Wind generation's contribution to supporting peak electricity demand: meteorological insights

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ABSTRACT

Wind generation's contribution to meeting extreme peaks in electricity demand is a key concern for the integration of wind power. In Great Britain (GB), robustly assessing this contribution directly from power system data (i.e., metered wind-supply and electricity demand) is difficult as extreme peaks occur infrequently (by definition) and measurement records are both short and inhomogeneous.

Atmospheric circulation-typing combined with meteorological reanalysis data is proposed as a means to address some of these difficulties, motivated by a case study of the extreme peak demand events in January 2010. A preliminary investigation of the physical and statistical properties of these circulation types suggests that they can be used to identify the conditions that are most likely to be associated with extreme peak demand events.

Three broad cases are highlighted as requiring further investigation. The "High-over-Britain" anticyclone, is found to be generally associated with very low winds but relatively moderate temperatures (and therefore moderate peak demands, somewhat in contrast to the classic "low-wind cold-snap" that is sometimes apparent in the literature). In contrast, both longitudinally-extended blocking over Scotland/Scandinavia and latitudinally-extended troughs over western Europe appear to be more closely linked to the very cold GB temperatures (usually associated with extreme peak demands). In both of these latter situations, wind-resource averaged across GB appears to be more moderate.

1. Introduction

A primary concern in the integration of wind-energy into the power system of Great Britain (GB) is the contribution of wind during peak demand periods, which are generally reckoned to dominate the generation adequacy risk[1]. This is widely referred to as capacity value/credit (2) and is a distinct issue from the available energy resource year-round and additional flexibility requirements for short-term system operation.

As large-scale storage of electricity remains impractical, this essentially reduces to the question of wind-resource during peak demand conditions. The occurrence of "low-wind cold-snaps" (3) has been the subject of some debate in the literature, with sometimes apparently conflicting results (c.f. 4; 5).

Zachary et al (6) recently reviewed the challenges facing direct statistical analyses of this problem using recorded electricity demand and wind output. They concluded that the available data (≤ 25 years) was insufficient for robust statistical analysis of these extreme events[2] as the data is dominated by a very small number of distinct periods. Such analysis is further complicated by the gradual evolution of both the power and climate systems, along the peculiarities of human behaviour (e.g., weekends vs. weekdays).

It is, however, well established that physical weather properties have a strong impact on electricity demand (7) and wind electricity generation ($power \sim wind^3$). Indeed, while

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[1] Generation adequacy risk is the risk of the available generating capacity being insufficient to meet required demand. A comprehensive overview of generation adequacy risk assessment methods may be found in (1).

[2] "Extreme" events are here defined and interpreted (rather loosely) as events which have a low probability of occurrance, for example, an average return period of greater than one year.

weather properties cannot be used to unambiguously identify extreme peak electricity demand events (as human factors uncorrelated to weather undoubtedly play an important role), the prevailing weather conditions can be interpreted as determining the *susceptibility* of a given day to an extreme demand event. The assumption is therefore made that demand, D, can be separated into a "weather driven" part, $D_W(W)$, and a "human" part, $D_H(H)$, which is unrelated to weather; i.e., $D(W, H) \approx D_W(W) + D_H(H)$. This paper investigates wind speed's relationship to D_W, focussing primarily on demand's inverse response to temperature - subsequent studies will examine wind *power* and its relationship to more sophisticated models for D_W (following 7).

Analysis of wind resource directly from historic energy system data is also heavily constrained by the current deployment wind farms, most of which are in northern GB. When considering future deployments of wind farms, it is therefore important to assess the geographical distribution of wind resource and its temporal correlations (for discussion of spatio-temporal correlation of wind speeds and its impact on Nordic energy systems see, e.g., 8; 9).

Weather- or circulation- typing is proposed here as means to address some of these difficulties by maintaining information on the geographical distribution of wind speeds. By understanding and objectively identifying the meteorological patterns that are associated with high susceptibilities to winter extreme peak demand events, power system properties can be related to continuous meteorological "re-analysis" datasets (such as ERA-40 and ERA-Interim: 10; 11), thereby providing greater information on the spatio-temporal distribution of wind during periods that are particularly susceptible to high peak demands.

Many circulation-typing schemes exist (e.g., 12). Here, Grosswetterlagen (GWLs) are used (13; 14, updated to January 2010 from the German Meteorological Service website, www.dwd.de) alongside ERA-40 and ERA-Interim reanalyses. A recent discussion of the GWL scheme can be found in (15).

Section 2 examines the recent extreme demand event of January 2010. The use of GWLs to identify situations that are likely to be associated with high peak demand conditions over a longer period is then discussed (Section 3). Section 4 concludes by discussing "low-wind cold-snaps", along with future plans for developing a more quantitative methodology.

2. Peak demand in January 2010

Table 1 lists the five periods (18 days) during winters 2001/02 to 2009/10 where GB electricity demand exceeded 99% ACS peak[3]. January 2010 is highlighted because eight of these days (including the highest peak and seven of the top ten peaks) occurred during a single period from 4th to 14th. This is illustrated in Figs. 1 and 2 and discussed below.

Immediately before this period (2nd/3rd January), there is high pressure over Greenland/Iceland with weak low pressure systems (cyclones) west of Spain and developing over Scandinavia, moving east and south-west respectively. By the 4th, northerly flow over much of GB is associated with low surface temperatures (Fig. 1(a) and Fig. 2), leading to demand above 100% ACS peak.

From 5th to 7th January the cyclones merge, producing a north-south trough across western Europe (Figs. 1(b) and 1(c)). Cold air advection from northern/central Europe towards GB is associated with very cold surface air temperatures (Fig. 1(c)) and snow-

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[3] Please refer to Table 1 for a description of data and definitions.

fall. The highest recorded demand occurs at 17:00 on 7th January (Fig. 2). By the 8th, the combined cyclone lies in the North-West Mediterranean with a longitudinally-extended anticyclone forming over Scotland into Scandinavia (Fig. 1(d)).

The anticyclone maintains its orientation, increasing in size and intensity, while the Mediterranean cyclone weakens (8th-10th). Cold easterly air flow into GB is maintained. Temperatures are low but, as 9th/10th is a weekend, peak demands are moderate (Fig. 2).

By the 11th the northern anticyclone is weakening and tilting northeast-southwest (Fig. 1(e)), bringing slightly milder southeasterly winds into GB (Fig. 2). Peak demand remains high, but by 13th (Fig. 1(f)) the high pressure system begins to move southeastward, leading to milder air-flow over GB.

Two meteorological components appear to be associated with the highest peak demands in this period. Firstly, the particular cyclone systems passing across western Europe (the formation of a latitudinally-extended trough through western Europe, 4th-7th); and, secondly, the north-south pressure dipole (high over Scandinavia, low over the north-western Mediterranean, 8th-11th/12th). Both of these situations brought cold air into GB, particularly from the east/north-east, reversing the usual west/south-westerly flow. Fig. 2 shows the associated GWL patterns. In general terms, these situations appear to be linked to trough GWLs (TRW/TRM/TM, perhaps with WS or HNA as a precursor) and the "High Scandinavia-Iceland" GWLs (HNFA/HNFZ) respectively. The latter of these is part of a broader category of GWLs referred to as "blocking" (e.g., 16).

There is an extended period (7th-10th) where GB transmission-metered wind output[4] remains at less than 10% of its maximum capacity (Fig. 2, thin solid blue line). This

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[4] Please refer to Fig. 2 for details.

includes the highest peak demand period (17:00, 7th). The meteorological data, however, suggest that this may be related to the location of the recorded turbines rather than a GB-wide absence of wind[5] (Figs. 1, hatching/dots), e.g., while there are low wind areas during 7th/8th at no point do these cover GB. Indeed, on the 8th, there are *above average* winds over south-east England and the southern North Sea. Wind-speeds averaged separately over northern and southern GB (Fig. 2, blue dotted lines) suggest that wind-speeds were low in the north but moderate in the south during 7th-10th.

Clearly these patterns require further investigation to validate against direct weather observations and to examine the role of geographical variations in supply and demand. It is also interesting to speculate whether persistent snow-cover might also play a role in driving demand. The initial results, however, suggest that a well distributed deployment of wind farms could have made a greater-than-observed contribution to meeting demand during this period. This reinforces the conclusions of (6) in that direct records of metered wind-supply and demand are not only found to be too sparse to derive robust statistical estimates of extreme peak demand conditions, but that they are also likely to be unrepresentative of the future aggregated wind-supply (when a much greater geographical spread of wind-farms may be expected).

3. Circulation types

While single event case-studies provides useful insight into processes, the capacity contribution of wind (or indeed other generation technologies) can only be assessed quantitatively

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[5] This wind-supply record is dominated by Scottish output, see caption Fig. 2.

through probabilistic risk analysis. GWL identification is intended as a first step towards this. To illustrate, Fig. 3 shows GB-averaged mean daily 10m wind-speeds and 2m temperatures for each of the 29 GWL types during the extended winter season (November - March) from ERA-40 in the period Jan 1958 - Dec 2001[6].

There has been some debate about "low-wind cold snap" events in the literature and their relationship to demand (Section 1). This situation often appears to be conceptually linked to a high-pressure anticyclone directly over GB (GWL: HB or "High-over-Britain", Fig. 4(a)). This circulation type is indeed associated with low mean winds (Fig. 3). However, Fig. 3 also shows that HB's mean surface air temperatures are, on average, rather moderate compared to other circulation types. Given that GB winter electricity demand is typically inversely related to temperature and positively related to wind-speed (7), it seems rather unlikely that HB would be particularly susceptible to producing very extreme demand conditions. Indeed, the circulation types above and to the left of HB in Fig. 3 might be expected to be more susceptible to extreme demands (e.g., HNA/HNZ/HNFZ/HNFA are, on average, colder and windier). The importance of these types (HNFZ in particular) is confirmed in Table 1, which catalogues the extreme peak demand days between 1987 and 2006. The 15 days are split into 8 periods, of which three contain an HNFZ type (7 days, including the four most extreme).

The remaining days in Table 1 are associated with other high-pressure systems over Europe (e.g., SEA, HFA, HM and HB), although the high-pressure centre is shifted in each. High-pressure "blocking" therefore appears to be a key ingredient for extreme demand, with

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[6] It should be noted that there is considerable spread in the properties of individual days within each GWL type average in Fig. 3, so differences in the mean values should be interpreted with some caution.

the position of the block being important. In HNFZ/HNFA, the high pressure lies north of GB (Fig. 4(b)) and is associated with cold easterly continental winds over GB. In HB, however, the high pressure lies directly over GB (Fig. 4(a)) and the cold air advection occurs to the south and east. It is therefore perhaps unsurprising that Table 1 contains only one HB occurrence (15th of 15).

4. Summary

This paper reports on a preliminary attempt to use meteorological techniques to better understand wind-power availability during extreme peak demand in GB. While the links between GWLs and power system properties undoubtedly need refinement, such approaches have been demonstrated to enhance the understanding of this problem. The results presented here are rather qualitative but future efforts will focus on the development of quantitative statistics. Such an approach would be able to feed into probabilistic risk assessments of generation adequacy, while recognising the inevitable trade-off between cost and risk level.

It is suggested that at least three distinct types of situation are important for understanding wind's contribution to meeting GB winter peak demand (Fig 4):

- HB (High-over-Britain),
- HNFZ/HNFA/HNA/HNZ (or, more generally, blocking with north/northeasterly/easterly winds into GB),
- TRW/TRM/TM (or, more generally, extended north-south troughs over western Europe).

The HB type is associated with very low winds and a moderate susceptibility to high demand events, i.e., the "weather" component of demand forcing, $D_W(W)$, is moderate. Such events may therefore correspond to the actual peak demand recorded in any single year (2003 in Table 1, and 2006 in (4)) given an appropriately strong (and meteorologically unrelated) "human" demand forcing, $D_H(H)$. It is, however, unlikely that HB would to be associated with the most extreme peak demands on multi-annual timescales. Indeed, given the same $D_H(H)$, one would expect that the most extreme events, $D = D_H(H) + D_W(W)$, would be more likely to be associated some easterly wind from the continent, often (but not universally) associated with a longitudinally-extended high pressure system from Scotland into Scandinavia giving colder temperatures and a higher $D_W(W)$.

Future work will focus on understanding how these circulation types and their transitions can be used to produce quantitative statistics of wind-power and electricity demand, and how this methodology can be related to the findings of previous statistical studies (such as 5). One promising approach appears to be separating the problem into two components: firstly, the meteorology (the frequency, predictability and character of the atmospheric circulation) and, secondly, to construct essentially separate probability models describing the quantitative impacts of the relevant circulation types on the power system. Automated GWL identification algorithms (15) are also being used to investigate the impact of a variable and changing climate on GWL frequencies using climate model simulations.

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Declaration of conflicing interests

The authors declare that there are no conflicts of interest.

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List of Tables

GB demand 2001-2010, $\geq$ 99% ACS peak		
Dates	Days	GWL
10-11 Dec 2002	2	HFA
7-9 Jan 2003	3	HB
17 Dec 2007	1	HM
5-8 Jan 2009	4	NWZ/BM
4-14 Jan 2010	8	WS/TRW/HNFZ/SEA

England & Wales demand 1986-2005, $\geq$ 98% VCS peak		
Rank	Date	GWL
1	12 Jan 1987	HNFZ
2	14 Jan 1987	HNFZ
3	13 Jan 1987	HNFZ
4	15 Jan 1987	HNFZ
5	19 Jan 1987	BM
6	11 Dec 1991	HM
7	12 Dec 1991	HM
8	29 Nov 1993	SEA
9	25 Jan 1996	HNFZ
10	10 Dec 2002	HFA
11	15 Dec 1987	BM
12	7 Jan 1997	HNFZ
13	8 Jan 1997	HNFZ
14	29 Jan 1996	HNA
15	8 Jan 2003	HB

TABLE 1. Very high peak demand days in GB (top half) and England and Wales (bottom half). ACS (Average Cold Spell) peak is the standard measure of underlying transmission peak system demand in GB, independent of the demand in the particular year (17). VCS peak is the analogous peak demand measure used before the GB market was unified in 2004, and is about 2% higher than ACS peak for the same year.

List of Figures

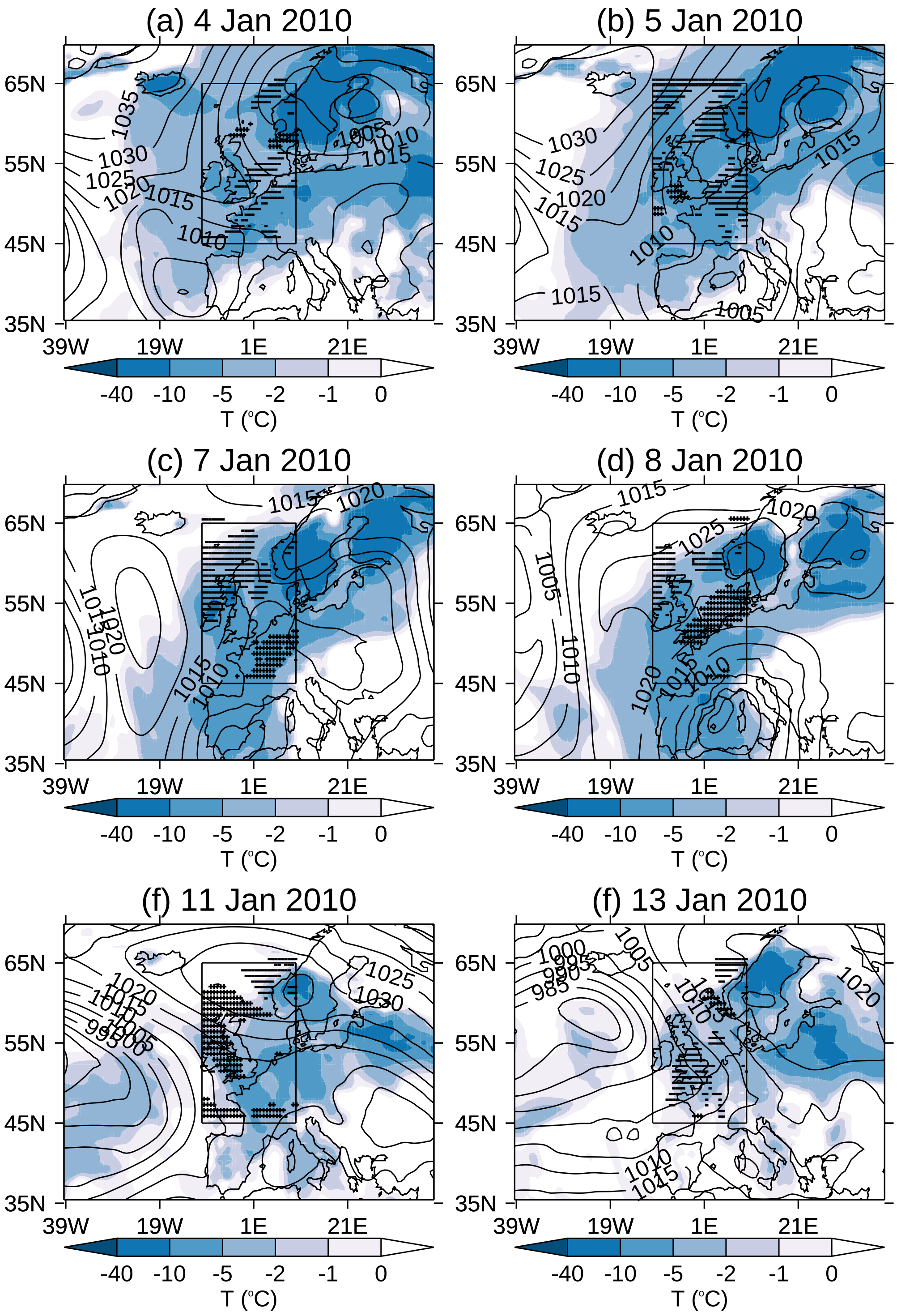
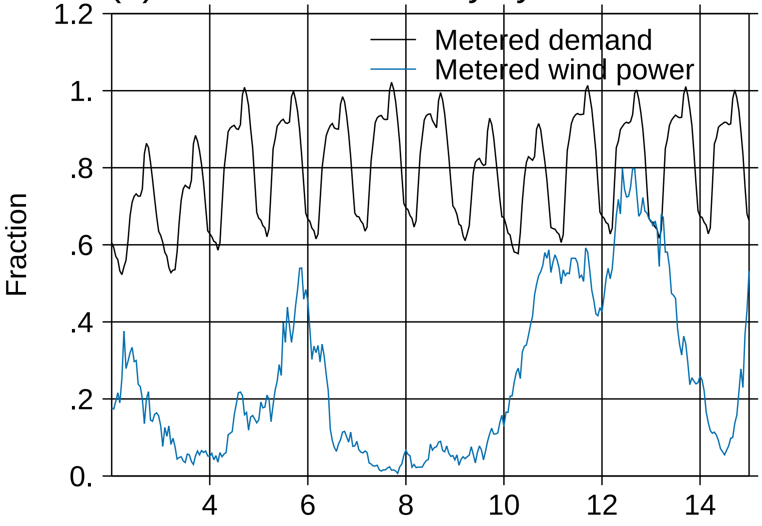


FIG. 1. Synoptic situation from 4th to 13th January 2010 showing surface air (2-metre) temperature (colours, °C) and daily-average mean sea level pressure (contours, hPa). Areas within the marked box where the local wind-speed departs from its local long-term mean by more than one standard deviation are marked with '+' (if wind-speed is greater than the mean) and '-' (if wind-speed is lower then than the mean).

(a) Historical electricity system records



(b) Meteorological reanalysis data

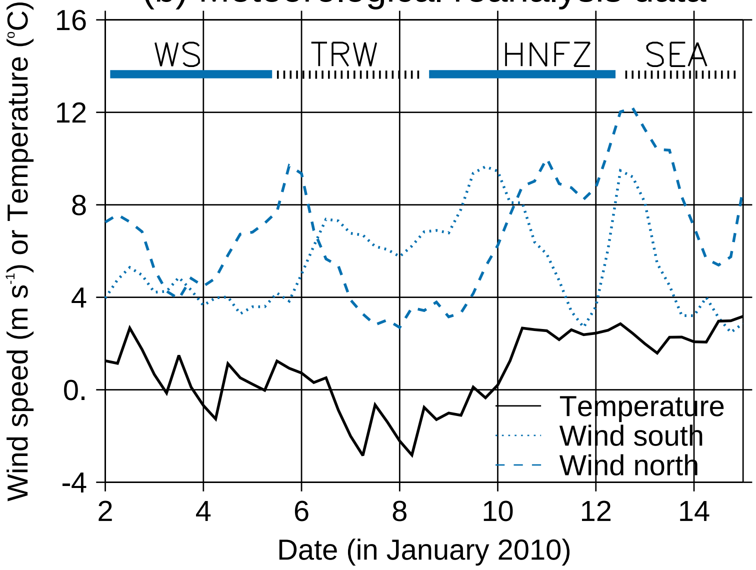


Fig. 2. Electricity demand, wind generation, wind speeds and surface air temperature 2nd-14th January 2010. (a) GB demand as a fraction of ACS peak (black line) and GB transmission-metered wind output as a fraction of its maximum capacity (solid blue line). (b) 6-hourly instantaneous wind-speed recorded in ERA-Interim averaged over northern and southern GB (7-1^{o}W, 54-59^{o}N, dashed blue line; 4^{o}W-1^{o}E, 50-54^{o}N, dotted blue line; m s^{-1}) and 6-hourly instantaneous surface air (2-metre) temperature recorded in ERA-Interim averaged over GB (6^{o}W-2 ^{o}E, 50-58^{o}N, black line, ^{o}C). Note: the GB transmission-metered wind output in (b) is dominated by output in Scotland and only represents roughly half of the total - refer to (6) for further discussion.

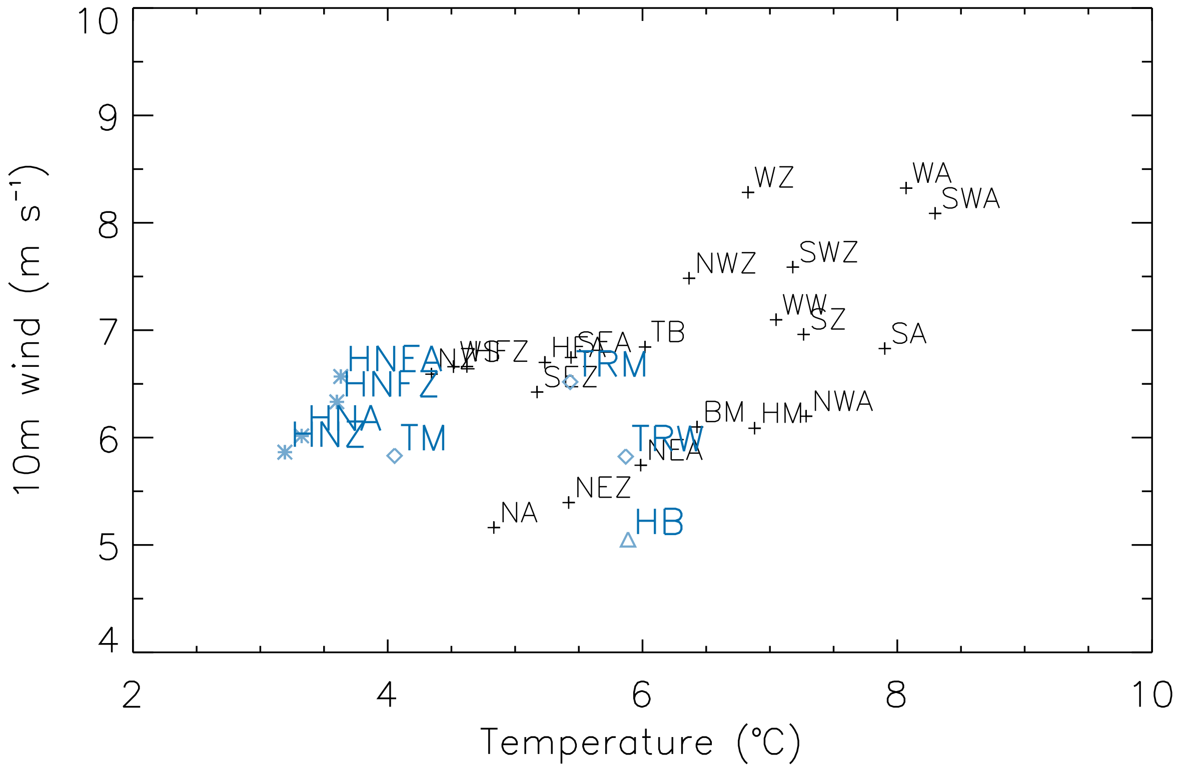
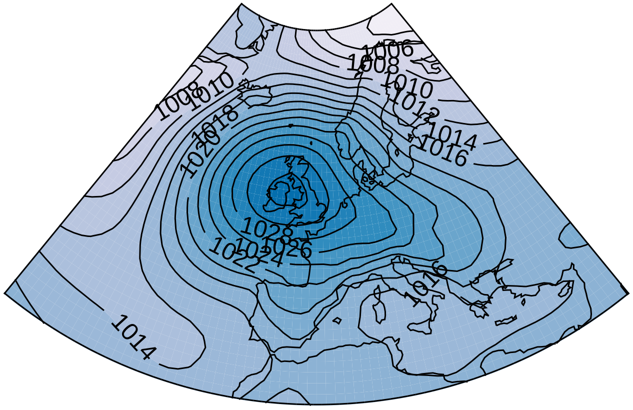
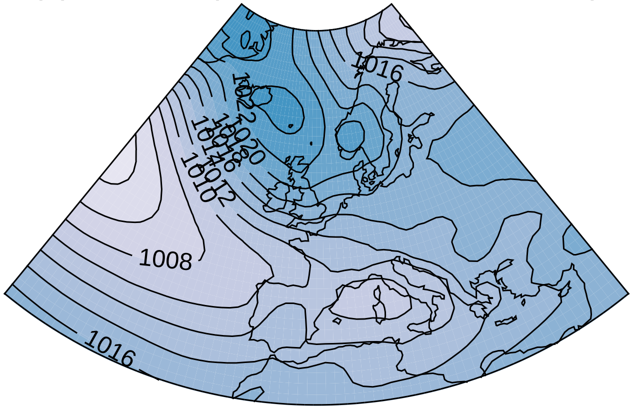


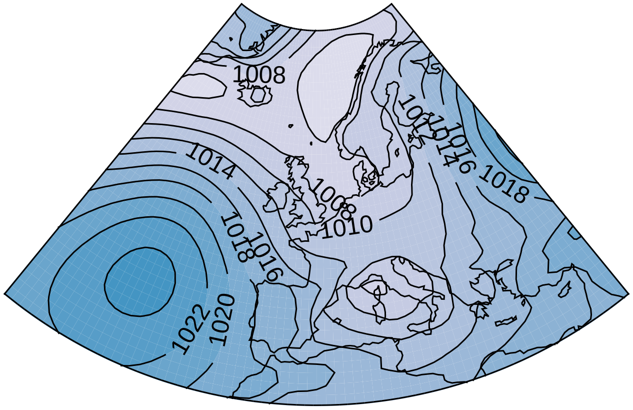
FIG. 3. Mean GB 10-metre wind-speed and surface air (2-metre) temperature for each GWL pattern (average over 8^oE-3^oW, 49^oN-59^oN). The means are constructed by averaging all the daily-mean wind-speeds/surface air temperatures that occurred during a given GWL type between November and March in the ERA-40 dataset (period Jan 1958 - Dec 2001). The main blocking, trough and High-over-Britain types discussed in the text and Fig. 4 are highlighted with larger letters (also marked in blue).



(a) High over Britain (HB)



(b) Blocked (HNFZ, HNFA, HNZ, HNA)



(c) Trough (TRW, TRM, TM)

Fig. 4. Mean sea level pressure patterns associated with the main GWL types discussed in the text (units hPa). (a) HB (High over Britain); (b) HNFZ/HNFA/HNA/HNZ (high pressure/blocking over Iceland and Scandinavia); and (c) TRW/TRM/TM (troughs). These patterns are intended to provide a qualitative picture of the circulation patterns associated with each of these broad catagories.