DOC ①

6 SATURDAY
065/300 Week 9

7:00

8:00

9:00

10:00

11:00

12:00

1:00

2:00 MELB WARNING UPDATED :
GRIM REAPER Very Dangerous Storm Rang SDO

3:00 2.15pm Golf ball hail at Melton Sth

2 30pm Update Melbourne/State warning Paged SDO

4:00

→ 36mm at Rockbank in 30 mins.

5:00 20 cent Hail at Taylors Lakes

100 SES Jobs

6:00 issues with Phone

3pm Flash flooding in city

7:00

YMML 18ML IN 10 MINUTES

MELB CITY 20 4mm BETWEEN 1450 and 1510

January 2010

S	M	T	W	T	F	S
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31						

February 2010

S	M	T	W	T	F	S
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28						

March 2010

S	M	T	W	T	F	S
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31			

April 2010

S	M	T	W	T	F	S
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	

May 2010

S	M	T	W	T	F	S
						1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30	31					

June 2010

S	M	T	W	T
		1	2	3
6	7	8	9	10
13	14	15	16	17
20	21	22	23	24
27	28	29	30	

SATURDAY

SUNDAY 7
066/299 Week 9

* See Spotter reports
for details

00

* Constant updates of warnings
& chats with SES SDO

00

:00

940 pm: Cancel STW ⇒ SWx warning
instead

:00

[redacted] [redacted]

:00

:00

:00

:00

:00

:00

5:00

7:00

July 2010

S	M	T	W	T	F	S
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	31

August 2010

S	M	T	W	T	F	S
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

September 2010

S	M	T	W	T	F	S
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30		

October 2010

S	M	T	W	T	F	S
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31						

November 2010

S	M	T	W	T	F	S
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30				

December 2010

S	M	T	W	T	F	S
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	

DOC 1A

IRRELEVANT MATERIAL - s 22

31823
5707
3466

DATE: 6/3/10

CALL TIME: 1.45pm **CALLER:** [redacted]

PHENOMENA:
• damaging wind ⇒ trees across Rd
• flash flooding

TIME: 1:30 - 1:45 **LOCATION:** Sth of Eddington near Maldon E of Maryborough

---

31824
3092
3467

DATE: 6/3/10

CALL TIME: 245 **CALLER:** [redacted]

PHENOMENA: 90 4mm in 15mins. Flash flooding
Force 8 winds Golf ball hail

TIME: 215 **LOCATION:** Melton Nth Melton

31824
3468
3093

DATE: 6/3/10

CALL TIME: 245pm **CALLER:** [redacted]

PHENOMENA: 2cm Hail
Flash flooding

TIME: 230 **LOCATION:** just west of YMM

31824
3095
3469

DATE: ~~[illegible]~~ ~~6/3/10~~ 6/3/10

CALL TIME: 3pm **CALLER:** [redacted]

PHENOMENA: 2cm Hail 20.6mm in 20mins

TIME: 225pm **LOCATION:** DalaHay Wst Suburb
(Delahey)?

DATE: 6/3/10

CALL TIME: 3pm **CALLER:** [redacted]

PHENOMENA: 3-4cm Hail

TIME: 3pm **LOCATION:** ??, City

31824
3101

DATE: 6/3/10

CALL TIME: 3pm **CALLER:** [redacted]

PHENOMENA: 50 cent Hail Leaves off trees

TIME: 3pm **LOCATION:** Ascot Vale

31824
3103
4470

DATE: 6/3/10

CALL TIME: 250pm **CALLER:** [redacted]

PHENOMENA: 3cm Hail / flash flooding

TIME: 250pm **LOCATION:** Nth Melb

31824
3104

DATE: 6/3/10

CALL TIME: 320pm **CALLER:** [redacted]

PHENOMENA: 4.5cm Hail

TIME: 310pm **LOCATION:** Heathmont

31824
3102

DATE: 6/3/10

CALL TIME: 320pm **CALLER:** [redacted]

PHENOMENA: Golf Ball Hail

TIME: 315pm **LOCATION:** Glen Waverley

31824
3105

DATE: 6/3/10

CALL TIME: 325pm **CALLER:** [redacted]

PHENOMENA: 2.5cm Hail

TIME: 320pm **LOCATION:** Ferntree Gully

-31824
3106

DATE: 6/3/10

CALL TIME: 330pm **CALLER:** [redacted]

PHENOMENA: 10cm Hail (verified by another caller)

TIME: 330pm **LOCATION:** Fentree Gully

IRRELEVANT MATERIAL REMOVED
- s.22.

Doc 2

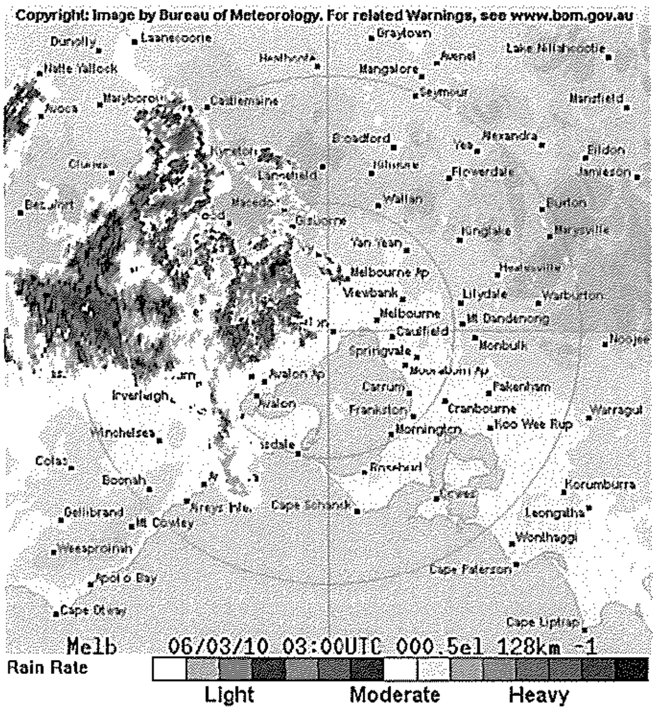
Australian Government
Bureau of Meteorology

Severe Thunderstorms in Melbourne 6 March 2010

Event Summary

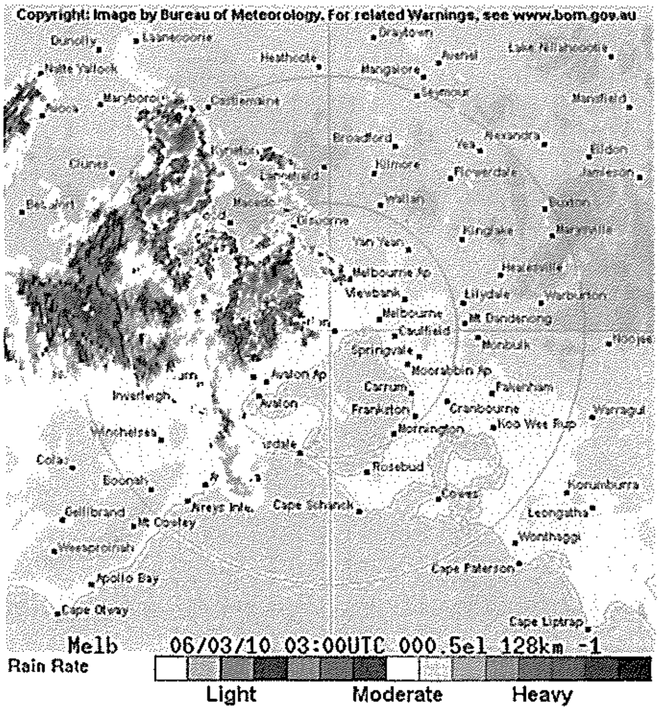
A developing low pressure system with an associated low pressure trough to the west of Victoria (refer Figure 1) combined with low level moisture and upper level forcing to generate showers and thunderstorms in the west of the State during the morning which spread eastward and intensified during the early afternoon. Severe thunderstorms developed to the northwest of the Melbourne Metropolitan Area and moved through the city from early afternoon progressing to the eastern suburbs and then into West Gippsland later in the afternoon.

Radar loop of the event

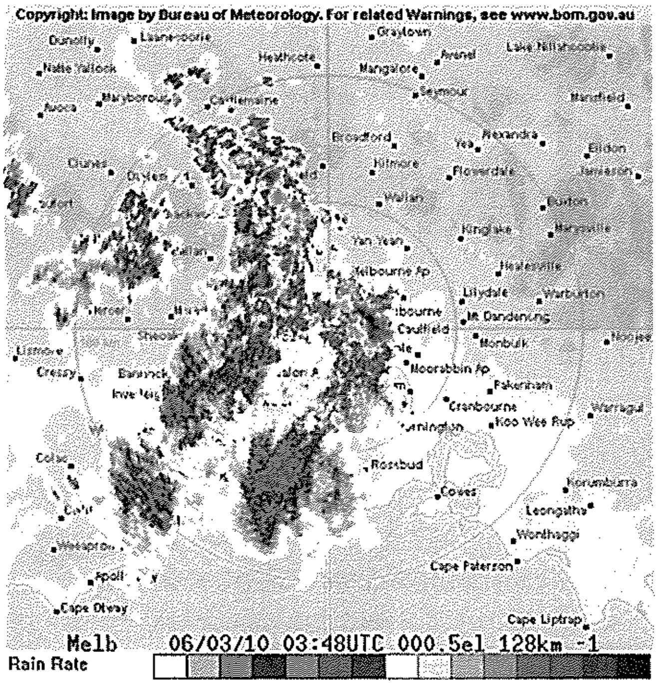


Radar reflectivity images from the Melbourne radar (Laverton) 03:00 UTC (2:00pm EDT) to 04:54 UTC (3:54pm EDT) on 6 March.

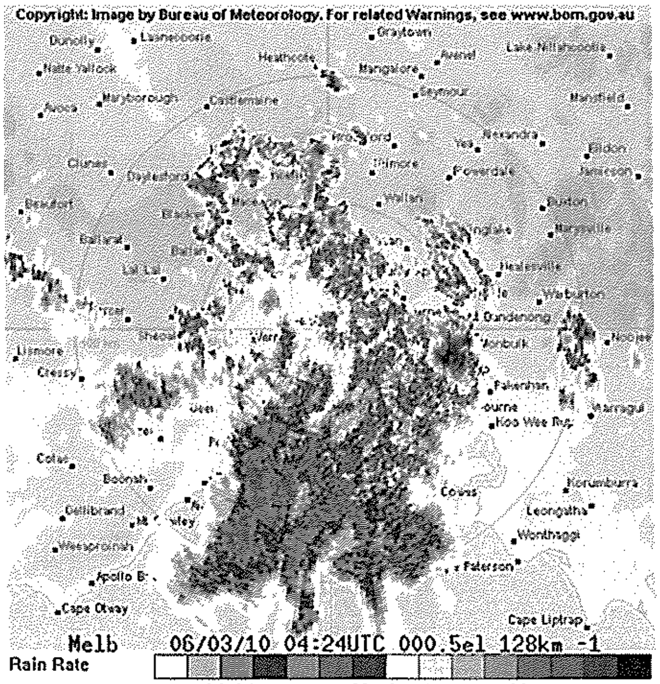
Selected radar images



Radar reflectivity image from the Melbourne radar (Laverton) at 03:00 UTC (2pm EDT) on 6 March.



Radar reflectivity image from the Melbourne radar (Laverton) at 03:48 UTC (2:48pm EDT) on 6 March.



Radar reflectivity image from the Melbourne radar (Laverton) at 04:24 UTC (3:24pm EDT) on 6 March.

The severe thunderstorms were associated with large hail and heavy rain resulting in widespread flash flooding and water and hail damage to property. There were some isolated severe wind gusts with the thunderstorms.

Rainfall totals in a 15 minute to 30 minute period included:

46mm at Maribyrnong,
45mm at Latrobe Valley Airport,
43mm at Rockbank,
40mm at Melton,
33mm at Deer Park,
And 25 mm at Melbourne Airport.

Hail:

10cm 3.30 pm Ferntree Gully,

7cm 3:30pm Ferny Creek
5cm 3:05 pm Blackburn
5cm 3:00 pm Glen Iris
4.5cm 3.20 pm Heathmont,
4.5cm 3:10 pm Mount Waverley
4.2cm 3:15 pm Boronia
4cm 3.20 pm Glen Waverley,

4cm 2:40 pm Malvern
4cm 2.45 pm North Melton.

Plenty of other reports of hail 2 to 4 cm hail from right across Melbourne.

Wind:

102 km/h Melbourne Airport,
95 km/h Latrobe Valley Airport,
91 km/h Ben Nevis.

MSL Analysis of the event

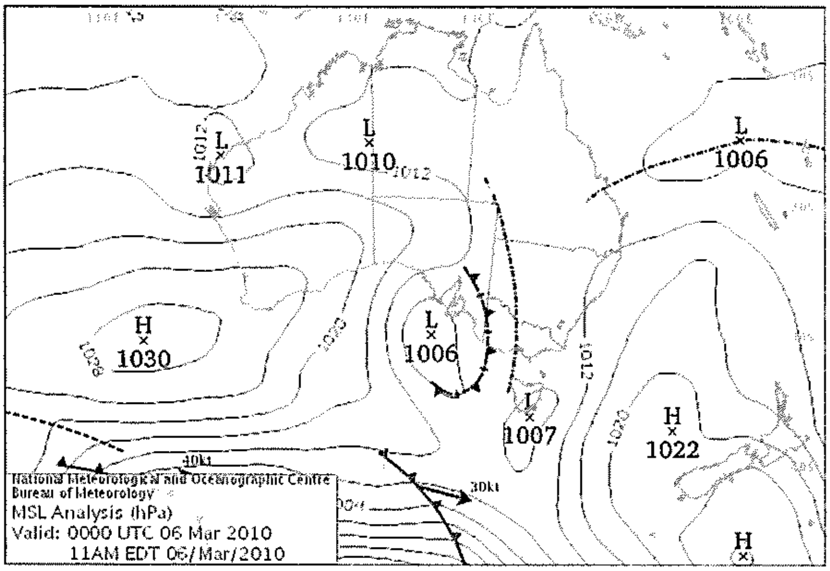


Figure 1: MSL Analysis 11am March 6 2010

Satellite image of the event

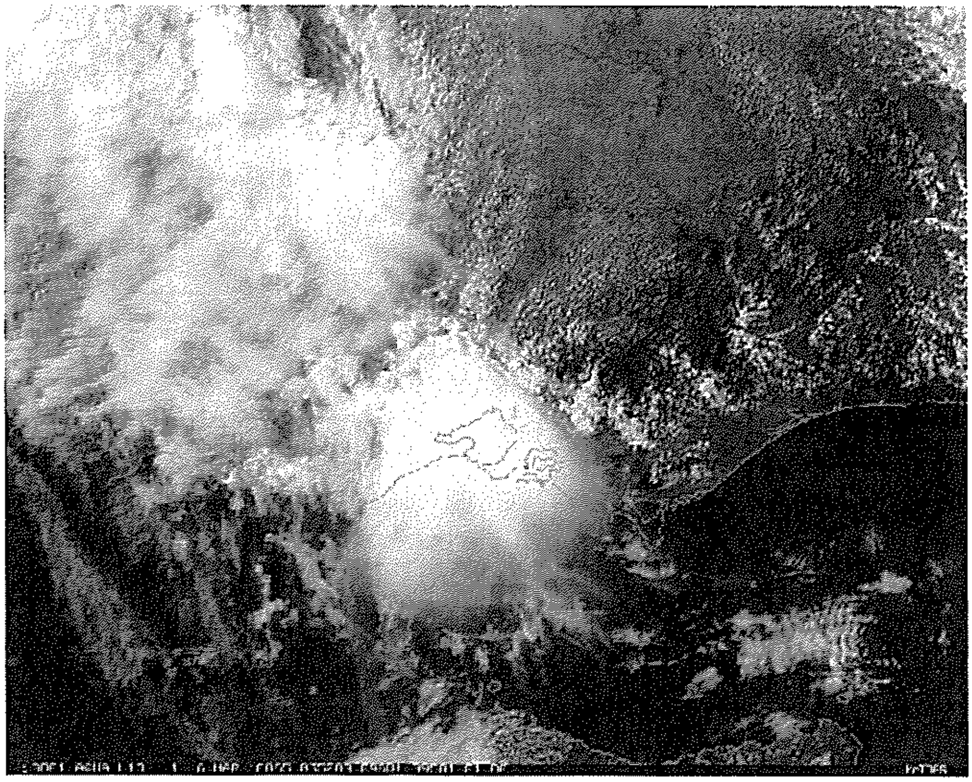


Image from Aqua/MODIS satellite courtesy of NASA at 03:52 UTC (2:52pm EDT) on 6 March.

Examples of some of the Severe Thunderstorm Warnings issued during the event.
Australian Government Bureau of Meteorology
Victoria Regional Office

TOP PRIORITY FOR IMMEDIATE BROADCAST

SEVERE THUNDERSTORM WARNING

for DAMAGING WIND, FLASH FLOODING and LARGE HAILSTONES

For people in the North Central and parts of the Mallee, Northern Country, Wimmera, Western and Central Forecast Districts.

Issued at 12:36 pm Saturday, 6 March 2010.

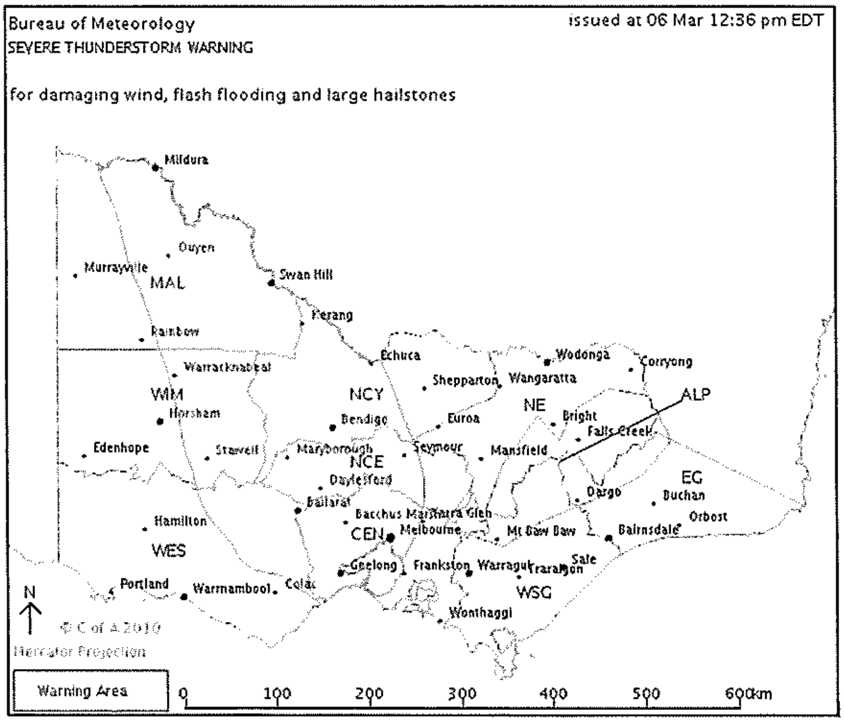
Severe thunderstorms are likely to produce damaging winds, very heavy rainfall, flash flooding and large hailstones in the warning area over the next several hours. Locations which may be affected include Mildura, Ballarat, Bendigo, Seymour, Maryborough, Geelong and Melbourne.

The State Emergency Service advises that people should:
- Keep clear of fallen power lines.
- secure any loose objects in the vicinity of your home.
- keep away from creeks and drains.
- do not drive vehicles through flooded areas.
- stay indoors if possible.
- Avoid using the phone during the storm.
- if you are outside, avoid sheltering under trees
- listen to the radio for storm updates
- switch off your computer and electrical appliances

The next warning is due to be issued by 3:40 pm.

If severe thunderstorms develop in the Melbourne Area, a more detailed Severe Thunderstorm Warning will be issued to people in this area.

Warnings are also available through TV and Radio broadcasts, the Bureau's website at www.bom.gov.au or call 1300 659 217. The Bureau and State Emergency Service would appreciate warnings being broadcast regularly.



Australian Government Bureau of Meteorology
Victoria Regional Office

TOP PRIORITY FOR IMMEDIATE BROADCAST

SEVERE THUNDERSTORM WARNING - MELBOURNE AREA

for DAMAGING WIND, FLASH FLOODING and LARGE HAILSTONES

For people in the Western, Geelong and Bellarine Peninsula and parts of the Inner, Northern and Port Phillip Local Warning Areas.

Issued at 1:25 pm Saturday, 6 March 2010.

The Bureau of Meteorology warns that, at 1:20 pm, severe thunderstorms were detected on weather radar near Daylesford and the area west of Ballan. These thunderstorms are moving towards the southeast. They are forecast to affect Bacchus Marsh, Brisbane Ranges and the area west of Lara by 1:50 pm and Geelong City, Melton and Werribee by 2:20 pm.

Damaging winds, very heavy rainfall, flash flooding and large hailstones are likely.

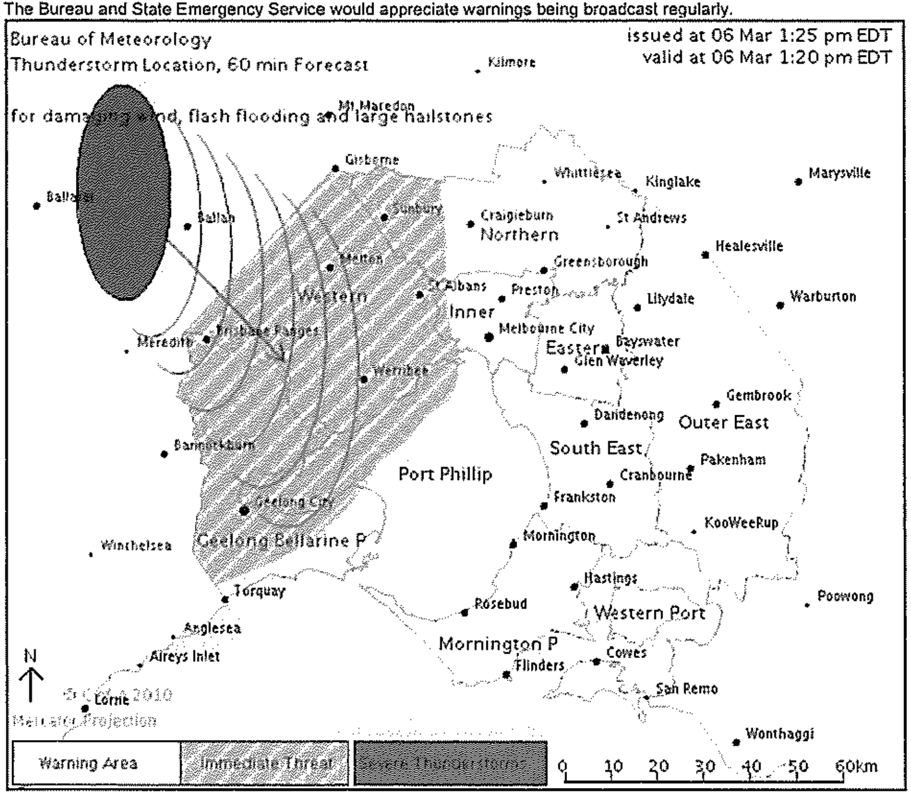
The State Emergency Service advises that people should:
- Keep clear of fallen power lines.
- secure any loose objects in the vicinity of your home.
- keep away from creeks and drains.
- do not drive vehicles through flooded areas.
- stay indoors if possible.
- Avoid using the phone during the storm.
- if you are outside, avoid sheltering under trees

- listen to the radio for storm updates
- switch off your computer and electrical appliances

The next warning is due to be issued by 2:25 pm.

A more general severe thunderstorm warning is also current for the North Central and parts of the Mallee, Northern Country, Wimmera, Western and Central districts.

Warnings are also available through TV and Radio broadcasts, the Bureau's website at www.bom.gov.au or call 1300 659 217. The Bureau and State Emergency Service would appreciate warnings being broadcast regularly.



Australian Government Bureau of Meteorology
Victoria Regional Office

TOP PRIORITY FOR IMMEDIATE BROADCAST

SEVERE THUNDERSTORM WARNING - MELBOURNE AREA

for DAMAGING WIND, FLASH FLOODING and LARGE HAILSTONES

For people in the Inner, Western, Geelong and Bellarine Peninsula, Port Phillip and parts of the South East, Eastern, Northern and Mornington Peninsula Local Warning Areas.

Issued at 2:02 pm Saturday, 6 March 2010.

The Bureau of Meteorology warns that, at 1:55 pm, very dangerous thunderstorms were detected on weather radar near Gisborne and Melton. These thunderstorms are moving towards the southeast. Very dangerous thunderstorms are forecast to affect Footscray, St Albans, Sunbury and Werribee by 2:25 pm and Caulfield, Craigieburn, Glen Waverley, Greensborough, Melbourne City and Preston by 2:55 pm.

Damaging winds, very heavy rainfall, flash flooding and large hailstones are likely.

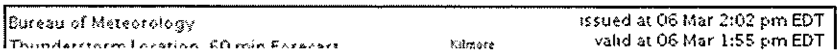
The State Emergency Service advises that people should:

- Keep clear of fallen power lines.
- secure any loose objects in the vicinity of your home.
- keep away from creeks and drains.
- do not drive vehicles through flooded areas.
- stay indoors if possible.
- Avoid using the phone during the storm.
- if you are outside, avoid sheltering under trees
- listen to the radio for storm updates
- switch off your computer and electrical appliances

The next warning is due to be issued by 3:05 pm.

A more general severe thunderstorm warning is also current for the North Central and parts of the Mallee, Northern Country, Wimmera, Western and Central districts.

Warnings are also available through TV and Radio broadcasts, the Bureau's website at www.bom.gov.au or call 1300 659 217. The Bureau and State Emergency Service would appreciate warnings being broadcast regularly.



Australian Government Bureau of Meteorology
Victoria Regional Office

TOP PRIORITY FOR IMMEDIATE BROADCAST

SEVERE THUNDERSTORM WARNING - MELBOURNE AREA

for DAMAGING WIND, FLASH FLOODING and LARGE HAILSTONES

For people in the Inner, South East, Eastern, Northern, Western, Port Phillip and parts of the Geelong and Bellarine Peninsula, Mornington Peninsula and Outer East Local Warning Areas.

Issued at 2:30 pm Saturday, 6 March 2010.

The Bureau of Meteorology warns that, at 2:25 pm, very dangerous thunderstorms were detected on weather radar near Melton, St Albans, Sunbury and Werribee. These thunderstorms are moving towards the southeast. Very dangerous thunderstorms are forecast to affect Caulfield, Craigieburn, Footscray, Glen Waverley, Greensborough, Melbourne City and Preston by 2:55 pm and Dandenong, Frankston, Ringwood and Scoresby by 3:25 pm.

Other severe thunderstorms were located near Ballan, the area south of Ballan, the area west of Gisborne and the area west of Woodend. They are forecast to affect Bacchus Marsh, Gisborne, the area west of Sunbury and the area west of Werribee by 2:55 pm and Whittlesea, the area south of Werribee, the area south of Whittlesea and the area west of Whittlesea by 3:25 pm.

Damaging winds, very heavy rainfall, flash flooding and large hailstones are likely.

Large hail has been reported at Melton from these thunderstorms.
Wind gusts to around 100 km/hr have been recorded at Melbourne Airport.

The State Emergency Service advises that people should:

- Keep clear of fallen power lines.
- secure any loose objects in the vicinity of your home.
- keep away from creeks and drains.
- do not drive vehicles through flooded areas.
- stay indoors if possible.
- Avoid using the phone during the storm.
- if you are outside, avoid sheltering under trees
- listen to the radio for storm updates
- switch off your computer and electrical appliances

The next warning is due to be issued by 3:30 pm.

A more general severe thunderstorm warning is also current for the Northern Country, North Central, Central and parts of the Mallee, Wimmera, West and South Gippsland and Western districts.

Warnings are also available through TV and Radio broadcasts, the Bureau's website at www.bom.gov.au or call 1300 659 217. The Bureau and State Emergency Service would appreciate warnings being broadcast regularly.

'The SES encourages community members to undertake simple measures to prepare for storms. More information on how to be StormSafe can be found on the SES website - www.ses.vic.gov.au'

This page was created at on

DOC 3

Australian Government

Bureau of Meteorology

DRAFT Melbourne Severe Hail Storm – 6 March 2010.

[redacted]

Contents

Melbourne Severe Hail Storm – 6 March 2010

Introduction

A developing low pressure system with an associated low pressure trough to the west of Victoria combined with low level moisture and upper level forcing to generate thunderstorms across the State during the period 6 to 7 March 2010. Severe thunderstorms occurred across the State during the late morning through to the early evening of Saturday 6 March 2010, affecting parts of the Mallee, Wimmera, Northern Country, North Central, Central and West and South Gippsland forecast districts. A particularly severe thunderstorm cut a swathe of damage through some of the most densely populated areas of the greater Melbourne region, extending from Melton in the outer west, through the central business district and Rowville in the outer east to Warragul in West and South Gippsland between 0300UTC and 0500UTC (1400 and 1600 Eastern Daylight Savings Time (EDT)).

The severe thunderstorm produced the largest recorded hail in Melbourne's 156 year meteorological history, rainfall rates equivalent to a 1 in 100 year event and damaging winds. The severe thunderstorm later proved to be one of Australia's most costly natural disasters with reported insurable damages of $1.044 billion (Insurance Council of Australia 2011). A total of 131,447 insurance claims were lodged ([redacted] Insurance Council of Australia, 2010, pers. comm., 22 Jul); the largest number of insurance claims for any event within Victoria (Buckley et al. 2010). Considerable damage was reported in the worst affected areas of the outer eastern suburbs of Melbourne, i.e. the suburbs of Rowville, Lysterfield and Ferntree Gully, where hail with diameters of up to 10cm were reported; severely damaging houses and cars and causing significant damage to Council infrastructure. The Victoria State Emergency Service (VICSES) received over 6300 Requests For Assistance (RFAs) across the Central forecast district while, the VICSES Knox unit, located in the worst affected area of the eastern suburbs of Melbourne, recorded the highest number of RFAs in its history with over 2700 (Victorian State Emergency Service 2010).

The meteorological aspects of the severe thunderstorm are investigated by means of analysis of the synoptic and mesoscale dynamics (Sections 1 and 2 respectively) and the convective environment and stability (Section 3). The severity of the thunderstorm is addressed in Section 4 via identification of the internal storm structure and processes as assessed via interrogation of the 1° S-band Laverton RADAR data. The meteorological observations of wind, rainfall and hail, including its severe characteristics, are also investigated in this section and, related to the resultant damage and socio-economic impacts. Furthermore, a brief summary of the forecast and warning service provided by the Victoria Regional Office Regional Forecasting Centre with regards to the storm are presented in Section 5.

Synoptic Analysis

A rare combination of meteorological conditions aligned over Victoria on 6 March 2010 to produce an atmospheric environment highly conducive to severe thunderstorms. Preceding the event, a tropical low pressure system generated prolonged precipitation which exceeded the 120 year Average Recurrence Interval (ARI) (Buckley et al. 2010) and resulted in widespread flooding over southern Queensland and northern New South Wales (the abundant surface moisture in an otherwise warm air mass increased the low-level moisture over the

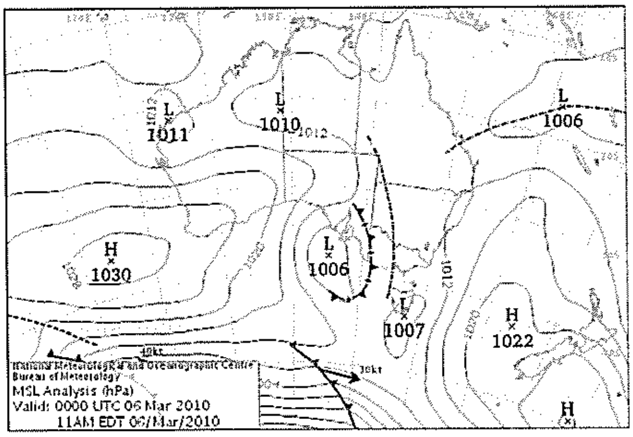


Figure 1: Bureau of Meteorology (BoM) National Meteorological and Oceanographic Centre (NMOC) Mean Sea Level Pressure (MSLP) analysis valid 0000UTC 6 March 2010 (1100EDT 6 March 2010).

region). A surface low pressure trough to the west of Victoria and, a meridional high pressure ridge over the Tasman Sea, combined to direct this warm, moist tropical air mass southwards over Victoria (Figure 1).

Figure 2 illustrates the Bureau of Meteorology's (BoM hereon in) Mesoscale Surface Analysis Scheme (MSAS) analyses of screen temperature and dewpoint temperatures representative of the warm moist sub-tropical air mass that was advected over Victoria. The MSAS exploits surface observation data to produce a 5km resolution gridded analysis field which acts as the basis for bias correcting Gridded Operational Consensus Forecasts and calculating error fields for Numerical Weather Prediction (NWP) models. The near surface air mass can be seen to consist of screen temperatures in the mid to high 20s and screen dewpoint temperatures in the mid to high teens. Actual surface observations for a selection of recording stations for 0000, 0300 and 0600UTC 6 March 2010 (all times in this paper are presented as UTC where Melbourne's local time (EDT) is +11UTC) can be seen in Figures ?a, ?a and ?a.

Meanwhile, an unseasonable deep, mature mid- to upper-level cut-off low, situated over the Great Australian Bight south of Kangaroo Island, South Australia, provided marked baroclinicity aloft. By qualitative quasi-geostrophic arguments, vertical motion typically occurs east of propagating mid-latitude baroclinic lows in the Southern Hemisphere via warm air advection and cyclonic vorticity advection, even in a slightly perturbed westerly thermal flow (weak baroclinic environment) (Bluestein 1992, Holton 2004). Inspection of the 2330UTC 5 March 2010 (Figure 3a) and 0630UTC 6 March 2010 (Figure 3b) infrared (IR) MTSAT-1R satellite imagery illustrates the rapid development of a mid- to upper-level cloud formation analogous to Weldon's baroclinic leaf (Semple 2003) along Victoria's western border, signifying the mid- to upper-tropospheric baroclinicity and vertical motion ahead of the cut-off low. The strong horizontal

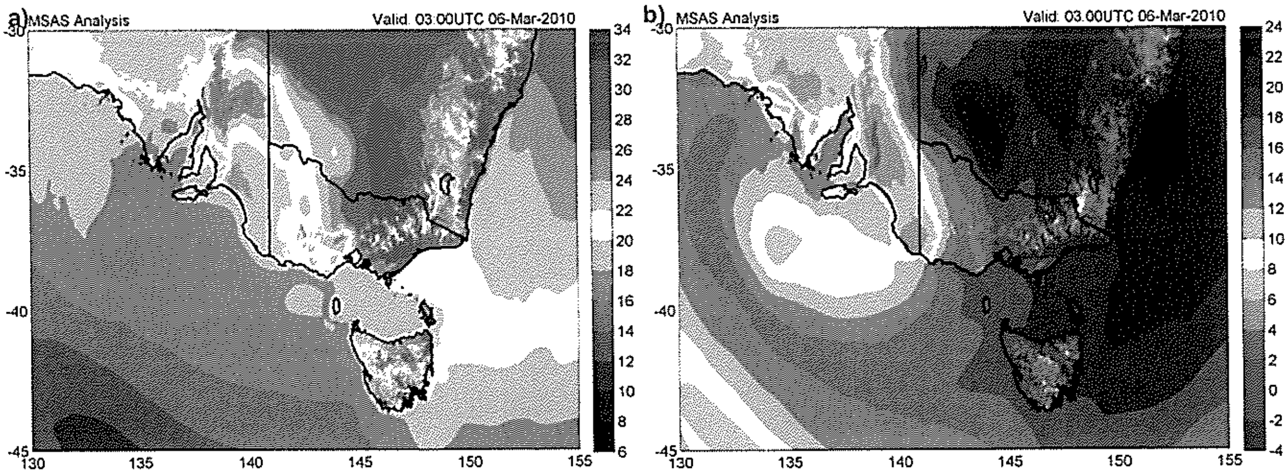


Figure 2: MSAS analyses of **a)** screen temperature (°C) and **b)** screen dewpoint temperature (°C) valid 0300UTC 6 March 2010 (1400EDT 6 March 2010).

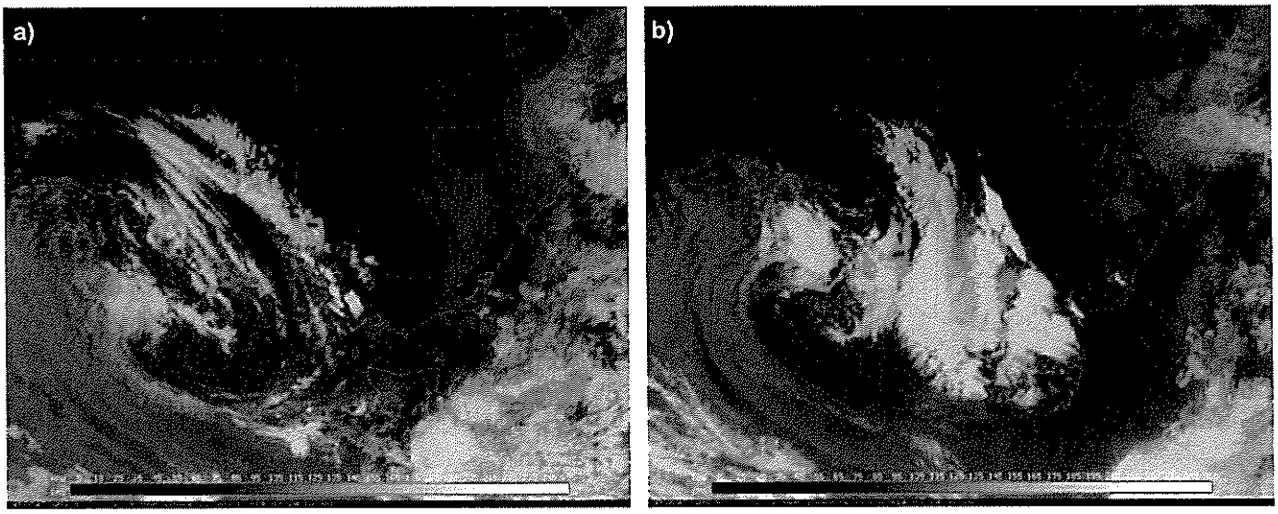


Figure 3: MTSAT-1R infrared satellite imagery for **a)** 2330UTC 5 March 2010 and **b)** 0630UTC 6 March 2010.

temperature gradients associated with the cut-off low further lead to the formation of a strong meridionally orientated upper-level jet stream over the State as illustrated in the 0000UTC analysis of the BoM's 12-km resolution Numerical Weather Prediction (NWP) model (ACCESS-A) in Figure 4.

A distinctive feature of this event was a marked split of the jet stream; i.e. two diverging jet streaks resulting in an intermediatry highly diffluent area (Figure 5). By simple qualitative quasi-geostrophic continuity arguments, the marked upper-tropospheric divergence resulting from the diffluent jet streaks can lead to enhanced vertical motion in the mid-levels of the troposphere. The striated zonal banding within the baroclinic leaf cloud formation illustrated in Figure 3b suggests the presence of strengthening upper-tropospheric divergence (e.g. Feren 1995) which is illustrated in the ACCESS-A 300hPa divergence analysis (Figure 6) and is consistent with the Cooperative Institute for Meteorological Satellite Studies (CIMSS) upper-level atmospheric divergence diagnostic (Appendix ?). Inspection of the 0000UTC 250hPa ACCESS-A wind analysis (Figure 4a) suggests that the poleward exit region of the jet stream was located within the western vicinity of the Melbourne area. Similarly, the 0000UTC 300hPa ACCESS-A wind analysis (Figure 5a) further shows the poleward exit region of the eastern-most jet streak was situated over a similar area. This region of jet streaks has been observed to be associated with severe convection (e.g. Rose et al 2004; Bluestein and Thomas 1984), and it has been suggested that this is a consequence of, or in part to, increased upper-level divergence resulting from transverse ageostrophic circulations (Beebe and Bates 1955; Bluestein and Thomas 1984). The mechanisms leading to the splitting of the jet stream are however, beyond the scope of this paper and are largely speculative. Regardless, there is the potential that feedback mechanisms stemming from the deep moist convective complexes aligned along a surface trough may have played a role in the splitting of the jet stream; or, at least enhanced mid-tropospheric vertical motion by means of generating upper-tropospheric anticyclonic absolute vorticity that, if sufficiently inertially unstable, could potentially have enhanced upper-tropospheric divergence. This is a particularly interesting topic which with further investigation and NWP modelling may provide clarification of the evolution of the upper-tropospheric dynamics and their influence on the intensification of the severe thunderstorm.

The upper-level cut-off low gradually propagated toward the northeast in the 12 hours leading up to the severe thunderstorm event. Cooler mid-tropospheric air advected eastward with the movement of the upper cut-off low, illustrated in

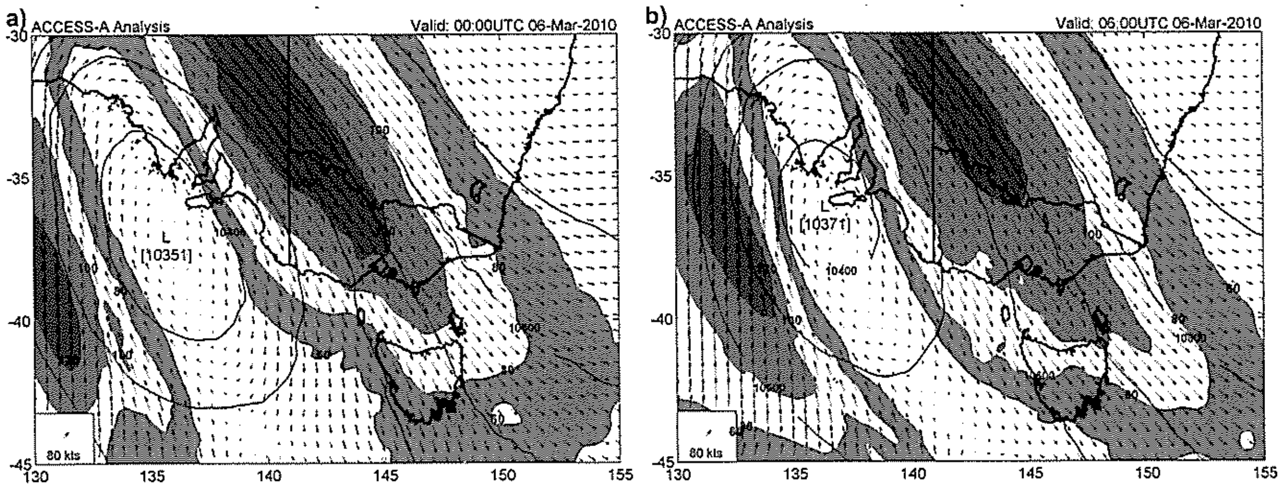


Figure 4: ACCESS-A analyses of 250hPa geopotential height, wind vectors and wind magnitude for **a)** 0000UTC 6 March 2010 and **b)** 0600UTC 6 March 2010.

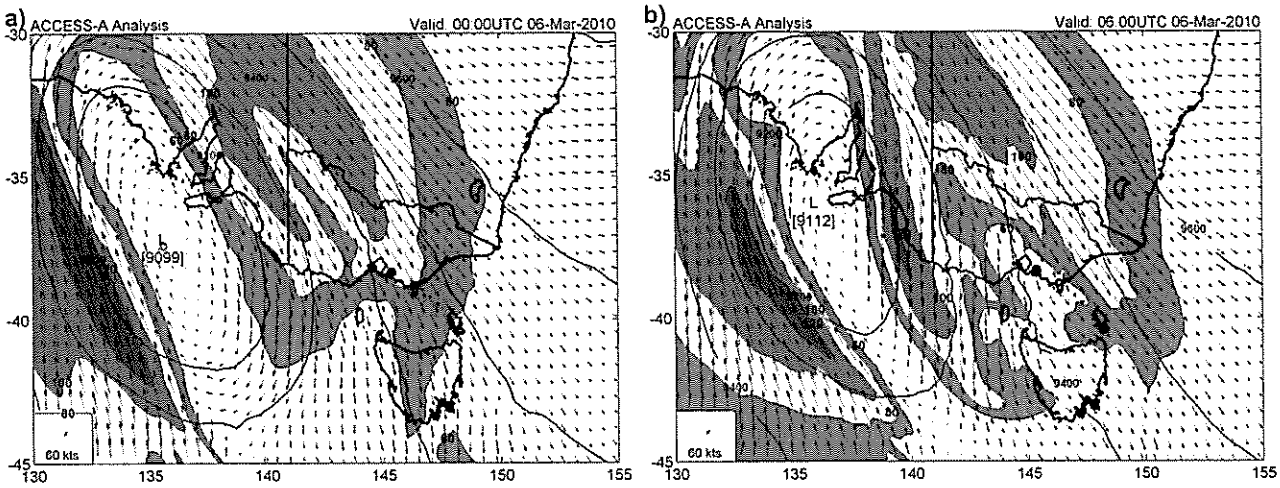


Figure 5: ACCESS-A analyses of 300hPa geopotential height, wind vectors and wind magnitude for **a)** 0000UTC 6 March 2010 and **b)** 0600UTC 6 March 2010.

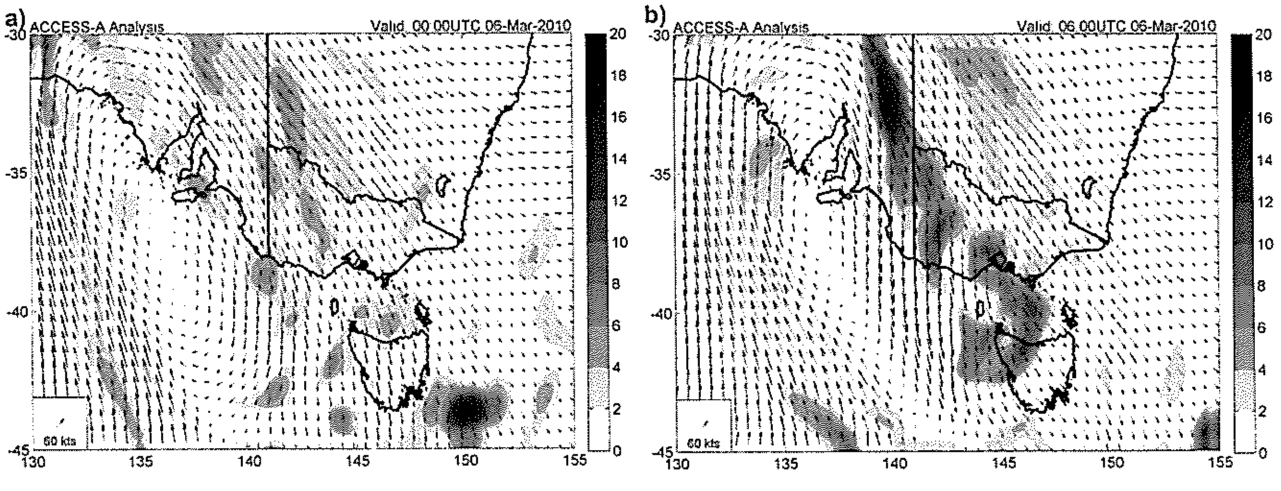


Figure 6: ACCESS-A analyses of 300hPa divergence and wind vectors for **a)** 0000UTC 6 March 2010 and **b)** 0600UTC 6 March 2010. The divergence field has been smoothed using a rectangular mean over a 5 grid point (~60km) radius of the underlying wind vector field calculated using a centered finite difference approach.

Figures 7a and 7b with the ACCESS-A 500hPa (~5500m) air temperature analyses. The ACCESS-A 700hPa (3000m AMSL) air temperature analyses also demonstrated this cooling trend but are not shown for brevity. It should be noted that the temperature fields verified well (within approximately 1°C) with the Mount Gambier and Melbourne Airport aerological sonde observation data, providing confidence in the ACCESS-A analyses. Based upon the 1100UTC and 2300UTC 5 March 2010 Melbourne Airport aerological sonde data, the 700hPa and 500hPa air temperature decreased over the Melbourne region by 2.5°C and 3.2°C respectively in the 12 hours to 2300UTC 5 March 2010, indicating significant cooling in the mid-troposphere and further verifying ACCESS-A analyses. Further using 1100UTC and 2300UTC 5 March 2010 Melbourne Airport aerological sonde data, cold air advection was confirmed within the 700 to 500hPa layer by thermal wind arguments, whereby a veering profile was observed between the WNW winds at approximately 700hPa and the NW winds at approximately 500hPa.

The evolution of the lower-troposphere in the overnight period leading up to the event is somewhat more complicated. Due to the prevailing synoptic northerly flow, one would expect warm air advection. By thermal wind arguments, the backing of the winds with height in the 950-850hPa layer at 1100UTC and the 886-~750hPa layer at 2300UTC (an inversion was present at 850hPa so the layer immediately above the inversion was used) from a northerly in the lower half of the layer to a northwesterly in the upper half of the layer suggests warm air advection. The 850hPa (~1500m) air temperature however decreased from 14.3°C to 12.6°C as measured by the 1100UTC and 2300UTC 5 March 2010 Melbourne Airport aerological sonde observations respectively. This is further suggested by the 0000UTC and 1200UTC ACCESS-A 850hPa air temperature fields in Figures 6c and 6d. It is suggested that this may be attributed in part to:

a) advection of slightly cooler air following the passage of a short-wave leading transient lower-tropospheric trough that traversed the Melbourne region and the eastern remainder of the State overnight as suggested by the 1200UTC 5 March 2010 and 0000UTC 6 March 2010 ACCESS-A 850hPa wind analyses (Figures 8a and 8b). Further evidence lies in the 1700UTC Melbourne Airport aerological wind sonde data (not shown) whereby, veering winds in the 925-850hPa layer due to winds in the lower half of this layer temporarily shifting southwesterly following the trough passage suggests subtle cold air advection by thermal wind arguments. Similar evidence also appears in Aircraft Meteorological Data Relay (AMDAR) data from Melbourne Airport between 1900 and 2100UTC in a similar layer.

b) the decrease in cloud following the passage of the short-wave trough (verified by MTSAT-1R IR satellite imagery and Melbourne Airport observation data) leading to relatively clear sky conditions and promoting nocturnal cooling of the layer.

c) adiabatic cooling by ascent associated with the passage of the short-wave trough.

Despite the passage of a low-level transverse shortwave trough, a reservoir of relatively warm air persisted over much of the State (the 2300UTC 850hPa air temperature of 12.6°C was above the 2000-2011 2300UTC March average of 10.7°C as recorded by aerological sondes) and the low-level air mass did not change significantly on the synoptic scale between 2300UTC and 0300UTC (approximate formation time of the severe thunderstorm).

The advection of cooler mid-tropospheric air during the 12 hour period between 11/1200UTC and 23/0000UTC, coupled with relatively warmer air in the lower-troposphere provided the synoptic ingredients supportive of thermodynamic destabilisation over the Melbourne region. This potential thermodynamic instability, in conjunction with enhanced mid-tropospheric vertical motion as a consequence of upper-tropospheric divergence, provided an atmosphere highly conducive to deep moist convection over Victoria and the Melbourne area.

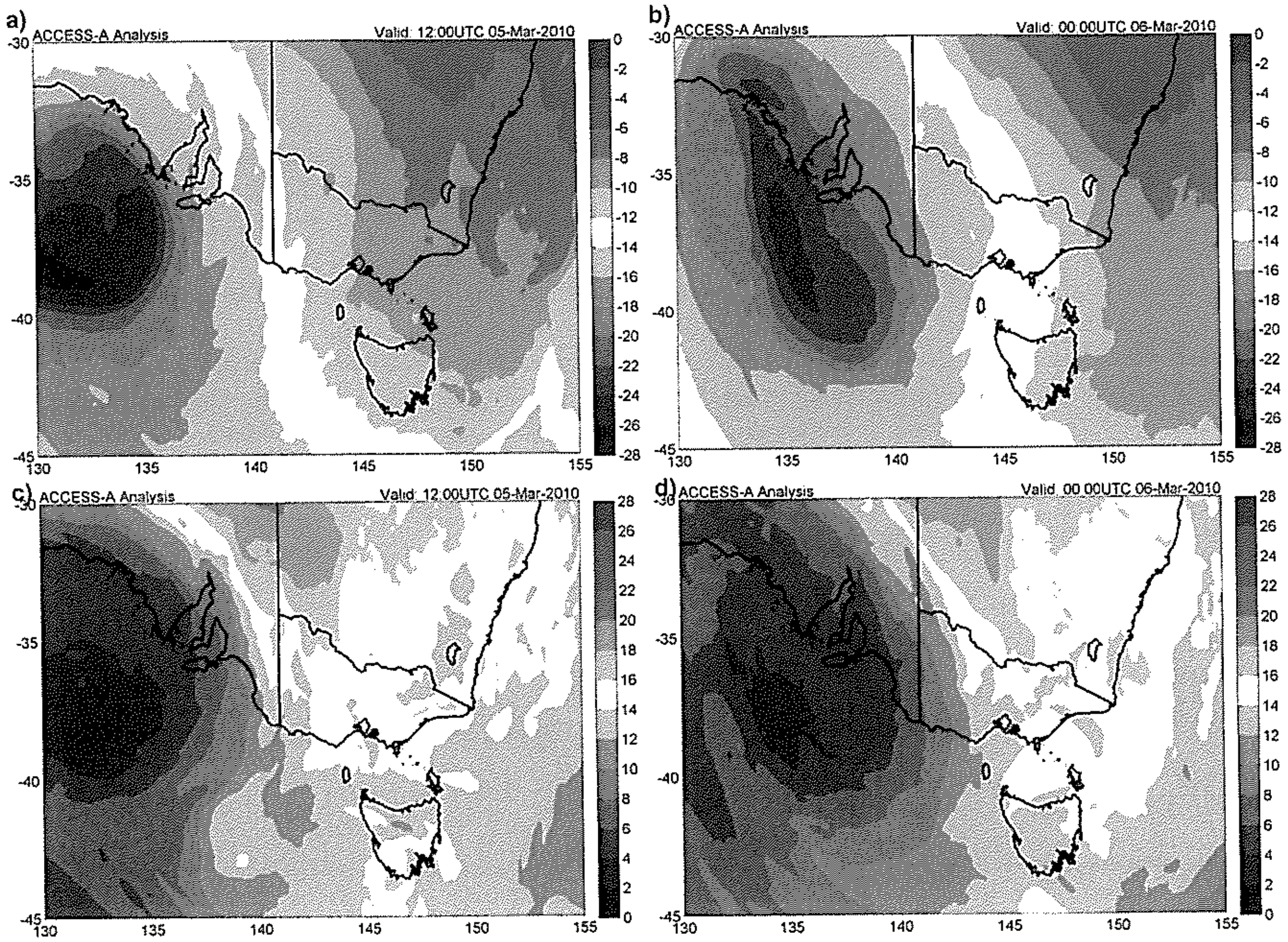


Figure 7: ACCESS-A analyses of 500hPa (~5500m AMSL) air temperature for **a)** 1200UTC 5 March 2010 and **b)** 0000UTC 6 March 2010 and, 850hPa (1500m AMSL) air temperature for **c)** 1200UTC 5 March 2010 and **d)** 0000UTC 6 March 2010.

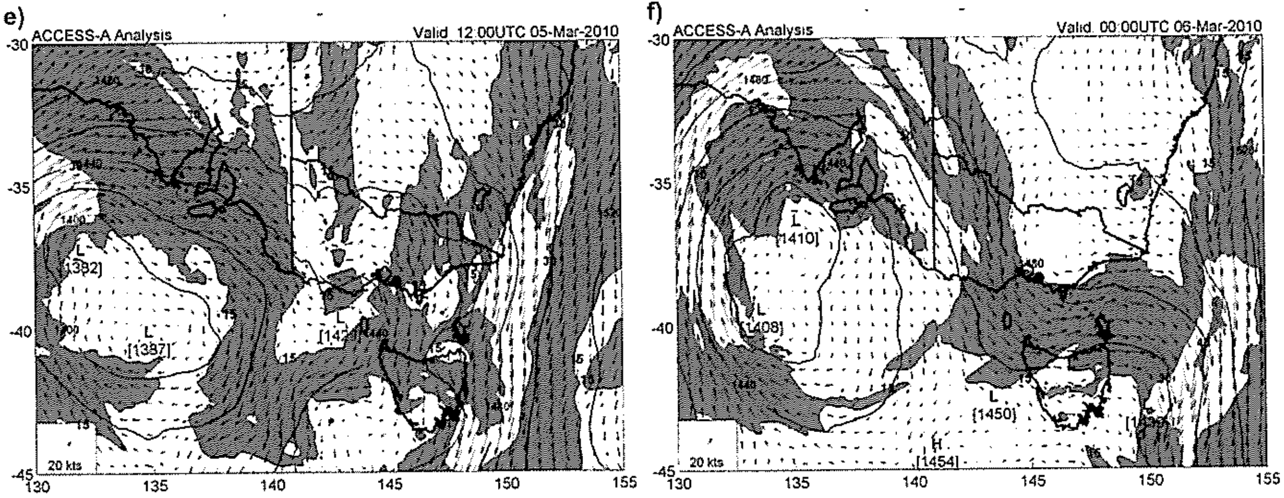


Figure 8: ACCESS-A analyses of 850hPa (~1500m AMSL) geopotential height and winds for **a)** 1200UTC 5 March 2010 and **b)** 0000UTC 6 March 2010.

Mesoscale Analysis

Given a synoptically favourable environment for thunderstorm development, the mesoscale environment, defined by horizontal scales between ten and several hundred kilometres (Johnson and Mapes 2001), was also assessed to identify additional ingredients that aided in thunderstorm development, promoted thunderstorm severity and defined areas of increased severe thunderstorm risk.

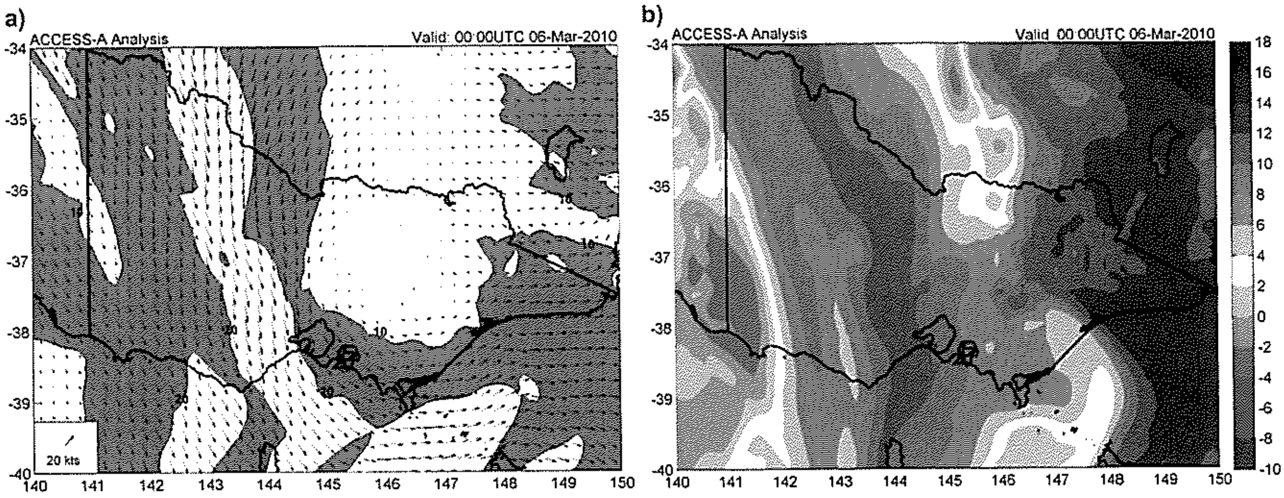
0000UTC (1100EDT) 6 March 2010

The mesoscale 0000UTC 6 March 2010 Mean Sea Level Pressure (MSLP) analysis (Figure 10a) shows a small low pressure centre situated to the northwest of Melbourne in between the regional cities of Ballarat (BLT) and Bendigo (BDG) in an otherwise light gradient flow. The low pressure centre was aligned vertically with the developmentally favourable poleward exit region of the 250hPa jet stream and eastern-most jet streak at 300hPa as illustrated in Figures 4a and 5a respecitvely. The surface low is suggested to be, in part, a consequence of increasing upper-tropospheric divergence enhancing mid-tropospheric vertical motion which, ultimately leads to lower-tropospheric cyclonic vorticity and a reduction in surface pressure (Bluestein 1993).

An associated trough of low pressure extended west of Bendigo and into southwest New South Wales (NSW), signifying the convergent axis between the opposing northerly and southwesterly surface flows. Basic continuity arguments imply surface convergence associated with a trough leads to vertical motion which can act as a trigger for thunderstorms in a thermodynamically unstable troposphere. Wilson and Schreiber (1986) showed that there is a high preference for thunderstorms to form within 20km of a convergent boundary. The surface trough also extended east to near Mount Baw Baw (BAWX) and then south linking to another low pressure centre situated southwest of Tasmania.

Mild conditions were evident on the 0000UTC analysis (Figure 10a) with screen temperatures to the east of the surface trough in the mid-twenties (°C), decreasing to the high teens to low twenties (°C) to the west of the trough.

Low-level moisture is an integral component of thunderstorm formation and genesis and contributes to the stability of the thermodynamic troposphere. Inspection of the 0000UTC mesoscale analysis (Figure 10a) reveals dewpoint screen temperatures in the high teens (°C) to the east of the trough and in the low teens (°C) to the west of the trough. This moisture discontinuity across the surface trough resembles a weak dryline; a feature typically seen during the warmer months over inland NSW and Queensland (Arnup and Reeder 2007). The convergence of the opposing winds, in



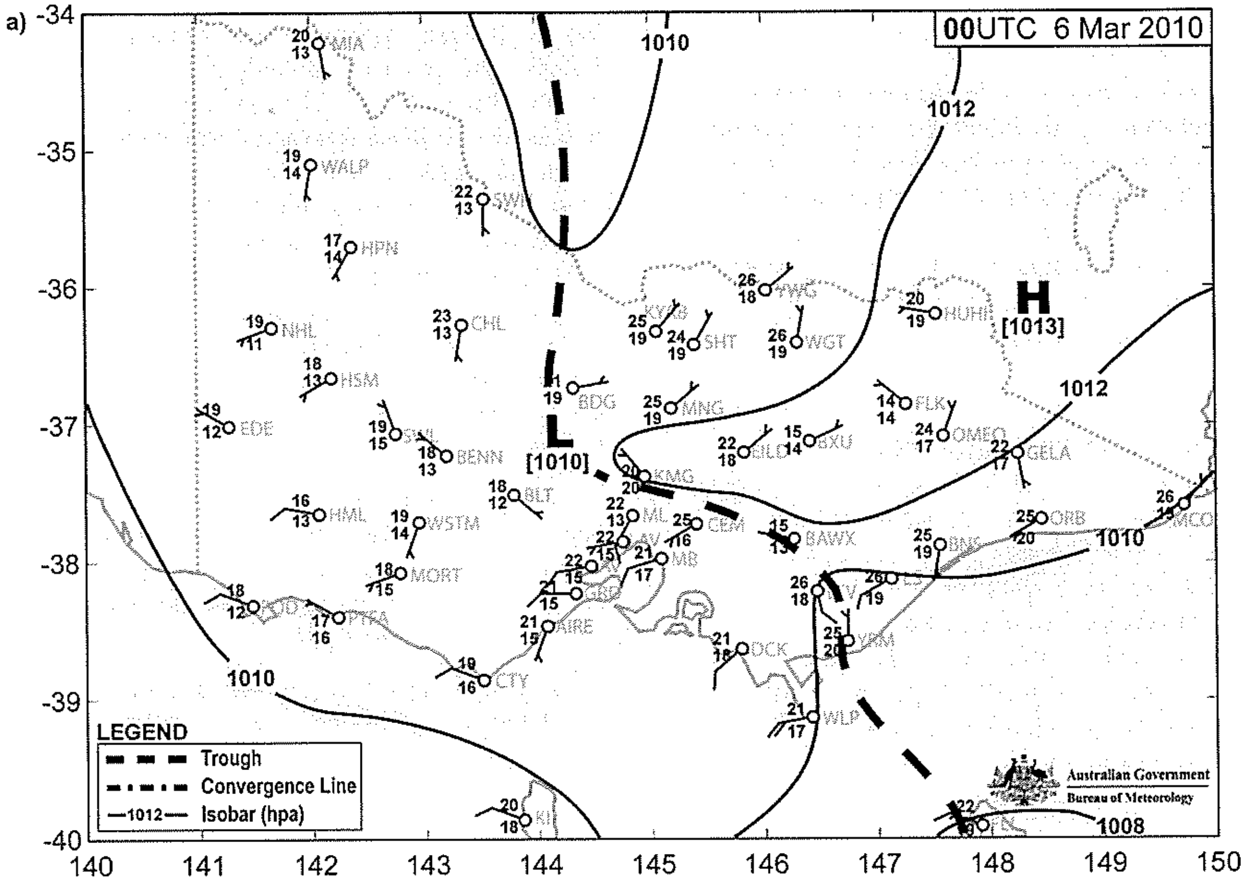


Figure 9: ACCESS-A 0000UTC 6 March 2010 analyses of 850hPa (~1500m AMSL) **a)** wind vectors and wind magnitude and **b)** dewpoint temperature (°C).

b)

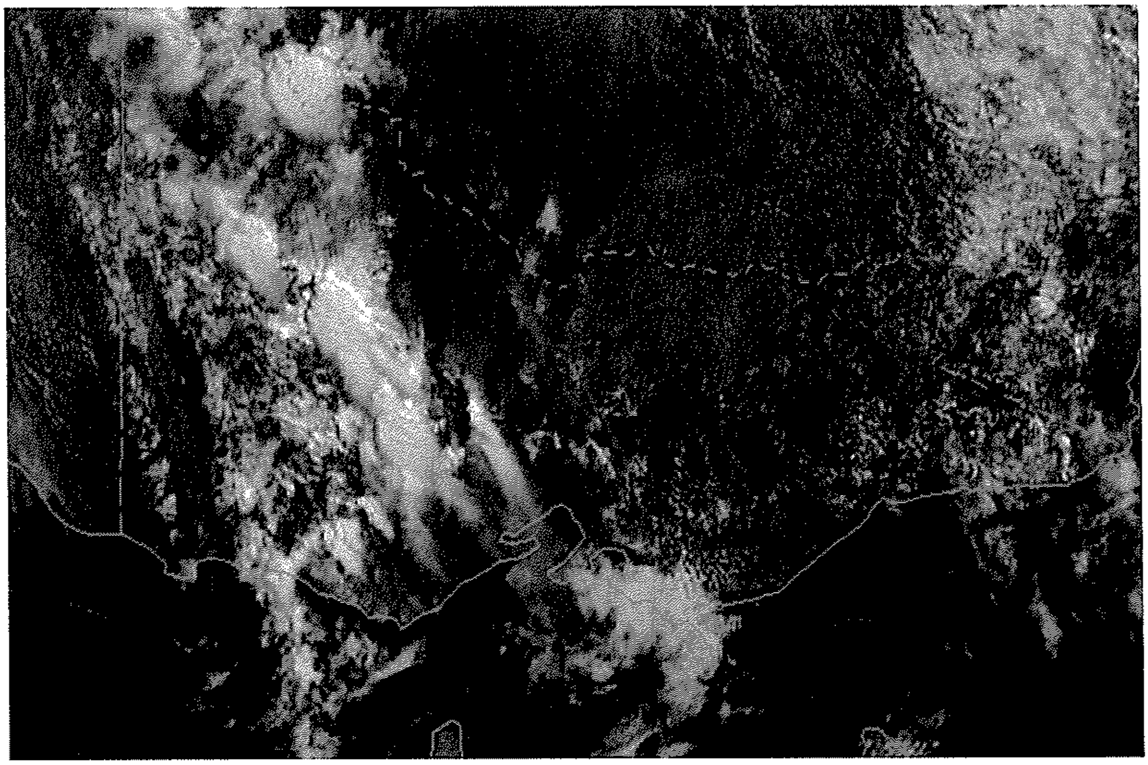


Figure 10: a) MSLP analysis and Automatic Weather Station (AWS) observations for 0000UTC 6 March 2010 and, **b)** the corresponding MTSAT-1R 1km resolution visible spectrum satellite imagery for 0030UTC 6 March 2010.

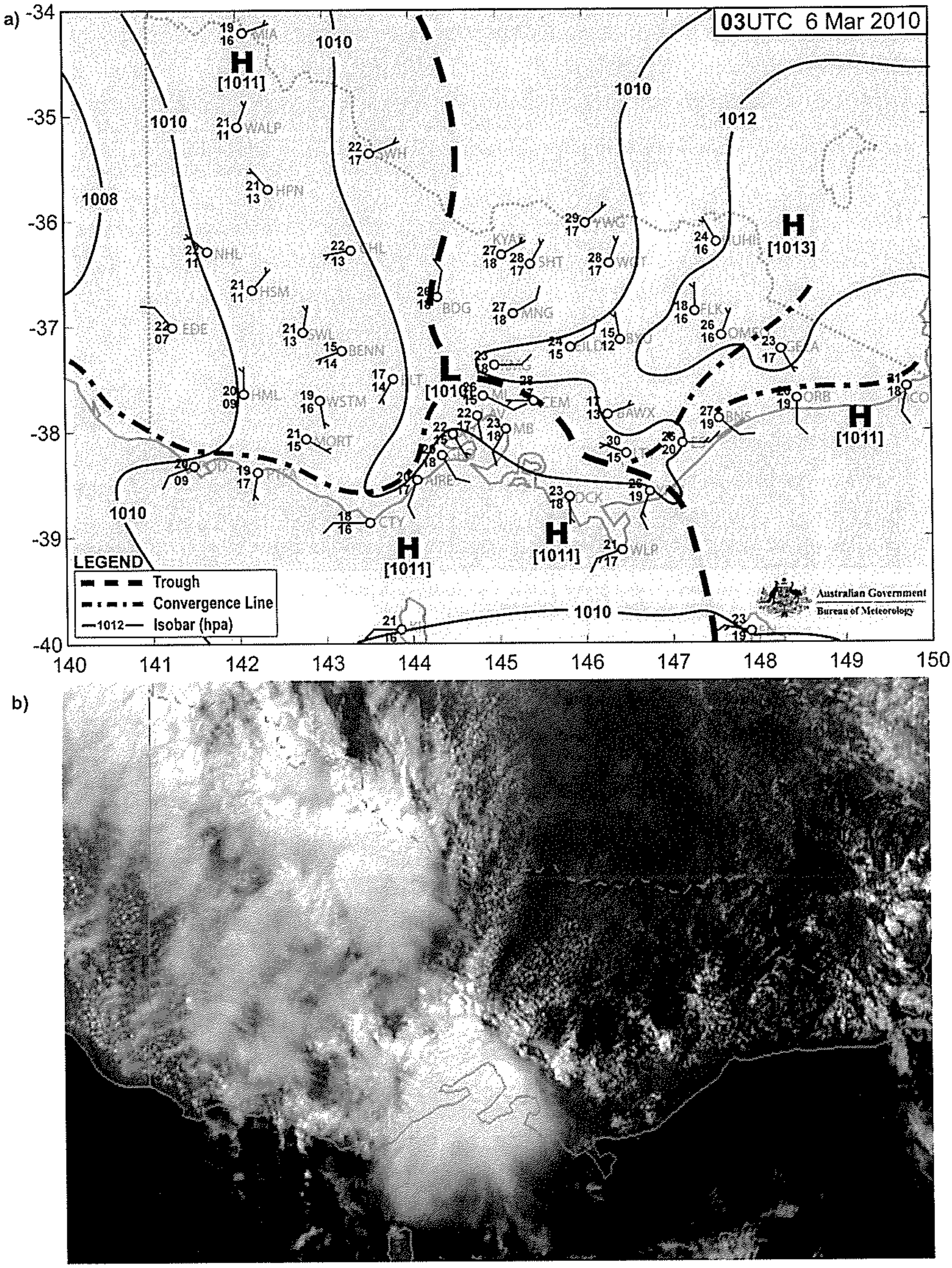


Figure 11: a) MSLP analysis and Automatic Weather Station (AWS) observations for 0300UTC 6 March 2010 and, **b)** the corresponding MTSAT-1R 1km resolution visible spectrum satellite imagery for 0330UTC 6 March 2010.

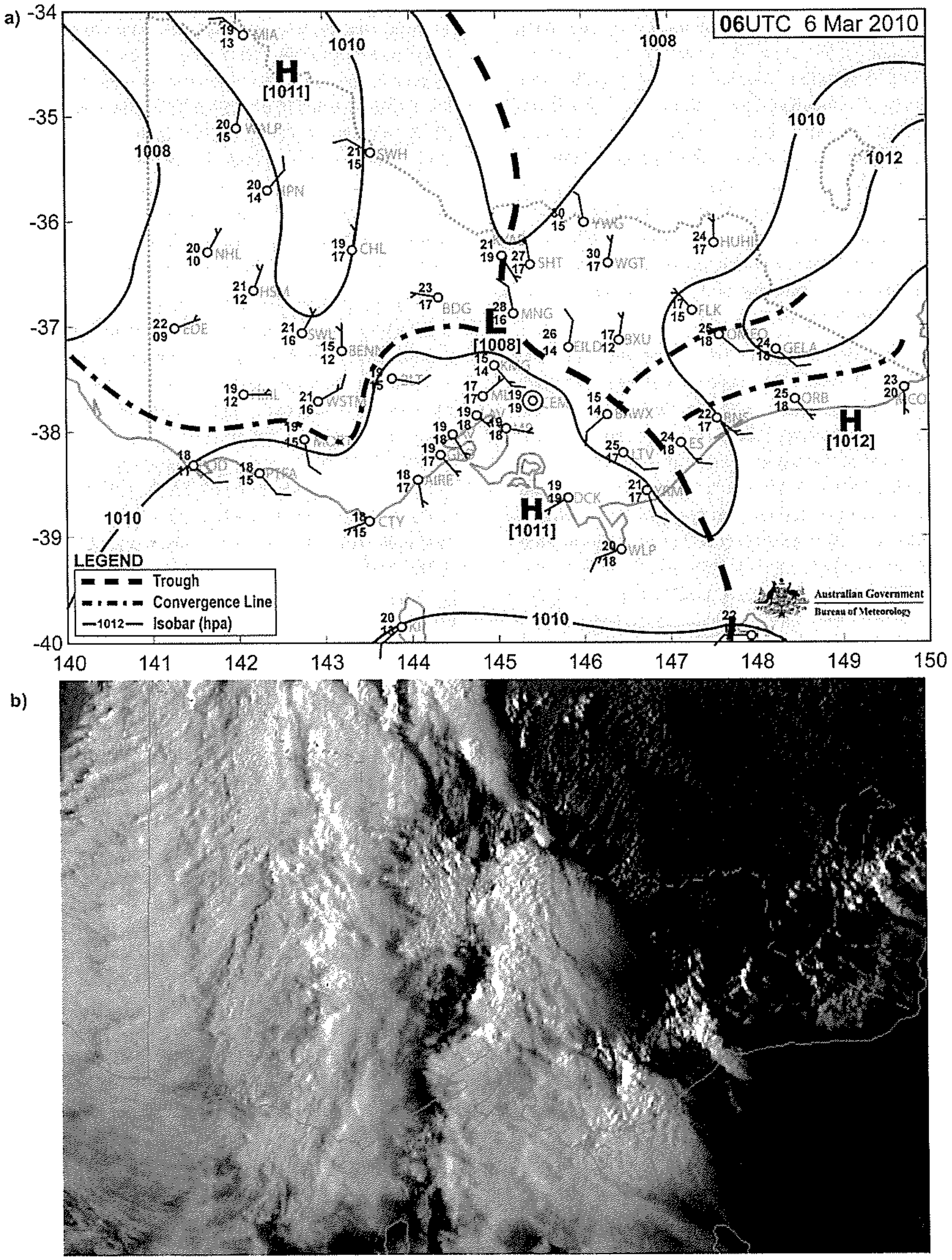


Figure 12: a) MSLP analysis and Automatic Weather Station (AWS) observations for 0600UTC 6 March 2010 and, b) the corresponding MTSAT-1R 1km resolution visible spectrum satellite imagery for 0630UTC 6 March 2010.

conjunction with the deformation of the flow along the trough axis, acts to contract the moisture gradient orientated parallel to the trough axis (moisture convergence). Such a moisture discontinuity has been shown to possess characteristics of weak atmospheric density currents (Atkins et.al. 1998) that can further enhance vertical motion near the surface trough. Consequently, the surface trough with the potentially enhanced vertical motion provided by the aforementioned mechanisms is important to thunderstorm initiation.

Thunderstorms can be observed in the 0030UTC MTSAT-1R visible satellite imagery (Figure 10b) over the western half of the State. Some of these storms had already become severe, with reports of damaging winds causing trees to fall and block roads. Convective activity had initiated along a lower-tropospheric short-wave trough where a north to northeasterly flow to the east of the trough converged with a northwesterly flow to the west of the trough, as illustrated in Figure 9. Note the lack of enhanced convection along the surface trough due to the presence of a capping inversion at an altitude of approximately 2100m which is discussed in the next section.

0300UTC (1400EDT) 6 March 2010

By 0300UTC (1400EDT), the northern extent of the surface trough and associated convergence had remained relatively stationary, while the surface low had drifted southeastward to be situated near Bacchus Marsh, approximately 53km north northwest of Melbourne and subsequently deepened. The southern extent of the surface trough was also quasi-stationary with minor deviations from the 00UTC positioning.

Convergent boundaries are also analysed on the MSLP analysis (Figure 11a). In the southwest of the State, the convergence was a result of coastal sea breezes, while in the southeast, two convergence boundaries existed. The northern most boundary was a result of the convergence between the prevailing north to northeasterly flow and a developing southeasterly flow resulting from an increase in the pressure gradient between the high pressure ridge over the Tasman Sea and the decreasing pressure of the mesoscale low. The sea breeze did however begin influencing coastal Gippsland as indicated by the 10 metre winds at East Sale (ES), Bairnsdale (BNS) and Orbost (ORB) tending south to southeasterly and constitutes the second convergence line. Convective cloud formations in the form of Cumulus clouds can be observed in the visible satellite imagery (Figure 11b) near the convergence lines over the east of the State.

Of particular interest and significance to this event is the intersection of the surface trough and the sea breeze boundary near the low. Referred to as the *triple point*, it signifies an area of marked convergence which can lead to vigorous convection (Johnson and Mapes 2001). The 0300UTC (1700EDT) MSAS 10 metre wind vector analysis with calculated convergence (shaded), as illustrated in Figure 13, shows the marked convergence associated with the triple point. Wilson and Schreiber (1986) revealed that thunderstorms commonly formed within 5km of the point of intersection between colliding boundaries, such as the interaction of the sea breeze and the trough in this case. Enhanced convection can be clearly seen in close proximity to the triple point in the 0330UTC (1430EDT) visible satellite imagery (Figure 11b). As will be shown later, in the case of the Melbourne Hail Storm, the responsible thunderstorm had already been in existence but dramatically intensified in close proximity to the triple point.

A mesoscale ridge of relatively higher pressure had developed over the western half of State, extending from Mildura in the Mallee forecast district to near Westmere in the Western forecast district. This area of relative higher pressure is the likely result of a combination of subsiding air associated with convective precipitation, and increased subsidence associated with the descending branch of the secondary ageostrophic circulation stemming from the deep convection along the lower tropospheric shortwave trough. Further localised high pressure regions are evident offshore as a result of the descending branches of the sea breeze circulations.

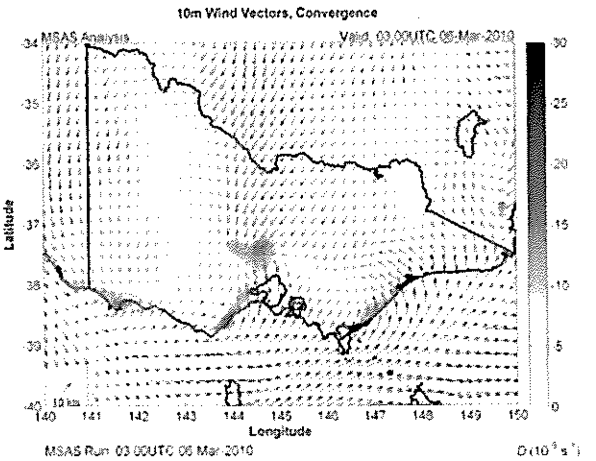


Figure 13: MSAS 0300UTC 6 March 2010 (1400EDT 6 March 2010) 10m wind vector analysis and convergence.

Screen temperatures had increased from the 00UTC observations (Figure 10a) ranging in mid to high twenties (°C) in the northeast ahead of the surface trough and in the high teens to low twenties (°C) to the west of the surface trough. Temperatures near coastal areas experienced only minor deviations from the 00UTC observations due to the advection of relatively cooler bay/sea breeze air offsetting the effect of surface heating. Screen dewpoint temperatures had decreased by 1 to 2°C since 00UTC due to thermal and mechanical mixing in the planetary boundary layer. The marginal decrease in dewpoint temperatures in the northeast of the State east of the surface trough is of particular importance. Assessment of the 2300UTC 5 March 2010 (1000EDT 6 March 2010) Wagga Wagga aerological sonde observation (not shown) revealed a deep layer of moisture in a planetary boundary layer with a mixing depth of approximately 1500-1800m. Given that the dewpoint temperatures east of the surface trough only decreased by 1 to 2°C upon convective mixing confirms that a deep layer of moisture was evident which was significant to thunderstorm inflow.

The moisture convergence along the trough axis and the role of the trough to promote vertical motion can be seen in the visible satellite imagery (Figure 11b) as Cumulus cloud development near and east of the trough location. Horizontal banding orientated northeast to southwest in the Cumulus cloud field can also be identified, suggesting the organisation of convection by streamwise vorticity (an important ingredient for organised severe thunderstorms). An interesting feature of the visible satellite imagery is the presence of convective outflow boundaries over southwest NSW from thunderstorms in the Mallee forecast district.

The severe thunderstorm that would impact the Melbourne CBD a short time later was located near Melton, approximately 35km west northwest of Melbourne in close proximity to the triple point; the mammoth anvil of the storm clearly defined in the visible satellite imagery (Figure 11b) over the Melbourne region and extending into Bass Strait.

0600UTC (1700EDT) 6 March 2010

At 0600UTC (1700EDT), the severe thunderstorm that affected Melbourne and Melbourne's southeastern suburbs had propagated into the West and South Gippsland forecast district. Although it had weakened somewhat in comparison to its intensity over the Melbourne metropolitan area, it remained severe.

By 0600UTC, the situation had become quite complex and the analysis of the MSLP was difficult due to contamination of AWS observations by thunderstorm outflows. Regardless, the surface trough had moved gradually eastward while the mesoscale low had propagated northeast to be situated near Seymour (Figure 12a).

The sea breeze was observed to have propagated further inland in both the southwest and southeast of the State, particularly about the western half of the Central forecast district. The sea breeze over the Melbourne area and in the southwest of the State however, had weakened and deflected to become a light to moderate southeasterly. This has been shown to be primarily the result of the anticyclonic intertial oscillation (Haurwitz 1947; Neumann 1977).

The southeasterly flow over the southeast of the State had strengthened with an onshore flow of 15 knots recorded at East Sale (ES) and Bairnsdale (BNS) as the mesoscale low moved eastward, increasing the horizontal pressure gradient. As a result, the convergence line associated with the southeasterly flow had moved further inland to be orientated parallel with the Great Dividing Range.

Screen temperatures had further increased ahead of the surface trough in the northeast of the State with temperatures generally ranging in the high twenties to low thirties (°C). Temperatures to the west of the surface trough however varied by only 1 or 2°C from the 03UTC observations due to extensive cloud cover associated with convective activity within the proximity of the lower-tropospheric shortwave trough and mid- and upper-tropospheric cloud from the increasing baroclinic instability. Lower temperatures were evident in coastal areas with respect to the 03UTC observations due to the mature sea breeze. Screen dewpoint temperatures had remained relatively constant ahead of the surface trough in the northeast of the State while in the west, dewpoint temperatures increased near the mesoscale high pressure ridge as a consequence of evapouration of precipitation from shower and thunderstorm activity. Dewpoints decreased further west and across the South Australian border due to the advection of a drier continental airmass by the cyclonic northwesterly flow associated with the approaching surface low pressure system situated over the Great Australian Bight.

A severe thunderstorm initially developed near Noojee (situated approximately 128km east of Melbourne) in close proximity to a secondary triple point prior to 06UTC. At 06UTC, the secondary triple point had been analysed just east of Noojee, near Mount Baw Baw (BAWX). The pronounced convergence associated with the secondary triple point is illustrated in the 06UTC MSAS 10 metre wind vector and convergence analysis (Figure 14). Further recall from Figures 4b and 5b that at this time, strong upper-tropospheric divergence was evident, enhancing mid-tropospheric ascent over the region. The thunderstorm tracked through the Latrobe Valley resulting in flash flooding and strong wind gusts in Warragul and Traralgon. The anvil of the storm can be seen in the 0630UTC (1730EDT) visible satellite imagery (Figure 12b) near Sale (ES).

Further inspection of the visible satellite imagery shows extensive deep convection, marking the northern extent of the surface trough throughout the Northern Country, North Central and Central forecast districts. Deep convection can also be observed throughout the eastern half of the Mallee, Wimmera and Western forecast districts associated with the lower-tropospheric shortwave trough. Figure 15 shows the rapid strengthening of the 850hPa northwesterly flow to the west of the shortwave trough (compared to the 00UTC 850hPa winds in Figure 9), converging with the much lighter northerly flow east of the trough. The mesoscale ridge of higher pressure over the west of the State also tracked gradually eastward following the subsidence associated with the convective precipitation.

An interesting observation of the visible satellite imagery is the reduced cloud cover in a narrow filament between the convection associated with the surface trough within the Melbourne region and the convection associated with the lower-tropospheric shortwave trough. This can be attributed to the dry adiabatic subsiding branch of the secondary ageostrophic circulation; a counter-current that develops in response to the in-balance of mass transport between the convective cloud updrafts and the surrounding free troposphere (Schaefer et.al., 1986).

The following section will address the convective environment and stability of the troposphere leading up to development and during the Melbourne hail storm.

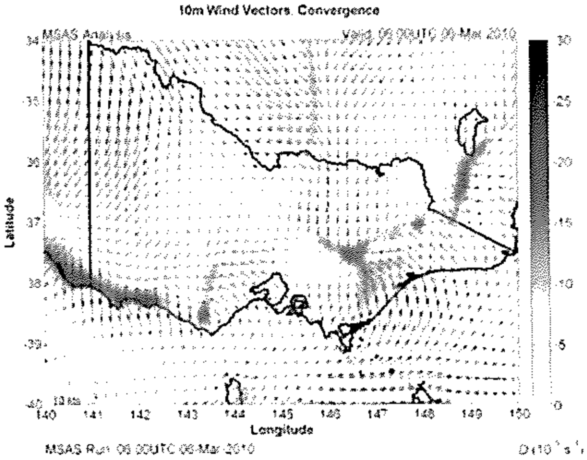


Figure 14: MSAS 0600UTC 6 March 2010 (1700EDT 6 March 2010) 10m wind vector analysis and convergence.

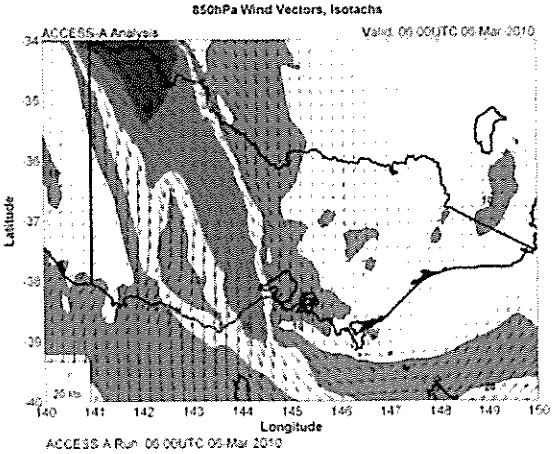


Figure 15: ACCESS-A 0600UTC 6 March 2010 (1700EDT 6 March 2010) 850hPa (~1500m) wind vector and wind magnitude analysis.

Convective Environment and Stability

In the previous sections, the synoptic and mesoscale processes and dynamics that lead to an environment highly favourable for severe deep convection were analysed. The significant features of the aforementioned analyses were:

- A warm, moist modified tropical airmass in the lower troposphere.
- A broad region of marked upper-tropospheric divergence resulting from diffluent jet streaks.
- Upper-tropospheric divergence and enhanced mid-tropospheric vertical motion associated with a poleward exit region of the eastern-most jet streak that was co-located with a surface trough.
- Substantial thermodynamic destabilisation over the Melbourne region provided by the advection of cooler mid-tropospheric air, coupled with the warm moist air advection in the lower-troposphere.
- Enhanced lower-tropospheric convergence associated with a triple point between a surface trough and sea breeze boundary.

Three main ingredients are necessary for thunderstorm development: sufficient low-level moisture, low static stability (thermodynamic instability) and a lifting mechanism to enable air parcels to ascend to their Level of Free Convection (LFC) (Doswell 1987). Perhaps two additional ingredients that are equally as important in determining whether thunderstorms become severe are: strong deep layer wind shear and upper-tropospheric forcing. Each of these ingredients will be analysed independently in this section and along with their consequence on the potential severity of thunderstorms.

Moisture

It has been shown that there was an abundance of low-level moisture over the State on 6 March 2010, courtesy of a warm, moist modified tropical airmass in the lower troposphere characterised by screen dewpoint temperatures in the mid to high teens (°C). Moisture plays an integral role in promoting deep and possibly severe convection by lowering the Lifting Condensation Level (LFC) and Level of Free Convection (LFC), increasing the Convective Available Potential Energy (CAPE) that can be extracted by latent heat release upon condensation within the thunderstorm, increasing the maximum amount of potential precipitation (Precipitable Water) and by enabling shallow moist convection in the planetary boundary layer (PBL) which acts to erode convective inhibitions (discussed later in this section) (Johnson and Mapes 2001).

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Each of these ingredients were provided in the mesoscale environment: Screen dewpoint temperatures in the mid to high teens (°C) provided abundant low-level moisture; the advection of cooler mid-tropospheric air, coupled with warm air advection in the lower-troposphere provided thermodynamic instability; while the surface trough and presence of a triple point potentially provided a suitable lifting mechanism for air parcels to ascend

Severe Characteristics

For a thunderstorm to be classified as severe in Australia, it must produce phenomena that meet the following criteria:

- Hail with diameter ≥2cm at the surface
- Wind gusts ≥90km/h (as recorded by standard Bureau of Meteorology anemometers at a height of 10m above the surface)
- Very heavy rainfall leading to flash flooding (defined within Victoria as a rainfall rate that equals or exceeds the 10 year Average Recurrence Interval (ARI))
- Produces a tornado.

    - ➢ Address Richter and Deslandes four large-hail assessment techniques.
    - ➢ Refer to Tucker's Characteristics of Severe Hail in Eastern Australia finding for Melbourne.