicates a north surface wind of 2 m s^{-1}. Wind speed was almost constant up to 700 hPa. The Comodoro Rivadavia 0900 sounding (Figure 7(*b*)) indicates a west-south-west surface wind of 5.1 m s^{-1}, and the presence of a low-level jet with wind speed reaching 13.4 m s^{-1}. Both soundings show stable lapse rates in the 950–850 hPa layer (0.5 °C/100 m at Santa Rosa; 0.3 °C/100 m at Comodoro Rivadavia).

At the time coincident with the soundings, records of the three surface stations show winds from the west

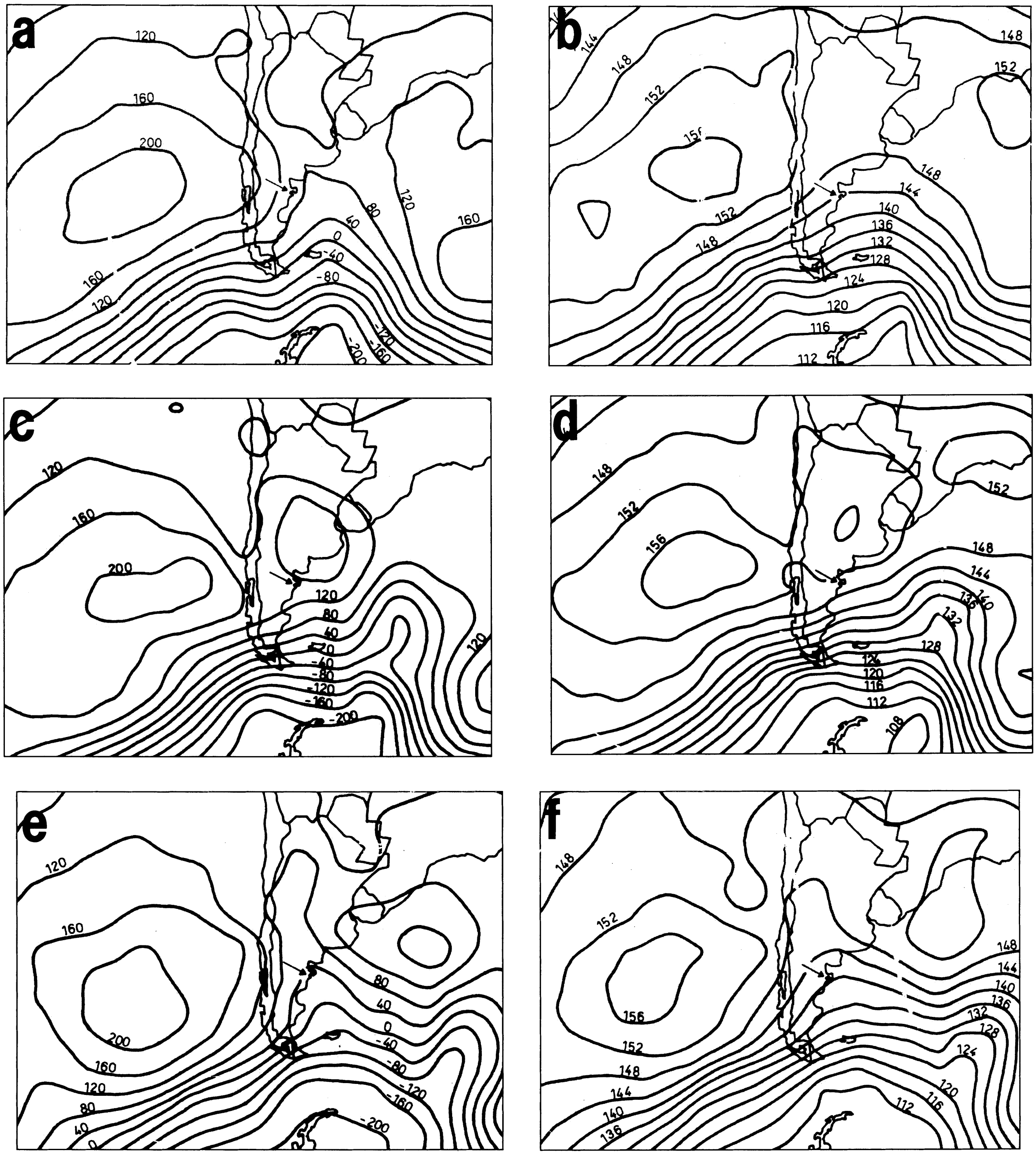

Figure 5. *Synoptic analysis of (a) 1000 hPa and (b) 850 hPa conditions at 0900 on 20 January 1994. The arrow indicates the area in which the fire occurred. (c) and (d) as (a) and (b) but for 0900 on 21 January 1994. (e) and (f) as (a) and (b) but for 0900 on 22 January 1994.*

with speeds of about 4 m s^{-1} (see Figure 6). By 1200 on 21 January, the two stations closer to the shore (Aluar and Cenpat) started to register easterly rotation of winds, indicating the development of the sea breeze (see Figure 6). At 1400, about the time the fire was detected, the breeze front had reached the plateau and wind direction at Airport was from the east; relative humidity was increasing and temperature slightly decreased from 26 °C at 1300 to 24 °C at 1400 (Figure 8). The comparison of the 0900 synoptic maps corresponding to 21 January (Figures 5(*c*) and 5(*d*)) and 22 January (Figures 5(*e*) and 5(*f*)) indicate an eastward displacement of the systems and a piercing of the trough north into the continent at 1000 and 850 hPa. A constant decrease in pressure was registered during 21 January, reaching a minimum at 0400 on 22 January. The 22 January, 0900 Santa Rosa sounding shows a low-level jet at 920 hPa with winds from the north at 14.9 m s^{-1} (Figure 9(*a*)). The low-level jet was not present in the Comodoro Rivadavia 0900 sounding (Figure 9(*b*)). The observed temperature lapse rates were 0.7 °C/100 m at Comodoro Rivadavia and 0.2 °C/100 m at Santa Rosa.

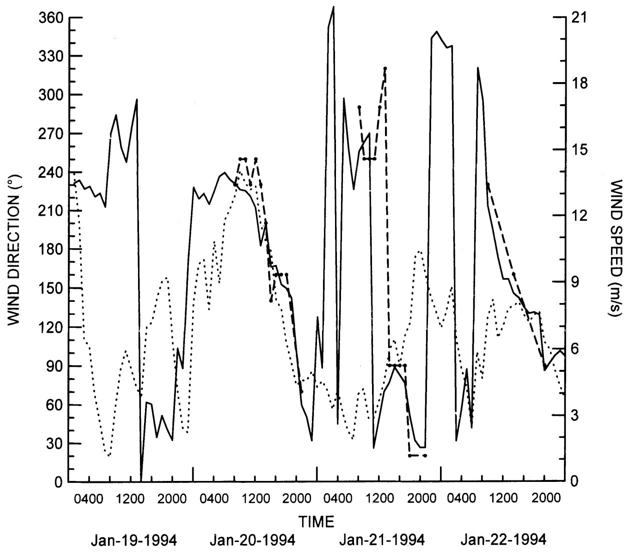

Figure 6. *Wind speed (dotted line) and direction (solid line) registered at Cenpat and wind direction (broken line) registered at Airport from 19 to 22 January 1994.*

3.3. Fire chronology

The fire occurred after a year in which precipitation had been 19.8 mm below normal. No rain had been registered in December and 13.9 mm was recorded in January. The day the fire occurred, the minimum temperature was 8.1 °C at 0600 (5.6 °C below average), and the maximum temperature was 32.0 °C at 1700 (4.6 °C above average). Mean wind speed was 8.3 m s^{-1} (3.3 m s^{-1} above the average). Mean relative humidity was 22% (27% below average).

At 1430 the fire was detected in the proximity of Puerto Madryn about 4 000 m to the south-west of point 1 in Figure 4(*b*). Three crews, with a total of 25 people, were dispatched from the Puerto Madryn Volunteer Fire-Fighters Department to suppress the fire. The initial assessment made by the crew leader was that the fire was small and easy to control. Airport records indicate that the temperature at 1400 was 24.4 °C, having decreased from 26.4°C since the 1300 reading; relative humidity was 26%, having increased from 17% registered at the previous reading at 1300. The tendencies of decreasing temperature and increasing relative humidity were due to the sea breeze front that by 1400 had reached the plateau. Records indicate an easterly wind of 5 m s^{-1}. By 1500, wind speed on the plateau had increased to 6.9 m s^{-1} and remained from the east. Relative humidity decreased to 21% and temperature was increasing.

According to technical reports, the fire at this time was spreading to the west at about 0.8 m s^{-1}, and slowly to the south at about 0.3 m s^{-1}. A convection column started to form with its upper part aligned towards the south-east, following the upper air synoptic pattern. Crews worked along the south flank. The wind speed increased to 7.8 m s^{-1} at 1600 and the wind direction was still from the east. Pressure was constantly decreasing. At 1700, records from Aluar and Cenpat indicate that the wind was starting to shift north (Table 1). At this time, temperature increased to 28.6 °C and relative humidity was 24%. A video tape of the fire shows a considerable increase in fire activity and the presence of a well-developed convection column with its upper part still heading south-east (Figure 10).

At about 1720 a logistics member of the Puerto Madryn Volunteer Fire-Fighters Department, who was at the place named 'Puesto Gallastegui' (Figure 4(*b*), point 2), reported to the crews a north-north-west shift in wind direction and a considerable increase in wind strength. A crew member replied that they were approximately 300 m from Puesto Gallastegui and could not perceive any change in fire activity. The approximate perimeter of the fire at that time is indi-

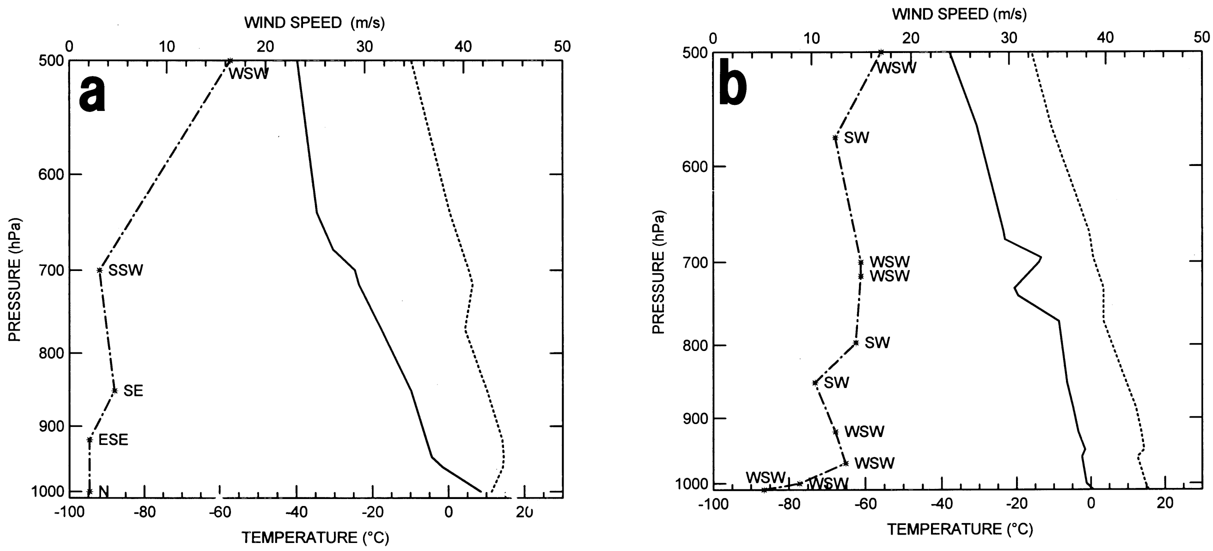

Figure 7. *Vertical profiles of wind speed, temperature (dotted line) and dew point (solid line) registered at (a) Santa Rosa and (b) Comodoro Rivadavia at 0900 on 21 January 1994.*

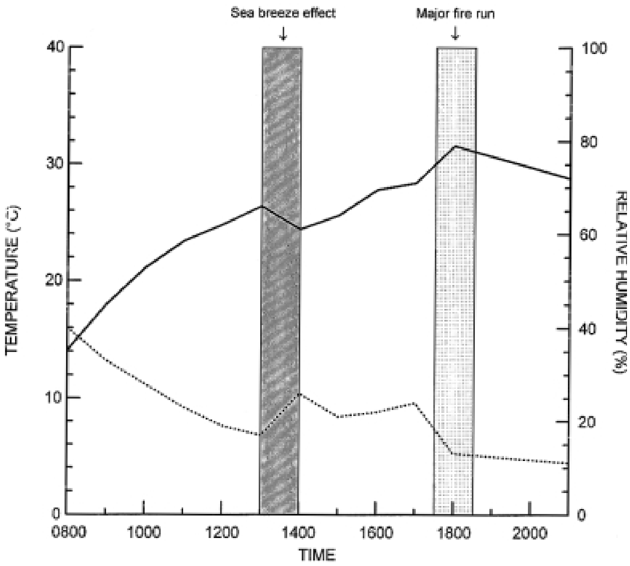

Figure 8. *Airport relative humidity (dotted line) and temperature (solid line) records for 21 January 1994.*

cated in Figure 4(*b*) and the crews kept working on the south flank, though exact positions could not be determined. At about 1730, the logistics officer at Puesto Gallastegui received a radio message from the crew leader reporting that they were surrounded by the fire. This message was the last contact with the members of the crews.

The logistics officer at Puesto Gallastegui stated later:

> *I perceived a sudden calm, saw the flames rising and forming like a flame wall. Then I heard an extremely loud sound and perceived a sudden increase in fire activity. I tried to reach, with my truck, the place were I assumed the crews were working, but the fire had already crossed the road that goes from Puesto Gallastegui [Figure 4b, point 2] to Puesto Elissalde [Figure 4b, point 3]. After a few minutes, I made a second attempt and managed to drive through the fire up to Puesto Elissalde. Since I could not see the crews, I went back to Puesto Gallastegui and drove to the Route N°3.*

He estimated later that in about 15 minutes he had reached the place named Laguna Blanca (Figure 4(*b*), point 6) where he saw the smoke at surface level, crossing Route No. 3 in a south-east direction. By then, he noticed that the convection column had vanished. It is very important to point out that at the time this occurred, temperatures had reached 32 °C (the highest for that day) and relative humidity was constantly decreasing (Figure 8), reaching 13% by 1800.

As detailed information on the evolution of surface wind speed and direction at the time of the major run is considered relevant in determining whether the changes in fire spread direction were due to changes in surface winds in the region or influenced by winds aloft, two-minute averages recorded every 10 minutes in Aluar are shown in Table 1. From 1730 to 1900 surface wind in the area was from the north-northeast. By 2000 the surface wind had rotated to the north with an approximate speed of 10 m s^{-1}. According to a video tape of the fire, by 2015 the fire had crossed National Route No. 3 at point 4 in Figure 4(*b*). After 2000, and in the southernmost zone of the affected area, the fire spread producing a finger shaped pattern (see Figures 4(*a*) and 4(*b*)).

At 2100, relative humidity had decreased to 11% and the temperature was still high (28.8 °C). At about 2200 the fire activity increased in the northern area, to the north of the ignition point. Fire activity gradually decreased during the night. At about 0600 on 22 January the bodies of the 25 crew members of the Puerto Madryn Volunteer Fire-Fighters Department

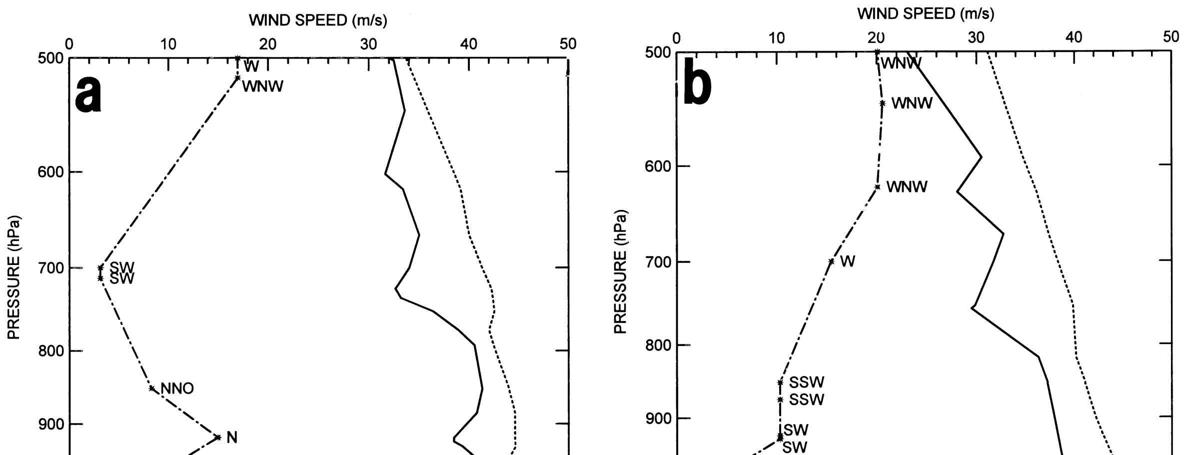

Figure 9. *Vertical profiles of wind speed, temperature (solid line) and dew point (dotted line) registered at (a) Santa Rosa and (b) Comodoro Rivadavia at 0900 on 22 January 1994.*

Table 1. *Two-minute averages of wind speed and direction registered every 10 minutes in Aluar from 1700 to 1900 on 21 January 1994.*

Time	Wind speed (m s^{-1})	Wind direction (°)
1700	6.2	42
1710	6.6	59
1720	5.7	52
1730	8.5	28
1740	6.4	39
1750	6.6	24
1800	8.8	15
1810	10.3	14
1820	7.6	21
1830	7.5	13
1840	9.5	13
1850	7.3	21
1900	10.3	13

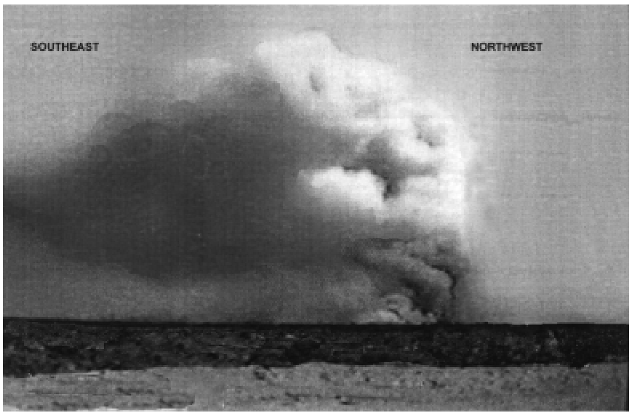

Figure 10. *Aspect of the convection column that developed over the Puerto Madryn fire at about 1700 on 21 January 1994, before the major fire run.*

were found along a 1720 m straight line, extending in a north–south direction (Figure 4(*b*)).

According to reports, by 0500 in the morning of 22 January, the fire seemed to be under control. At about 0700, a fire front of about 2000 m wide was detected spreading slowly to the north. At 0900, the wind was from the south-west at 7.2 m s^{-1}; the fire made a run to the north-east crossing Provincial Route No. 4. There were no major changes in the behaviour observed during 22 January, except for a change in spread direction which shifted north-west at 1600. This was probably coincident with the development of the sea breeze that gave the easterly component to the wind. By 2000 on 22 January the fire was finally under control, and completely suppressed shortly after.

4. Discussion

The area affected by the fire had not been grazed for at least 20 years, allowing the accumulation of standing dead material and litter from grasses and dead leaves that gave horizontal continuity to the fuel. Byram (1954) stated that doubling the amount of fuel might increase the apparent fire intensity four or five times, which suggests that the amount of fuel available to a fire has a considerably greater effect on fire behaviour than would be expected from the increase in the amount of fuel itself.

The precipitation during the year prior to the fire had been 19.8 mm below average, with a remarkably dry period during December when no precipitation was recorded. This fact could have reduced the availability of water to be absorbed through the roots by the arido-active vegetation, reducing the fuel moisture content of live fuel and consequently increasing the amount of available dry fuels.

The fact that crews were dispatched for initial suppression activities about one hour after the onset of the sea breeze front over the plateau, with the consequent increase of relative humidity and a decrease in air temperature, might have contributed to the first underestimation of the danger posed by the fire. Prior to the fire start and to the onset of the sea breeze, wind in the area was from the west. The entrance of the sea breeze from the east may have produced a zone of strong convergence and ascent that favoured the development of the convection column.

The strengthening of the north component of the wind as the trough penetrated into the continent and the geostrophic effect over the sea breeze, caused an east to north rotation of the wind, interrupting the advection of sea air and enhancing the temperature increase and the relative humidity decrease to extremely critical values.

By the time of the major run, on 21 January, the area of the fire was ahead of the moving trough, and upper-air characteristics associated with the sudden change in fire behaviour can be considered to be represented by the soundings made at Comodoro Rivadavia in the morning of 21 January and at Santa Rosa in the morning of 22 January, as both stations were ahead of the moving trough at the time of these observations. The wind profile observed in Comodoro Rivadavia on the morning of 21 January showed a low-level jet of 13.4 m s^{-1} which intensified as the trough moved east, reaching 14.9 m s^{-1} in Santa Rosa in the morning of 21 January. This particular characteristic of the wind shear favours the development of convective activity even for neutral or moderately stable atmospheres. Characteristics of these two wind profiles (i.e. surface wind speeds, height and intensity of the relative maximums in wind speed, and height and intensity of the relative minimums in wind speed) are similar to those of type 2-b wind profiles, according to the Byram (1954) classification of wind profiles related to major wildland fires.

Low-level jets have been associated with one out of three major wildfires in the United States (Brotak, 1976), and often occur shortly ahead of cold fronts or troughs (Chandler *et al*., 1981). The shift in the convection column suggested the presence of a maximum in wind speed at that level. The direction towards which the column was shifted suggests north-west upper-air winds, while surface winds at the time of the major run were east-north-east. This situation is considered particularly dangerous, since the development of a strong convection column can favour the mechanical transport of jet winds to ground level, changing what was a flank of the fire into its head (Chandler *et al.*, 1981).

Though the soundings indicated that the lower layers of the atmosphere were stable, stability could have diminished with diurnal heating and the advection of humid air due to the sea breeze. The energy produced by the fire would have overcome the existing stability, allowing the development of the observed strong convection column which favoured the surfacing of the low-level jet. The appearance of the flames, the apparent calm and the noise described by the logistics officer present in the proximity of the fire shortly after the time when the last message from the crews was received, are indicators of the strong convective dominance prior to the landing of the jet. The accumulation of smoke at surface level moving in a south-easterly direction across Route No. 3 suggests that north-west upper-air winds dominated the fire at the time of the major run.

The finger-shaped area produced by the fire could be the result of discontinuities in vegetation associated with changes in the topography posed by the divergent shoulders. It is likely though that they were enhanced by the dynamic finger process described by Clark *et al.* (1996), associated with the presence of a negative wind shear.

In this fire, biotic and atmospheric factors combined to produce a strong convection column, which favoured the occurrence of downbursts and the transport of winds aloft to surface level through turbulent mixing. All these factors combined, and led to the extreme fire behaviour reported for this fire.

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