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Shorter contribution

Severe storms inferred from 150 years of sub-daily pressure observations along Victoria's "Shipwreck Coast"

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A severe storm index is created for Cape Otway using twice-daily in-situ surface pressure observations between 1865 and 2006. Events are identified from the 1st and 99th percentile of the probability distribution of pressure tendencies between subsequent sub-daily observations for each month. Each of the severe storms was then hand-checked against the original hand-written weather logs and other available historical archives. Of the 951 events identified over the period of study, 12 per cent were discovered to be due to keying errors in the data. Using the remaining quality-controlled data, the results show that the number of severe storms at Cape Otway has decreased significantly by about 40 per cent since the mid-19th century.

Introduction

On 3 June 2007, after a two-year search, the Southern Ocean Exploration Team discovered the wreck of the cargo ship SS Alert in Bass Strait off the coast of Cape Schanck, Victoria. The ship was wrecked in severe weather on 28 December 1893. According to the National Shipwrecks Database (NSD; DEHWA 2009), over 700 ships have been wrecked along the Victorian coastline over the past 200 years. The NSD states that *"the weather off the coast of Victoria at the time of the* (SS Alert) *sinking was the worst for many months"* although the subsequent discovery of the wreck suggests that the Scottish-built ship was never designed for Southern Ocean sailing (The Age, 13 June 2007).

Despite the risks, Bass Strait was a major shipping route of significant economic importance during the 19th and early 20th centuries. Ship after ship carried supplies, convicts and immigrants past Victoria's coastline on the way to Melbourne, Sydney and other large and growing settlements. Many lives were lost, often after being ship-wrecked by fierce storms rolling in from the Southern Ocean. The sailor and explorer Matthew Flinders had *"seldom seen a more fearful section of coastline"*. Little wonder that the Victorian coast is sometimes called the *"Shipwreck Coast"*.

Fortunately, weather-related shipwrecks have declined over the past century. While this is undoubtedly due to improvements in ship-building techniques, technology and forecasting, was it also stormier along the Victorian coastline during the late 19th century than it is today? Given that the climate is changing due to global warming, has this produced a trend in the frequency or intensity of storms over the past 150 years?

A new data set from the Bureau of Meteorology is helping us address such questions. The data set consists of

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newly digitized in-situ sub-daily air pressure data from the pre-1957 period for about 50 observation stations around Australia. Rapid changes in pressure enable us to pin-point when storms and gales occurred, how often they occurred, and can even shed light on how intense the storms might have been.

Most studies using sub-daily to daily in-situ data have been limited to the northern hemisphere and particularly northern Europe where century and longer time scale observations are available (WASA Group 1998; Alexandersson et al. 2000; Barring and von Storch 2004). Alexander et al. (2005) and Allan et al. (2009) used an absolute change of 10 hPa over a 3-hour period as a measure of severe storm events over the British Isles and Iceland, while other studies have focussed on analysis of storminess using wind gust characteristics (e.g. Smits et al. 2005), daily pressure tendencies (e.g., Alexandersson et al. 2000) and geostrophic winds deduced from station triangles of pressure observations (e.g. Schmidt and von Storch 1993; Matulla et al. 2008). Studies have shown that measures of storminess calculated from pressure observations generally provide a much more homogeneous record for analysis than, for example, wind speeds, which are very sensitive to site moves and changing instrumentation (WASA Group 1998). In the southern hemisphere, while the structure, location, density and number of storms and extra-tropical cyclones have been studied (e.g. Simmonds and Keay 2000; Lynch et al. 2006; Frederiksen and Frederiksen 2007; Lim and Simmonds 2007; Pezza et al. 2007), attention has been largely limited to the last 50 years which is the period covered by reanalysis data. So while the study of in-situ pressure observations limits the space scale of the analysis of storms, it does allow us, for the first time, to study the variations in storms over a much longer period of approximately 150 years.

One of the stations included in the new data set is Cape Otway, situated near the eastern end of the "Shipwreck Coast". There has been a lighthouse at Cape Otway since 1849 and meteorological observations have been taken since 1861, probably making it the site with the longest-running continuous observational record in Australia. While there are other stations in the Bureau of Meteorology data set on the coasts of Tasmania and South Australia, the data are incomplete and do not provide the length of record that can be obtained from the Cape Otway site. The Cape Otway record therefore provides a unique and complete insight into climate variability and changes across the region since the 1860s. We will use data from this station to illustrate how severe storms can be diagnosed and the quality control procedures needed to ensure that the data are interpreted correctly.

Severe storm index

Cape Otway has an almost complete record of 0900 and 1500 (local time) pressure observations since 1865 (held at the National Archives of Australia). However, when the observations were digitised they were generally keyed "as read", and have not been homogenised to remove inconsistencies that may be introduced through changes in instrumentation, for example. By considering pressure tendencies (i.e. the difference in pressure between two observing times) as a proxy for "storminess" rather than actual pressure values, we can eliminate some of the bias that may have been introduced over time as instrumentation and observing practice changed (Alexander et al. 2005). For this reason, pressure tendencies from 0900 to 1500 (6-hour tendency) and 1500 to 0900 (18-hour tendency) have been calculated for each day for the period 1865 to 2006. Sub-daily tendencies should detect more of the faster moving, intense storms that would be missed if only one daily tendency were considered (Alexander et al. 2005). To identify the most severe storms, the 1st and 99th percentiles of all 6-hour and 18-hour pressure tendencies for each month were calculated using a simple rank percentile method. Station-level pressure data are used in this study in preference to mean sea level pressure data to reduce the risk of inhomogeneity in the record. This is because mean sea level pressure data are derived from station-level data and potential changes in the derivation process over time may introduce artificial changes in the mean sea level pressure measurements. Every occasion where a pressure tendency was below (above) the 1st (99th) percentile was classified as a "severe storm". The percentile threshold values for each month are shown in Table 1 and suggest that while the thresholds are generally larger in winter, the severe storm thresholds at Cape Otway vary little throughout the year. This indicates that storms can be as fierce in summer as in winter. One example of such an event in summer

Table 1. Thresholds (in hPa) for the 1st and 99th percentiles of 6-hour and 18-hour pressure tendencies at Cape Otway, 1865-2006.

	6-hour tendency (hPa)		18-hour tendency (hPa)	
	1%ile	99%ile	1%ile	99%ile
Jan	–7.1	6.7	–13.2	14.4
Feb	–6.9	6.7	–11.3	14.0
Mar	–6.7	6.7	–10.5	13.9
Apr	–6.9	7.1	–12.6	14.4
May	–7.2	7.1	–12.5	13.7
Jun	–7.4	6.9	–14.0	15.9
Jul	–7.9	6.8	–13.5	16.6
Aug	–8.0	8.3	–14.5	15.5
Sep	–8.6	7.7	–14.8	16.9
Oct	–8.4	8.7	–14.3	15.7
Nov	–7.8	6.8	–14.6	14.5
Dec	–7.0	7.0	–13.7	13.7

Fig. 1 Satellite image of the storm over Victoria at 0225 UTC (1325 EDST) on 3 February 2005 which was also identified by the severe storm index at Cape Otway. Satellite image originally processed by the Bureau of Meteorology from the geostationary satellite GOES-9 operated by the National Oceanographic and Atmospheric Administration for the Japan Meteorological Agency. Image obtained from Bureau of Meteorology (2009).

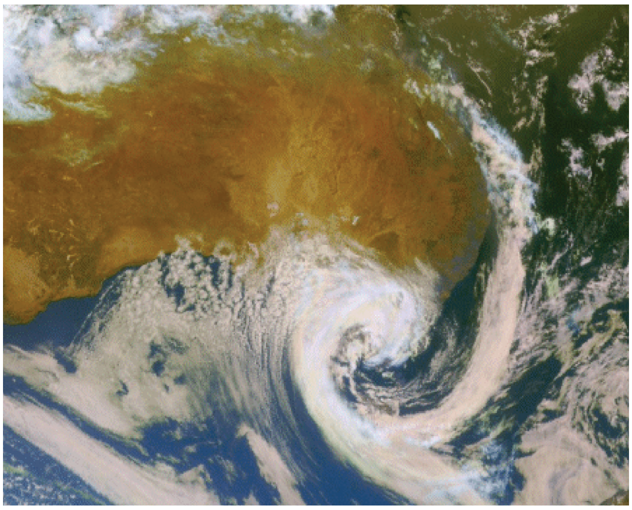
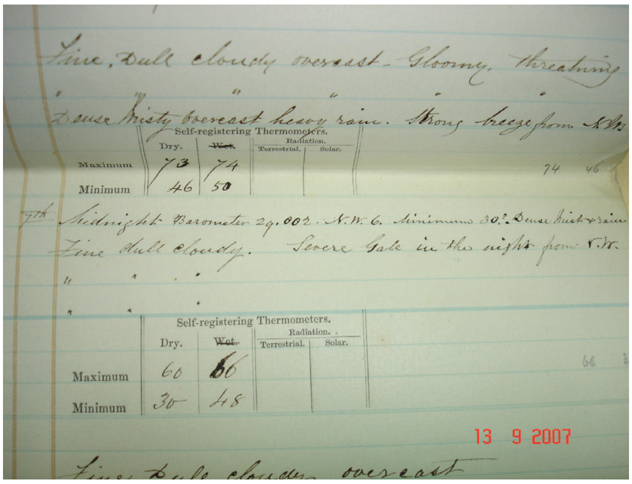


Fig. 2 Cape Otway weather log from 7th March 1866 which reads "Midnight barometer 29.002. N.W.6. Minimum 30°. Dense mist and rain. Fine dull cloudy. Severe gale in the night from N.W.". The ships Bitter Beer (schooner) and Pomona (ketch) were likely wrecked when caught in this gale, described in the National Shipwrecks Database (NSD) as "one of the fiercest gales ever experienced on the Victorian Coast".



Fine, Dull cloudy overcast - Gloomy, threatening

" " " "

Dense Misty overcast heavy rain. Strong breeze from N.W.

	Self-registering Thermometers.			
			Radiation.	
	Dry.	~~Wet.~~	Terrestrial.	Solar.
Maximum	73	74		
Minimum	46	50		

74 46

7th Midnight Barometer 29.002. N.W. 6. Minimum 30°. Dense Mist & rain

Fine dull cloudy. Severe Gale in the night from N.W.

" " "

	Self-registering Thermometers.			
			Radiation.	
	Dry.	~~Wet.~~	Terrestrial.	Solar.
Maximum	60	66		
Minimum	30	48		

66

13 9 2007

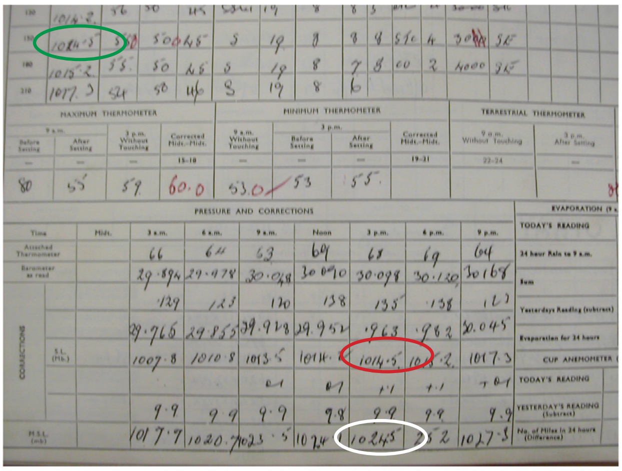
Fine, Dull cloudy overcast

occurred on 3 February 2005 (identified by the severe storm index since there was an 18-hour tendency decrease of 12 hPa). Figure 1 shows the striking satellite image of the event. In total, 951 severe storm events were identified between 1865 and 2006.

Unfortunately additional problems can arise whereby not all very large tendencies correspond to a severe weather event. For example, if a pressure observation was recorded or digitised incorrectly this will very likely produce an error in our severe storms index. To counter this, each of the 951 possible events identified in the raw index was hand-checked against the original weather logs for Cape Otway to determine whether a storm had actually occurred. Being historical documents, the weather logs are both valuable and fragile and need to be handled carefully, making the process of hand-checking very time consuming. However, they do provide much more information than can be obtained from the pressure tendencies alone. Barometer readings were generally available for many more time periods during the day than had been digitised and temperature, rainfall, wind speed and direction and other meteorological variables were also available. The observer notes (where available) also proved to be a valuable and interesting source of additional information about each event (see Fig. 2). Of the 951 events that we identified using the method described here, 115 (12 per cent) were identified as erroneous. This was mostly due to digits being transposed when keyed electronically or in some cases when observers have incorrectly recorded the observation in the original handwritten archive (see Fig. 3 for an example). The error rate is comparable to previous studies which have used similar techniques to identify severe storm events (e.g. Alexander et al. 2005; Allan et al. 2009).

The method described here does not necessarily pick up all the severe storms that occurred along the "Shipwreck

Fig. 3 An example of an incorrectly recorded value in the original handwritten archive (and hence wrongly digitised). The 3pm mean sea level pressure reading of 1024.5 hPa (white ellipse) has been incorrectly recorded in the observation column (green ellipse) rather than the station level pressure reading of 1014.5 hPa (red ellipse). This produced an 11 hPa increase in the storm index in a 6-hour period rather than the correct 1 hPa increase.



150	1024·5	50	50	45	5	19	8	8	8	5?0	4	3000	35
180	1015·2	55	50	45	5	19	8	7	8	00	2	4000	35
210	1017·3	54	50	46	5	19	8	6					

MAXIMUM THERMOMETER				MINIMUM THERMOMETER				TERRESTRIAL THERMOMETER	
9 a.m.		3 p.m. Without Touching	Corrected Midt.-Midt.	9 a.m. Without Touching	3 p.m.		Corrected Midt.-Midt.	9 a.m. Without Touching	3 p.m. After Setting
Before Setting	After Setting				Before Setting	After Setting			
—	—	—	15-18	—	—	—	19-21	22-24	—
80	55	59	60.0	~~53.0~~	53	55			

PRESSURE AND CORRECTIONS

Time		Midt.	3 a.m.	6 a.m.	9 a.m.	Noon	3 p.m.	6 p.m.	9 p.m.
Attached Thermometer			66	64	63	69	68	69	64
Barometer as read			29·894	29·978	30·048	30·090	30·098	30·120	30168
CORRECTIONS			·129	·123	·120	·138	·135	·138	·123
			29·765	29·855	29·928	29·952	·963	·982	30·045
	S.L. (Mb.)		1007·8	1010·8	1013·5	1014·	1014·5	1015·2	1017·3
					0·1	0·1	+·1	+·1	+0·1
			9·9	9·9	9·9	9·8	9·9	9·9	9·9
M.S.L. (mb)			1017·7	1020·7	1023·5	1024·	1024·5	25·2	1027·3

EVAPORATION (9 a

TODAY'S READING

24 hour Rain to 9 a.m.

Sum

Yesterdays Reading (subtract)

Evaporation for 24 hours

CUP ANEMOMETER

TODAY'S READING

YESTERDAY'S READING (Subtract)

No. of Miles in 24 hours (Difference)

Table 2. Dates between 1865 and 1900 identified as "severe storms" when ships were also wrecked along the Victorian coastline according to the NSD. Where no number appears in the last column, the number of fatalities is unknown (*According to the NSD, these wrecks were not weather-related).

Date of severe storm	Name of ship wrecked (from NSD)	Wreck found	Number of fatalities
8/2/1866	Pryde	N	0
7/3/1866 - 8/3/1866	Bitter Beer	N	–
	Pomona	N	–
11/8/1866	Nith	N	–
15/4/1867	Black Watch	N	0
18/4/1867 - 19/4/1867	Admiral	N	0
	Emily	N	0
11/10/1868	Lucy Lee	N	1
25/11/1869	Marie Gabrielle	Y	–
1/3/1870	Eliza	N	–
27/6/1870	Dunkeld	N	–
29/3/1876	Eva	N	–
31/8/1876	Cygnet	N	–
9/5/1881	Caroline	N	–
10/7/1887	Dart	N	0
19/7/1887	Magnolia	N	4
15/1/1888	Edinburgh Castle*	Y	0
11/12/1892	Kermandie	N	3
1/10/1897	Omega	Y	0
2/3/1898	SS Perseverence*	N	0
30/7/1898	Emily	N	2
13/7/1899	Excelsiour	N	–
25/3/1900	SS Glenelg	N	31
9/5/1900	Magnat	Y	1
	Sierra Nevada	Y	23

Coast", particularly some of the events occurring between 1500 and 0900, since the 18-hour tendency can miss some of the fast-moving events which develop over shorter time scales. For example, a gale on 25 April 1880 with maximum wind speed of 78 mph (126 km/h) does not show up in the severe storm index. However, the method used provides a consistent and objective technique for identifying severe storm events over a period of about 150 years.

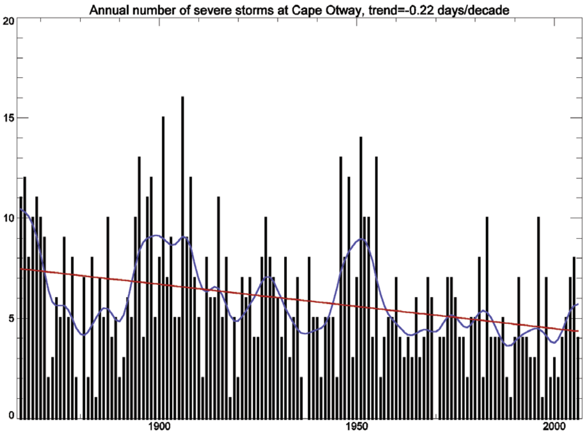
Shipwrecks

The dates when the storms mentioned above were identified were also compared with data from the National Shipwrecks Database. Table 2 lists occasions where the severe storms index coincides with shipwrecks along the Victorian coastline between 1865 and 1900. The NSD does not always contain full details about the shipwrecks - the reason for the wreck might be registered as *"unknown"* or the exact date of the wreck is not known. Not all shipwrecks in the database were weather-related and a lot of ships were deliberately *"scuttled"* or sank through human error such as in the case of one paddle steamer which burnt and sank while at anchor when *"crew away fishing"* or in another case simply *"ran ashore due to careless navigation"*. Conversely, some of the shipwrecks noted in the NSD as weather-related do not show up in the severe storms index. This is the case with perhaps one of the most famous shipwrecks, the Loch Ard, which was wrecked on 1 June 1878 with only two survivors out of the 54 people on board. Between 1500 on 31 May and 0900 on 1 June 1878, there was a large increase in pressure of 9.3 hPa in the 18-hour tendency at Cape Otway. However this is several hPa less than the 99th percentile threshold value of 13.7 hPa for this time of year (Table 1) so the event is not classified as a severe storm by our definition. Some of the shipwrecks listed in Table 2 are noted in the NSD as *"disappeared without a trace"*. This is the case with the Dunkeld which is noted as *"last seen near Wilsons Promontory, and became one of the many vessels that disappeared without trace along the Victorian coast"*. Our analysis sheds light on this long-standing mystery. The Dunkeld was last seen 40 nautical miles east of Wilsons Promontory on its voyage south from Newcastle on 27 June 1870 (Shipwrecks of Victoria 2009). On that very same day, there was a sharp pressure drop at Cape Otway of 10.2 hPa over a 6-hour period. A drop like this is consistent with severe weather. The mysterious disappearance of the Dunkeld, it seems, is a little less mysterious now. This connection was probably recognised at the time, but it does not seem to have been recorded in existing historical documents. Thus the Cape Otway pressure records have enabled us to make an interesting "re-discovery".

Variations in severe storms at Cape Otway

Following quality control, 836 severe storms were identified at Cape Otway between 1865 and 2006, implying a rate of approximately six severe storms per year. The trend in the annual number of severe storms was calculated using ordinary least squares regression and trend significance was calculated at the 5 per cent level using a non-parametric Mann-Kendall test (Mann 1945; Kendall 1975). Tests showed that there was not significant auto-correlation in the time series. Since 1865 there has been a significant decline of 0.22 days/decade in the number of severe storm events at Cape Otway (Fig. 4). This means that in recent times there have been about three fewer severe storms per year than at the end of the 19th century. This amounts to a decline of about 40 per cent. Figure 4 also shows marked decadal variability with peaks in storminess approximately every 25

Fig. 4 The number of severe storms per year at Cape Otway, 1865-2006 (vertical bars), the blue line is a 21-term binomial filter representing decadal fluctuations in the data and the red line is the linear fit to the data. The trend is significant at the 5 per cent level.



years. However the past 50 years or so have not seen such strong multi-decadal peaks, perhaps indicating a change in the large scale circulation and/or mechanisms driving these events.

The results presented here are consistent with studies over more recent periods, which indicate that there has been a southward shift in storm tracks in the southern hemisphere (e.g. Hope et al. 2006; IOCI 2005; Frederiksen and Frederiksen 2007; CSIRO-Bureau of Meteorology 2007). This southward shift has impacted the weather systems affecting southwest Western Australia and this has contributed to the large drying evident there (IOCI 2005; Power et al. 2005; Bates et al. 2008). Climate modelling studies suggest that, under anthropogenic climate change, storm tracks will continue to move polewards in the future (e.g. Bengtsson et al. 2006, Lynch et al. 2006). This is at least partly associated with shifts in the zonal sea surface temperature gradient. The conclusions drawn here are limited since only one station has been analysed, but the potential for this method to examine changes more broadly by incorporating a much larger selection of stations across southern Australia is very exciting. The newly digitized Bureau of Meteorology data grants us the opportunity to study trends in storminess in southern Australia for the first time on the time scales of northern European studies and highlights the importance of maintaining long-running, continuous meteorological stations for studies of long-term climate variability.

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