

Supplement

Abstract. GWL-REA is a new algorithmic method for classifying European Grosswetterlagen (GWL) from reanalysis, climate and/or forecast model data. This supplement to the main paper provides additional useful information about the classification and its background. Descriptions of the 30 GWL and their variants are given in Section S1, illustrated with many historical examples. The seasonality of the GWLs is discussed and the concept of natural synoptic seasons is introduced in Section S2. Various statistical tables of interest are presented in Section S3. The standard colours used for the GWLs and their groups are defined in Section S4. Several sets of climatological GWL composites, expanding on those published in the main paper, are shown in Section S5 for reference.

Section S1

The 30 Grosswetterlagen (GWL), as calculated in GWL-REA, are described in detail in the following sub-sections, grouped according to flow direction. Focus is placed on the typical synoptic characteristics of each type, on their typical regional weather impacts and on the typical type variants that commonly occur. Unless otherwise specified, weather descriptions refer to conditions over C Europe (CE for short), with a particular focus on Germany and immediate surroundings.

Dates of characteristic historical examples of various GWLs are referenced in square brackets and, in many of these cases, the composite mean synoptic situation during each GWL event is plotted. These plots show MSLP (3D-effect contours, interval 3 hPa, coloured from blue tones (low), via white, to orange tones (high)), 500-1000 hPa thickness (white contours with colour filling, interval 3 dam) and mean precipitation (dark blue contours with grey tone filling, contours at 1, 2, 4, 7, 10, 14, 20, 28, 38, 50, 64 and 80 mm/day). The respective periods for the plots are indicated in the top-right corner, the event length in days is shown in the bottom-right corner and the GWL type in the bottom-centre. To the left and right of this GWL label are shown the period mean 2m-temperature anomaly (de-trended) and the period mean precipitation (mm/day), respectively, both averaged over Germany and immediate surroundings (see area definition in Fig. 4 of James and Osterm ller, 2026). These are based on ERA5 data, but should be taken as approximations. For precipitation, note that the climatological mean value is around 1.7 mm/day. Hence, cyclonic GWLs would be expected to exceed this value in most cases, while anticyclonic GWLs would be expected to have less precipitation than this value typically.

For reference, since it is not shown with the plots, the thickness colour scale is as follows:

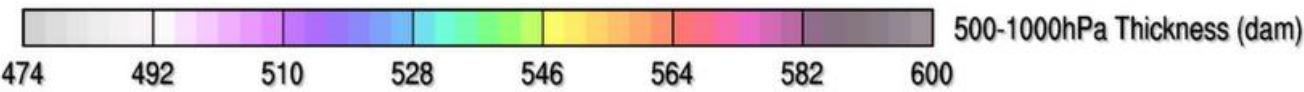


Fig. S1: Colour scale for the geopotential thickness fields shown in the backgrounds of the following GWL event composites, which are used throughout Section 1 to illustrate the GWL type descriptions

Note that the following sections also include discussions about air masses associated with the various GWLs. The dominant air masses that can affect CE are listed in Table S1 together with a short description. The naming convention is based on the European air mass catalogue of Geb (1979) and which has been used widely ever since.

The climatological areal-mean daily precipitation averages for each GWL, based on ERA5 reanalyses, are shown for reference in Table S2, while Tables S3 and S4 show the climatological seasonal frequency distributions of the GWLs using standard and natural seasons, respectively.

S1.1 Westerly circulation types (Wa, Wz, Ws, Ww)

Westerly types are typically associated with a strong, zonally-oriented upper jet that extends from the N. Atlantic into Europe, while low pressure systems form and move eastwards under this jet, bringing frontal precipitation or showers in largely westerly low-level winds. In the GWL system, westerly flow is split into an anticyclonically curved variant, **Wa**, and a cyclonic variant, **Wz**, which involves frequent frontal activity, in which both subpolar- und subtropical airmasses affect CE in sequence. Two further less frequent cyclonic westerly types are also defined: **Ws** (German: *Südliche Westlage*, South-Shifted Westerly) and **Ww** (German: *Winkelförmige Westlage*, Angular (Diffluent) Westerly).

S1.1.1 Wa – Westlage, antizyklonal (Anticyclonic Westerly)

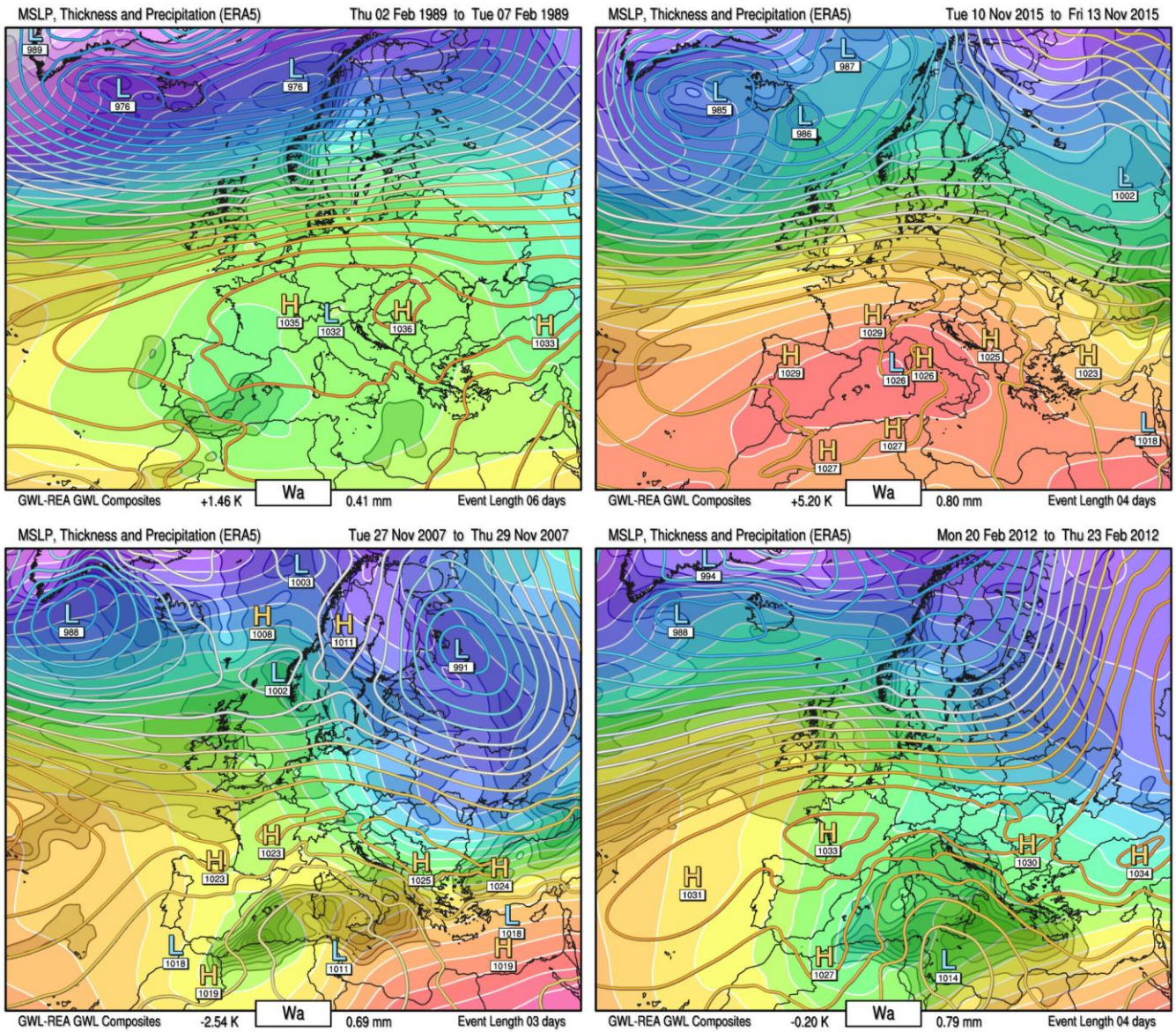


Fig. S2: Composite synoptic charts for selected historical GWL events classified as "Wa". For details see start of Section 1.

The anticyclonic type **Wa** is a predominantly warm type with mild mid-latitude air masses (mS , mS_p) moving across CE over a high-pressure zone to the south [2-7.2.1989; 31.12.1991 – 3.1.1992; 20-25.2.2008; 10-13.11.2015], with only weak frontal systems affecting northern areas at times. The upper zonal jet is typically centred near 55°-60°N, lying most often across Scotland and across the North Sea into S. Scandinavia. In the winter half-year, persistent orographic rainfall is common across western Scotland and southwestern Norway during **Wa** spells and westerly winds are often very strong in these regions.

In some winter cases, cold surface air may remain in place in light winds over southern regions of CE, with inversion conditions and warmer air aloft. This is especially the case if the **Wa** circulation has pushed quickly into a very cold air mass, in which case a trough may continue to affect regions south of the Alps in the form of a cut-off low [6-8.1.1979; 27-29.11.2007; 20-23.2.2012]. Otherwise, in most **Wa** cases, the weather is usually fine, mild and sunny over the Alps in particular. In the summer half-year, warm and moist air masses are more likely to be confined to the latitude of CE during **Wa** spells, where it can become oppressively humid, with a westerly flow of cooler *mP* or *mP_s* air further north [16-21.7.2015].

S1.1.2 Wz – Westlage, zyklonal (Cyclonic Westerly)

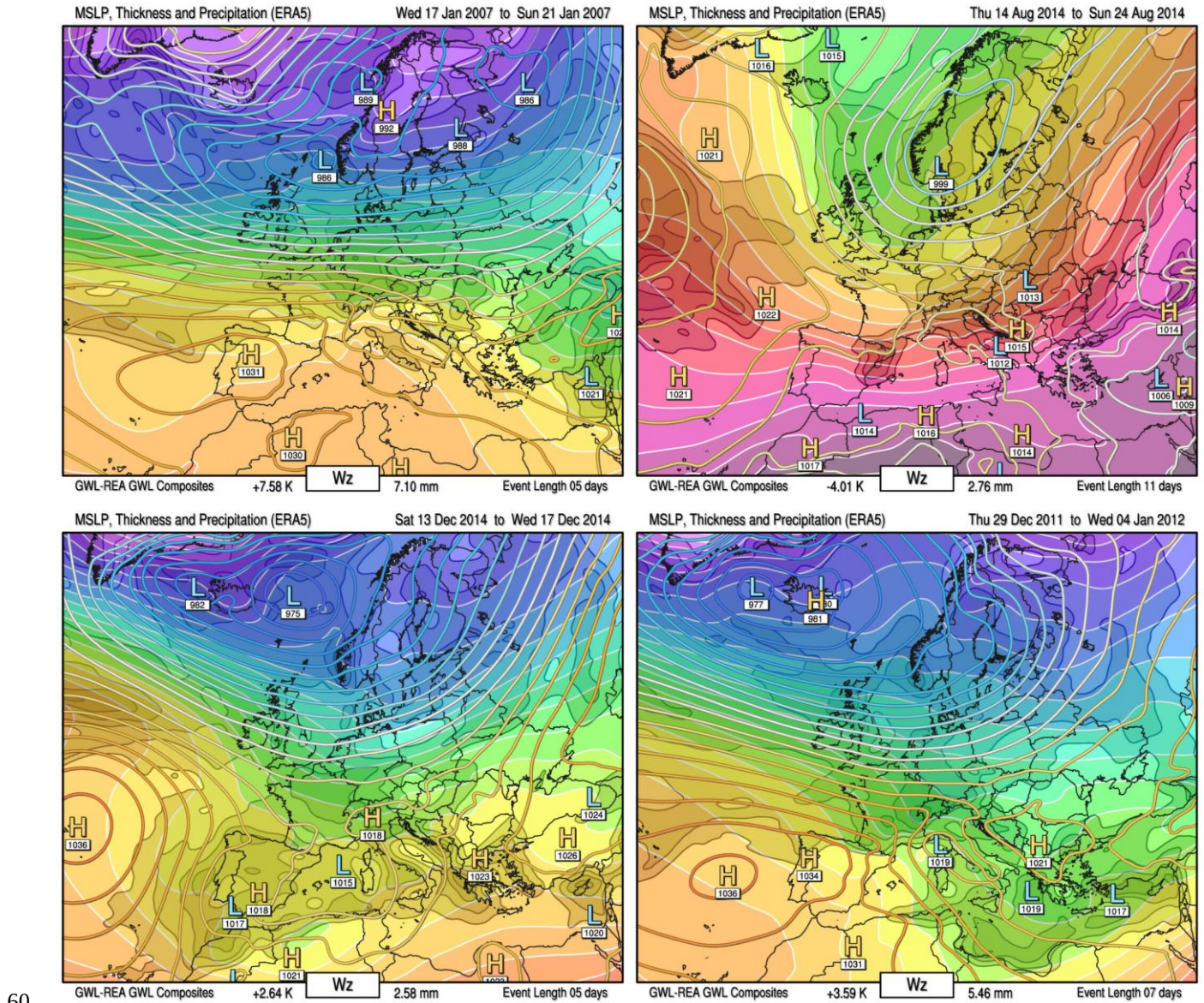


Fig. S3: Composite synoptic charts for selected historical GWL events classified as “Wz”. For details see start of Section 1.

The cyclonic type **Wz**, which is the most common GWL at over 9%, typically exhibits a strong upper jet extending across Europe, often at the latitude of CE, i. e. 45°-55°N. Vigorous low pressure areas bring frequent frontal systems and widespread precipitation, together with strong westerly winds, across much of W Europe and CE, often penetrating into E Europe too. Air masses vary between mild Atlantic air masses (*mS*, *mS_p*) and polar maritime air masses (*mP*, *mP_s*), often in quick succession with the passage of fronts. Temperatures over CE are usually higher than average in winter, but somewhat colder than average in summer. However, some **Wz** variants can occur at any time of year in which a specific air mass is strongly dominant.

In the first **Wz** variant warm mid-latitude air masses dominate. Typically, the flow is strong and nearly straight with a wide warm sector and the main frontal zone meanders across the northern half of CE, almost parallel to the flow. The weather is often persistently windy and occasionally stormy [23-28.1.1990; 17-21.1.2007], while heavy orographic rainfall is common on west-facing mountains and temperatures in winter are very mild [3-7.11.2010]. In the second variant, subpolar air dominates in a wide band of nearly straight westerlies with the main frontal zone meandering largely to the south of the Alps [14-24.8.2014]. The weather is colder than average, especially in summer, while precipitation falls mainly as showers. The extent to which cyclonic westerly flow also affects the Iberian Peninsula and the W. Mediterranean regions can vary considerably. While the first variant above typically features predominantly dry, anticyclonic conditions across those regions, **Wz** variants exist in which a cut-off low and upper trough splits from the vigorous westerly flow or is a remnant from the preceding GWL. Such troughs can sometimes be seen somewhere near Iberia or the W. Mediterranean [e. g. 13-17.12.2014]. However, more common are small-scale troughs forming near N. Italy in the lee of the Pyrenees or French Alps, usually following the incursion of polar maritime air masses behind cold fronts [e. g. 29.12.2011 - 4.1.2012]. These features, once formed, then typically move more slowly than the westerly circulation further north.

S1.1.3 Ws – Südliche Westlage (South-shifted Westerly)

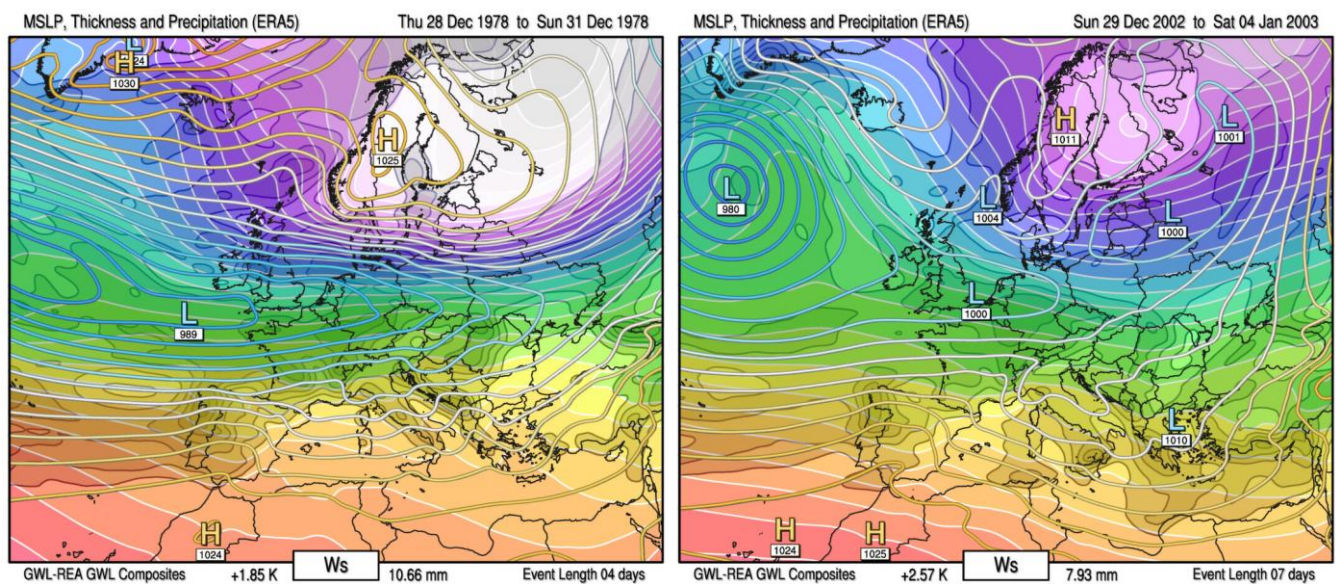


Fig. S4: Composite synoptic charts for selected historical GWL events classified as “Ws”. For details see start of Section 1.

In the **Ws** type the upper zonal jet lies even further south, typically around 40°-50°N. A zonally elongated surface low pressure zone extends across CE underneath this jet, with individual systems moving from west to east. South of this region, mild westerly surface flow is common, while to the north, cold easterly flow dominates [15-26.3.2001; 29.12.2002 – 4.1.2003]. The distance between the cold easterlies and mild westerlies can be relatively small in some cases, with heavy large-scale snowfall a risk on the northern edge of the frontal zone in winter. The extreme situation during the last few days of December 1978 is a good example, known for the record blizzards over northern Germany, when as little as 50 km separated exceptionally contrasting air masses for a time.

S1.1.4 Ww – Winkelförmige Westlage (Angular (diffluent) Westerly)

In the **Ww** type the zonal upper flow often becomes diffluent from CE eastwards. The westerly surface flow stagnates and/or turns northwards behind CE, often ahead of a persistent blocking high over Russia [4-6.12.2001]. In many cases, fronts approaching from the west occlude and decay over CE in situ, mainly because polar maritime air masses following on behind these fronts overrun the narrowing band of milder Atlantic air pushing towards the polar continental air lying further east. This

results in weakening temperature gradients, leading to a frontolytic situation. When especially cold air lies to the east, frontal waves may form and run in a southeasterly direction on the edge of this cold air [20-23.1.2018].

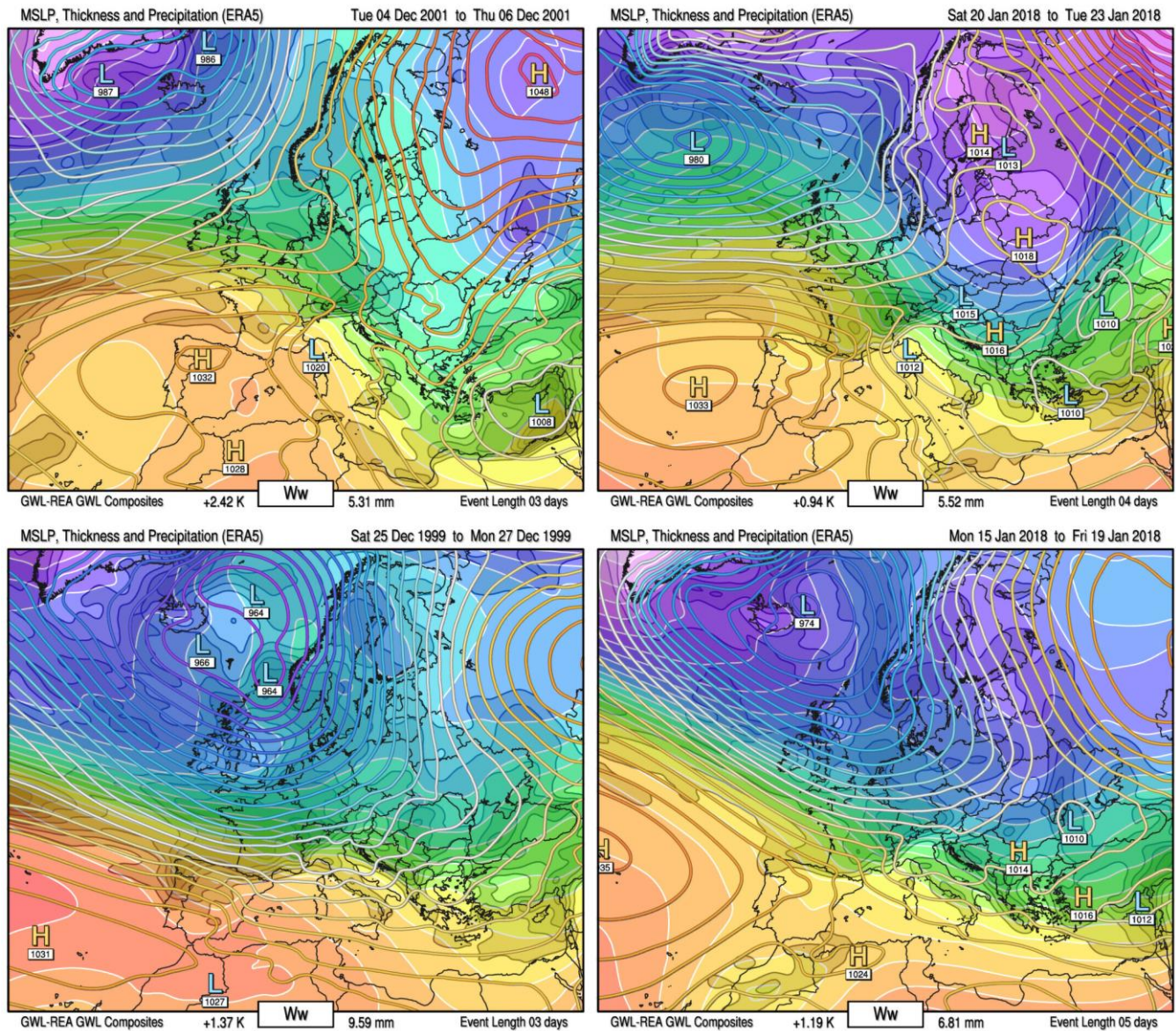


Fig. S5: Composite synoptic charts for selected historical GWL events classified as “Ww”. For details see start of Section 1.

100 In some rarer winter cases, **Ww** can be associated with an intensely stormy period over W Europe with a deep area of low pressure near the British Isles under a substantial mass of cold *mP* air. Intense secondary lows can form, tracking sometimes even south of 50°N and running quickly into CE, but then decaying quickly under the diffluent flow over the eastern half of CE. Before the decay process sets in, very damaging winds can develop in places [11-16.2.1990; 25-27.12.1999 (storms Lothar and Martin); 15-19.1.2018 (including storm Friederike)].

105 S1.2 South-Westerly circulation types (SWa, SWz)

S1.2.1 SWa – Südwestlage, antizyklonal (Anticyclonic South-Westerly)

The anticyclonic **SWa** type brings warm, moist air (*mS*, *mSp*) to CE on the edge of a high-pressure zone over SE Europe and under an upper ridge [17-24.2.1990; 26.11 – 2.12.2006; 14-21.12.2013]. Even in winter, there can be sufficient mixing to allow the warm air aloft to bring mild conditions down to low-levels. Despite anticyclonic curvature, the weather can be very windy towards the north in the winter half-year. In summer, **SWa** brings hot and oppressive weather, with high humidity and often leads to the development of (short-lived) heatwaves [19-21.6.2000; 13-17.7.2007; 17-21.8.2012].

In some winter cases, the high-pressure zone straddles a cold air mass that extends from SE or E Europe into CE. In cases where the upper flow is northwesterly, with cold air over the eastern half of CE, warm advection may occur [3-5.1.2011], albeit with little if any precipitation due to the proximity of high pressure. Otherwise, the cold air lies over SE Europe parallel to the high-pressure zone and there is little temperature advection over CE itself. Here, in light winds, low-level inversions can develop, with persistent frost in valleys and on plains. Further north, the influence of a strong, southwesterly flow across the British Isles and into Scandinavia begins to be felt, such that mild and windy weather is common closer to the North Sea coast [11-19.1.2002; 22-28.12.2007].

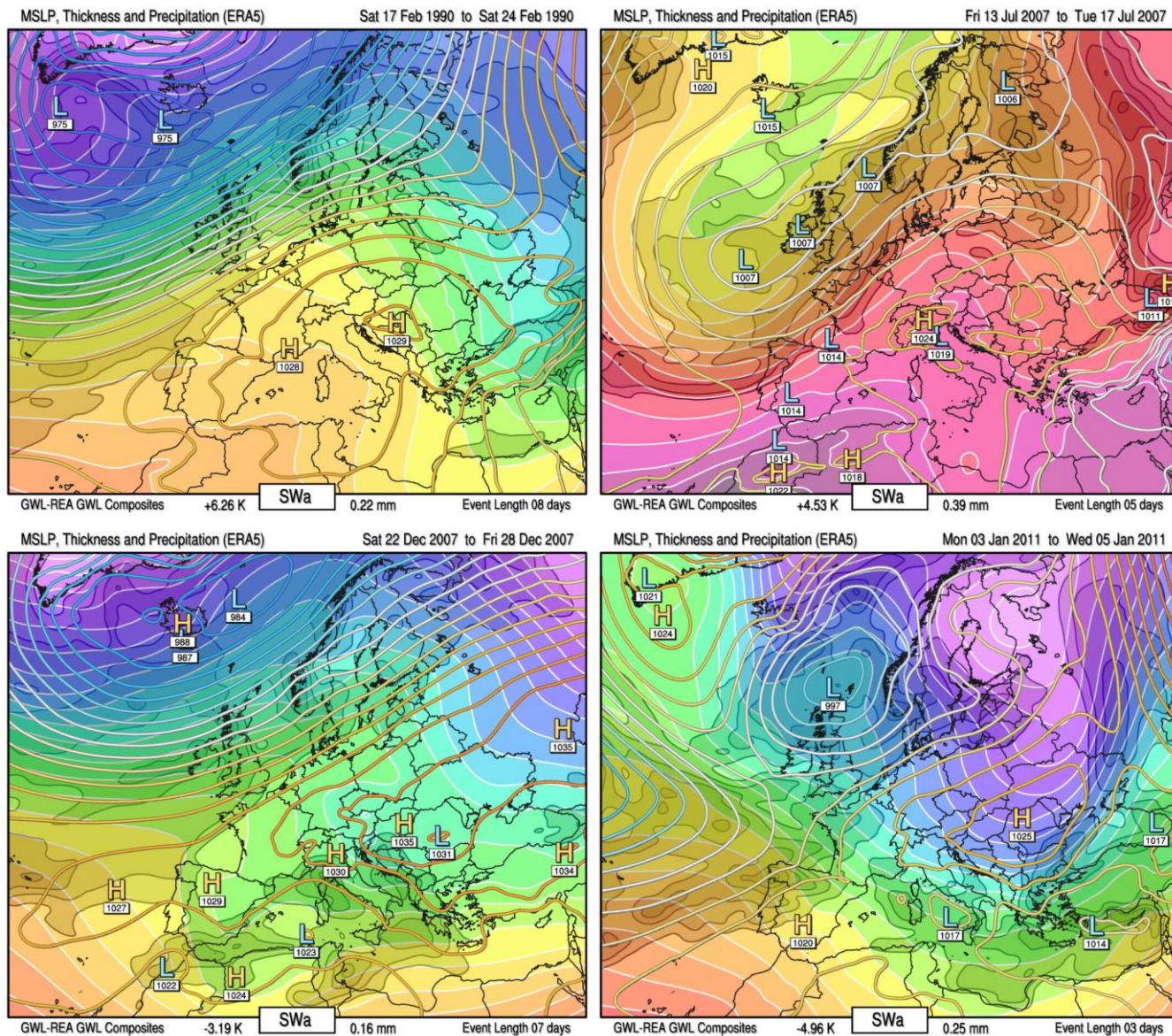


Fig. S6: Composite synoptic charts for selected historical GWL events classified as “SWa”. For details see start of Section 1.

S1.2.2 SWz – Südwestlage, zyklonal (Cyclonic South-Westerly)

The cyclonic type **SWz** typically features deep areas of low pressure passing close to the British Isles, with a frontal zone encroaching on CE bringing very mild, moist air (mS , mS_p) from the south-west, broadly parallel to the upper flow, interspersed with short spells of returning mP , air [3-8.12.2006]. In some cases, a long south-westerly fetch may be present, bringing very warm, moist tropical Atlantic air from beyond the Iberian Peninsula (mT in rare cases) [16-21.12.1989; 18-21.10.2004; 23-30.1.2025].

The weather during **SWz** spells is very mild, rainy and often windy, with heavy and persistent rain at times on some western and southwestern facing mountain ranges. Föhn conditions can occur on the northern side of the Bavarian and Austrian Alps.

In summer, **SWz** can bring widespread, severe thunderstorm outbreaks, as well as oppressive, humid heat to the eastern and southern regions of CE [16-20.8.2004; 18-22.6.2006].

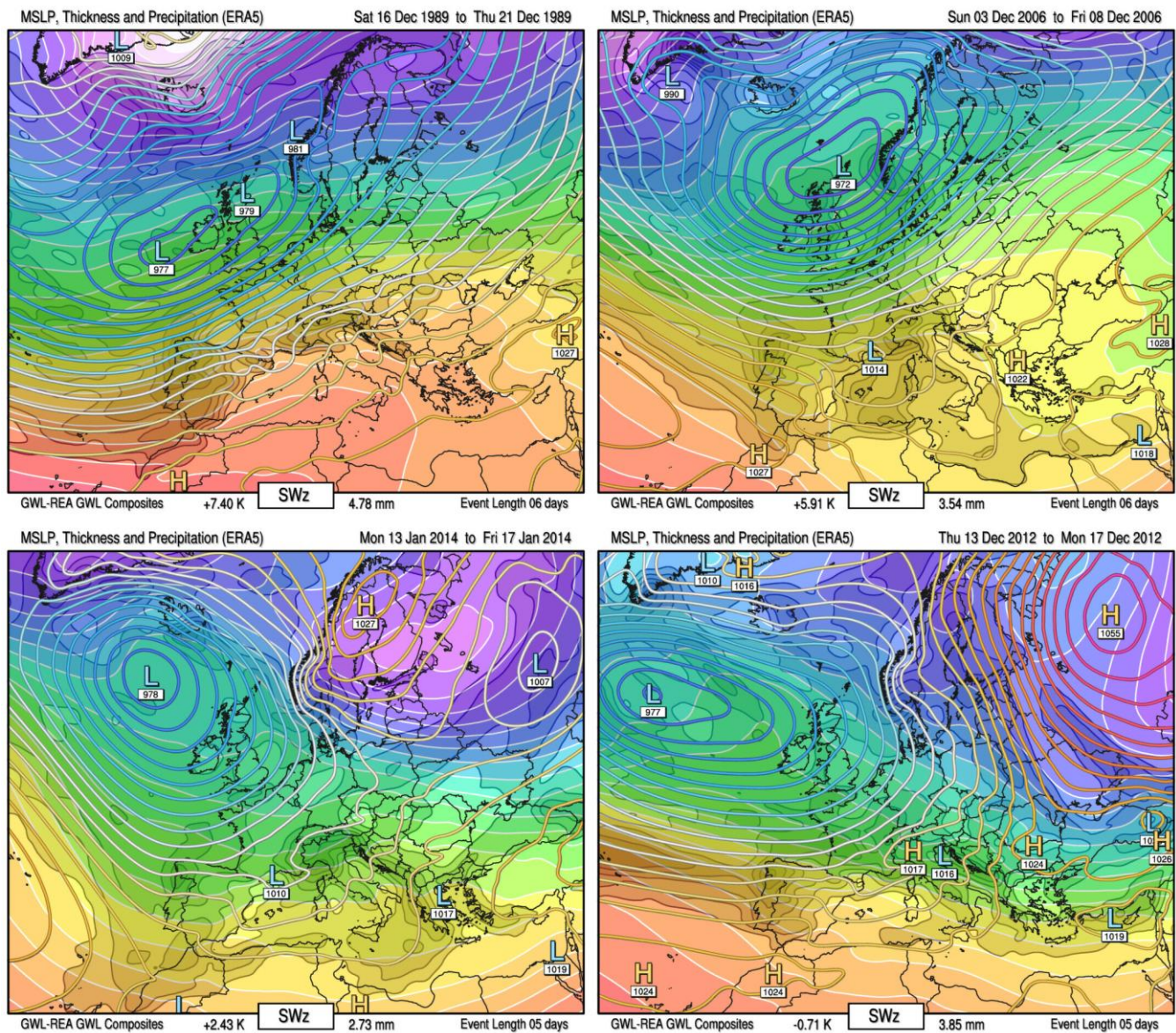


Fig. S7: Composite synoptic charts for selected historical GWL events classified as “SWz”. For details see start of Section 1.

Analogous to the **Wz-Ww** distinction, a variant of **SWz**, which occurs mainly in the winter half-year, features an angular cyclonic southwesterly flow over CE under a diffluent upper flow. While frontal systems bring mild, moist air into CE, they are far less effective in pushing this air further eastwards. The fronts become occluded more quickly and slow down or even stall near the eastern edge of CE with the flow sometimes turning to a southeasterly [13-17.1.2014]. In cases with a more vigorous southwesterly flow [13-17.12.2012], the occluding fronts penetrate further east but the initially mild airmasses dissipate quickly. Over E Europe mean temperatures may remain near or even below normal and are noticeably lower than is normally seen with the more typical **SWz** cases.

140 S1.3 North-Westerly circulation types (NWa, NWz)

S1.3.1 NWa – Nordwestlage, antizyklonal (Anticyclonic North-Westerly)

Analogous to the **Wa** type, **NWa** primarily brings mild, returning mS_p air across CE, resulting in largely mild and benign weather [30.1 - 5.2.2007; 9-14.3.2012], which in summer can sometimes lead to very warm conditions [16-21.6.2017]. This mild air typically pushes right across CE, reaching the eastern half of CE. Despite the warm air aloft, inversion conditions can

145 develop in winter closer to the high-pressure cell over the southwestern quadrant of CE, leading to overcast and rather cold weather at low altitudes here. Further towards the north-east, strong winds can occur, especially near the Baltic coast. The upper flow shows a northwesterly flow over CE between a broad ridge over the western edge of Europe and a trough over Finland. In some cases, influxes of polar maritime air masses behind weak frontal system are more dominant and colder weather may ensue, even in summer [19-23.6.2014].

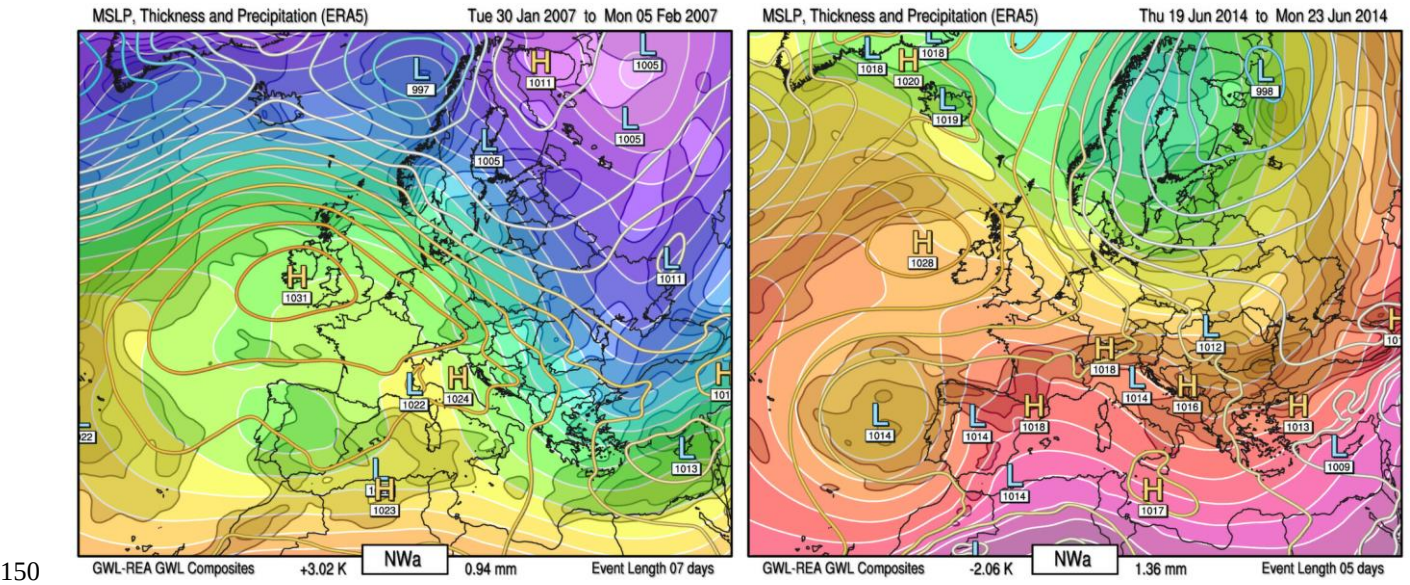


Fig. S8: Composite synoptic charts for selected historical GWL events classified as “NWa”. For details see start of Section 1.

S1.3.2 NWz – Nordwestlage, zyklonal (Cyclonic North-Westerly)

The cyclonic **NWz** type also has a north-westerly upper flow over CE, but the Scandinavian trough is closer to CE and the western ridge further out in the Atlantic. There are three typical variants of **NWz** to mention. The primary **NWz** variant includes frequent frontal passages bringing changeable air masses, but also frontal boundary situations where a wide, tilted warm sector reaches CE at times, bringing returning mild air masses (mS_p), with colder polar-maritime air (mP) further to the north-east [8-15.3.2000; 6-11.11.2007; 19-26.12.2023].

In some **NWz** cases notable storms can develop on the North Sea and Baltic Sea coasts during this type [12-18.2.1962 (devastating coastal flooding), 3-6.1.1976 (Storm Capella)]. The weather is generally windy during this type, with persistent precipitation over north-west facing topography, notably over the Erz Mountains of Saxony and on the northern side of the Alps. In winter, heavy snowfall is likely at higher altitudes in these regions and at times at low altitudes towards the northeast. Across the northern Alps, the risk of major avalanches can become very high if the **NWz** type persists over a number of days, especially if the air masses are persistently moist, e. g. the Galtür avalanche disaster in W Austria [16-24.2.1999]. However, in the west and south of CE, precipitation falls mainly as rain at low altitudes.

The second **NWz** variant has cyclonically curved flow of mP (in some cases mA) air across the whole of CE. In all cases, this variant is often associated with strong winds, especially on the North Sea and Baltic Sea coasts [14-17.1.1986]. The weather is rather cold with a high wind chill factor. Showers are likely to develop at times, especially near the Baltic coast, particularly in autumn when the still relatively warm sea surface helps to generate convection in the cold air. Strong mistral winds are very common over the Mediterranean coast of S France during **NWz** spells, especially with the first and second variants.

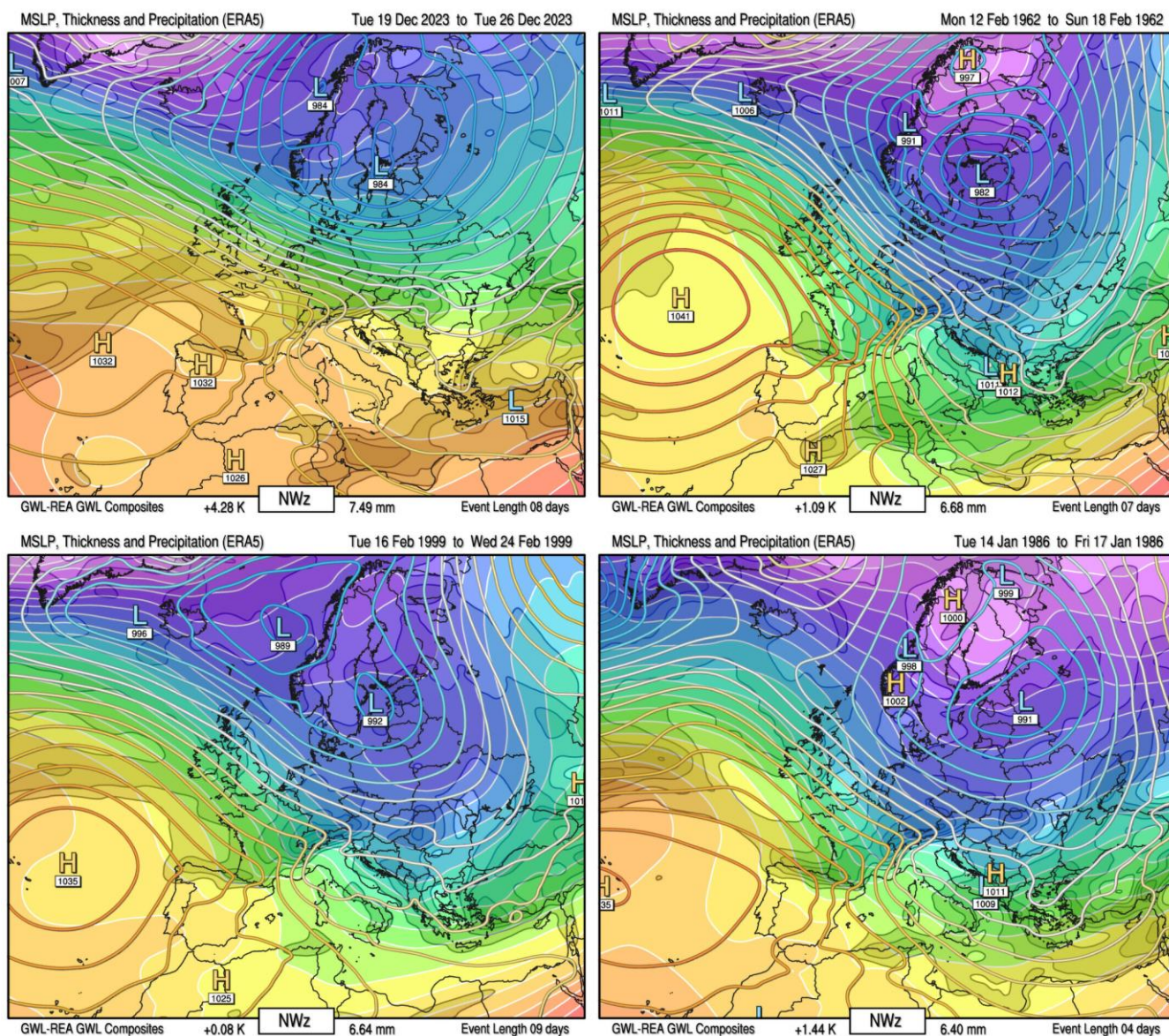


Fig. S9: Composite synoptic charts for selected historical GWL events classified as “NWz”. For details see start of Section 1.

A third **NWz** variant exhibits warm advection from the north-west pushing slowly into persistent cold air on the edge of a marked trough over E Europe, whereby the eastern half of CE remains largely within the cold air mass. This warm advection can be strong enough to result in significant precipitation, even if the surface pressure is relatively high, especially if orographically enhanced [1-11.1.2013: Parts of the Bavarian Alps recorded unusually high precipitation totals during this period, especially during the period 4-6.1.2013 that featured a strongly anticyclonic pressure pattern]. This precipitation is increasingly likely to be wintry (snow or freezing rain) towards the east. The upper air flow is more meridional with this variant, being close to a northerly over CE.

When this variant lasts for several days, it is often characterized by a sequence of successively occluding frontal systems and/or a sequence of frontal waves forming along the warm front and moving nearly parallel to the air mass boundary from north to south. Following each of these fronts, the progression of the warm air is held up for a time, before the next front or wave arrives [21-27.2.2009]. For the major north-facing mountain chains (Bavarian and Austrian Alps, the Erz mountains in Saxony and the Tatras), very heavy, disruptive snowfall may occur, especially when the northerly flow in the lower troposphere is strong and sufficient low-level moisture is arriving from the north-west. A good example of this was seen in early January 2019 [5-8.1.2019; 12-17.1.2019], while the worst avalanche disaster in the modern era in the northern Alps (Blons / Vorarlberg, Austria) was also associated with this **NWz** subtype [9-12.1.1954]. Another notorious winter avalanche period in 1951 was also caused by a week-long **NWz** event of this type [15-21.1.1951].

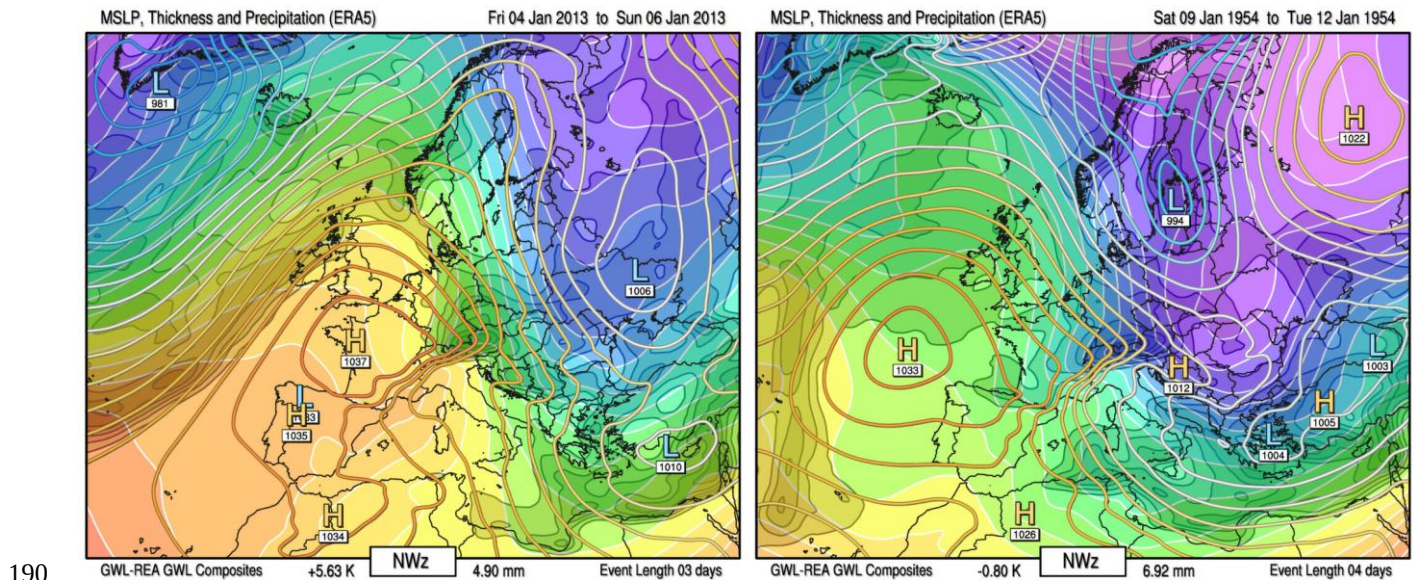


Fig. S10: Further composite charts for selected historical GWL events classified as “NWz”. For details see start of section 1

S1.4 Central High, Bridge or Low over Central Europe (HM, BMa, BMz, TM)

S1.4.1 HM – Hoch Mitteleuropa (High over Central Europe)

The type **HM** exhibits a large surface high-pressure zone centred over or near CE, typically lying just to the east of a strong upper ridge over W Europe. Typically, mild air flows around the western and northern flanks of the surface high, while colder continental air stagnates near the centre and to the south and east. In winter, low-level inversions are common, while in summer the weather is largely sunny and warm.

The most common **HM** variant [8-13.12.2004; 27.9 – 2.10.2011] brings very mild and often sunny weather to the mountains, with low-level inversions in winter, often leading to persistent low cloud and low temperatures in valleys and on plains. In some winter cases, persistent low-level cloud and nearly calm conditions can lead to so-called “*Dunkelflauten*” (winds lulls in gloomy conditions) during which little renewable energy can be generated at all [2-7.11.2024]. In summer, by contrast, this type leads to hot, sunny and largely dry weather at all levels, with humid and oppressive conditions developing readily, especially towards the west [1-4.8.1990; 16-24.6.2005; 28-30.6.2019; 14-18.6.2022]. In many summer cases, however, the high straddles a weak, inactive air mass boundary with cooler and drier air to the north-east under north-westerly upper flow [19-22.6.2025].

In some **HM** cases, especially in winter, the centre of the surface high sits within a deep cold air mass underneath a northerly mid-tropospheric flow. A substantial upper trough lies just to the east and/or southeast. This variant is associated with very dry air and very hard frosts and can be notably cold, albeit sunny, in the mountains too [3-7.1.2002]. In some cases, the high may be centred further north, often near Denmark, with a tilted upper trough and a cold, anticyclonically curved easterly flow across the Alps [17-19.12.2007].

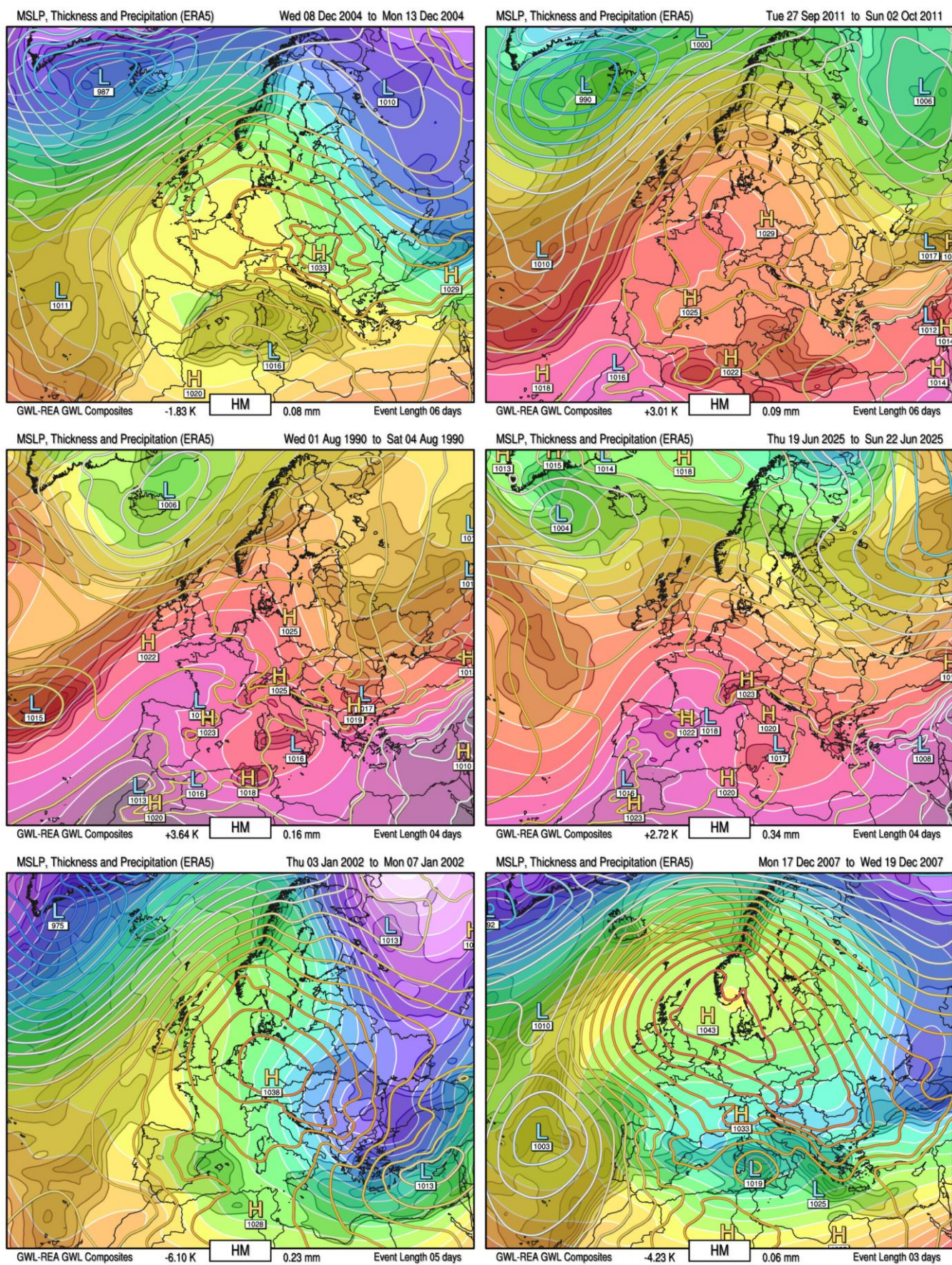
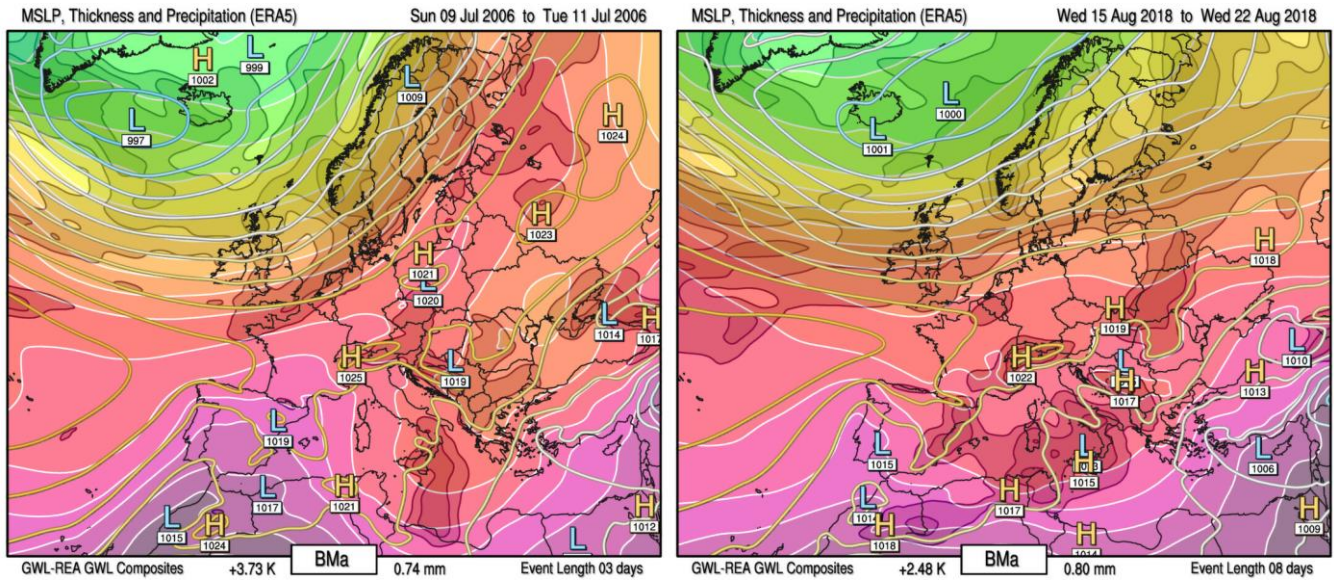


Fig. S11: Composite synoptic charts for selected historical GWL events classified as “HM”. For details see start of Section 1.

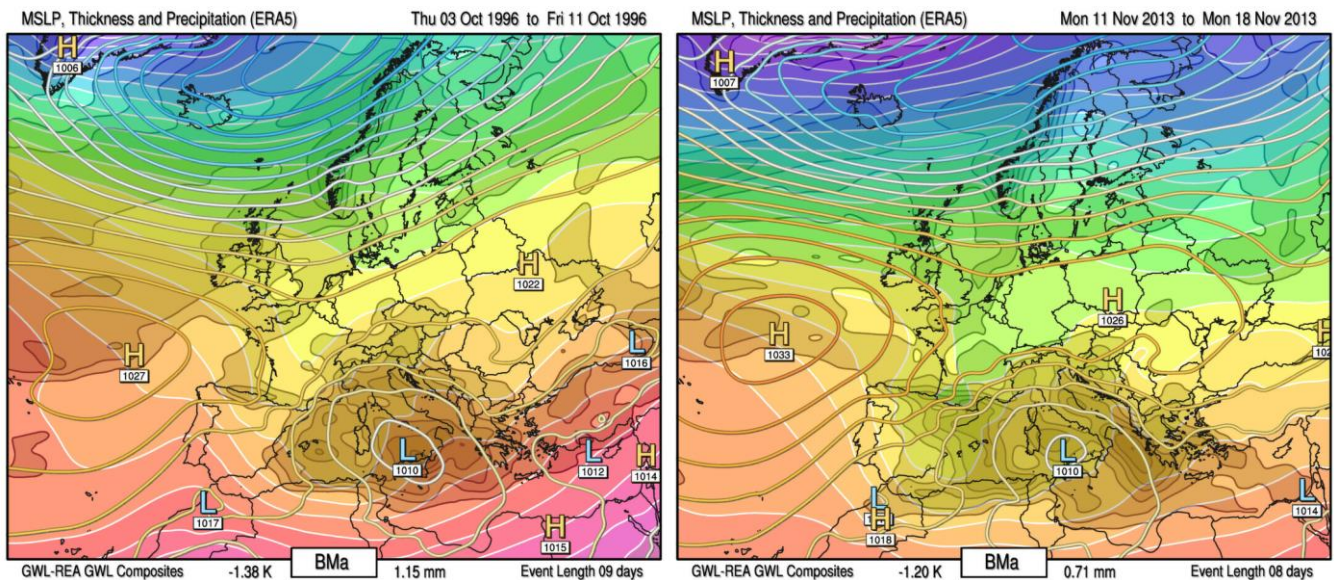
S1.4.2 BMa – Brücke Mitteleuropa, antizyklonal (Anticyclonic Bridge over Central Europe)

The type **BMa** refers to a zonal high-pressure zone across CE which joins an Atlantic high-pressure cell to a second cell over E Europe and/or W Russia. This type has a number of variants with somewhat different upper air patterns.



220 Fig. S12: Composite synoptic charts for selected historical GWL events classified as “BMa”. For details see start of Section 1.

The first variant sees a high-pressure zone at the surface across CE, stretched out zonally, underneath an upper ridge with warm air aloft. In some cases, an upper trough may be seen over the Eastern Mediterranean, more especially in winter, but such features do not affect CE at all. In winter, the typically light winds across CE can lead to low-level inversions with moderately low temperatures at the surface, despite the warm air aloft. In summer most of CE lies in stagnating, very warm and humid cS air, while cooler air masses may encroach on the north-west of the region at times. In some cases, prolonged heatwave conditions can develop widely across CE [9-11.7.2006; 15-22.8.2018].



230 Fig. S13: Further composite charts for selected historical GWL events classified as “BMa”. For details see start of Section 1.

The second variant shows a col-like situation over CE with a cut-off trough forming over the central or western Mediterranean. Typically, a tilted trough stretches initially across CE from northeast to south-west. This trough becomes cut-off to the south, with the cold air over CE attenuated by warmer air encroaching from both the west and the southeast. At the surface a weakly anticyclonic zonal bridge forms across CE, resembling a col situation at times (higher pressure to the west and east, low pressure to the north and south), with a slow-moving, stagnant, mixed air mass [3-11.10.1996; 10-13.4.2005]. The weather is

largely dry across most CE, but otherwise can fairly be referred to as “non-descript”. More interesting are the conditions over the Mediterranean, where strong cyclogenesis can occur, especially in winter, and over Scandinavia where a mild westerly flow is common. In some cases, a further trough can break near CE, reinforcing the cut-off trough in the south and the col situation over CE [11-18.11.2013]. Meanwhile, the Mediterranean trough can result in local convergence near the Alps, with some prolonged precipitation, more especially on the southern side of the mountain range.

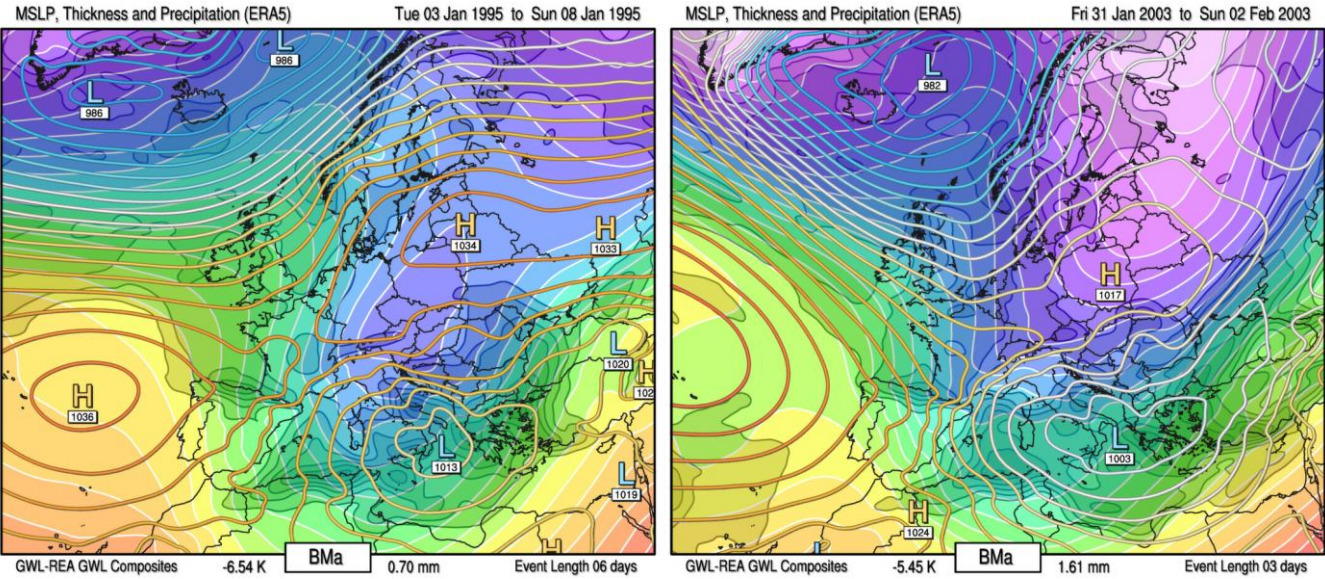


Fig. S14: Further composite charts for selected historical GWL events classified as “BMa”. For details see start of Section 1.

A third winter variant exhibits in its primary form a zonal bridge across CE underneath a quasi-northerly upper flow near a strong trough to the east. This bridge often links an Atlantic high-pressure zone to a surface High centred over Belarus, Ukraine or Russia [3-8.1.1995; 31.1 - 2.2.2003]. The weather is typically cold with hard frost, especially towards the east. Occasionally, transient frontal systems can penetrate the high-pressure zone from the west or north-west, introducing moisture and possible warm advection, leading to some regional snowfall and/or freezing rain, but the weather remains largely dry most of the time.

S1.4.3 BMz – Unterbrochene Brücke Mitteleuropa (Disrupted Bridge over Central Europe)

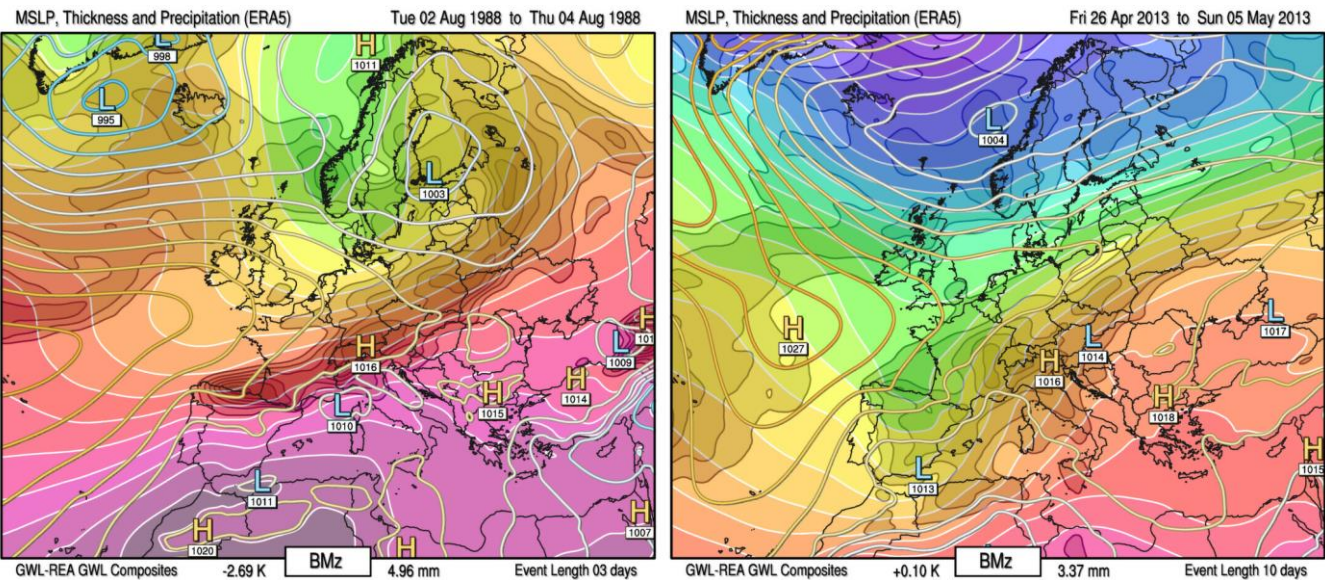


Fig. S15: Composite synoptic charts for selected historical GWL events classified as “BMz”. For details see start of Section 1.

250 The newly defined cyclonic **BMz** type represents a disrupted bridge-like structure. At the surface a high-pressure zone stretches from the west across CE. However, at the same time, an air mass boundary becomes quasi-stationary across the southern half of CE under a west-south-westerly upper flow. Despite the relatively high surface pressure, significant precipitation can occur here, while weak and slow-moving surface low-pressure troughs can develop along the frontal boundary, embedding within the high-pressure zone. The mid-tropospheric flow is sometimes convergent with a local jet over the Alps. Further north, the weather is largely dry and relatively cool. To the south of the convergence zone, very warm and humid weather persists with heatwave conditions across much of SE Europe in summer [2-4.8.1988; 26.4-5.5.2013; 13-21.8.2024].

S1.4.4 TM – Tief Mitteleuropa (Low over Central Europe)

The cyclonic type **TM** involves a quasi-stationary low-pressure centre directly over CE, usually sitting over an air mass boundary on the edge of an upper trough over or near France, which may be in the process of cutting off. To the west, inflowing polar maritime air leads to cold and often cloudy weather with widespread rainfall, which may fall as snow in winter. To the east, mild *cS*, *cSp* or *xS* air dominates. In summer, heavy thundery or persistent rain may lead to flooding in places [12-16.8.2010; 29.5 – 2.6.2016; 28.6 - 2.7.2017]. In some cases, the air masses can become inverted, with warm air to the north and cold air to the south [6-9.5.2004], while in other cases, the centre of the low may be located further south, over N Italy and/or may exhibit a meridional extension [19-21.11.2013]. In further cases, the low may be centred just to the west of CE, with warm, moist air over CE, with widespread thunderstorms in summer, and very cool and wet weather over France and the British Isles [26-30.6.1997].

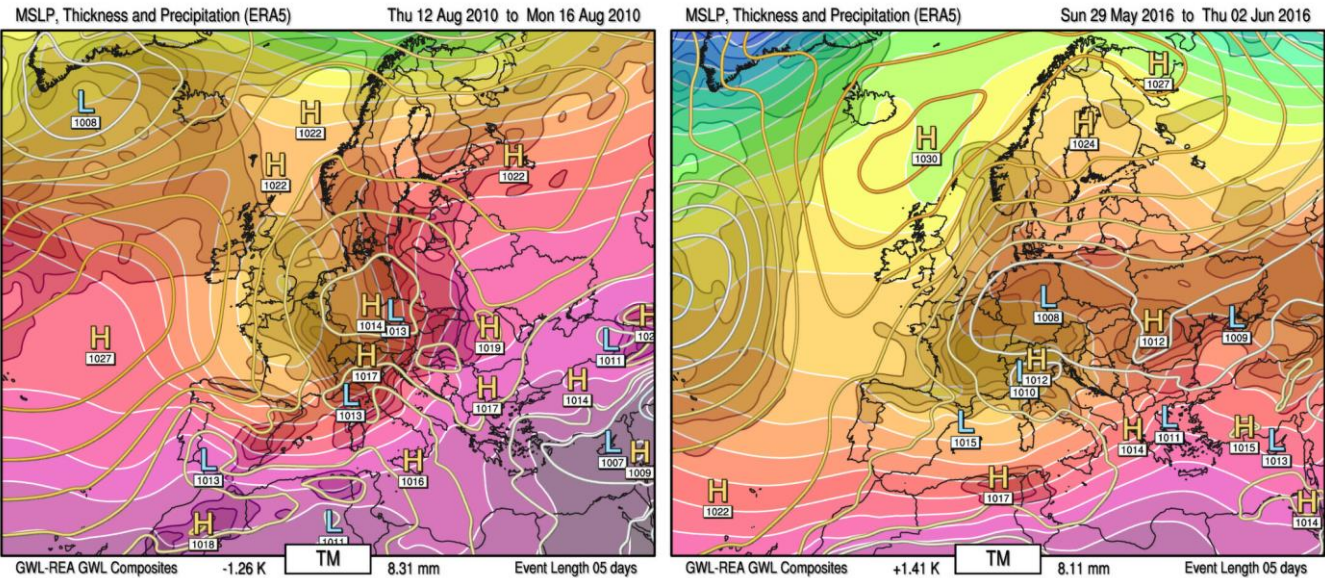


Fig. S16: Composite synoptic charts for selected historical GWL events classified as “TM”. For details see start of Section 1.

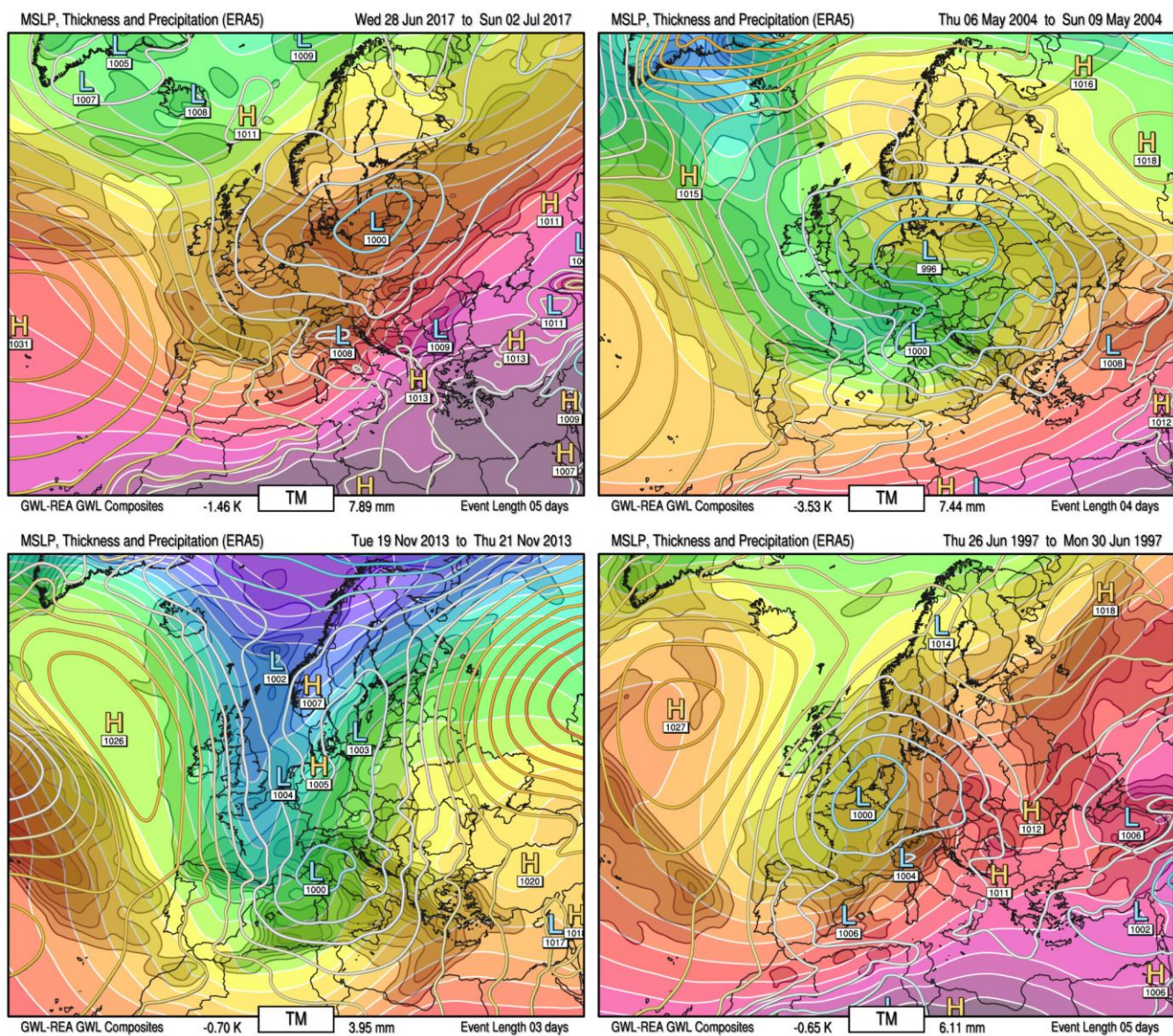


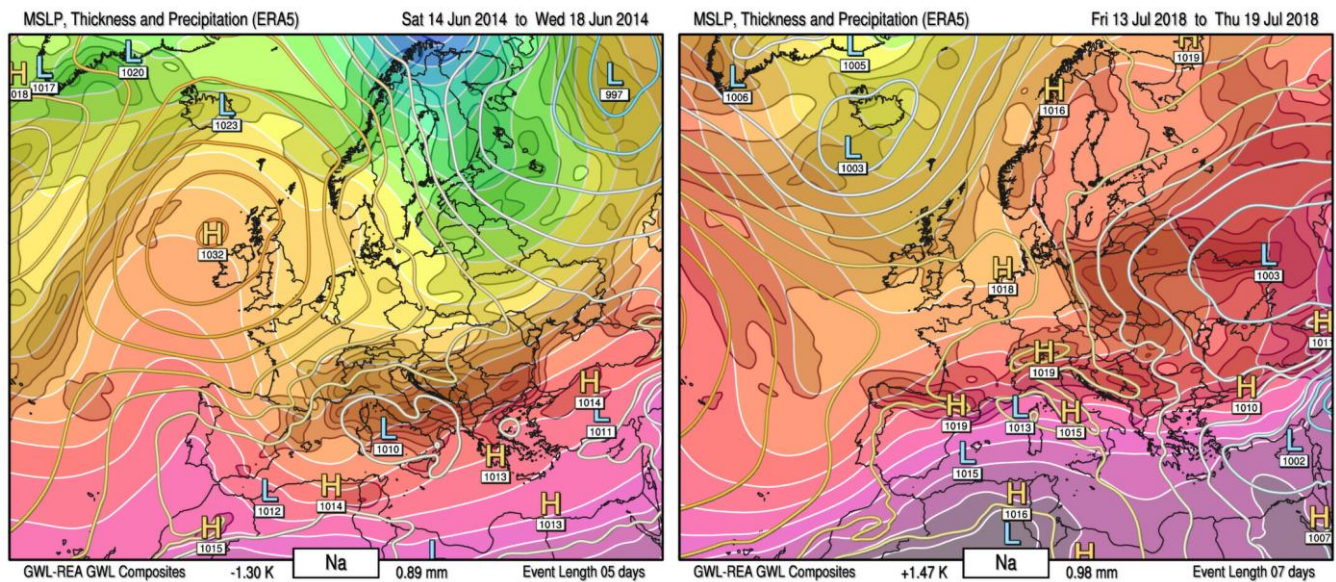
Fig. S17: Further composite synoptic charts for selected historical GWL events classified as “TM”. For details see start of Section 1.

S1.5 Northerly and Hybrid Northerly circulation types (Na, Nz, HNa, HNz, HB, TrM)

The first two northerly circulation types, **Na** and **Nz**, are set up when a meridionally extensive ridge exists to the west of Europe over the Atlantic, often bringing very cold *mA* air masses from the far north, with an extensive trough centred over E Europe. In winter, temperatures may not be quite as low as they can be during easterly spells, due to the long passage of the arriving air over the relatively warm ocean surface. In summer, however, these types usually bring notably cold weather.

S1.5.1 Na – Nordlage, antizyklonal (Anticyclonic Northerly)

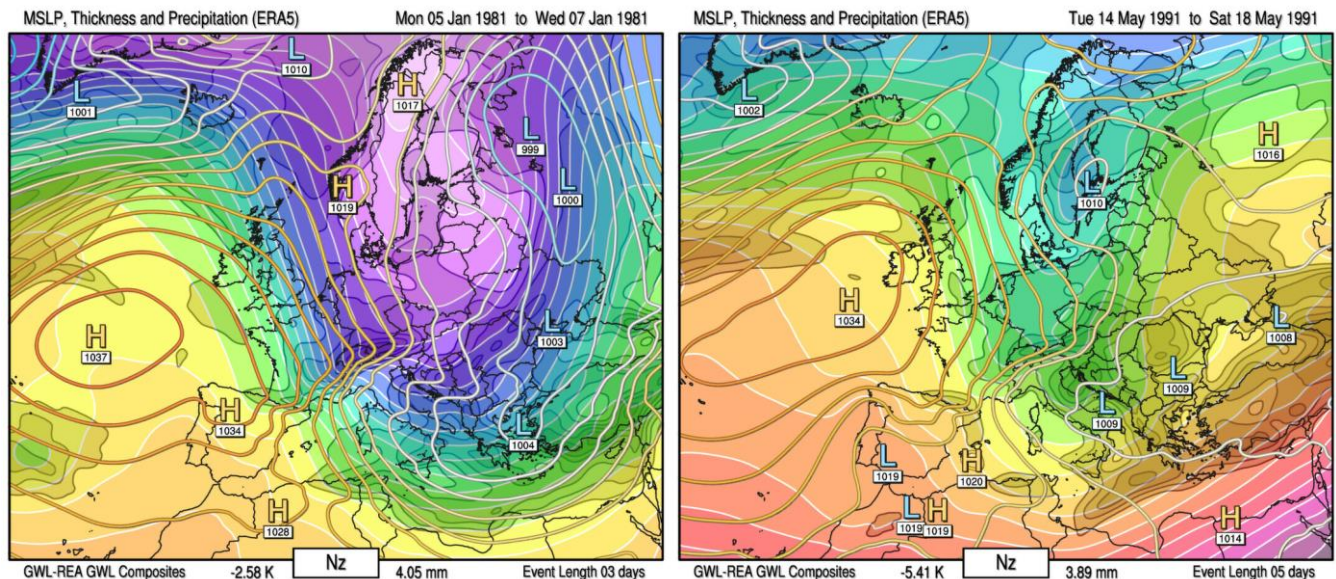
With the type **Na**, the meridional ridge lies over the western edge of Europe. A surface high often lies near or over the British Isles and extends its influence across at least the western half of CE so that the weather remains predominantly dry [8-11.6.2005; 14-18.6.2014]. Nevertheless, showery precipitation cannot be ruled out, especially towards the east, and on average, this type is the least dry of all the GWLs classed as anticyclonic (see Table S2). In some summer cases, the air mass over W Europe can become quite warm, aided by solar insolation, and this warmed air mass can spread into CE too [13-19.7.2018; 15-17.7.2019]. In winter, however, this type usually brings hard frost.



285 Fig. S18: Composite synoptic charts for selected historical GWL events classified as “Na”. For details see start of Section 1.

S1.5.2 Nz – Nordlage, zyklonal (Cyclonic Northerly)

With the **Nz** type the ridge lies further west over the Atlantic and the surface flow often shows a long-fetch of northerly winds into CE with showery precipitation [7-13.1.1968; 5-7.1.1981; 14-18.5.1991; 1-4.11.1995]. Cyclonic systems can develop in this flow bringing cold weather and spells of rain, often falling as snow in winter. Significant snowfalls can occur, especially on high ground exposed to the northerly flow, such as in the northern Alps, where fresh snowfall is possible even in summer [28-31.8.1995; 30.5 – 4.6.2006]. Strong mistral winds are very common over the Mediterranean coast of S France during **Nz** spells and the surface isobars often display a small-scale ridge-trough pattern across the Alps due to the orographic damping effects on the flow crossing the mountain chain.



295 Fig. S19: Composite synoptic charts for selected historical GWL events classified as “Nz”. For details see start of Section 1.

In some rare **Nz** cases, a quasi-stationary frontal zone can exist across CE in a strong north- to northwesterly flow, separating relatively mild returning mid-latitude air masses (mP_s) in the west, from much colder air (mA) in the east [17-21.1.2000]. In other **Nz** cases, northerly flow over CE can be associated with a quasi-circular cyclone over the Baltic states, bringing cold air masses from the north-east out of Scandinavia [29.10-2.11.1974].

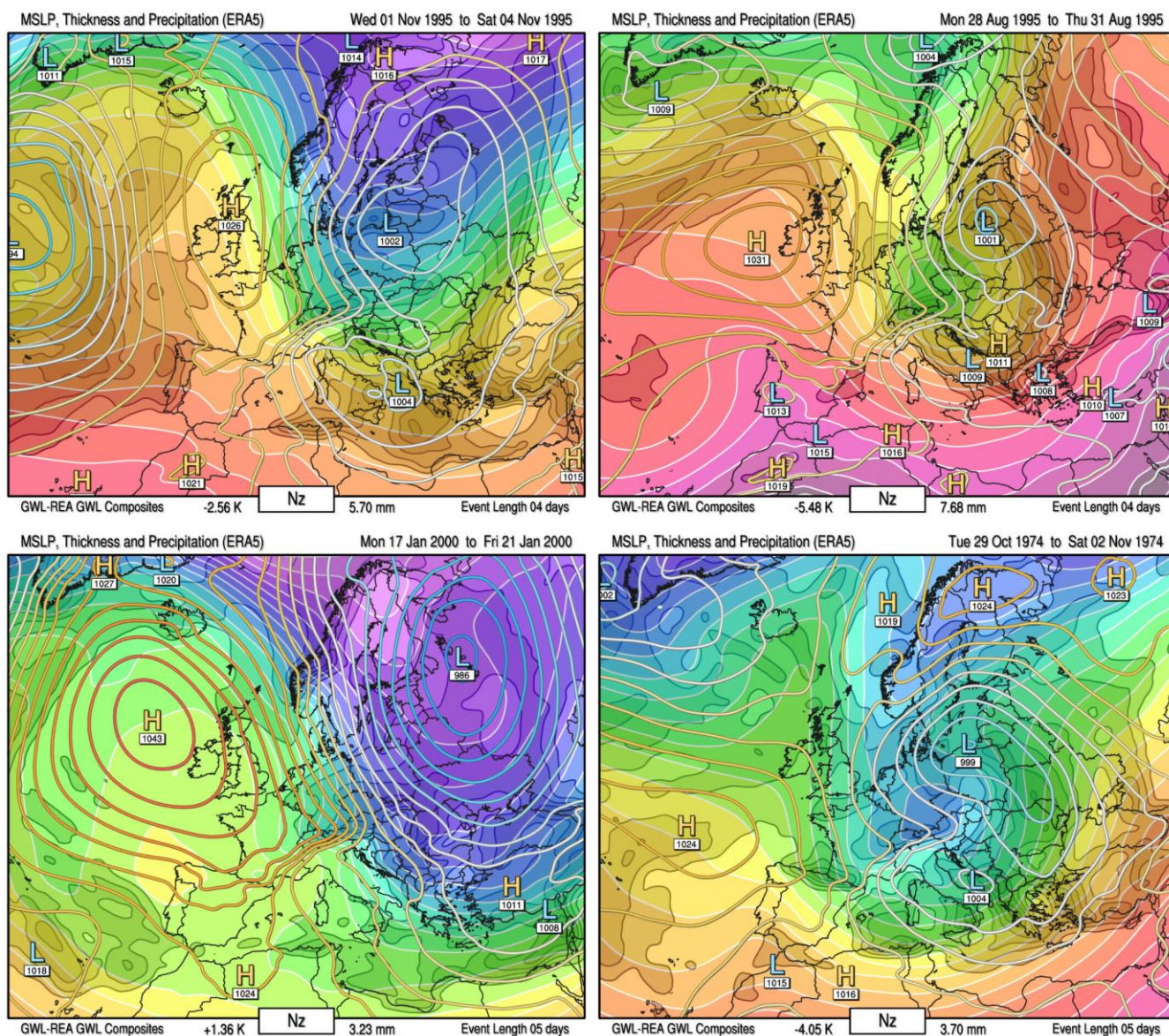


Fig. S20: Further composite synoptic charts for selected historical GWL events classified as “Nz”. For details see start of Section 1.

S1.5.3 HNa – Hoch Nordmeer, antizyklonal (High over the Norwegian Sea, anticyclonic over C. Europe)

The types **HNa** and **HNz** feature a surface high-pressure zone over the Norwegian Sea and/or near Iceland (German: *Hoch Nordmeer*). Both types are associated with an upper ridge-trough structure between Iceland and N. Scandinavia, respectively.

In the case of **HNa** the upper ridge extends north-westwards out of W Europe, with a north-westerly upper flow across CE. However, in **HNz** the Scandinavian trough extends south-westwards, sometimes cutting off and isolating the upper ridge near Iceland. Hence, the upper flow is typically south-westerly from CE southwards.

In a **HNa** variant during the summer months, a high-pressure ridge extends across CE from the north- to north-west, straddling a quasi-stationary air mass boundary [23-26.8.2003]. The mid-tropospheric flow is typically between westerly and northwesterly, typically with cool, dry air to the northeast and warm, moist air persisting to the south-west. The cold air in the north-east is quickly warmed up by solar insolation towards the west where the stagnant warm air masses can lead to heatwave conditions developing in some cases [2-6.6.2018; 23-27.6.2019]. In other summer cases where sufficient moisture is available, weak convergence zones may develop in the weak flow over the western half of CE leading to widespread, slow-moving thunderstorms [6-10.6.2016].

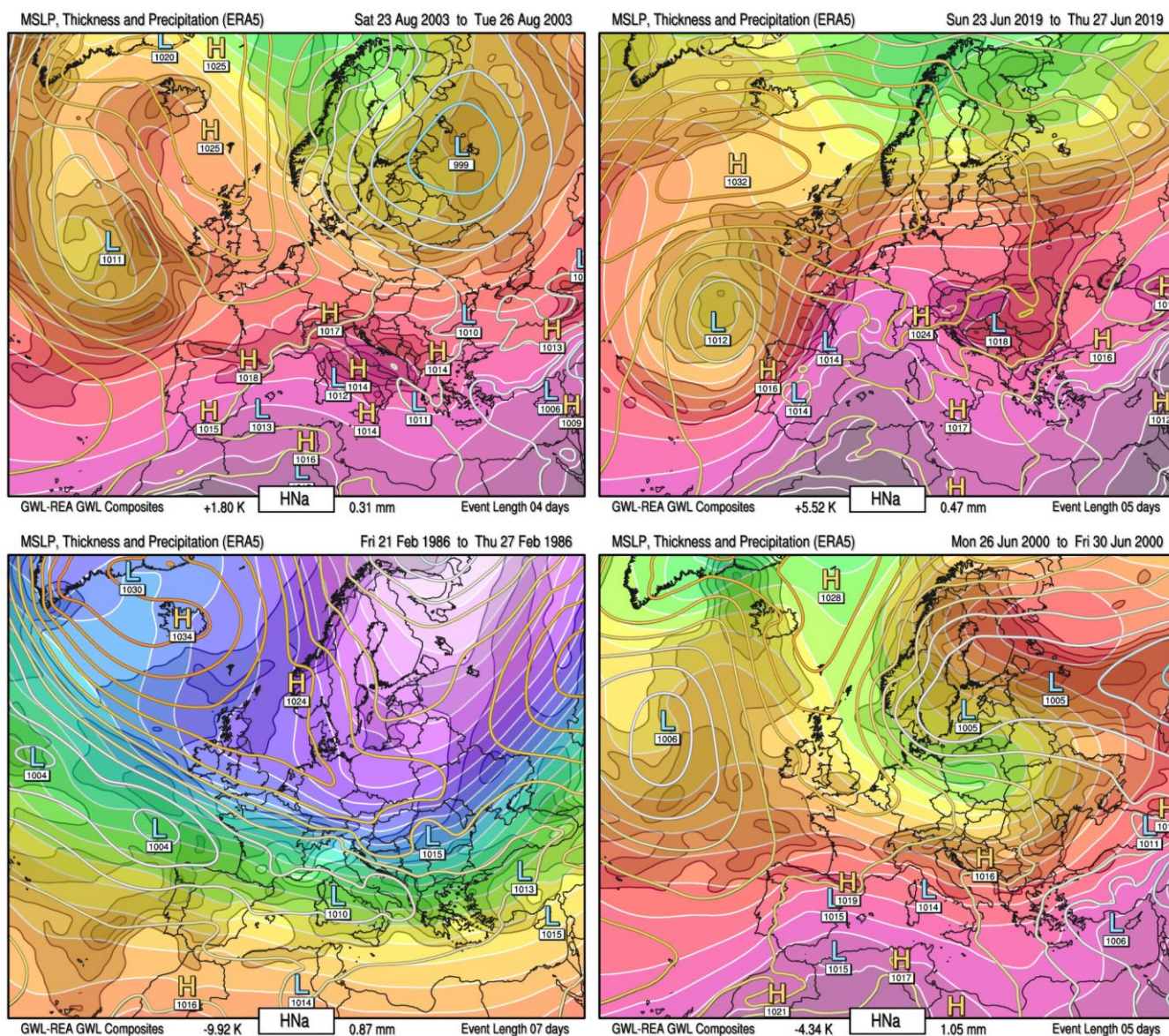


Fig. S21: Composite synoptic charts for selected historical GWL events classified as “HNa”. For details see start of Section 1.

In winter, however, **HNa** typically features a blocking ridge stretching from the Iceland region across CE along the edge of a major trough over Scandinavia. This pattern entirely blocks the progression of mild Atlantic air into CE, resulting in very cold weather with persistent hard frost in light winds [20-27.2.1986; 21-24.12.1996]. Heavy snow can develop over the British Isles and France in some cases where moist maritime air pushes into the cold air. When such an active frontal zone with a NW-SE orientation occurs further east, affecting CE directly, such a situation would be classified as a variant of the cyclonic **HNz** type [e. g. 7-11.1.1982; 18-20.12.1996], even though the upper flow is more typical of **HNa**.

In the summer equivalent of the cold **HNa** variant, solar insolation warms out the initially cool air to an extent, at least towards the south-west [26-30.6.2000]. Over the northeastern quadrant of CE, the air moves in from the Baltic leading to mostly fair weather in fresh, cool air with low humidity. In some cases, localized showers can develop here, more especially in autumn when the relatively warm sea triggers convective activity more readily.

S1.5.4 **HNz** – Hoch Nordmeer, zyklonal (High over the Norwegian Sea, Cyclonic over C. Europe)

With the **HNz** type, a pronounced low-pressure zone and/or frontal trough lies across CE in a SW-NE orientation, underneath a west-south-westerly upper flow [29.12.2009 – 2.1.2010; 10-14.5.2020]. The Icelandic high typically extends south- or south-westwards into the central North Atlantic. In winter, much of CE lies on the cold side of the frontal zone, with north-easterly

winds bringing cold air and some wintery precipitation, especially close to the frontal zone where heavy, prolonged snowfall is possible [23-25.12.2010; 10-13.3.2013]. Further to the south and southeast, very mild, moisture-laden southwesterly winds can bring copious rainfall, particularly to parts of Italy and the Adriatic coast. In summer, the circulation is weaker, with increasingly warm and humid weather towards the southeast and widespread thundery and/or frontal rain across much of CE [27-31.7.2005; 10-14.6.2007].

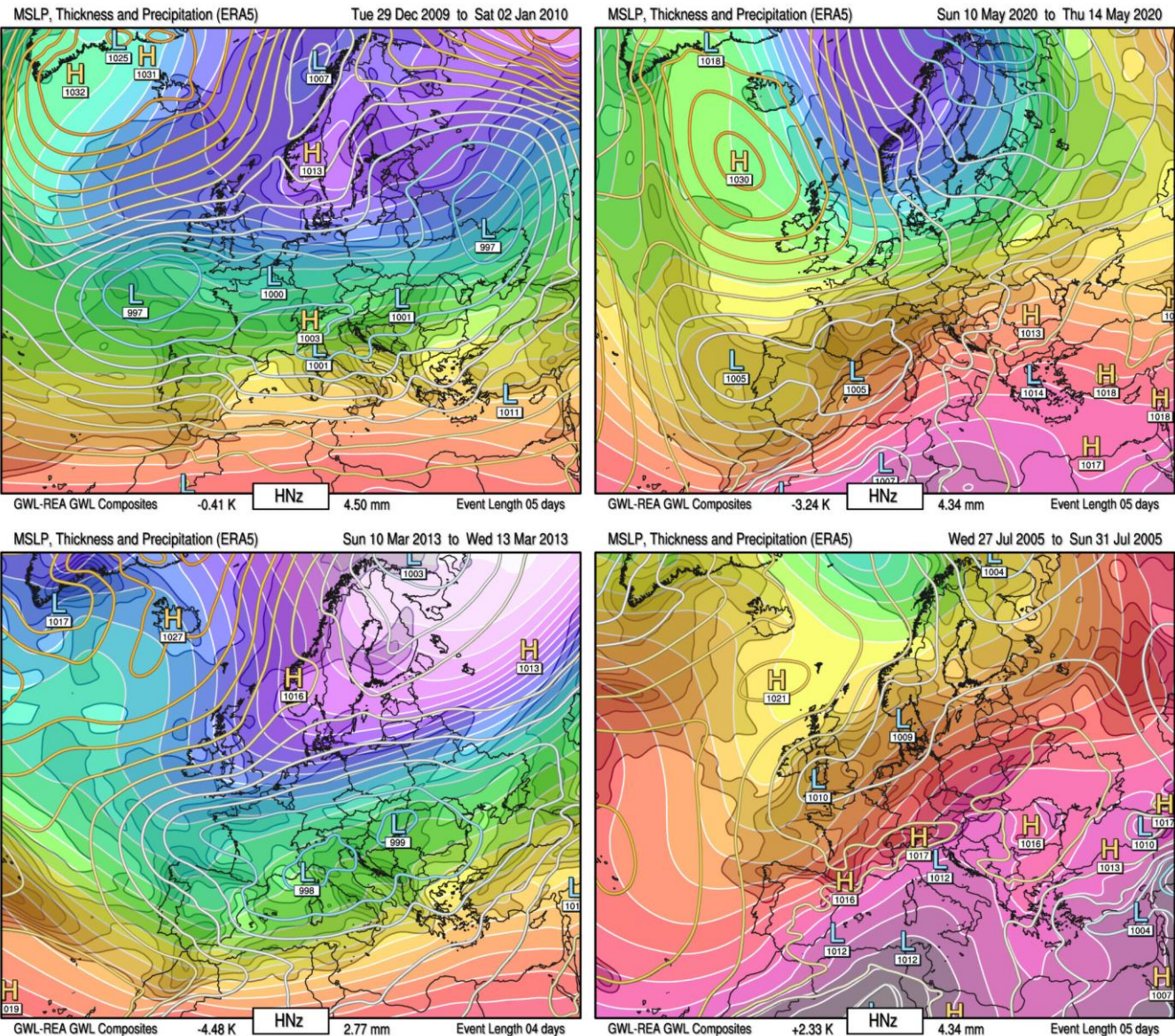


Fig. S22: Composite synoptic charts for selected historical GWL events classified as "HNz". For details see start of Section 1.

S1.5.5 HB – Hoch Britische Inseln (High over the British Isles)

The northerly type, **HB**, involves a strong surface high centred over the British Isles underneath a strong upper ridge. This can often have the form of a Rex block with a cut-off trough to the south, over or just to the west of the Iberian Peninsula. There are three typical **HB** variants.

In the first variant, mostly in summer, an upper ridge is found over W Europe without a significant cut-off trough, with a northwesterly upper flow over CE. The surface high extends a surface ridge over CE across an air mass boundary, with weak cold advection penetrating into CE from the north. The weather is often sunny in summer, especially across the northwestern quadrant of CE, and the strong solar insolation can produce quite high temperatures across SW Germany and especially France in the light northeasterly flow [14-20.7.2013]. Indeed, heatwave conditions can sometimes occur over France with this type.

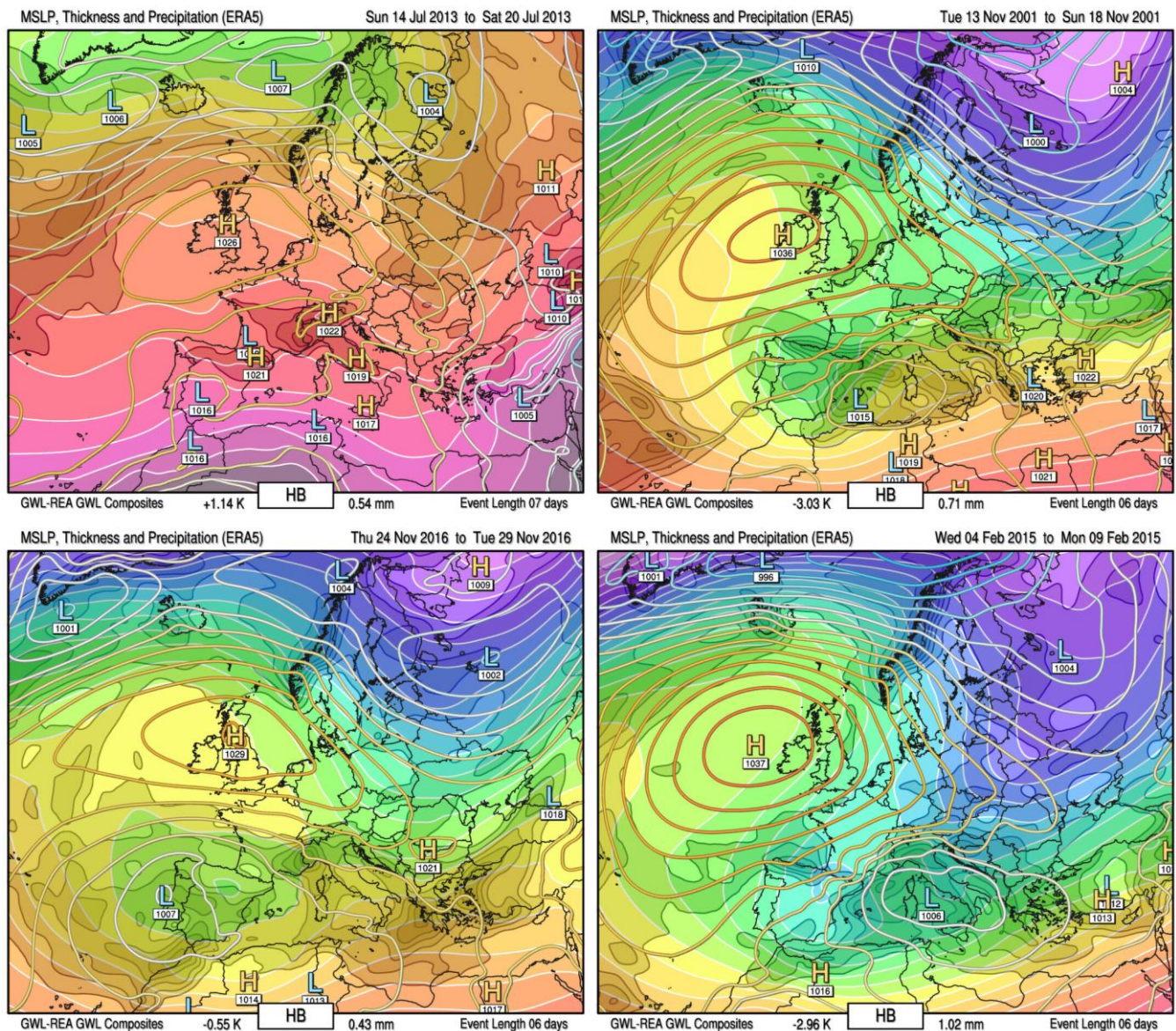


Fig. S23: Composite synoptic charts for selected historical GWL events classified as “HB”. For details see start of Section 1.

350 The second variant is a classic Rex block over W Europe in which a ridge over the British Isles becomes isolated to the north of an Iberian trough, forming a dipole structure which is most common in winter [13-18.11.2001, 24-29.11.2016]. Over CE, a benign, inversion conditions develop with rather low temperatures on plains and in valleys and a mixed air mass at higher levels. The weather is often dry, but some precipitation is possible when warm advection from the North Sea occurs with a sufficient strength. In some cases, the Iberian trough can result in severe weather over Spain and southern France with prolonged heavy rainfall and strong easterly or north-easterly winds [11-13.11.2024].

355 In the third **HB** variant, mainly in winter, a tongue of cold air is drawn across CE from between north-east and north on the edge of the surface high which usually extends a ridge underneath the cold air across most of CE. Easterly winds are common across France. In winter, hard frost is typical across CE [4-10.2.2015; 5-8.4.2015].

S1.5.6 TrM – Trog Mitteleuropa (Trough over C. Europe)

360 The Trough over CE type, **TrM** is defined not in terms of the surface pressure pattern, but rather as a result of having a dominant upper trough centred over CE. This type differs from the preceding northerly types above in that it features an upper ridge pattern further to the east. Although the surface pressure pattern is not specified directly in the type description, **TrM** events often fall into three main variants.

The first variant exhibits low surface pressure and/or cyclonically curved flow under the upper trough. This is typically the result of the troughing out of the surface pattern that occurs following the arrival of very cold air in depth, usually from the north. This can end up in the form of flabby, slow-moving areas of low pressure under the upper cold air [11-16.2.1991; 2-5.3.2005; 30.1 – 3.2.2015]. In extreme cases, a zonally extensive trough covering Western and Central Europe exists, associated with a major southward shift of the polar vortex towards Europe. This then brings major severe winter weather outbreaks to a wide area, including the British Isles, France and CE [notably during the early winter of 2010/11, e. g. 16-18.12.2010]. Very low temperatures and major snowfall episodes occur, the latter especially towards the main frontal zone, which is typically far south of normal. In some winter cases, somewhat milder and moister air masses associated with frontal systems may briefly run into the major trough from the north-west, but with colder air following behind, the trough re-establishes itself quickly [30.11 – 12.12.2012].

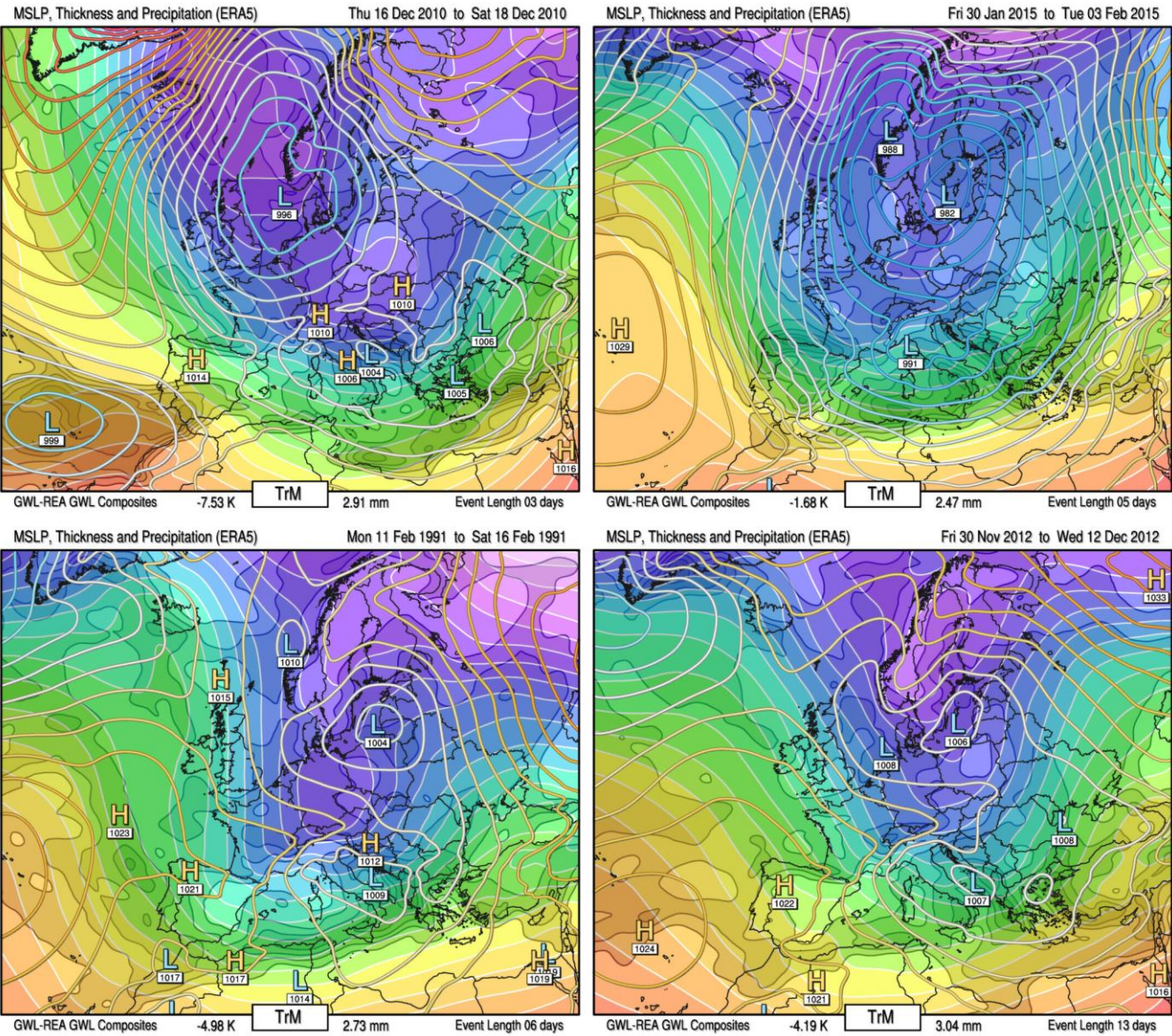
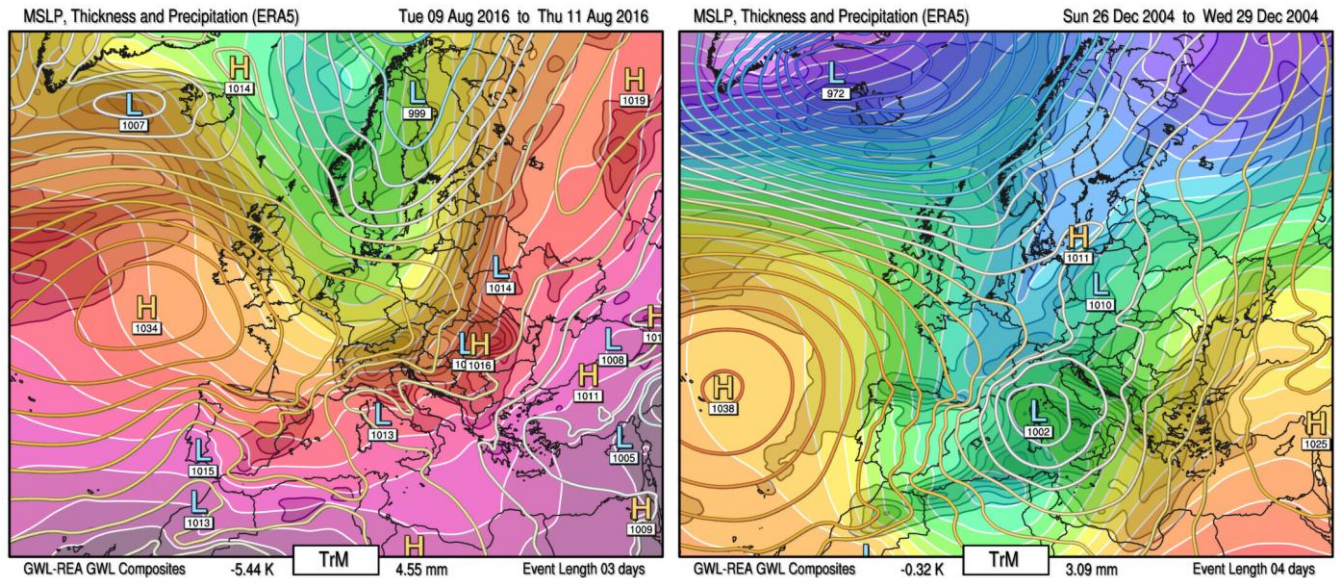


Fig. S24: Composite synoptic charts for selected historical GWL events classified as "TrM". For details see start of Section 1.

The second **TrM** variant has an anticyclonic ridge at the surface extending into CE from the west underneath a compacter upper trough [25-27.5.2015; 9-11.8.2016]. This leads to largely dry weather over the northern and western regions of CE with hard frost at night in winter. However, further to the southeast, prolonged heavy precipitation can occur if a slow-moving frontal trough becomes embedded near the boundary to much warmer air over E and SE Europe. Such troughs are often diagonally tilted, being oriented from northeast to south-west, with the eastern Alps (Austria, southern Bavaria) especially at

risk from flooding in summer and large snowfall accumulations in winter. Furthermore, it is quite common to find a deep low forming over the Central Mediterranean, often leading to strong mistral winds over southern France [26-29.12.2004] and heavy orographic precipitation near the Adriatic coast (Slovenia, Croatia).



385 **Fig. S25: Further composite charts for selected historical GWL events classified as “TrM”. For details see start of Section 1.**

In the third **TrM** variant, the upper trough is typically tilted cyclonically from north-west to southeast. A meridional frontal boundary is located over the eastern half of CE with a low-pressure system developing and moving north along this boundary, eventually leading to substantial warm advection from the north-east and persistent heavy precipitation after the system develops a sufficient circulation. This type of event is widely known as a “Vb”-track (i. e. synoptic type 5b as defined by van

390 Bebbber, 1898), leading to widespread severe flooding across parts of eastern and southern Germany, Austria, Poland and the Czech and Slovak Republics (Mudelsee et al., 2004).

Despite the importance of Vb-events for flooding risk, they are not captured specifically in the GWL system. Vb-track cyclones have a smaller spatial and temporal scale than the mean scale of a GWL structure. Hence, they can occur in a number of different GWLs: in fact, any type that can include an upper trough over or on the western side of CE and where a surface low

395 can form and move north on its eastern flank. In the GWL-REA classification, they most often classify as **TrM**, but can also fall into the **TM**, **NEz**, **HFz** or **TrW** types, noting that the temporal filtering can also influence the final choice of GWL.

Examples of Vb events are the Oder River floods [TrM: 5-7.7.1997], the Elbe River floods [HFz: 7-13.8.2002], the Danube (and elsewhere) floods [TrM: 31.5 – 3.6.2013] and the Bavarian and Austrian floods in 2024 [TrM: 30.5 – 2.6.2024; NEz: 13-16.9.2024]. The catastrophic floods in western Germany and Belgium of July 2021 were also caused by a Vb-like event, albeit

400 somewhat further west than normal. In GWL terms, this event was associated with a transient **TM** situation embedded (after low-pass filtering) within a **TrW** event [especially 9-15.7.2021].

However, not all situations classed as this **TrM** variant (or the respective variants of the neighbouring GWLs) will feature a significant Vb-track low. In many cases, even when the large-scale flow yields the potential for a Vb development, this may not actually occur if the necessary triggers are not ideal.

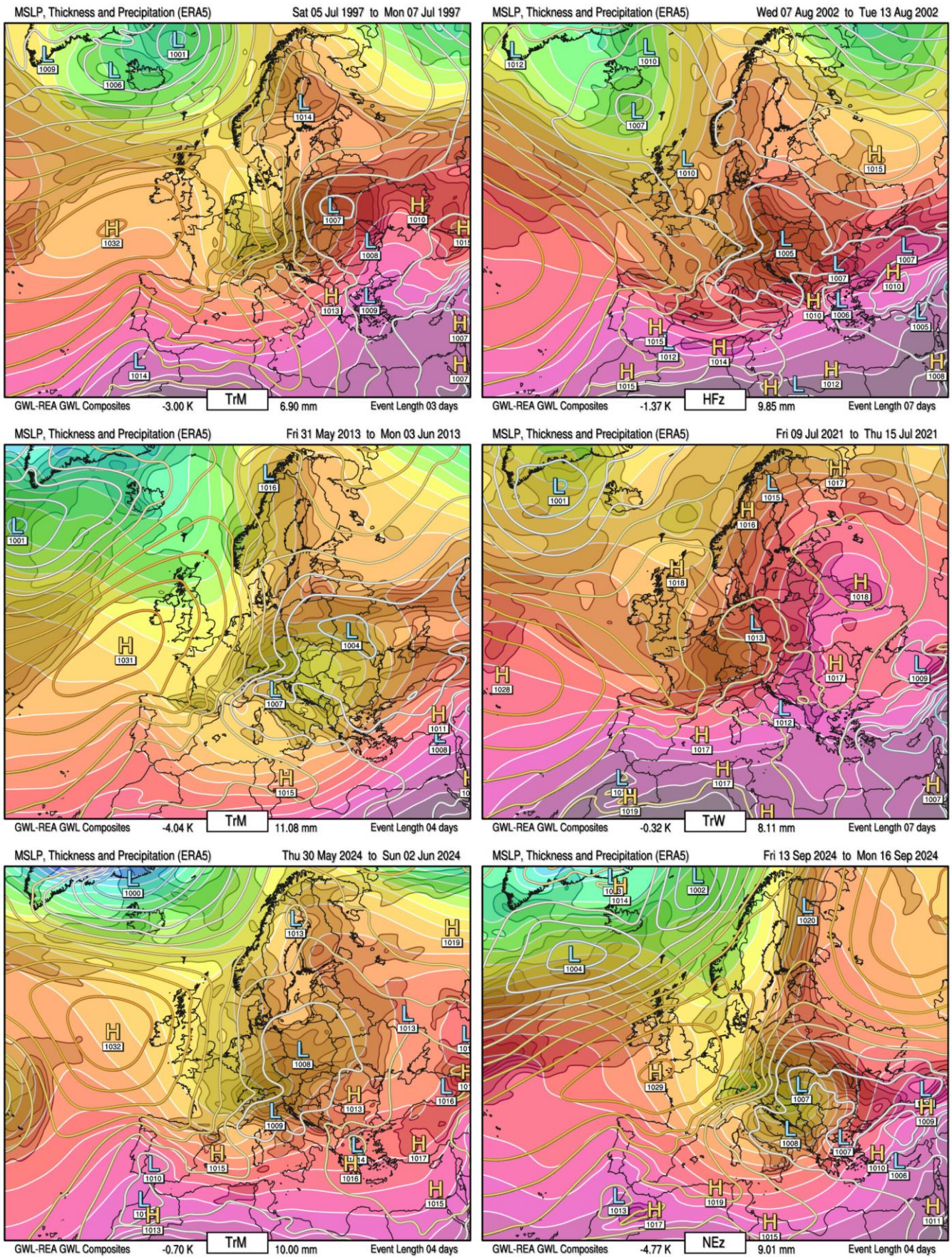


Fig. S26: Composite synoptic charts for selected historical events featuring a Vb-track cyclone on the edge of an upper trough leading to major flooding over parts of Central Europe. The GWL classification of each event is indicated in the box at the bottom of each plot. For details see start of Section 1.

S1.6 North-Easterly circulation types (NEa, NEz)

North-easterly types typically feature a strong surface ridge of high pressure, extending across the British Isles into Scandinavia, with a north-easterly flow across CE on its southern flank. In some cases, a quasi-circular high-pressure region is centred over or near the British Isles, resembling the **HB** type to an extent. An upper trough is often present, close to or over CE. Both north-easterly types can generate a strong Bise wind across the Swiss Alps in particular, blowing along the main Alpine axis.

S1.6.1 NEa – Nordostlage, antizyklonal (Anticyclonic North-Easterly)

The anticyclonic type **NEa** is usually a cold type, especially in winter. The high-pressure zone lies close to CE and the surface isobars are usually anticyclonally curved. A pronounced upper trough approaches from the north-east, bringing very cold *cP* and even *cA* air from NW Russia, which in some cases may even originate in Arctic Russia and/or Siberia [22-25.12.1962; 11-16.12.2001; 7-10.2.2012]. This type often brings intense frost, both day and night, with the cold air penetrating well into W Europe too.

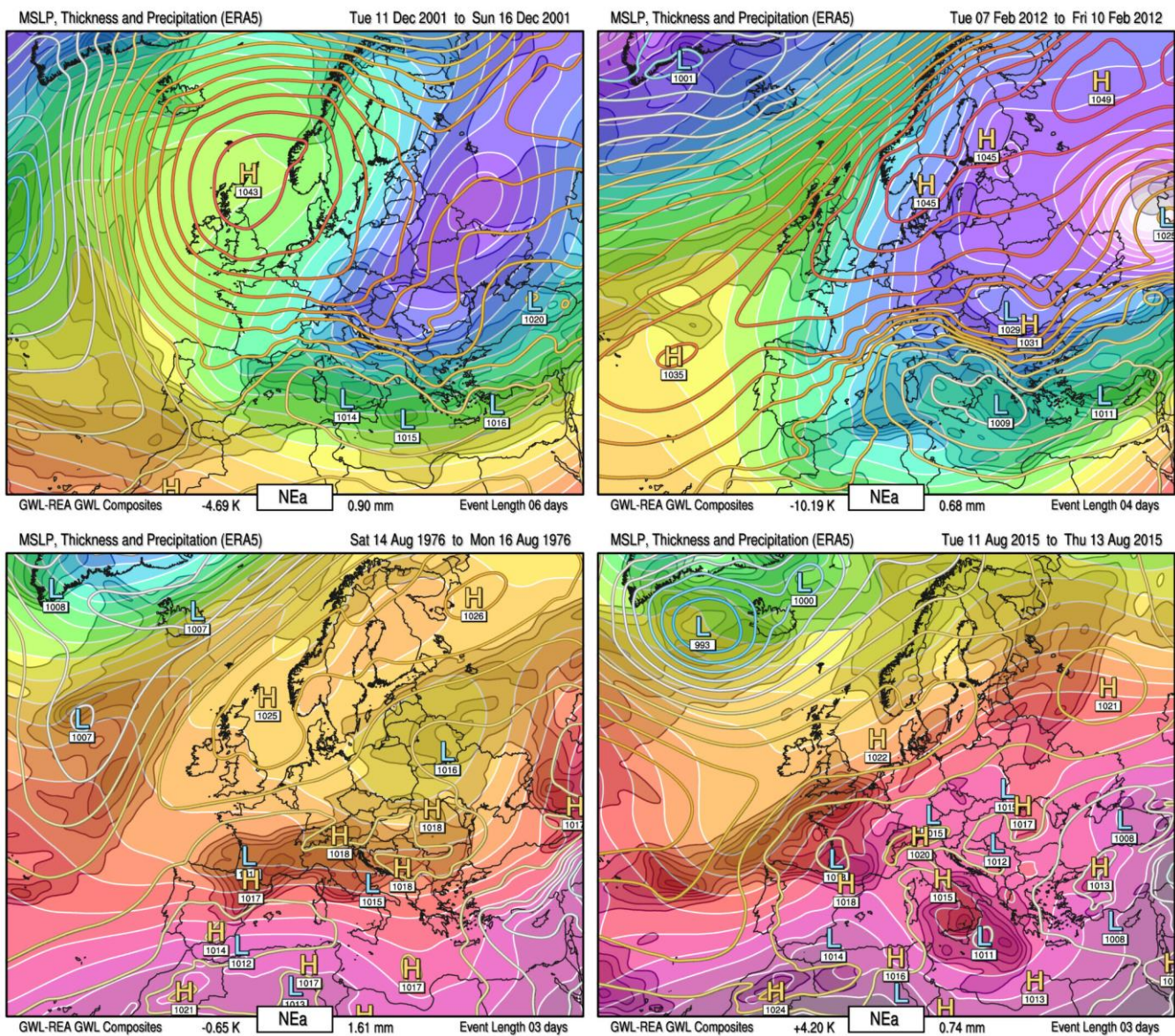


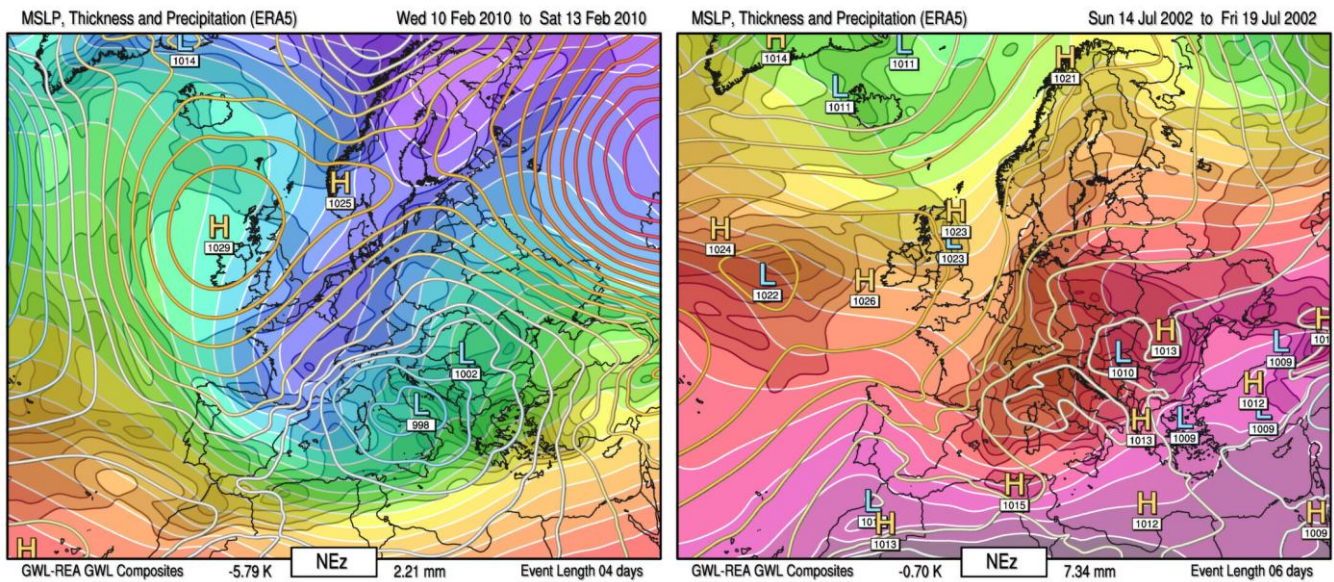
Fig. S27: Composite synoptic charts for selected historical GWL events classified as “NEa”. For details see start of Section 1.

425 In **NEa** events in summer, the initially cool air is gradually warmed due to the long continental track, often leading to moderately warm weather, without oppressive humidity [8-14.8.2022]. In cases where an upper trough to the east is more prominent, the weather may remain cooler with some showery rainfall persisting towards the Alps, although northern CE remains largely dry [14-16.8.1976]. Occasionally a variant occurs in summer in which a light northeasterly to easterly flow of already very warm cS or cS_p air occurs over CE [16-22.8.1995, 11-13.8.2015], which can lead to heatwave conditions towards the west in some cases [12-16.7.2006].

S1.6.2 NEz – Nordostlage, zyklonal (Cyclonic North-Easterly)

When the cyclonic **NEz** type occurs in winter, a substantial low-pressure system is located over SE Europe. Cold air over CE under an upper trough is gradually overrun with warmer cS_p air pushing in from Eastern Europe. The resulting large-scale warm advection leads to widespread cloud and precipitation, which can fall as snow widely [10-13.2.2010].

435 In summer **NEz** cases, the low-pressure systems, as well as the upper troughs, are usually smaller in scale and more diverse in character. The weather is humid and rather cloudy, with the risk of widespread thundery or large-scale rain, which may lead to localized flooding in places. Sometimes, Vb-events can develop within an **NEz** event, leading to major regional flooding [14-19.7.2002; 7-11.8.2007, 13-16.9.2024].



440 Fig. S28: Composite synoptic charts for selected historical GWL events classified as “NEz”. For details see start of Section 1.

S1.7 Easterly circulation types (HFa, HFz, HNFa, HNFz)

Easterly types result from situations with a dominant high-pressure region centred over or near Scandinavia. In the classic GWL system, easterly types are grouped into four sub-types as a function of whether the high is largely confined to the Scandinavian land mass (HF: “High over Scandinavia”, German: *Hoch Fennoskandien*) or extends westwards towards Iceland (HNF: “High Norwegian Sea to Scandinavia”, German: *Hoch Nordmeer-Fennoskandien*) and as a function of (anti-) cyclonicity over CE, resulting in an “a” or “z” suffix.

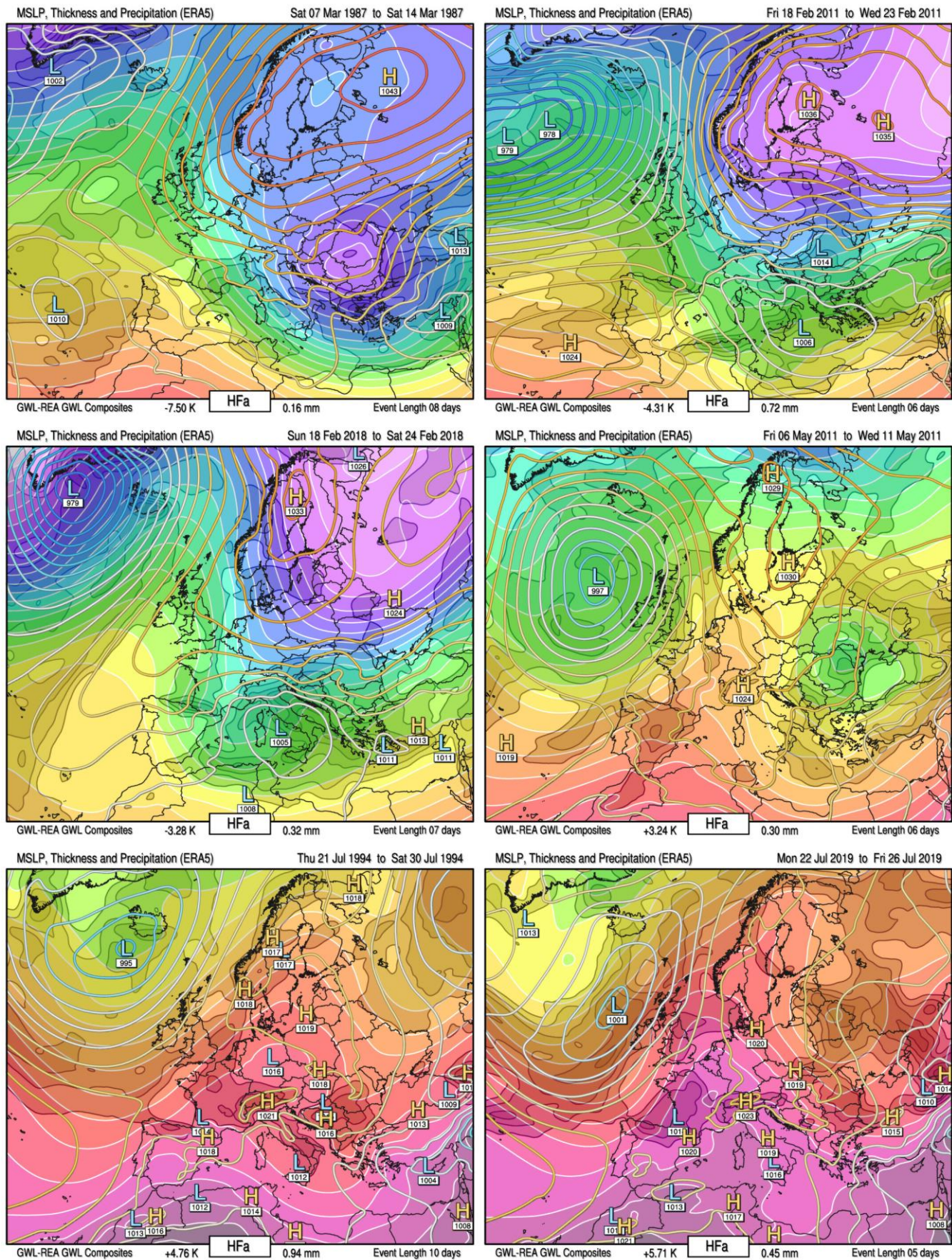
445

S1.7.1 HFa – Hoch Fennoskandien, antizyklonal (High over Fennoscandia, anticyclonic over C. Europe)

With the anticyclonic type **HFa**, the upper flow typically shows a ridge over the western edge of Europe extending up to the Norwegian Sea and an upper trough over E Europe. In winter this upper trough often extends westwards to cover CE and, in some cases, even W Europe. The surface high-pressure zone over Scandinavia is quasi-circular with southerly flow west of

450

Norway, while an east- to south-easterly flow over CE brings cold *cP* air masses, resulting in dry weather with very hard frost in winter [7-14.3.1987; 16-22.11.1993; 18-23.2.2011; 25.1 – 6.2.2012; 18-24.2.2018].



455 Fig. S29: Composite synoptic charts for selected historical GWL events classified as “HFa”. For details see start of Section 1.

In late spring and summer, cold air arriving from the east is gradually warmed out by solar insolation, while the western ridge is often more dominant and may cover much of W Europe. Its remnants may trigger local convective showers, but the weather can become pleasantly warm without oppressive humidity [6-11.5.2011]. Similar to **NEa**, some **HFa** cases can develop with very warm cS air already in place over CE under a strong upper ridge over W Europe. Then, major heatwave conditions can develop, especially towards the west [21-30.7.1994; 27-31.7.2018; 22-26.7.2019].

S1.7.2 HFz – Hoch Fennoskandien, zyklonal (High over Fennoscandia, cyclonic over C. Europe)

The cyclonic **HFz** type typically occurs when the blocking high and upper ridge over Scandinavia become isolated and cut off by a trough over or to the west of CE. At low levels over CE, low pressure systems encroach from the west or develop near to an air mass boundary. **HFz** can be usefully separated into two distinct variants, which are associated with strongly contrasting air mass patterns.

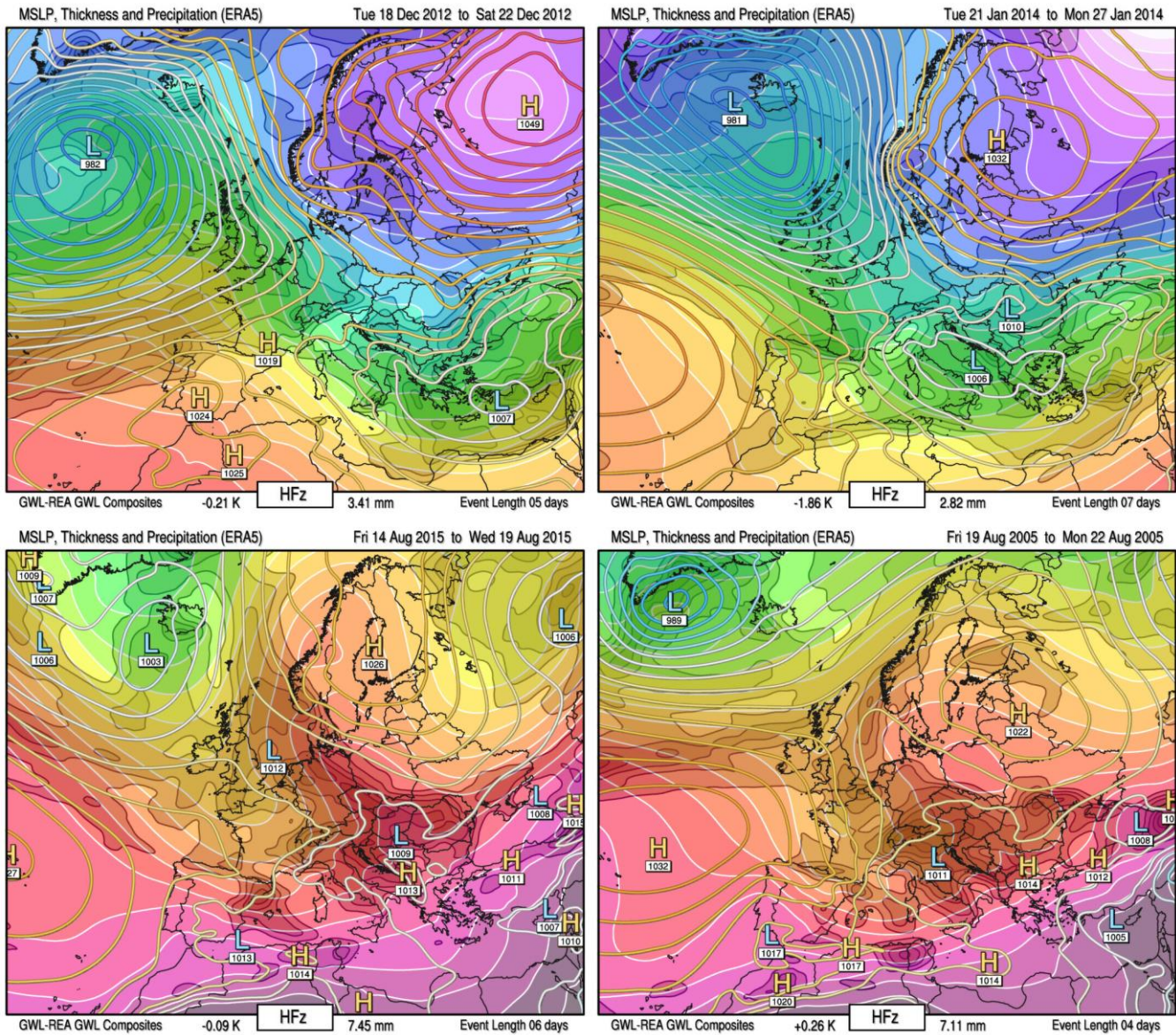


Fig. S30: Composite synoptic charts for selected historical GWL events classified as "HFz". For details see start of Section 1.

The first of these, more common during the winter half-year, shows a strong blocking high centred over NW Russia with cold cP air extending into CE from the east. Frontal systems push in from the west and south-west but become stalled near the southern-western quadrant of CE, leading to some rain, snow or freezing rain there, and usually fail to shift the cold air significantly, except perhaps in the south-western quadrant itself [18-22.12.2012; 21-27.1.2014; 2-7.1.2016]. This pattern is

in fact rather similar to the **Ww** type, except that the frontal stalling process occurs further east with **Ww**, so that the latter is generally milder over CE, while the flow in the **HFz**-variety is more tilted from south-westerly to south-easterly.

475 The second **HFz** variant, more common during the summer half-year, exhibits a quasi-stationary frontal surface trough across CE, usually oriented from north-west to southeast, on the edge of a high-pressure system over NW Russia. To the northeast of this surface trough, stagnant warm, humid (cS_p) air is found, while to the south-west, cool mP air flows in from the north-west. Near the surface frontal trough, heavy and in some cases thundery rain develops, which can lead to local flooding [14-19.8.2015]. Indeed, some Vb-like events can occur with this type, resulting in major flooding episodes, notably in the Alpine
480 regions [19-22.5.1999, 19-22.8.2005].

S1.7.3 HNFa – Hoch Nordmeer-Fennoskandien, antizyklonal (High Norwegian Sea to Fennoscandia, anticycl. CE)

The anticyclonic type **HNFa** features a broad surface high pressure ridge extending across from Scandinavia to Iceland, with anticyclonic ridging across much of CE. The upper air flow is similar to that of **HFa**, with an upper ridge over W Europe or the nearby Atlantic and an upper trough to the east. In winter, this trough is often more dominant and may extend westwards
485 over CE and into W Europe.

In its typical winter variant, **HNFa** brings very cold air masses (cP or cA) to CE with hard or even severe frost, but largely dry weather [13-18.2.1947; 9-12.2.1956; 16-21.1.1963, 28.12.1996 – 4.1.1997; 25.2 – 2.3.2018].

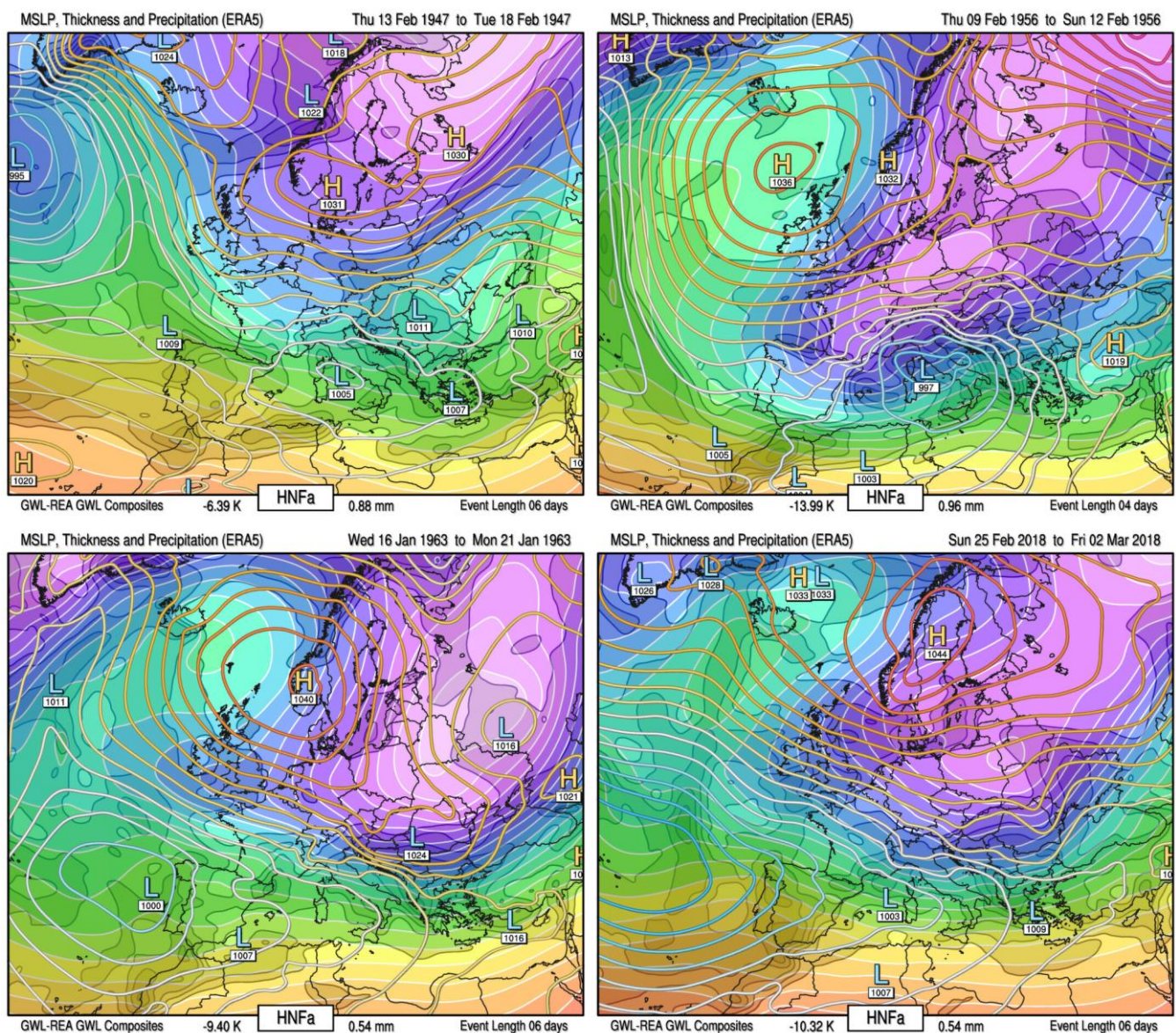
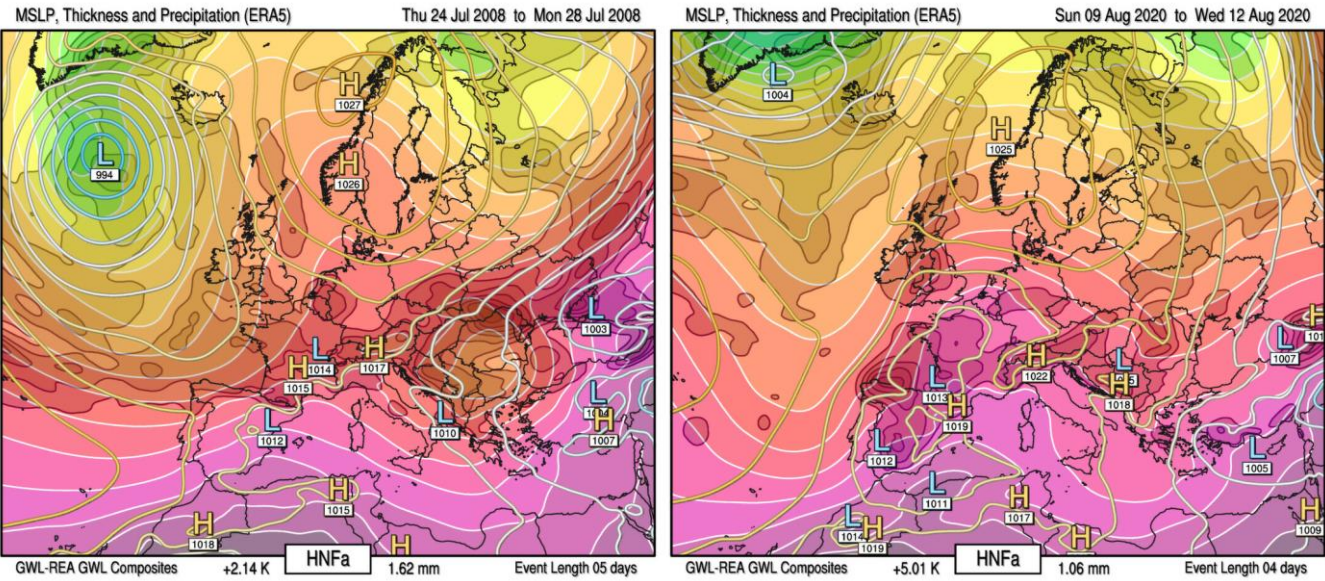


Fig. S31: Composite synoptic charts for selected historical GWL events classified as "HNFa". For details see start of Section 1.

490 In summer, however, the W European upper ridge is typically much more dominant, often extending its influence into CE, while colder air masses being advected in from the east are warmed up by solar insolation. As a result, **HNFa** in summer is often a warm and dry type, especially towards the west, where heatwaves can develop [24-28.7.2008; 21-26.7.2013; 9-12.8.2020].

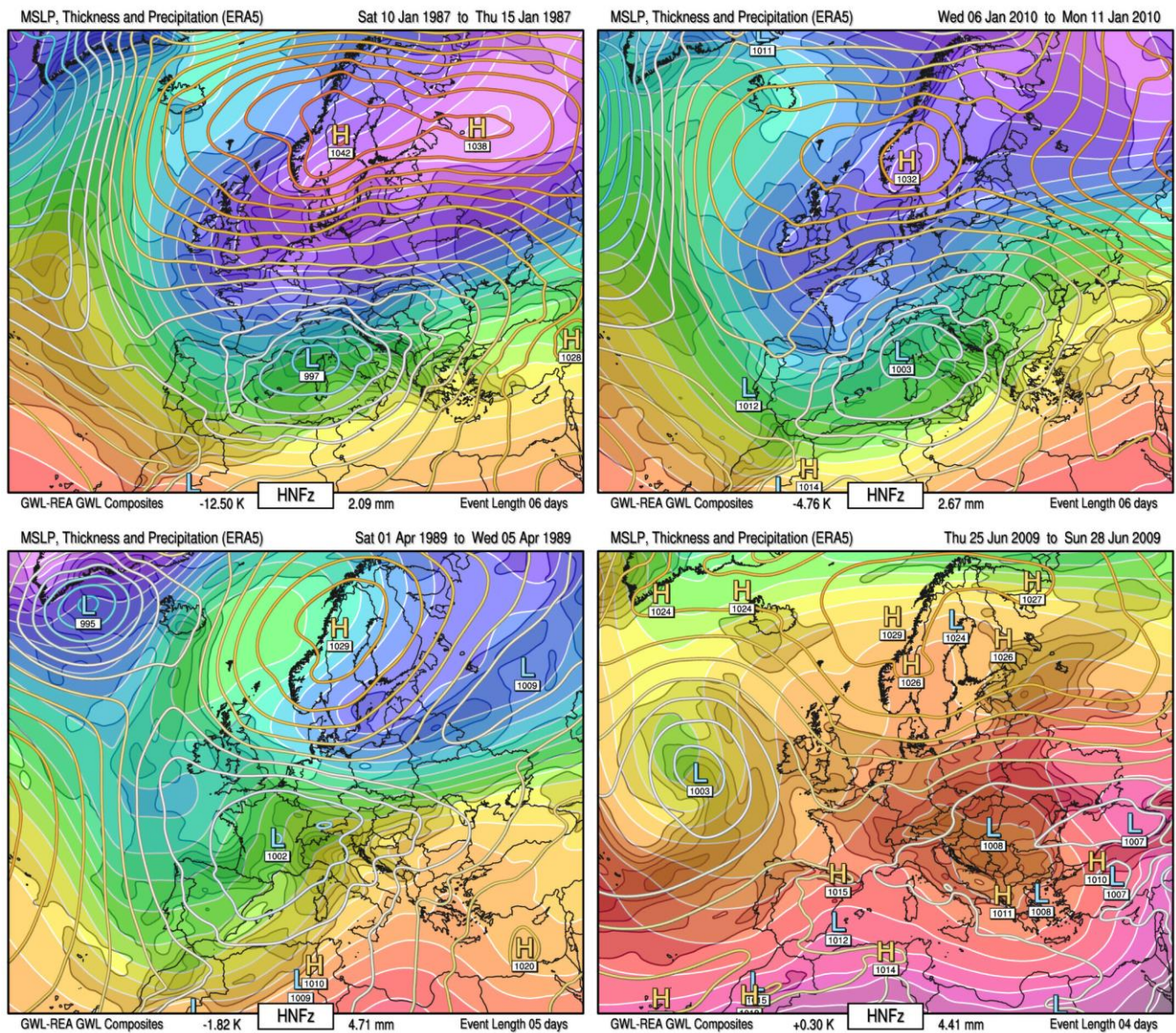


495 Fig. S32: Further composite synoptic charts for selected GWL events classified as “HNFa”. For details see start of Section 1.

S1.7.4 HNFz – Hoch Nordmeer-Fennoskandien, zyklonal (High Norwegian Sea to Fennoscandia, cyclonic over CE)

The cyclonic **HNFz** type in winter is usually a very cold type, similar to **HNFa**, with a tendency for surface low pressure systems to develop in the easterly flow over CE bringing wintery precipitation. In cases where an intense upper cold pool is advected in from the north-east, temperatures can become extremely low [10-15.1.1987]. Warm advection can bring milder air from SE Europe into at least the southern half of CE, however, adding a risk of large-scale snowfall or freezing rain [6-11.1.2010]. A strong temperature gradient can also develop between very cold air to the north and mild air to the south [1-5.4.1989]. In summer, this type brings cloudy and humid weather with the risk of widespread thundery rain [25-28.6.2009].

500



505 **Fig. S33: Composite synoptic charts for selected historical GWL events classified as "HNFz". For details see start of Section 1.**

S1.8 South-Easterly circulation types (SEa, SEz)

S1.8.1 SEa – Südostlage, antizyklonal (Anticyclonic South-Easterly)

510 Southeasterly types characterise situations bringing usually mild or warm air up from SE Europe. There are two primary variants of the classic anticyclonic southeasterly (**SEa**) GWL, leading to different weather characteristics across CE itself, notably in winter. In the generic **SEa** type, a high-pressure centre sits near Belarus with a broad flow of relatively warm air aloft (cS_p) arriving from the southeast over CE [7-11.12.1996]. Due to surface cooling, however, the weather in winter may still be relatively cold at low levels, while remaining mild in the mountains. In summer, **SEa** brings generally hot, dry and sunny weather, sometimes with cS air masses, with few disturbances and the highest temperatures in the west [17-21.8.1997; 24-27.8.2019].

515 Alternatively, the surface high straddles an air mass boundary, sometimes with strong vertical shear over the eastern half of CE, between the surface southeasterly flow and a northwesterly flow in the mid-troposphere [28.11 – 1.12.2014]. In some of these **SEa** cases, a weak surface convergence can be set-up with very cold air arriving over the eastern half of CE, while relatively mild air lies further west in a weak southerly low-level flow. The large-scale anticyclonicity around this weak convergence zone typically prevents significant precipitation amounts from accumulating. Hence, even though the MSLP field may show a weak cyclonic curvature in some cases, precipitation is insufficient for such events to count as **SEz** [14-17.2.2011].

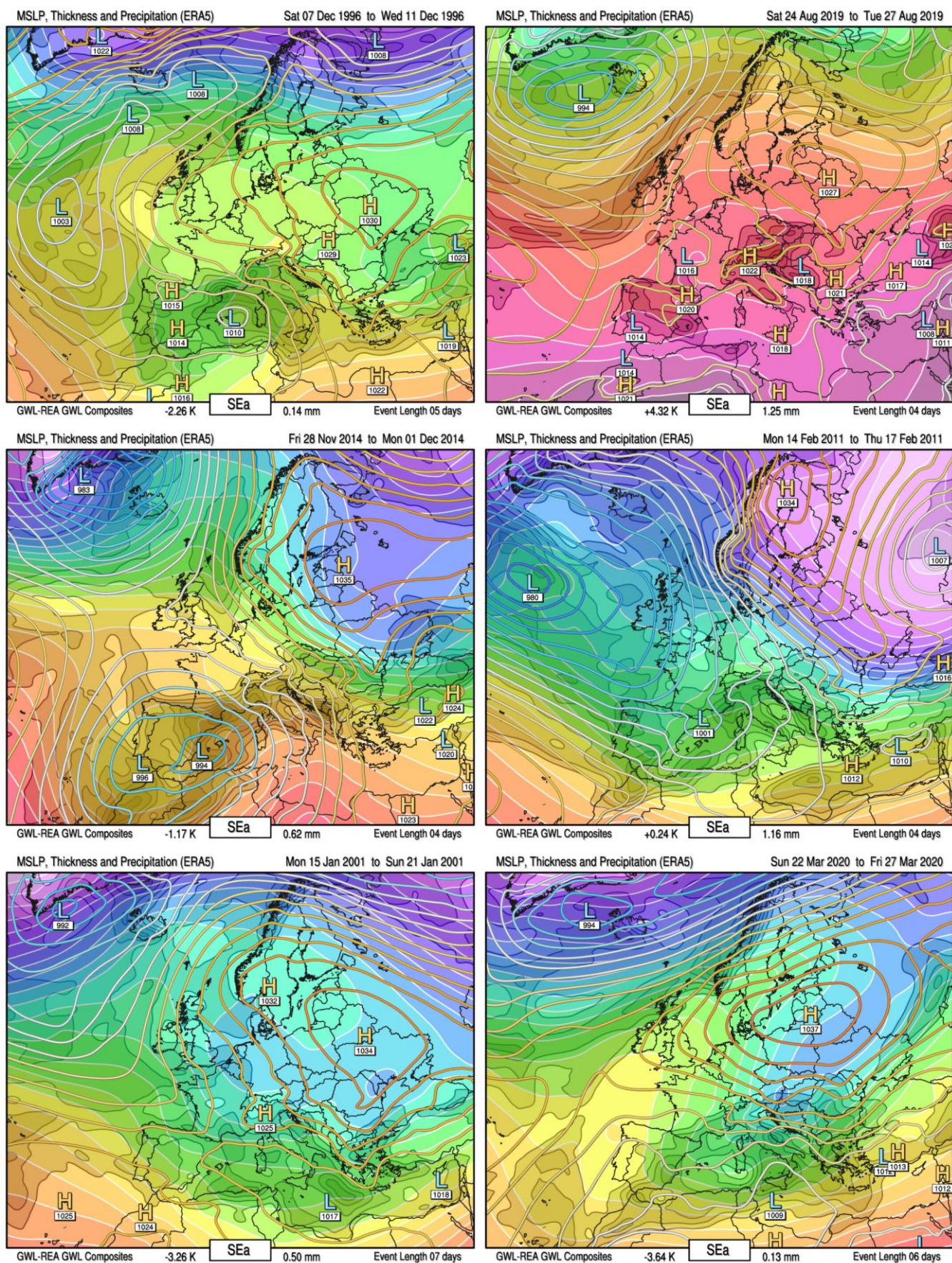


Fig. S34: Composite synoptic charts for selected historical GWL events classified as “SEa”. For details see start of Section 1.

In summer, initially cold air masses are warmed out under anticyclonic conditions, such that sharp air mass boundaries cannot occur, although the different air masses may still be detectable in terms of humidity levels, which are typically lower to the east in these cases.

In some winter **SEa** cases, very cold air has previously spread into SE Europe and is then advected back as cP_s air into CE. Here, there is no warm air nearby and no air mass boundary, although further afield much milder air can spread into Scandinavia from the south-west [15-21.1.2001; 22-27.3.2020]. In some other cases, a cut-off trough may form over the Mediterranean, from where it does not affect CE directly [19-24.5.1992].

530 S1.8.2 SEz – Südostlage, zyklonal (Cyclonic South-Easterly)

The cyclonic type **SEz** typically exhibits a low-pressure complex stretching southeastwards from the British Isles across France into the western Mediterranean underneath a backward-tilting W European upper trough. A broad SE flow is then set up on the edge of a blocking high over W Russia, bringing mild air up from the Central Mediterranean [2-7.11.2008; 15-18.11.2014]. In some cases, surface low pressure can become cut-off over SW Europe with higher pressure near the British Isles. In winter, low temperatures may persist at low levels in some cases, especially in the north, where warm advection can lead to widespread snowfall. Where warm air aloft overruns the cold surface air, freezing rain can also occur in places [19-22.1.2013; 7-9.3.2013; 25-29.1.2026]. Rain can be especially heavy and persistent on the southern side of the Alps with this type.

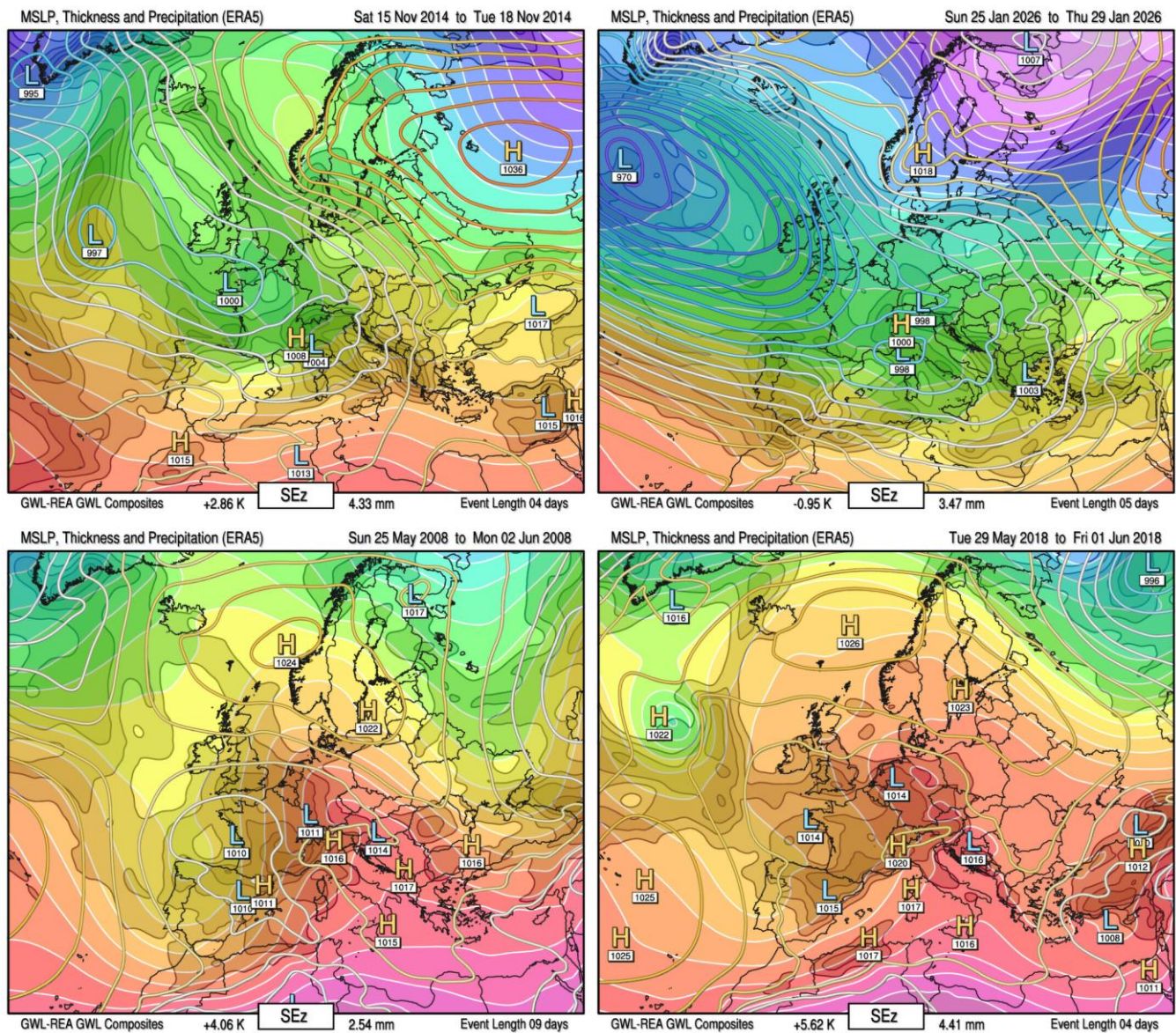


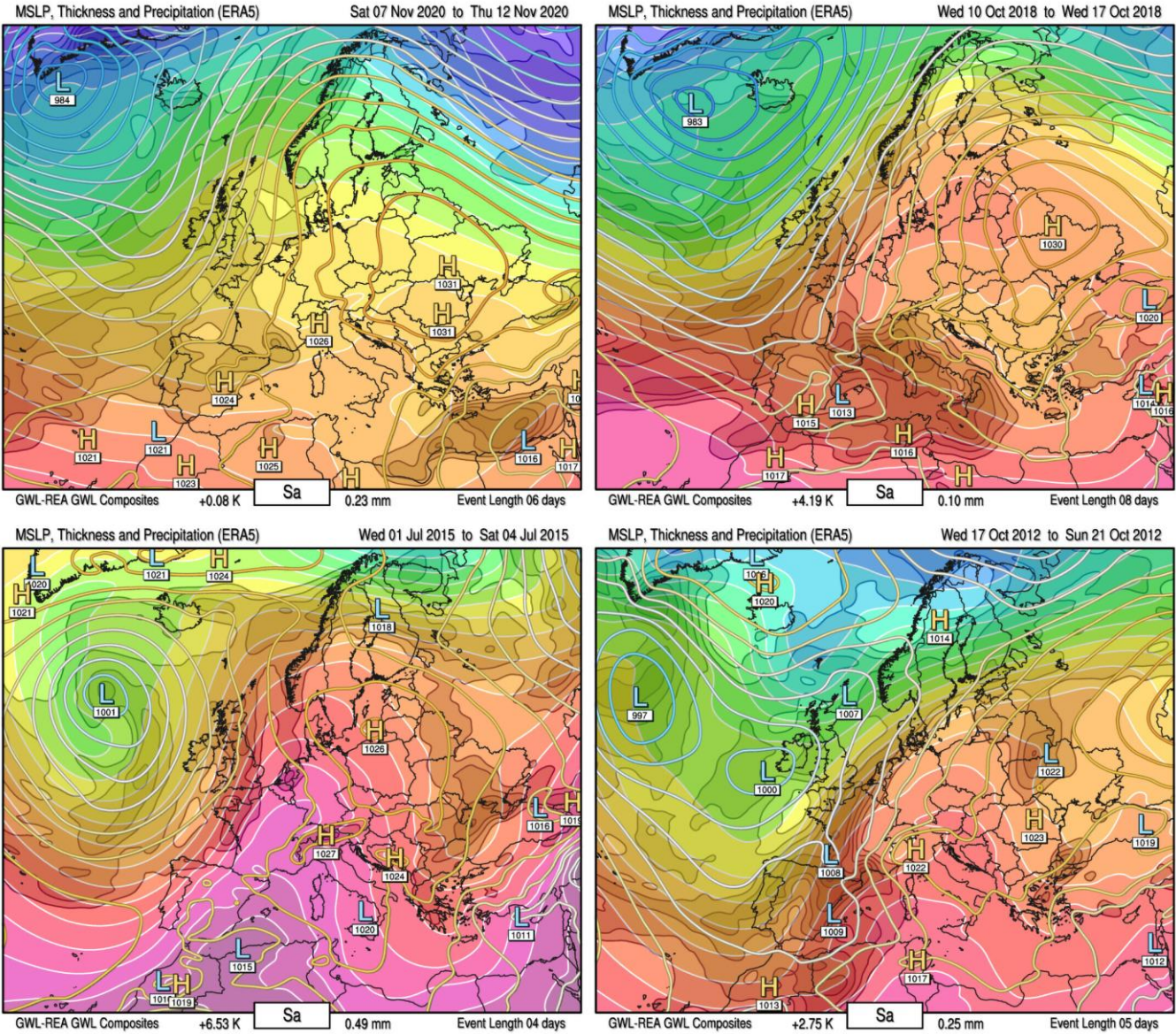
Fig. S35: Composite synoptic charts for selected historical GWL events classified as “SEz”. For details see start of Section 1.

540 In summer, **SEz** is associated with warm, sultry weather over CE in summer, with a risk of thunderstorms increasing strongly towards the south-west [25.5 – 2.6.2008; 29.5 – 1.6.2018], but with largely dry and hot weather persisting towards the north-east. In all seasons, returning polar maritime air can sometimes encroach on the southwestern quadrant of CE, immediately behind the leading frontal zone, resulting in significantly colder weather there under cloudy skies.

S1.9 Southerly and Hybrid Southerly circulation types (Sa, Sz, TB, TrW)

545 **S1.9.1 Sa – Südlage, antizyklonal (Anticyclonic Southerly)**

Southerly types bring usually mild or warm air from the Mediterranean and/or from SE Europe to CE. In the anticyclonic type, **Sa**, a high-pressure zone sits over Eastern Europe with weakly anticyclonically curved southerly winds over CE, which can penetrate into southern Scandinavia in some cases, especially in autumn and winter. A pronounced upper trough-ridge pattern exists between the nearby Atlantic and E Europe, respectively. The weather is largely dry and relatively mild in winter, especially in the mountains [7-12.11.2020], although inversion conditions can persist in places with low temperatures at low levels. At all other times of year, this type is associated with very warm or hot conditions, with largely dry and sunny weather [17-21.10.2012; 6-10.6.2014; 1-4.7.2015; 3-7.8.2015; 10-17.10.2018]. Intense heat can indeed develop in summer over CE with this type, but is usually relatively short-lived.



555 **Fig. S36: Composite synoptic charts for selected historical GWL events classified as “Sa”. For details see start of Section 1.**

In some winter episodes of **Sa**, the high-pressure centre lies on the edge of very cold air to the east, usually within a meridional upper flow pattern. The low-level trajectories then spread cold (cP_s) surface air from SE Europe across a large part of CE, except perhaps the far west of the region. At upper levels, the air is relatively warm across the western half of CE, so that the weather is very mild and mostly clear in the Alps, for example. In winter, temperatures at low levels are relatively low with widespread hard night frost, except possibly in the far west of CE [4-9.2.2005; 28.12.2015 – 1.1.2016]. In summer this variant is rare. When it occurs, remnants of an upper trough to the east, in combination with strong solar insolation by day, typically lead to the air being quite dry so that nights can be rather cold in the east [10-14.9.2006]. Further west, hot weather can develop, but without being humid or oppressive.

A further variant of **Sa**, most common in the late Autumn, is associated with very strong Föhn conditions over the Alps ahead of a deep low or surface trough near the Bay of Biscay, France. In the lee of the Alpine chain the weather is largely dry over CE, despite the strongly cyclonic flow nearby to the west and the generally strong pressure gradients. Hence, this type is classified as **Sa**. Nevertheless, over Southern France, the French and Italian Alps and, in some cases, also the Pyrenees, exceptionally heavy rain can occur, leading to landslides and regional flooding [1-5.11.2011]. Furthermore, a violent Föhn storm can afflict the Alpine and Pyrenees regions in rare cases, leading to widespread structural damage [6-8.11.1982].

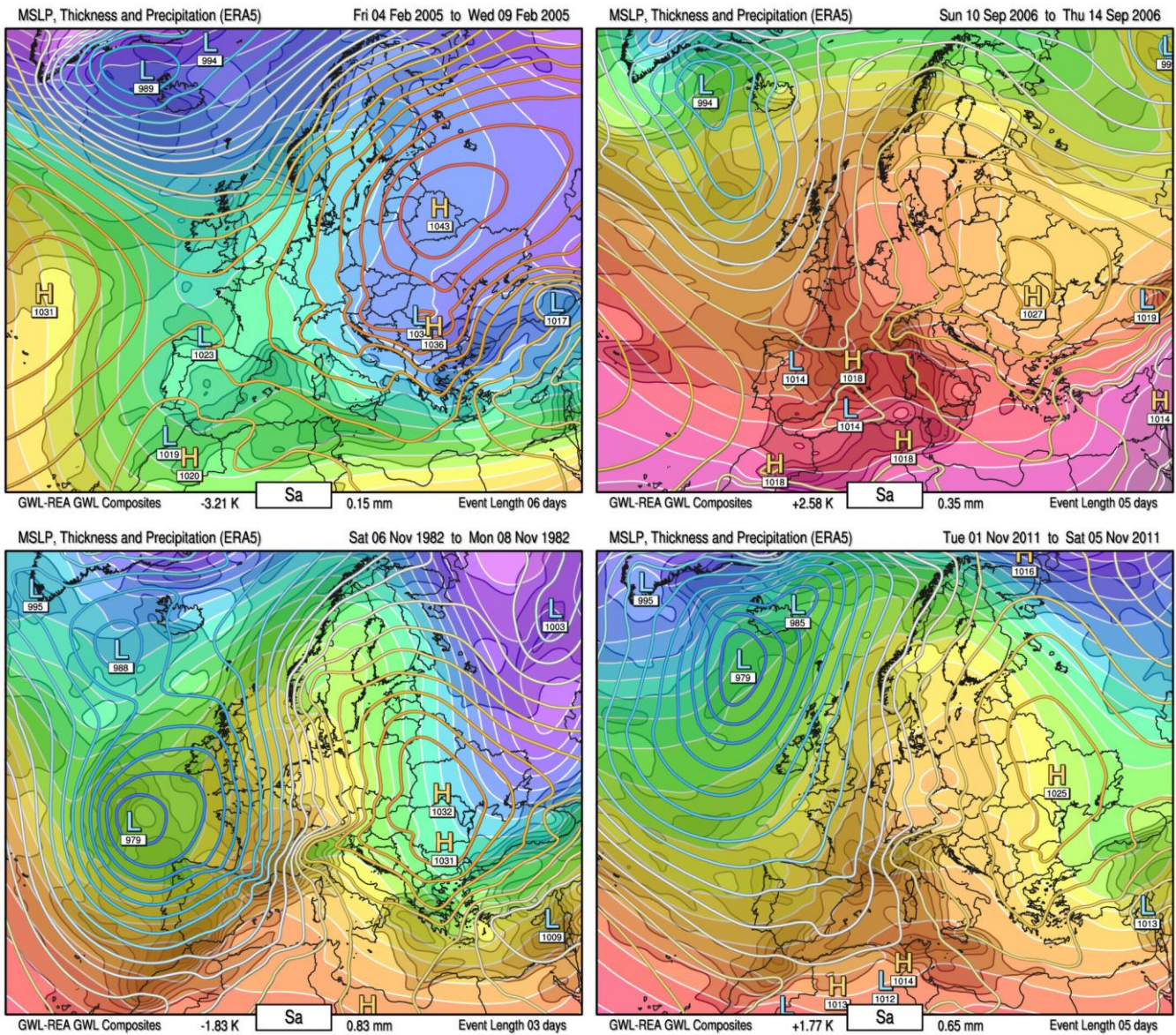


Fig. S37: Further composite synoptic charts for selected historical GWL events classified as "Sa". For details see start of Section 1.

S1.9.2 Sz – Südlage, zyklonal (Cyclonic Southerly)

In the cyclonic southerly type, **Sz**, the high-pressure zone lies further east, allowing a meridionally extensive frontal zone to encroach on CE. Very mild, moist air masses (xS) from the Mediterranean bring warm weather at all times of the year, while persistent heavy rain is common on the south side of the Alps, especially in the French Alps [20-25.11.2002; 22-25.5.2014]. Föhn conditions are common with this type on the north side of the Alps, leading to clear, warm weather there at times. Despite its “z” label, the weather is largely dry and very warm (in summer very hot) across the eastern half of CE. Further west, individual low-pressure systems may develop along the main frontal zone and move northwards, bringing widespread and sometimes thundery precipitation there.

In some southerly flow cases, more often in spring or autumn, a dome of very warm cT air from the Sahara can be advected north into CE on the edge of a low-pressure complex over Biscay, leading to exceptionally high temperatures over CE for a short time. Although the weather is often dry and clear, the surface pressure is relatively low and the main frontal zone lies not far to the west. This variant is sometimes classified as **Sz** [27-30.4.2012; 21-23.11.2016] and sometimes as **Sa** [17-21.10.2012], depending on how close the frontal zone is relative to CE.

Due to the long track over land masses before reaching CE and the rain shadow effect of the Alps, mean precipitation amounts are lower with **SEz** and **Sz** than with any of the other cyclonic GWLs, as shown in Table S2.

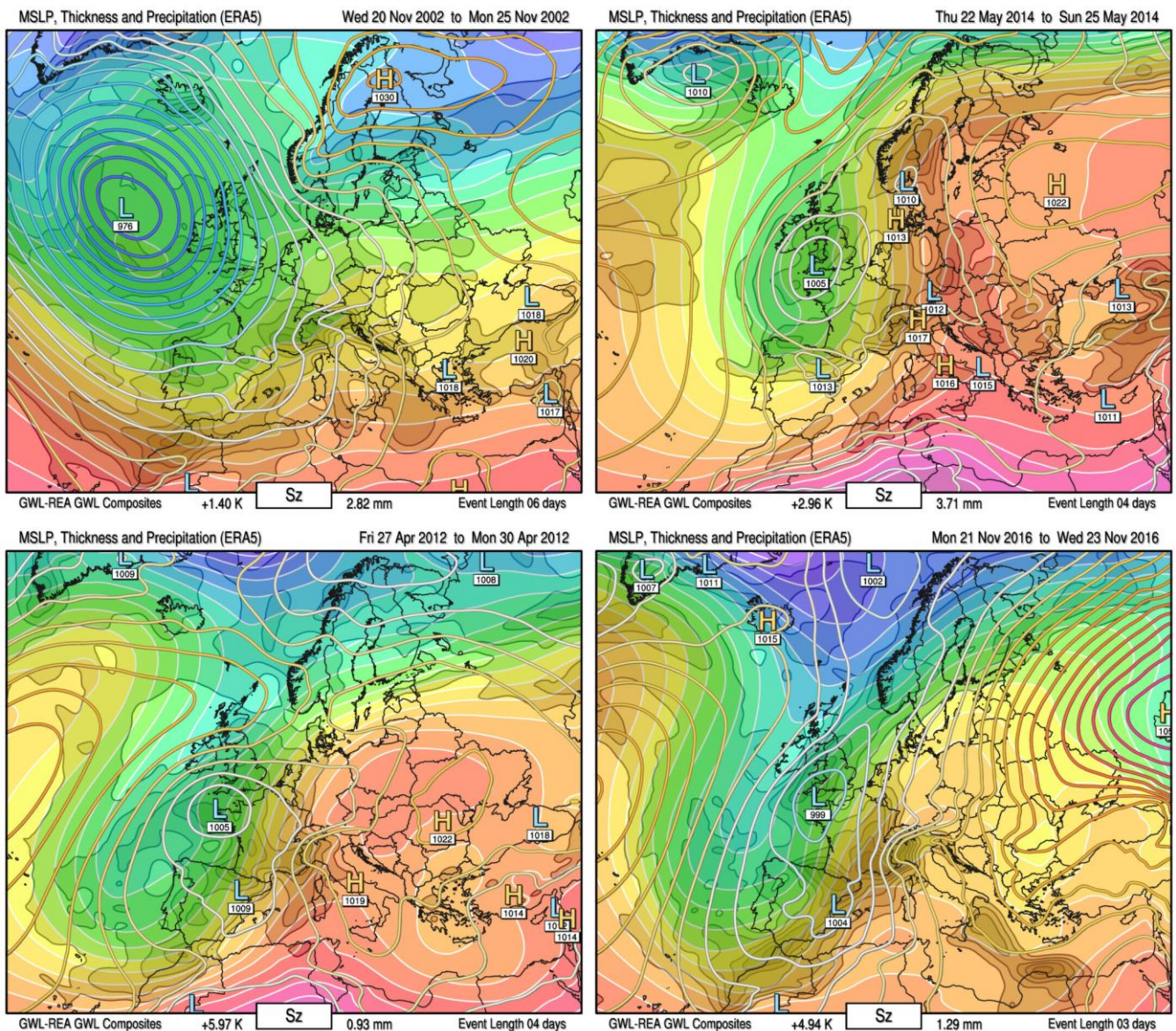


Fig. S38: Composite synoptic charts for selected historical GWL events classified as “Sz”. For details see start of Section 1.

The final two GWL types are characterised by having an upper trough over W Europe, either with a defining central low-pressure area (**TB**) or with an elongated frontal zone (**TrW**). In the case of **TB** the trough has a broader, long-wave character, whereas the **TrW** trough is more pronounced in a meridional sense, with a more substantial push of warm air northwards over E Europe upstream of a ridge further east.

595 The cyclonic type **TB** occurs when a quasi-circular low-pressure complex lies over or just to the west or south-west of the British Isles. A broad upper trough is also seen in the mid-troposphere, often centred over or very close to the British Isles. CE lies in a south-westerly (sometimes southerly) flow, which is often of relatively cold, returning polar maritime air [17-26.4.2012], although warm air from the central Mediterranean may be entrained into the flow on occasion over the eastern half of CE [14-17.10.2004; 12-17.9.2015]. The weather is unsettled and quite cloudy with frequent precipitation, especially south

600 of the Alps and near the Adriatic coast, with variable temperatures. In some cases, a south-easterly surface flow of cold *cP*_s air can persist across the north-eastern section of CE, with milder air further towards the south-west [28-30.1.1979; 29-31.12.1981].

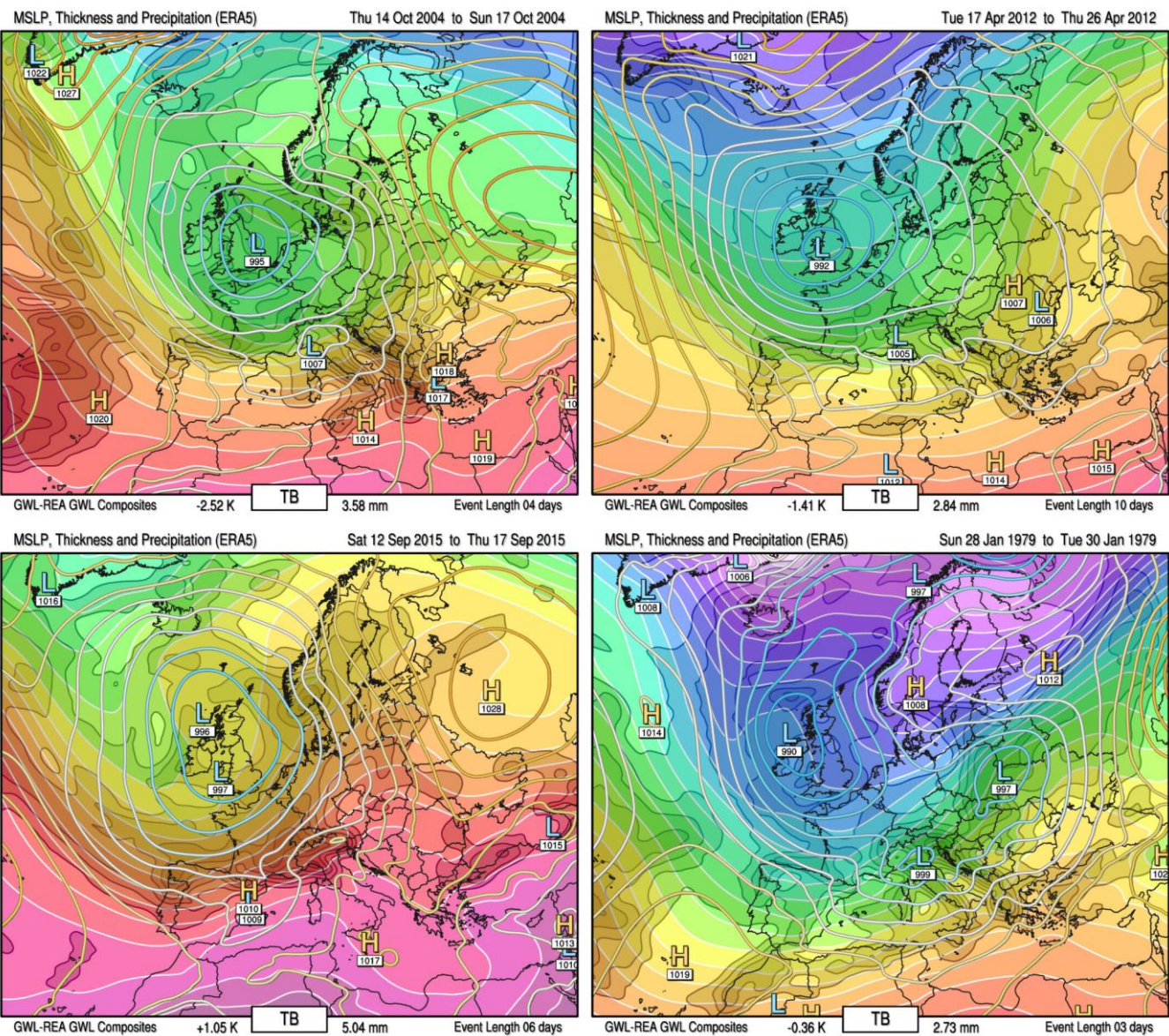


Fig. S39: Composite synoptic charts for selected historical GWL events classified as “TB”. For details see start of Section 1.

S1.9.4 TrW – Trog Westeuropa (Trough over Western Europe)

The cyclonic “Trough over Western Europe” type **TrW** is characterized by a meridional circulation pattern, with a pronounced upper trough over W Europe that often extends southwards into the Iberian Peninsula and a ridged pattern over E Europe. At the surface, the western edge of CE typically lies in a flow from between south-westerly and westerly of (returning) polar maritime air (mP_s) under the forward edge of the trough, while further east the flow may be closer to a southerly, with pre-frontal mild air (xS , mS). In detail, however, there can be considerable variability in the circulation characteristics, especially over western and southwestern Europe.

In winter, the weather over CE is generally mild, especially towards the east, with spells of frontal precipitation moving in from west. These can become quasi-stationary and persistent in some cases. Heavy precipitation is quite common on the southern side of the Alps, occasionally leading to river plain flooding. In summer, the weather is hot and humid in the east, but significantly cooler and fresher to the west. Severe, organised thunderstorms may break out along the frontal axis, while quasi-stationary regions of persistent rainfall can develop, with the Alpine regions most at risk.

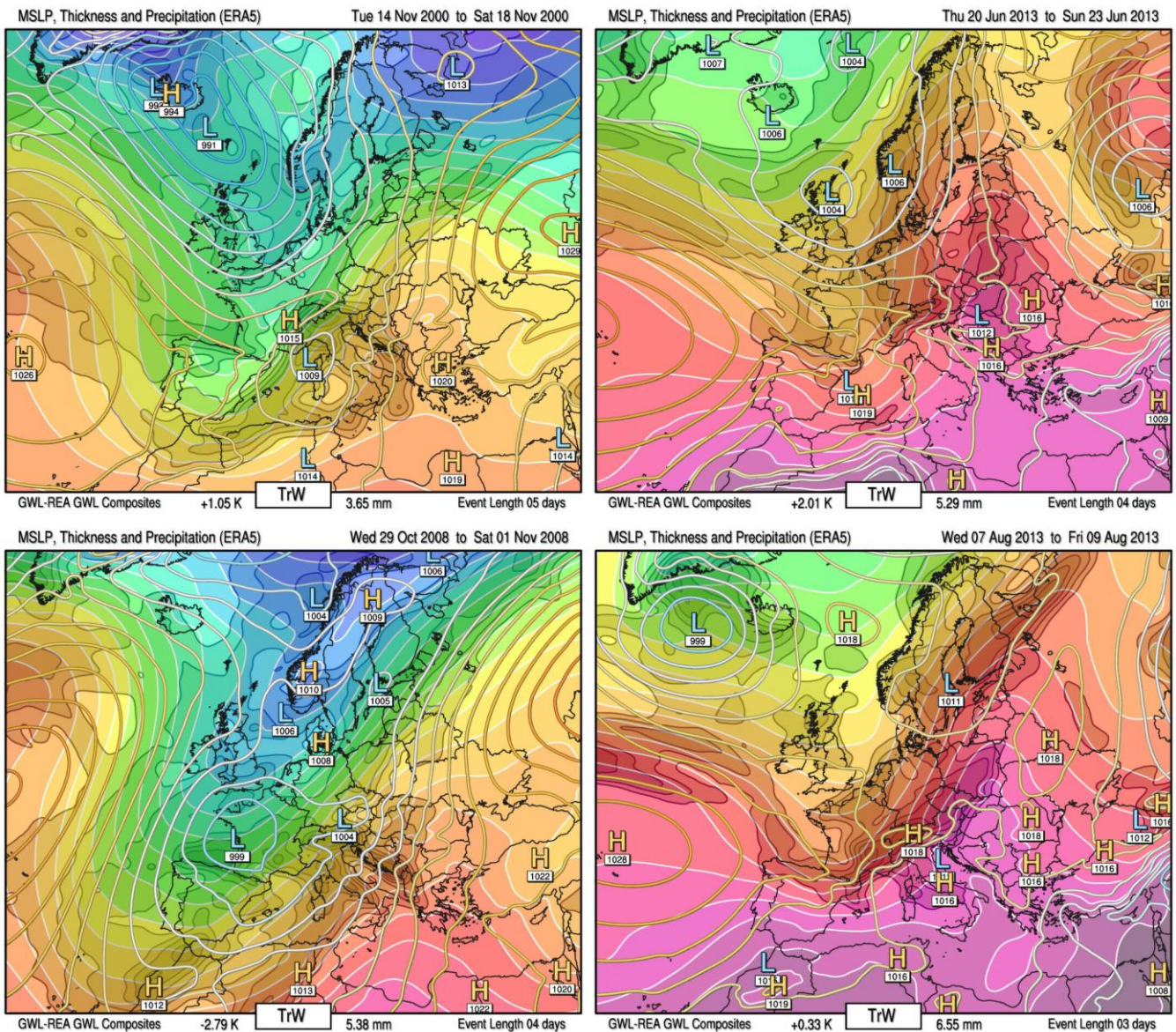


Fig. S40: Composite synoptic charts for selected historical GWL events classified as “TrW”. For details see start of Section 1.

There are two major **TrW** variants, which can be usefully separated. The key distinction between these relates to the extent of the meridionality of the surface flow pattern over W Europe. In the first **TrW** variant, a strongly cyclonic and broadly westerly flow develops over Western Europe. This surface flow is often diffluent, with a slowly progressing cold front and air mass

boundary over CE. To the east of this boundary, a southwesterly or southerly flow of warmer and moist air occurs. Although this type is somewhat similar to **SWz** at times, the upper flow is more meridional with a more substantial body of cold air pushing south-eastwards into the Iberian Peninsula and W. Mediterranean, where cyclogenesis in the lee of the Pyrenees can occur [14-18.11.2000; 20-23.6.2013; 23-26.2.2024]. The surface pattern of this **TrW** variant can also resemble that of the angular westerly type, **Ww**. However, the upper flow and the air mass structures are quite different to the east. While **Ww** features diffluent upper flow and cold air to the east, **TrW** features an upper ridge and warm air to the east.

The second **TrW** variant exhibits a strongly meridional surface pattern, often with northerly or northwesterly surface flow along the western edge of Europe. In some cases, surface high-pressure may extend across the western edge of Europe under the upper trough, the latter often extending well to the south, across the Iberian Peninsula and/or the western Mediterranean [29.10 – 1.11.2008; 7-9.8.2013].

In some cases, significant cyclogenesis can occur on the leading edge of the upper trough, sometimes resulting in severe weather with gales and/or very heavy precipitation and flooding, e. g. on the Balearics, Corsica and Sardinia, as well as adjacent regions in Spain, southern France and Italy. In some further cases the cyclogenesis over Iberia and the W Mediterranean becomes the dominant synoptic feature and the upper trough starts to cut-off. Across CE a col structure can sometimes develop for a time [24-26.3.2015; 21-23.9.2025].

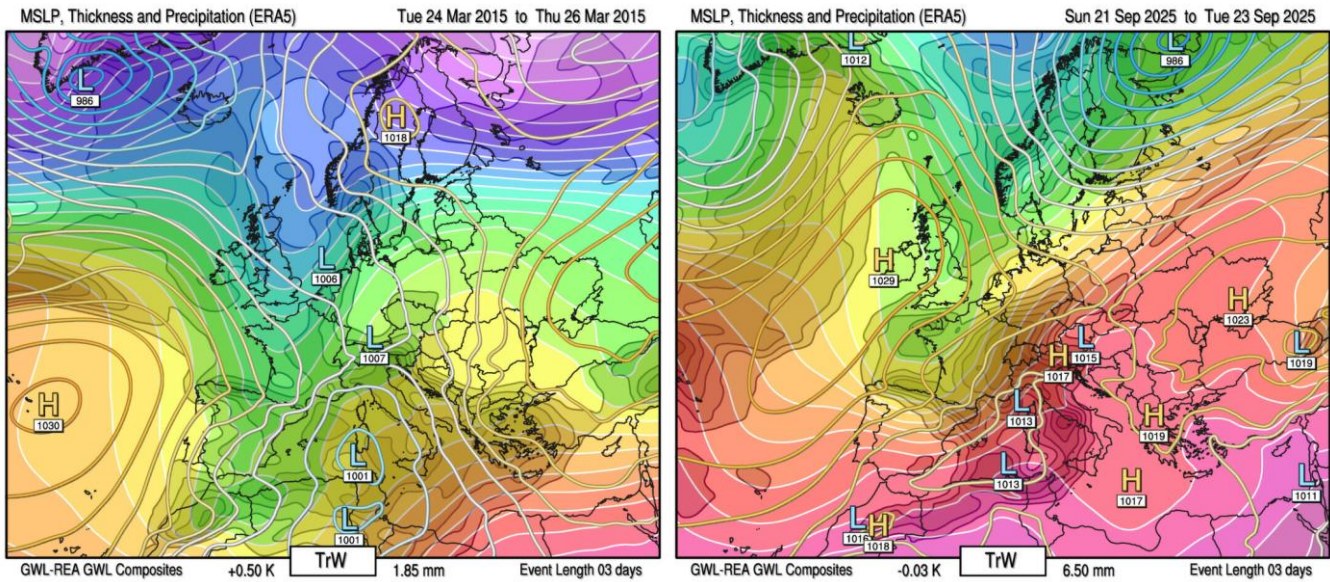


Fig. S41: Further composite charts for selected historical GWL events classified as “TrW”. For details see start of Section 1.

Section S2

Monthly mean frequencies of the GWLs show characteristic seasonal biases, such as an increase in flow directions between northerly and easterly in spring, or between southeasterly and southwesterly in autumn. These monsoon-like features are primarily caused by large-scale temperature contrasts between the European land mass and the adjacent sea areas to the north and west (e. g. Radinović and Ćurić, 2012). In spring the land areas warm up more quickly than the sea, resulting in an increased likelihood for a compensatory northerly flow into central Europe, while an increased likelihood of blocking to the north results in more frequent winds from the north-east and east. In the autumn, this tendency is reversed with the land masses, especially those to the east and north-east, cooling quicker than the sea areas, resulting in a greater likelihood of continental blocking and outflowing compensatory flow from a broadly southerly direction. Further seasonal biases are well known, such as the tendency for zonal westerly flow to occur more frequently during the mid- to late summer with warm and settled weather to the south, while frequent Atlantic frontal systems affect areas further north.

These characteristic biases strongly suggest that GWL frequencies could be used meaningfully to define “natural” synoptic seasons in which the traditional 3-calendar-month definitions of winter, spring, summer and autumn could be modified if necessary. Natural synoptic seasons are then the four seasons whose start and end dates are shifted to maximise differences in mean frequencies of the GWLs, i. e. pull out the optimum periods that are most different from each other.

An analysis of the low-pass filtered GWL data from GWL-REA over the entire available period, 1940-2025, has been carried out. The biases in the seasonal frequency distributions of the GWLs are maximised by shifting the seasonal transition dates by a consistent number of days in either direction, while keeping the seasons’ lengths the same as in the traditional calendar. After performing the calculations, the optimal seasons are found to start 24 days later than the traditional calendar-month definitions of the seasons (DJF, MAM, JJA, SON). Thus, according to these results, the natural first day of spring, based on GWL frequencies, is the 25th March, the first day of summer the 25th June, the first day of autumn the 25th September and the first day of winter the 25th December.

These natural transition dates of the seasons are remarkably close to the solar solstices and equinoxes, respectively, which are traditionally considered in popular culture to be the starting point of the seasons. This result also appears to be quite robust when subsets of the GWL series are taken, with no apparent trend. The seasonal mean frequencies of the low-pass GWL series, corresponding to these natural seasons, for the entire series 1940 to 2025, are shown in Table S4.

The results also fit well to the concept of weather singularities in folklore, i. e. frequently recurring weather biases at certain specific times of the year, such as cold or warm spells or wet or dry spells. While such events capture the public’s imagination, they are found to have been less consistent or frequent than is popularly believed, when checked against occurrences of GWLs and their cold or warm subtypes during the last 75 years. In spring, for example, some cold, northerly outbreak periods have occurred in clusters between April and mid-June. These are an unnamed April cold spell that has most often occurred between 13th-15th April, the “Ice Saints” (German: *Eisheiligen*) cold spell most often during 13th-17th May and the Sheep’s Cold (German: *Schafskälte*) most often during 11th to 17th June. Not surprisingly, these periods all fall into the natural spring season, which has an enhanced frequency of northerly types.

Despite being regularly cited in popular media, analyses with GWL-REA show that such singularities are only barely detectable in the 1940-2025 catalogue. Of the above, the Ice Saints period appears to be entirely a myth that has no factual basis in terms of temperatures. However, there has been a wet cluster from 14th - 23rd May, representing a period of frequent unsettled weather that may give the impression of being “cold” due to lack of sunshine. The cold singularities in mid-April and mid-June have been somewhat stronger clusters, however, with cold weather almost 50% more common than warm weather in both cases.

Nevertheless, a detailed analysis of the GWL-REA catalogue clearly shows that such apparent singularities are not statistically significant. They occur due to random noise effects and would almost certainly shift to other calendar dates in the future, or if

685 analysed further into the past. However, within a typical human lifespan, this random noise can give the impression that certain types of weather are favoured on specific dates in the calendar. Hence, these ideas persist in folklore, despite long-term statistics disproving them.

Only the longer timescale monsoonal seasonal biases are statistically significant, such as the more frequent northerly types during spring, as mentioned above. The opposite southerly bias in early to mid-autumn, with more frequent continental 690 blocking highs, leads to characteristic dry spells. These are called *Altweibersommer* (Old Wives' Summers) in German-speaking regions, i. e. longer periods of fine, settled weather, which occur before more unsettled autumnal weather finally sets in. Such events have tended to cluster around 18th - 22nd September, 8th - 20th October and 25th - 31st October, but without significant temperature biases. Note that a frequently discussed pre-Christmas warm spell has also appeared as a cluster, primarily from 22nd - 24th December, marking the end of the natural autumn season, but even this is not statistically significant.

695 GWL-REA has been run provisionally on older historical data over the period 1851 to 1939 from the NOAA-CIRES 20CR v2c reanalysis dataset (Compo et al, 2011) and over the period 1900-1939 with the ERA-20C reanalysis dataset (Poli et al., 2016). These reanalyses assimilate surface observations only into general circulation models, which somewhat reduces their accuracy in capturing the synoptic circulation in comparison with ERA5. For example, some smaller-scale synoptic features are less well resolved, which causes a bias in the GWL classification. There are also some systematic biases in the input field 700 values that can also lead to biases in the AI precipitation estimates. When the GWL frequency distributions are compared with ERA5 over a common period (1940-2010), systematic biases are indeed seen initially. These can be corrected, however, by adjusting some of the parameters and thresholds to calibrate GWL-REA for the reanalysis data in question, allowing the resulting catalogue for earlier periods to be compared meaningfully to the recent ERA5 period.

The shift in the natural seasons during 1851-1939 with 20CR and during 1900-1939 with ERA-20C are identical to each other 705 and very similar to the later period with ERA5, but just slightly less pronounced: the natural seasons start on the 21st of the respective months in both cases. This suggests that the concept of natural synoptic seasons, which transition around the times of the solstices and equinoxes, is a very robust result and a natural phenomenon.

Turning to the question of analysing singularities, the period 1851 to 1939 also shows many apparent singularities. However, as expected, these bear little resemblance in their timing to those found for 1940-2025. Hence, such singularities should be 710 viewed as insignificant statistical quirks related to random noise. Curiously, the Sheep's Cold singularity is also present during 1851-1939 at exactly the same time in mid-June, but is still not a sufficiently strong feature to reach statistical significance.

Air Mass	Description, typical geographical origin
<i>cA</i>	Continental arctic air, Siberia / Arctic Russia
<i>xA</i>	Mixed arctic air, Northern Scandinavia
<i>mA</i>	Maritime arctic air, North Atlantic edge of Arctic Ocean
<i>cP</i>	Continental subpolar air, Western Russia
<i>xP</i>	Mixed subpolar air, Southern Scandinavia
<i>mP</i>	Maritime subpolar air, northern North Atlantic
<i>cP_s</i>	Warmed continental subpolar air, Eastern Europe
<i>mP_s</i>	Warmed or returning subpolar air, North Atlantic
<i>cS_p</i>	Mid-latitude, mild continental air, Eastern and Central Europe
<i>mS_p</i>	Mid-latitude, mild maritime air, North Atlantic
<i>cS</i>	Continental subtropical air, South-East Europe
<i>xS</i>	Mixed subtropical air, Southern Europe / Mediterranean
<i>mS</i>	Maritime subtropical air, North Atlantic
<i>cT</i>	Continental tropical air, North Africa
<i>mT</i>	Maritime tropical air, North Atlantic

Table S1: Air mass types affecting Central Europe and their descriptions

GWL		Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)	Year
01	Wa	0.9	1.0	1.2	0.9	1.0
02	Wz	4.6	4.4	4.4	4.3	4.4
03	Ws	4.6	4.5	4.4	5.0	4.7
04	Ww	4.8	4.8	4.8	4.7	4.8
05	SWa	0.8	1.0	1.0	0.8	0.8
06	SWz	3.6	3.5	4.2	3.9	3.8
07	NWa	1.0	0.8	1.1	0.9	1.0
08	NWz	4.8	4.5	4.3	4.5	4.6
09	HM	0.3	0.4	0.6	0.3	0.4
10	BMa	0.7	0.8	1.0	0.7	0.8
11	BMz	2.5	3.3	3.7	3.3	3.6
12	TM	3.1	4.5	6.2	5.1	5.0
13	Na	1.1	1.1	1.0	1.3	1.1
14	Nz	3.4	3.5	4.2	4.4	3.8
15	HNa	0.9	1.0	1.2	0.8	1.0
16	HNz	3.5	3.9	5.0	4.1	4.3
17	HB	0.9	0.8	1.1	0.8	0.9
18	TrM	3.2	4.1	5.4	4.1	4.3
19	NEa	0.7	0.9	1.0	0.9	0.9
20	NEz	2.7	3.6	5.1	4.5	4.1
21	HFa	0.6	0.8	0.8	0.7	0.7
22	HFz	3.4	3.7	4.9	3.9	4.1
23	HNFa	0.8	0.8	1.3	0.6	0.9
24	HNFz	2.4	3.2	4.4	3.5	3.4
25	SEa	0.5	0.6	1.0	0.5	0.5
26	SEz	2.5	3.0	4.4	3.7	3.3
27	Sa	0.6	0.7	1.0	0.6	0.7
28	Sz	3.0	3.0	4.1	3.1	3.3
29	TB	2.9	3.4	5.0	3.9	3.8
30	TrW	2.6	4.2	5.7	4.8	4.8

Table S2: Seasonal and areal mean daily precipitation over Germany and immediate surroundings during the period 1950 to 2025 for each GWL, based on ERA5 reanalyses of total precipitation (mm). Rows are coloured according to the cyclonicity of each GWL: sand – anticyclonic, aquamarine – cyclonic.

GWL		Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)	Year
01	Wa	6.2	2.9	2.8	6.1	4.5
02	Wz	9.9	6.2	12.1	9.8	9.5
03	Ws	3.6	2.2	0.5	1.7	2.0
04	Ww	5.0	3.4	2.3	2.5	3.3
05	SWa	7.8	3.7	2.9	8.3	5.7
06	SWz	5.3	3.4	2.5	5.9	4.3
07	NWa	2.2	3.1	4.8	3.9	3.5
08	NWz	9.8	4.4	4.3	4.6	5.7
09	HM	4.5	3.2	3.2	3.8	3.7
10	BMa	7.9	6.0	7.7	7.9	7.4
11	BMz	0.2	2.0	10.5	1.5	3.6
12	TM	0.5	2.9	1.5	1.5	1.6
13	Na	0.8	1.7	2.7	1.0	1.6
14	Nz	1.3	2.5	1.5	1.5	1.7
15	HNa	1.9	2.8	2.1	1.7	2.1
16	HNz	1.6	4.6	5.0	1.3	3.1
17	HB	3.1	3.8	1.5	2.6	2.8
18	TrM	3.7	3.6	4.9	4.0	4.1
19	NEa	1.5	2.9	3.5	0.8	2.2
20	NEz	1.2	2.7	2.7	0.9	1.9
21	HFa	3.3	3.2	2.4	2.1	2.8
22	HFz	1.9	3.2	3.6	2.2	2.7
23	HNFa	2.2	3.5	2.0	1.2	2.2
24	HNFz	1.1	3.1	1.8	1.5	1.9
25	SEa	5.6	4.7	0.9	5.5	4.2
26	SEz	0.9	2.6	0.6	1.9	1.5
27	Sa	4.2	3.5	1.5	6.2	3.9
28	Sz	0.4	1.8	1.7	2.1	1.5
29	TB	1.3	2.5	1.5	2.8	2.0
30	TrW	1.0	3.8	5.2	3.2	3.3

Table S3: Seasonal and annual frequency distributions of the GWL types in GWL-REA over the period 1940 to 2025 in percent, based on ERA5 reanalyses and using standard definitions of the four seasons.

GWL		Nat. Winter 25.12 - 24.3	Nat. Spring 25.3 - 24.6	Nat. Summer 25.6 - 24.9	Nat. Autumn 25.9 - 24.12	Year
01	Wa	5.7	2.1	4.4	5.9	4.5
02	Wz	9.4	6.7	12.2	9.7	9.5
03	Ws	3.9	1.3	0.6	2.3	2.0
04	Ww	4.5	2.9	2.5	3.3	3.3
05	SWa	6.7	2.7	3.9	9.4	5.7
06	SWz	4.8	3.1	3.1	6.1	4.3
07	NWa	2.6	3.0	5.0	3.3	3.5
08	NWz	9.3	3.2	4.3	6.3	5.7
09	HM	4.5	3.2	3.1	4.0	3.7
10	BMa	7.4	5.9	8.7	7.6	7.4
11	BMz	0.2	4.8	8.6	0.5	3.6
12	TM	0.4	3.3	1.2	1.4	1.6
13	Na	0.9	2.4	2.2	0.8	1.6
14	Nz	1.9	2.3	1.3	1.3	1.7
15	HNa	1.8	3.3	1.6	1.7	2.1
16	HNz	1.5	6.3	3.3	1.3	3.1
17	HB	3.8	2.8	1.8	2.7	2.8
18	TrM	3.1	4.4	4.4	4.2	4.1
19	NEa	1.7	3.3	3.0	0.8	2.2
20	NEz	1.2	3.4	2.1	0.9	1.9
21	HFa	4.2	2.2	2.9	1.8	2.8
22	HFz	2.0	3.4	3.4	2.1	2.7
23	HNFa	2.6	3.2	2.0	1.1	2.2
24	HNFz	1.4	3.4	1.4	1.3	1.9
25	SEa	5.9	3.1	1.8	5.9	4.2
26	SEz	1.6	2.2	0.9	1.2	1.5
27	Sa	4.7	2.7	2.0	6.1	3.9
28	Sz	0.3	2.2	1.4	2.1	1.5
29	TB	1.2	2.5	1.8	2.7	2.0
30	TrW	0.8	4.8	5.3	2.3	3.3

Table S4: Seasonal and annual frequency distributions of the GWL types in GWL-REA over the period 1940 to 2025 in percent, based on ERA5 reanalyses and using natural season definitions.

Section S4

The standard colour schemes for the GWLs and their groups (GWG, see James and Osterm ller, 2026) are detailed in Table S5. Anticyclonic types are given light, pastel colours beneath black text, while cyclonic types are given much darker colours beneath white text. The respective colour spectra have been spread out evenly and widely in terms of hue, in so far as possible, while maintaining a similar respective brightness level in most cases. The colour spectrum moves from greens (westerly flow) to blues (northerly) to violet (easterly) and yellow-orange / browns (southerly). The ordering of the colours follows the order of the GWLs in many cases, but also takes the group assignments into account. In this sense, the HB hue is located between Na and HNa, whereas its position in the GWL system falls between HNa and NEa.

GWL		HTML code	GWL-group		HTML code
01	Wa	#C7FDC7	01	AW	#C5FAC2
02	Wz	#287128	02	AS	#FFECC3
03	Ws	#174017	03	AN	#C7F7FA
04	Ww	#1F5139	04	AA	#FAFABD
05	SWa	#E7FFB7	05	AB	#E3DEFC
06	SWz	#4A6321	06	AE	#FFDCF3
07	NWa	#C2FCE1	07	ZW	#3A6A3A
08	NWz	#1E6363	08	ZS	#655839
09	HM	#FFFFFF	09	ZN	#386262
10	BMa	#FCF7C0	10	ZT	#555555
11	BMz	#5B5B28	11	ZR	#4E4E85
12	TM	#333333	12	ZE	#6F445F
13	Na	#BBF3F3			
14	Nz	#2B5681			
15	HNa	#D4D4FF			
16	HNz	#474791			
17	HB	#C6E1FD			
18	TrM	#2E2E5E			
19	NEa	#E5CDFF			
20	NEz	#5A377A			
21	HFa	#F8CAF8			
22	HFz	#793D79			
23	HNFa	#FFCFE8			
24	HNFz	#753556			
25	SEa	#FFD3D3			
26	SEz	#844141			
27	Sa	#FFE1C3			
28	Sz	#724D28			
29	TB	#4F321C			
30	TrW	#3D4113			

Table S5: Colour scheme used for displaying the GWLs and the GWL-groups in web-based tables and catalogues.

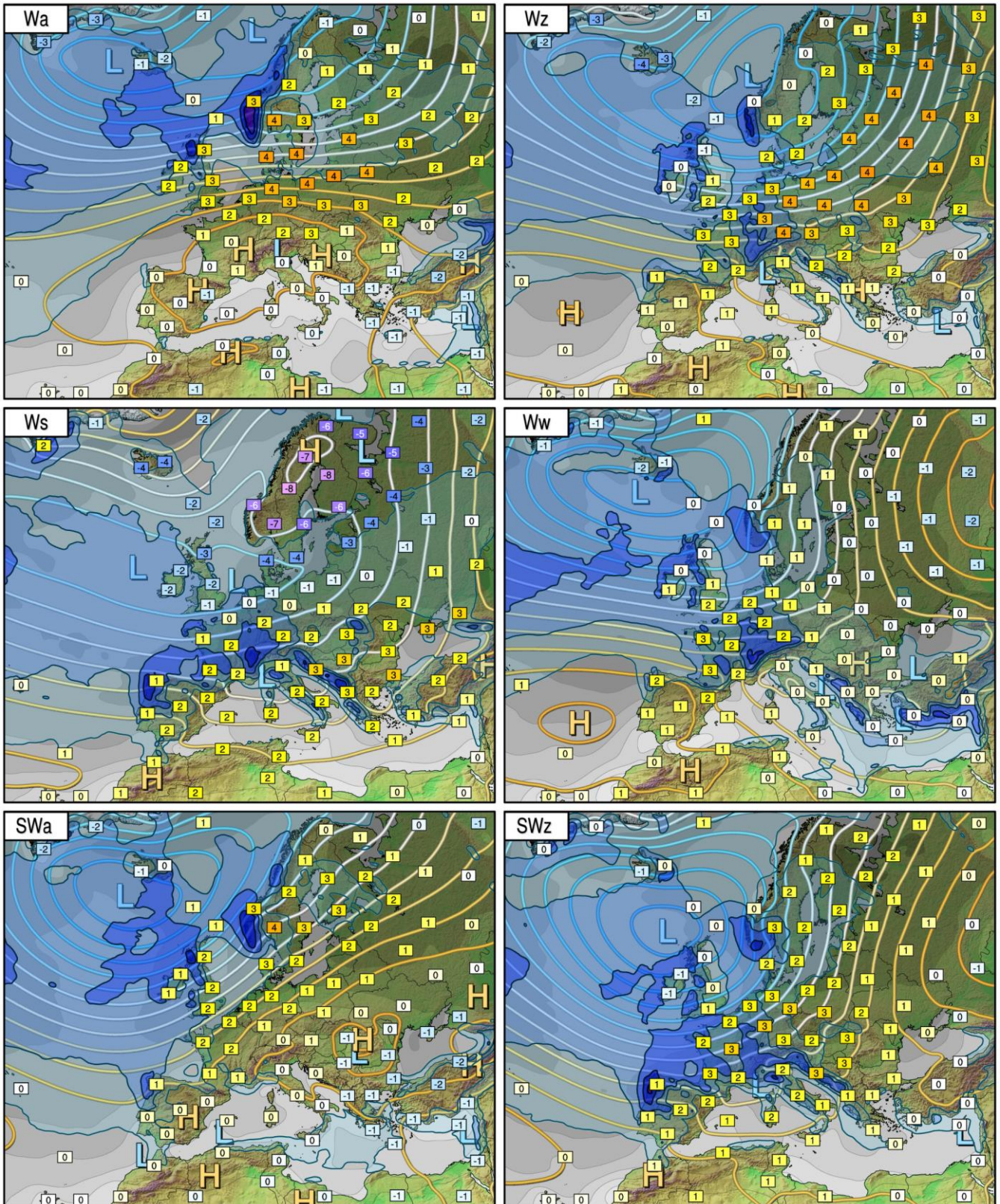


Fig. S42: Climatological GWL composites of surface weather during the WINTER half-year, based on ECMWF ERA5 reanalyses, 1950-2024, showing mean sea-level pressure (contours, 3 hPa interval), mean daily precipitation (blue colour-filled contours at 2, 4, 6, 10 and 16 mm/day), total cloud cover (grey colour-filled contours in background, 10% interval) and 2m-temperature anomalies at selected locations (K), for GWL nos. 1-6.

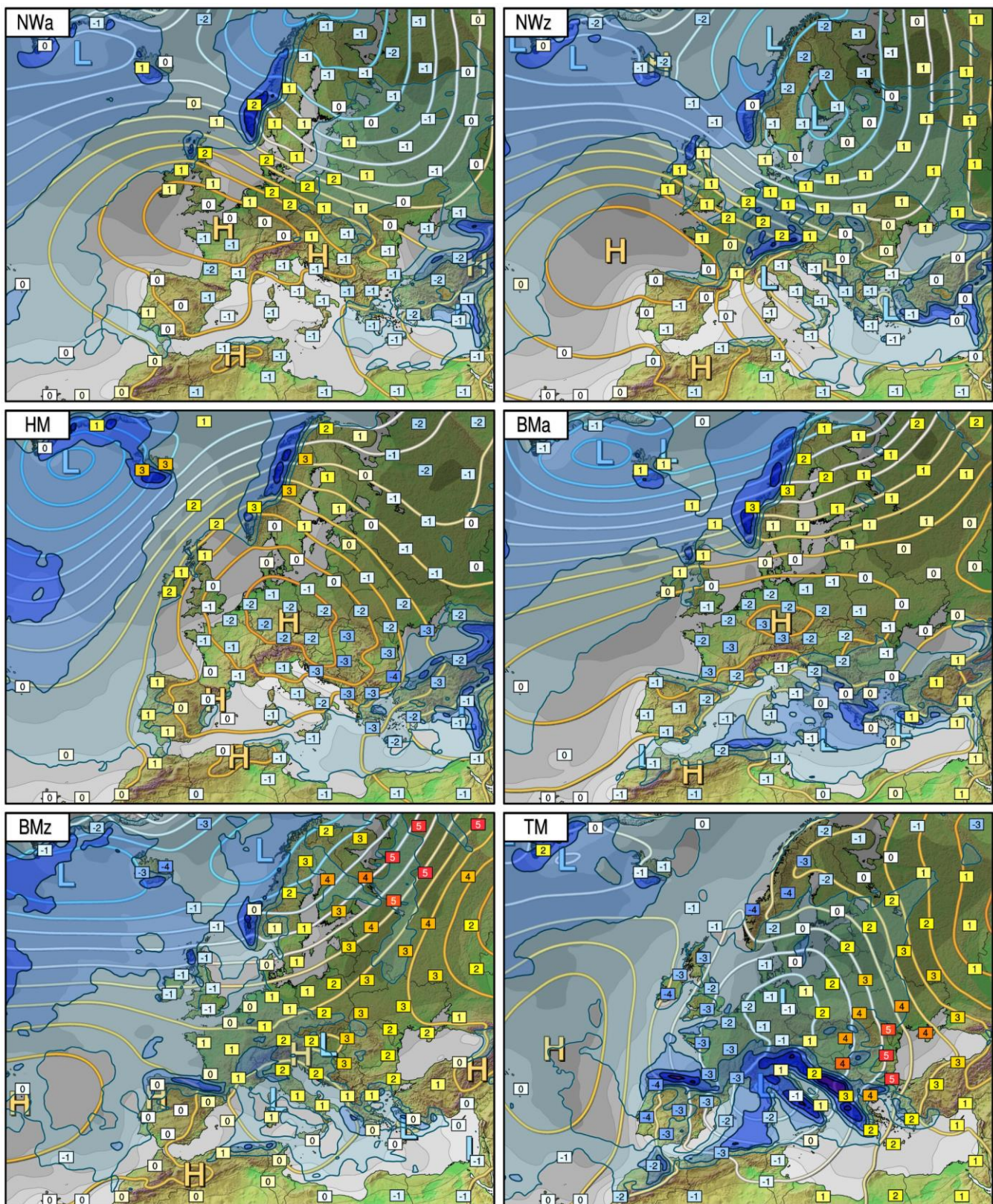


Fig. S43: Climatological GWL composites of surface weather during the WINTER half-year, based on ECMWF ERA5 reanalyses, 1950-2024, showing mean sea-level pressure (contours, 3 hPa interval), mean daily precipitation (blue colour-filled contours at 2, 4, 6, 10 and 16 mm/day), total cloud cover (grey colour-filled contours in background, 10% interval) and 2m-temperature anomalies at selected locations (K), for GWL nos. 7-12.

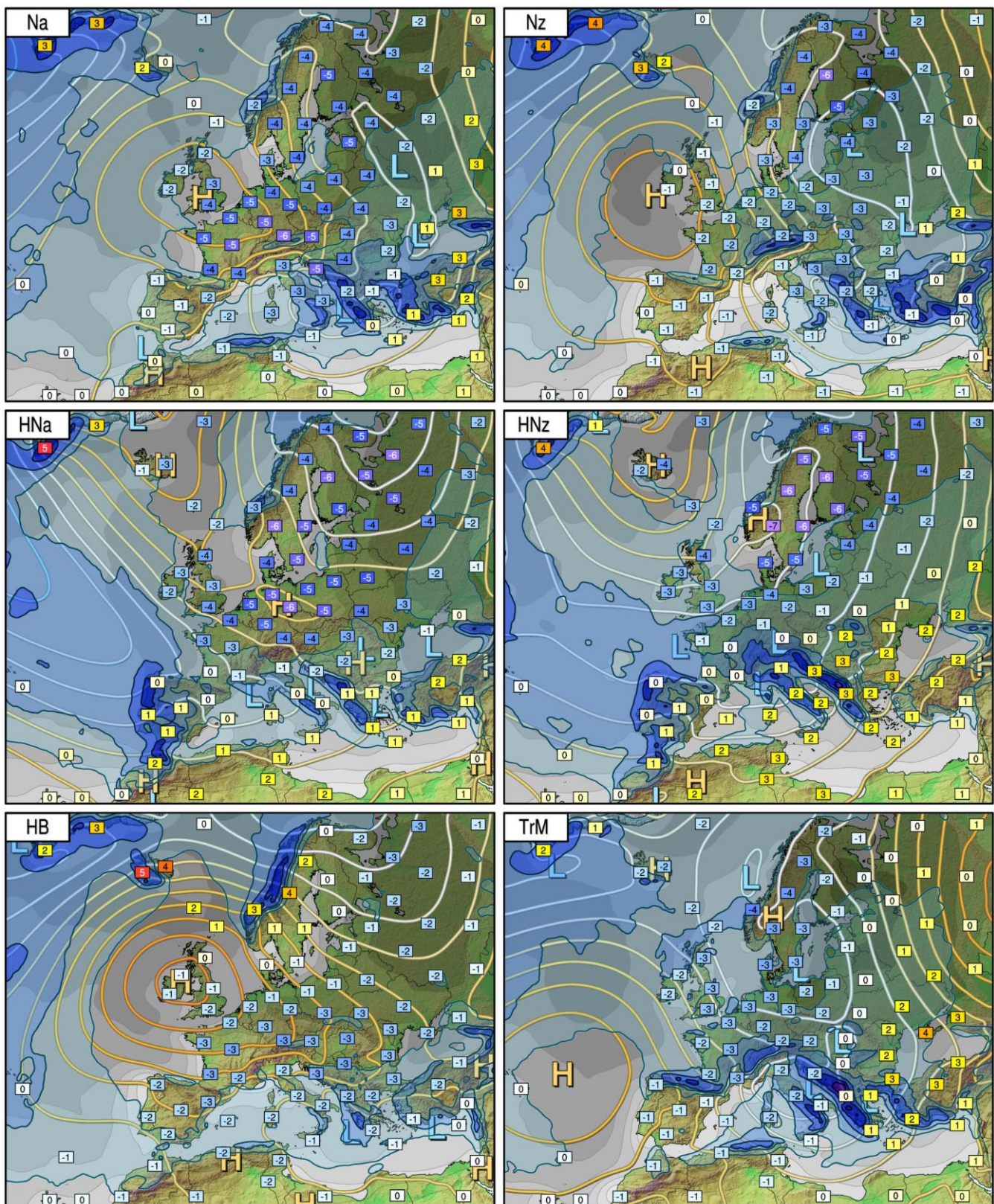


Fig. S44: Climatological GWL composites of surface weather during the WINTER half-year, based on ECMWF ERA5 reanalyses, 1950-2024, showing mean sea-level pressure (contours, 3 hPa interval), mean daily precipitation (blue colour-filled contours at 2, 4, 6, 10 and 16 mm/day), total cloud cover (grey colour-filled contours in background, 10% interval) and 2m-temperature anomalies at selected locations (K), for GWL nos. 13-18.

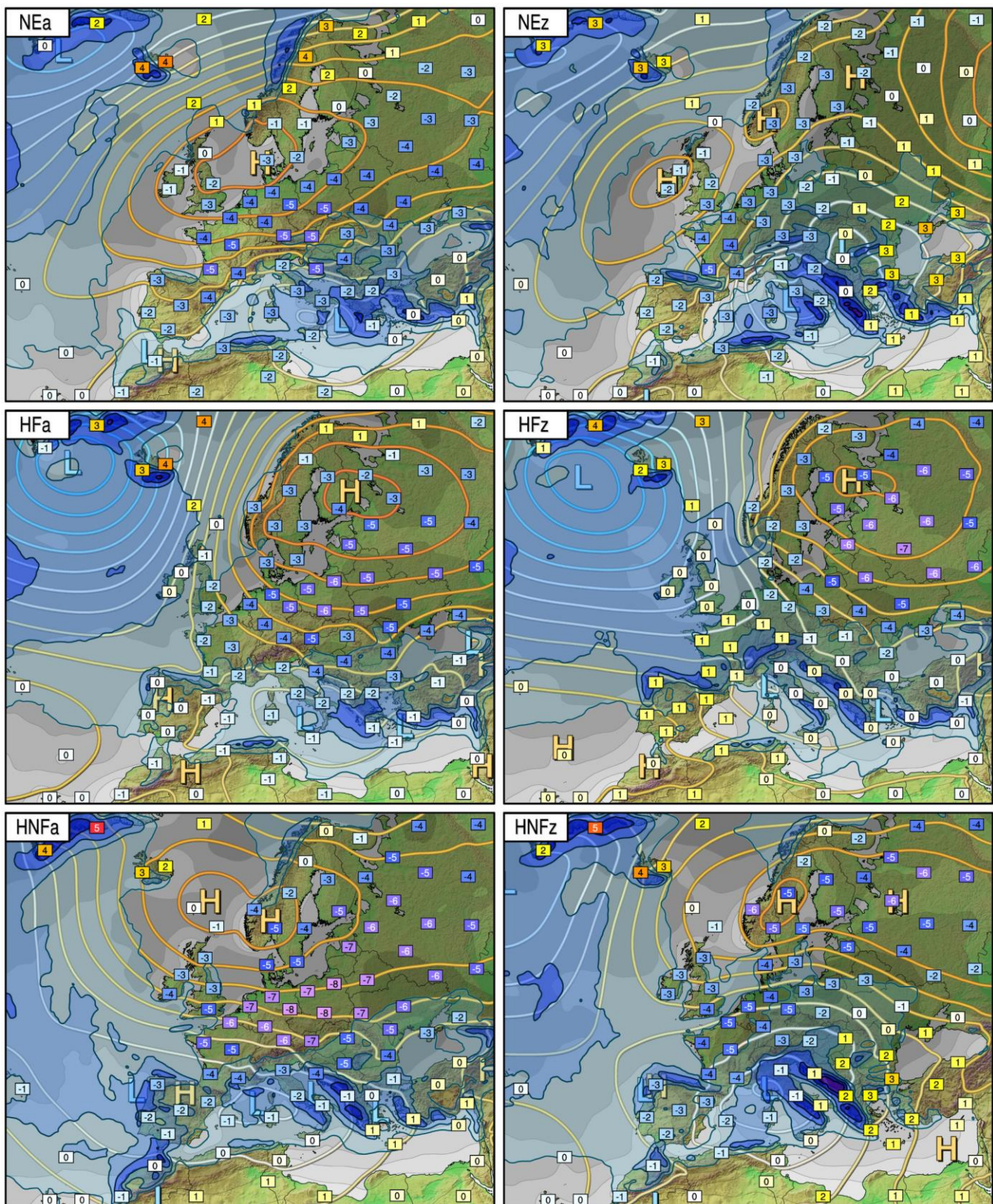


Fig. S45: Climatological GWL composites of surface weather during the WINTER half-year, based on ECMWF ERA5 reanalyses, 1950-2024, showing mean sea-level pressure (contours, 3 hPa interval), mean daily precipitation (blue colour-filled contours at 2, 4, 6, 10 and 16 mm/day), total cloud cover (grey colour-filled contours in background, 10% interval) and 2m-temperature anomalies at selected locations (K), for GWL nos. 19-24.

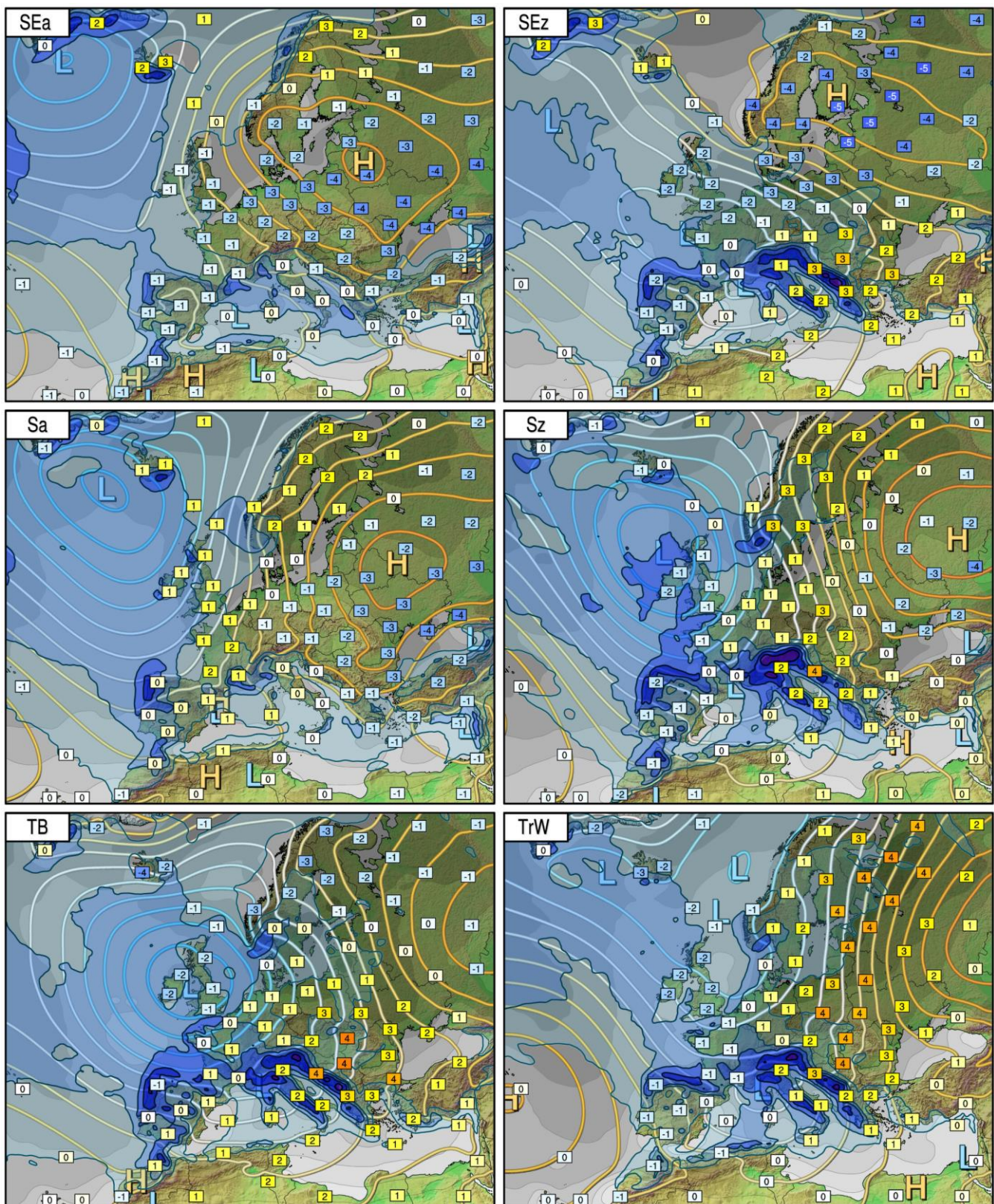


Fig. S46: Climatological GWL composites of surface weather during the WINTER half-year, based on ECMWF ERA5 reanalyses, 1950-2024, showing mean sea-level pressure (contours, 3 hPa interval), mean daily precipitation (blue colour-filled contours at 2, 4, 6, 10 and 16 mm/day), total cloud cover (grey colour-filled contours in background, 10% interval) and 2m-temperature anomalies at selected locations (K), for GWL nos. 25-30.

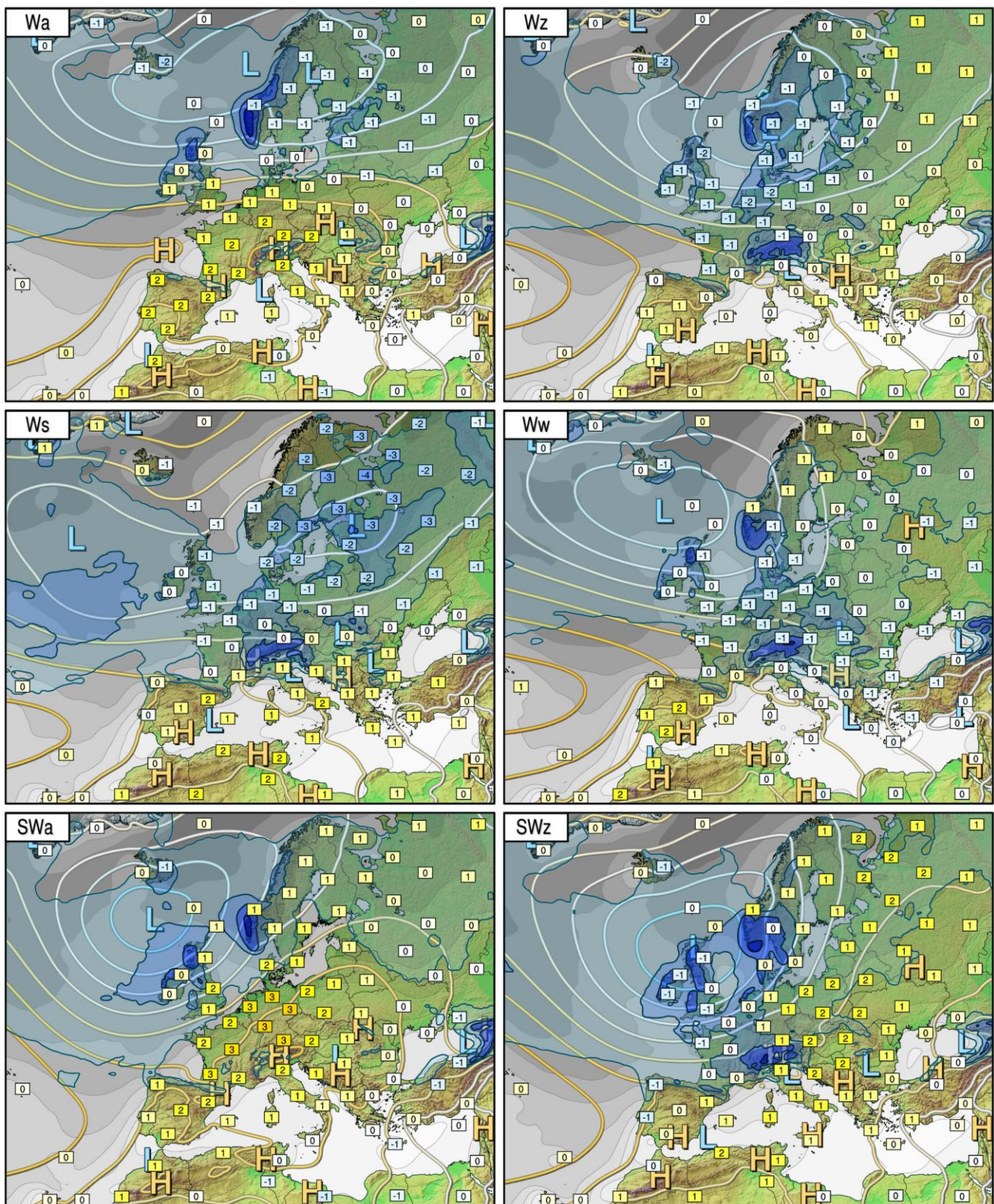


Fig. S47: Climatological GWL composites of surface weather during the SUMMER half-year, based on ECMWF ERA5 reanalyses, 1950-2024, showing mean sea-level pressure (contours, 3 hPa interval), mean daily precipitation (blue colour-filled contours at 2, 4, 6, 10 and 16 mm/day), total cloud cover (grey colour-filled contours in background, 10% interval) and 2m-temperature anomalies at selected locations (K), for GWL nos. 1-6.

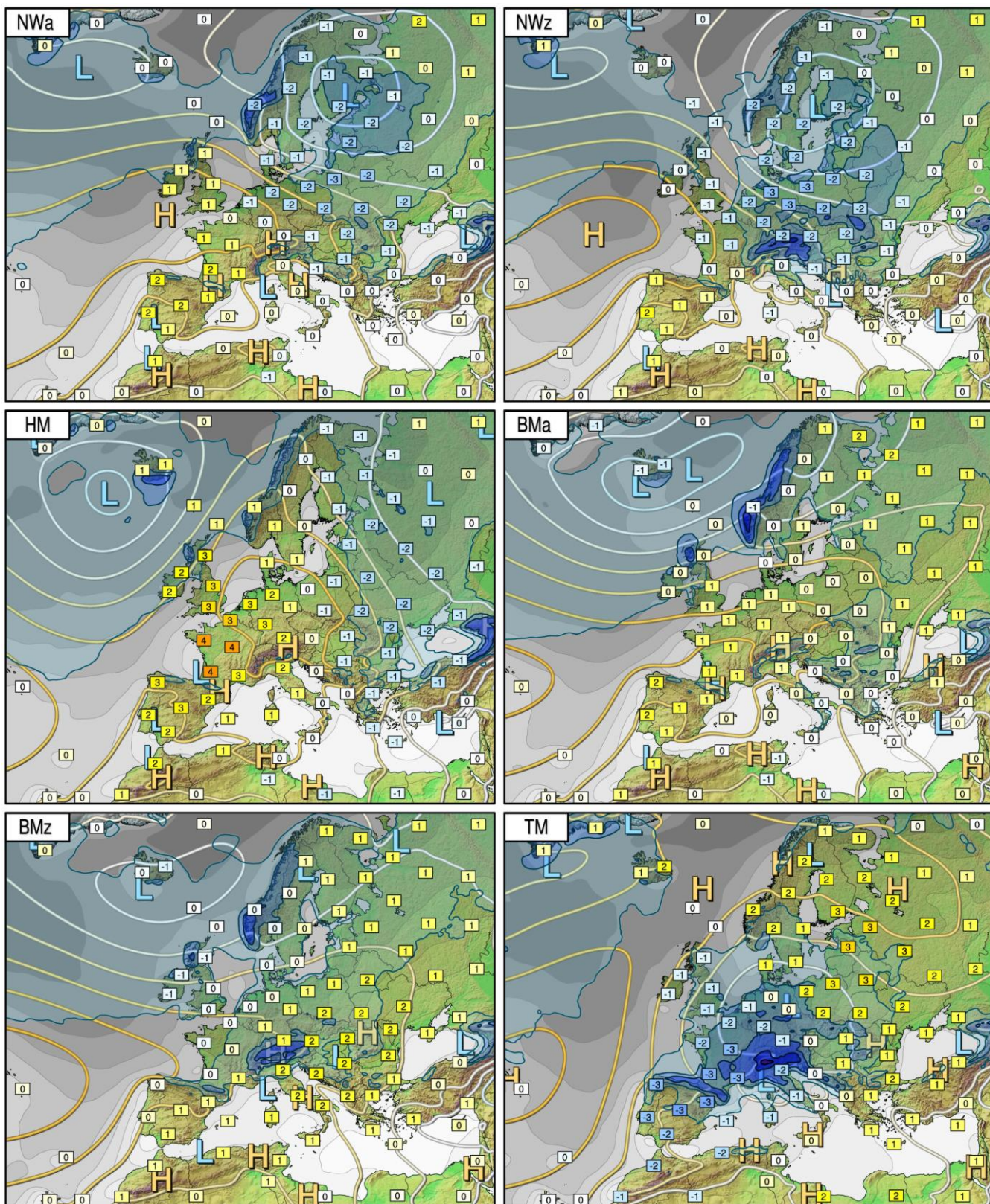


Fig. S48: Climatological GWL composites of surface weather during the SUMMER half-year, based on ECMWF ERA5 reanalyses, 1950-2024, showing mean sea-level pressure (contours, 3 hPa interval), mean daily precipitation (blue colour-filled contours at 2, 4, 6, 10 and 16 mm/day), total cloud cover (grey colour-filled contours in background, 10% interval) and 2m-temperature anomalies at selected locations (K), for GWL nos. 7-12.

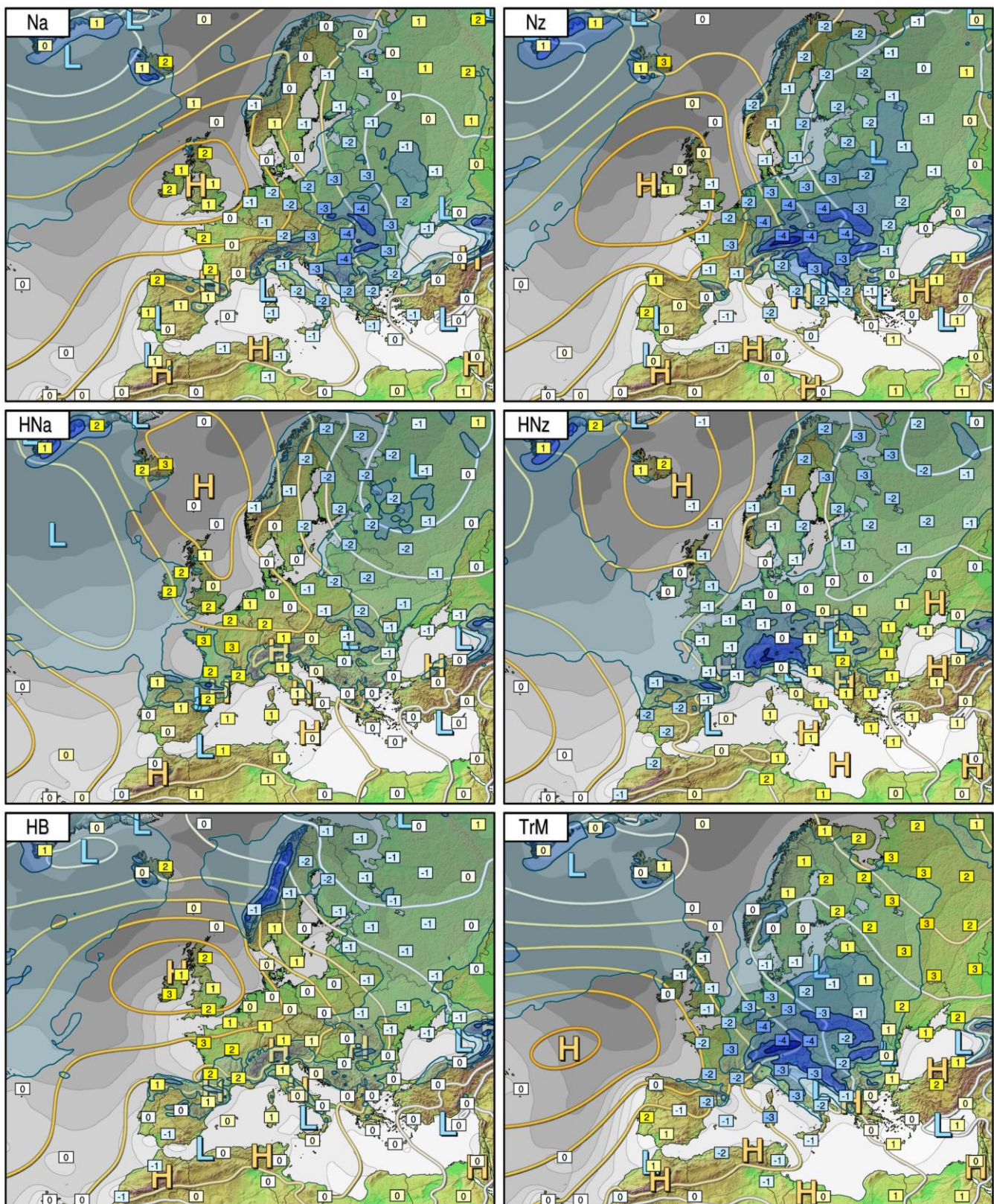


Fig. S49: Climatological GWL composites of surface weather during the SUMMER half-year, based on ECMWF ERA5 reanalyses, 1950-2024, showing mean sea-level pressure (contours, 3 hPa interval), mean daily precipitation (blue colour-filled contours at 2, 4, 6, 10 and 16 mm/day), total cloud cover (grey colour-filled contours in background, 10% interval) and 2m-temperature anomalies at selected locations (K), for GWL nos. 13-18.

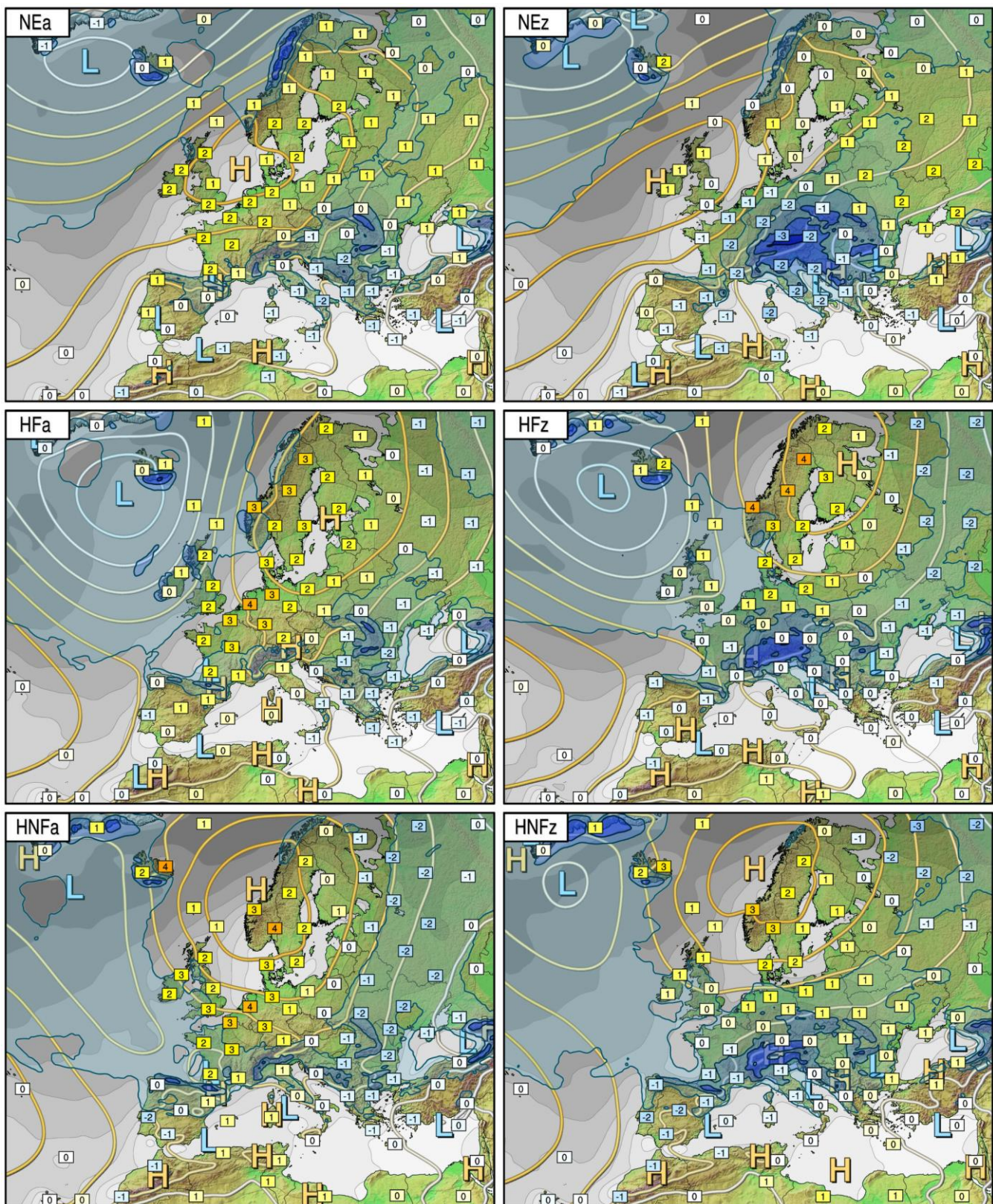


Fig. S50: Climatological GWL composites of surface weather during the SUMMER half-year, based on ECMWF ERA5 reanalyses, 1950-2024, showing mean sea-level pressure (contours, 3 hPa interval), mean daily precipitation (blue colour-filled contours at 2, 4, 6, 10 and 16 mm/day), total cloud cover (grey colour-filled contours in background, 10% interval) and 2m-temperature anomalies at selected locations (K), for GWL nos. 19-24.

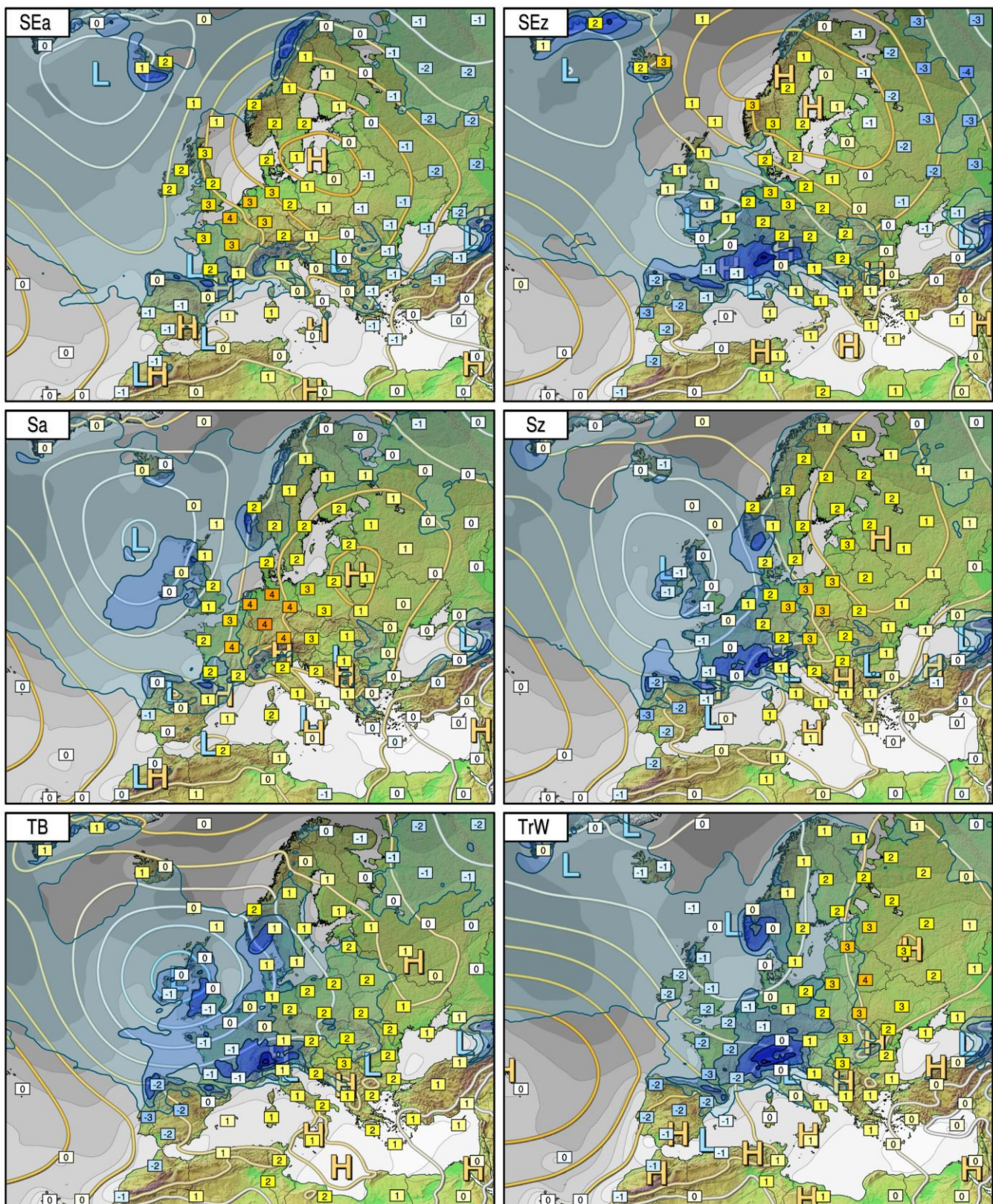


Fig. S51: Climatological GWL composites of surface weather during the SUMMER half-year, based on ECMWF ERA5 reanalyses, 1950-2024, showing mean sea-level pressure (contours, 3 hPa interval), mean daily precipitation (blue colour-filled contours at 2, 4, 6, 10 and 16 mm/day), total cloud cover (grey colour-filled contours in background, 10% interval) and 2m-temperature anomalies at selected locations (K), for GWL nos. 25-30.

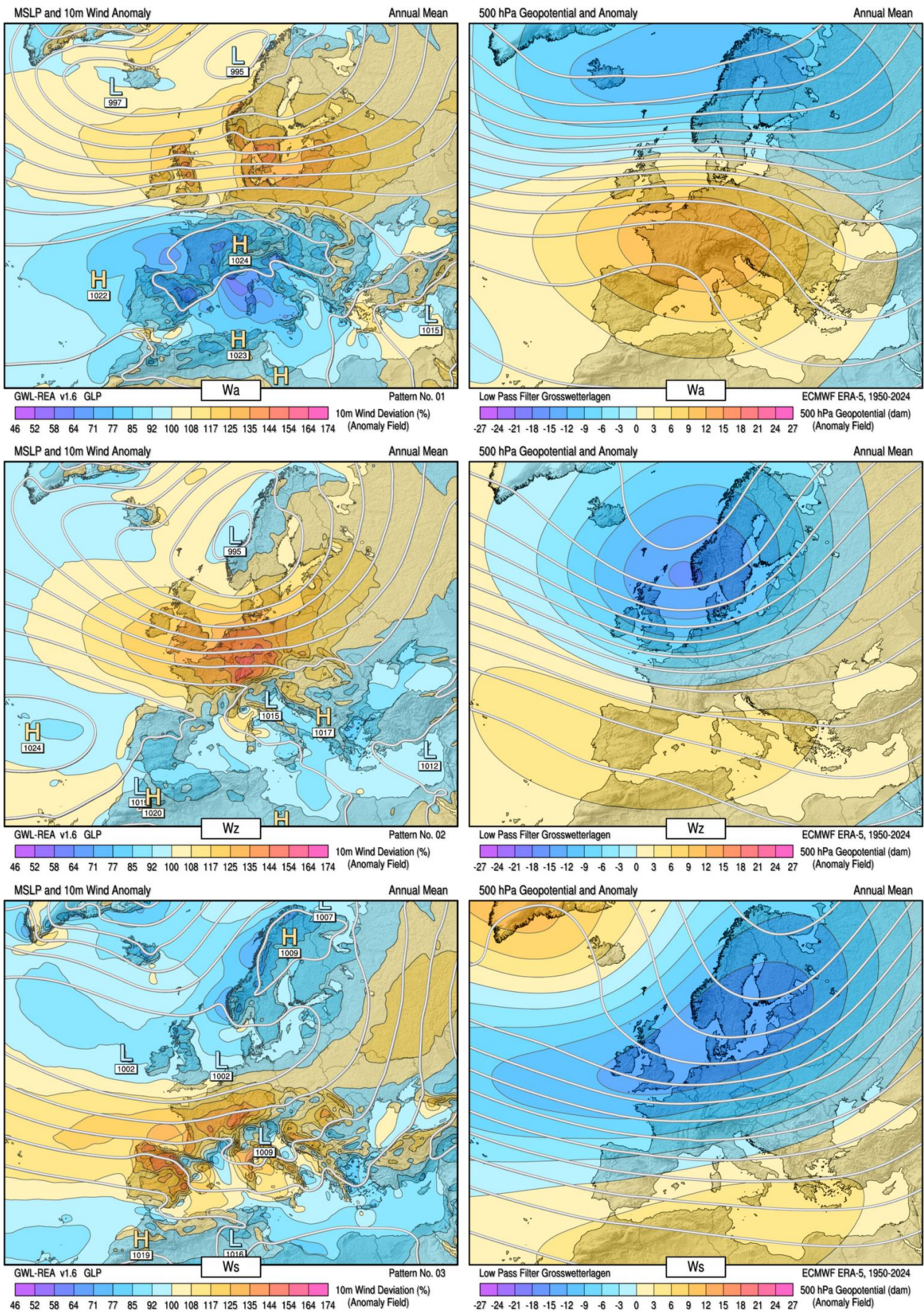


Fig. S52: Climatological GWL composites based on ECMWF ERA5 reanalyses, 1950-2024, for all times of the year, showing (left) mean sea-level pressure (contours, 3 hPa interval) and 10m-windspeed anomalies (colour-filled contours, %) and (right) 500 hPa geopotential height (interval 5 dam) and anomalies (colour-filled contours, interval 3 dam), for GWL nos. 1-3.

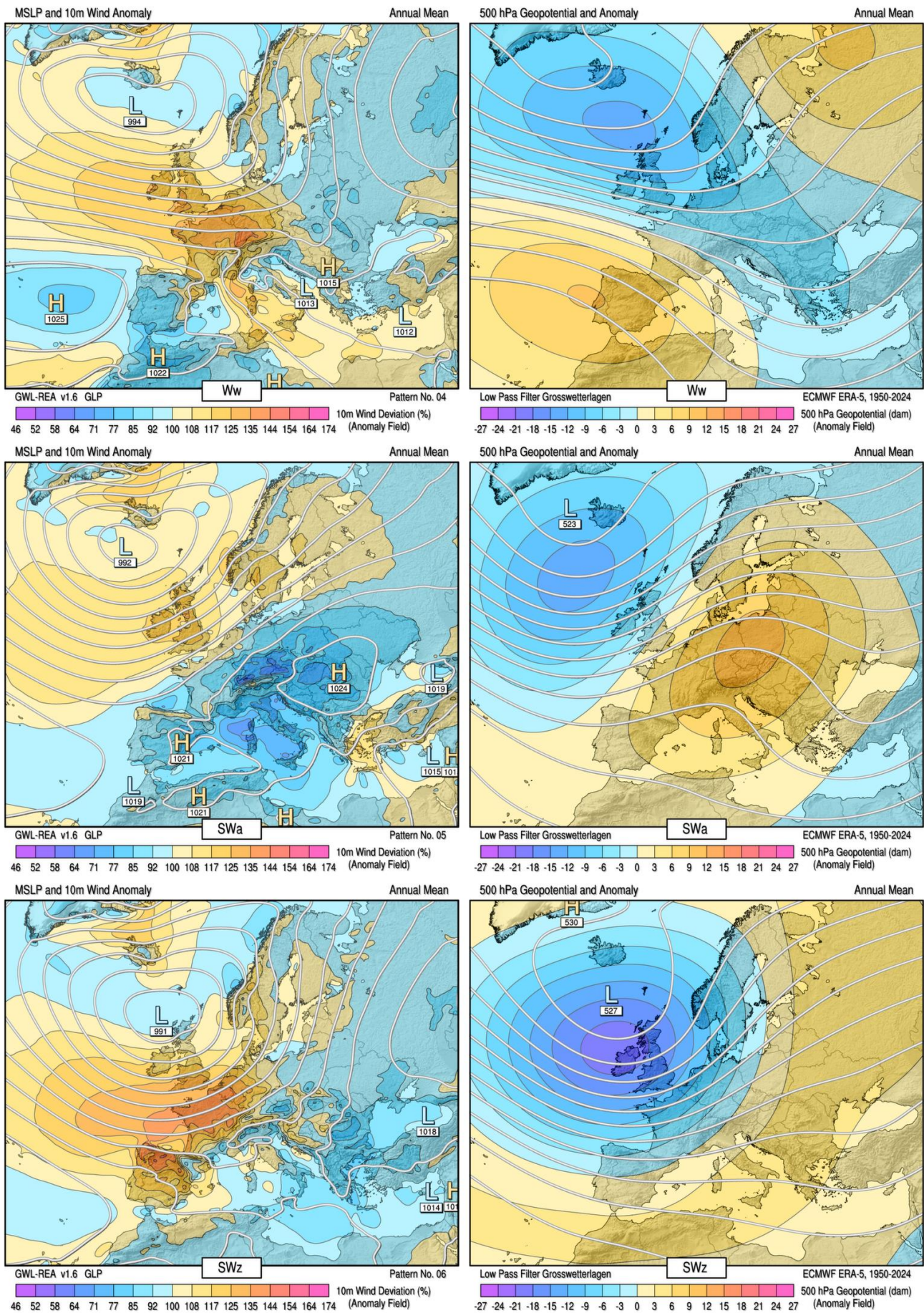


Fig. S53: Climatological GWL composites based on ECMWF ERA5 reanalyses, 1950-2024, for all times of the year, showing (left) mean sea-level pressure (contours, 3 hPa interval) and 10m-windspeed anomalies (colour-filled contours, %) and (right) 500 hPa geopotential height (interval 5 dam) and anomalies (colour-filled contours, interval 3 dam), for GWL nos. 4-6.

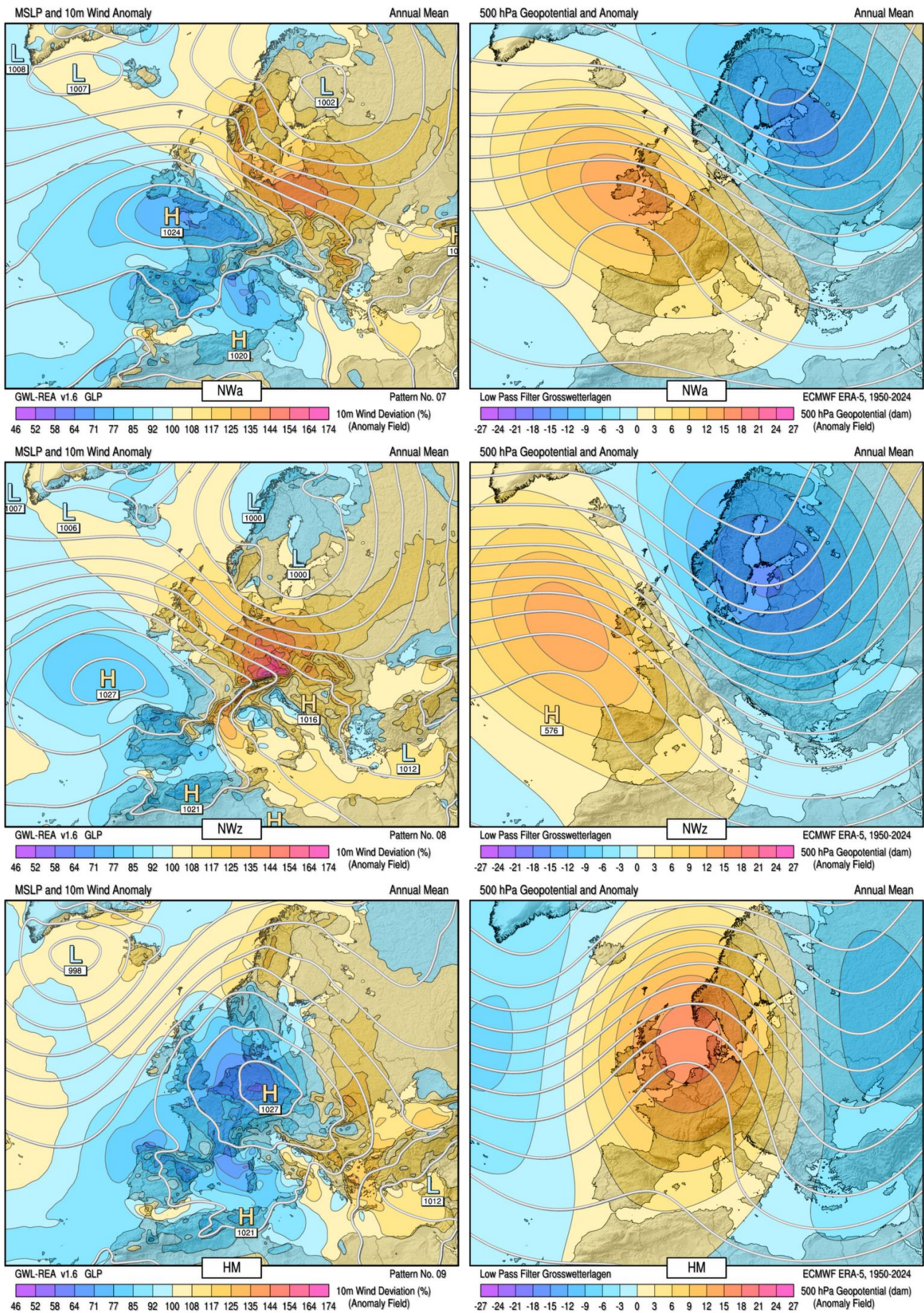


Fig. S54: Climatological GWL composites based on ECMWF ERA5 reanalyses, 1950-2024, for all times of the year, showing (left) mean sea-level pressure (contours, 3 hPa interval) and 10m-windspeed anomalies (colour-filled contours, %) and (right) 500 hPa geopotential height (interval 5 dam) and anomalies (colour-filled contours, interval 3 dam), for GWL nos. 7-9.

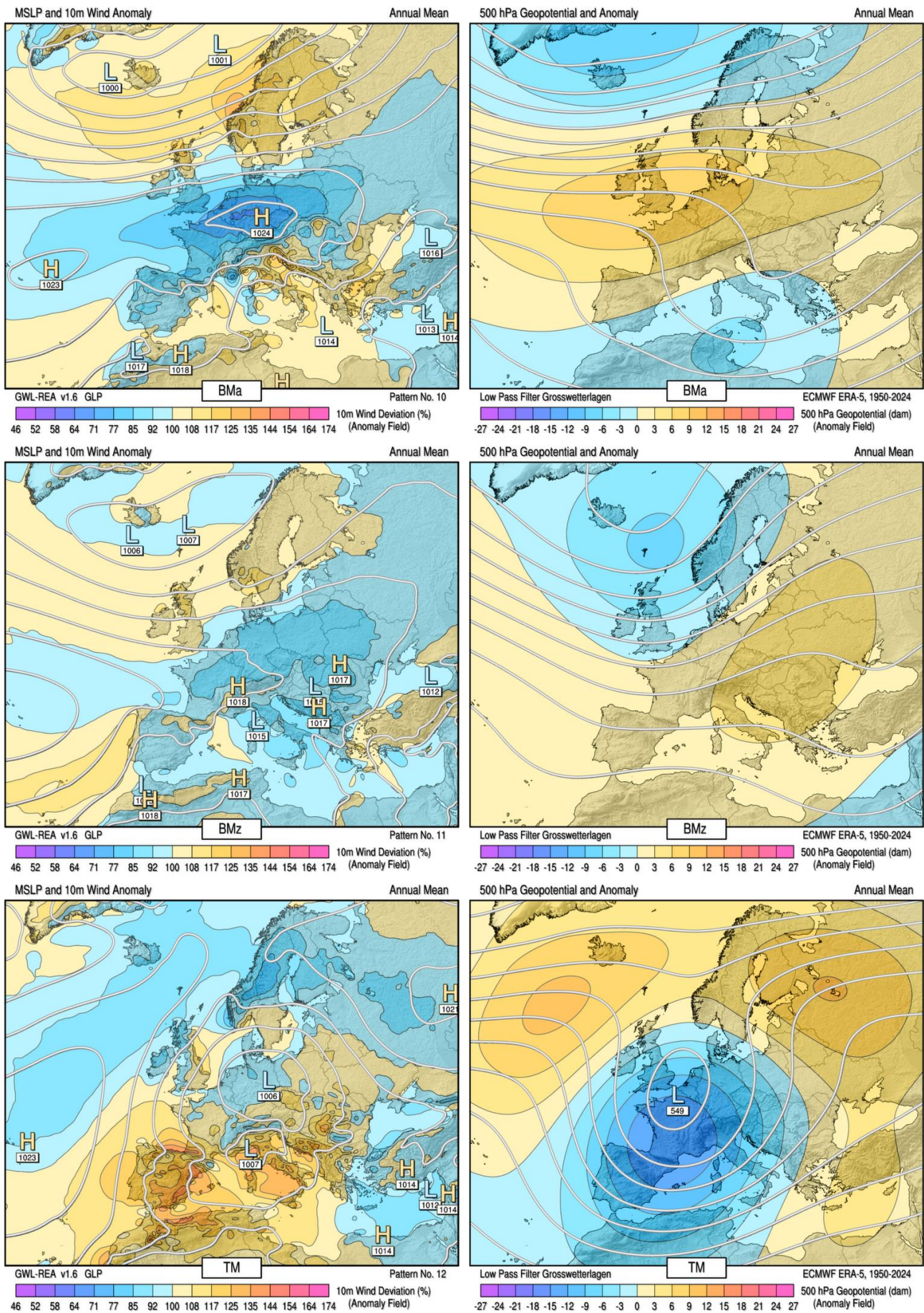


Fig. S55: Climatological GWL composites based on ECMWF ERA5 reanalyses, 1950-2024, for all times of the year, showing (left) mean sea-level pressure (contours, 3 hPa interval) and 10m-windspeed anomalies (colour-filled contours, %) and (right) 500 hPa geopotential height (interval 5 dam) and anomalies (colour-filled contours, interval 3 dam), for GWL nos. 10-12.

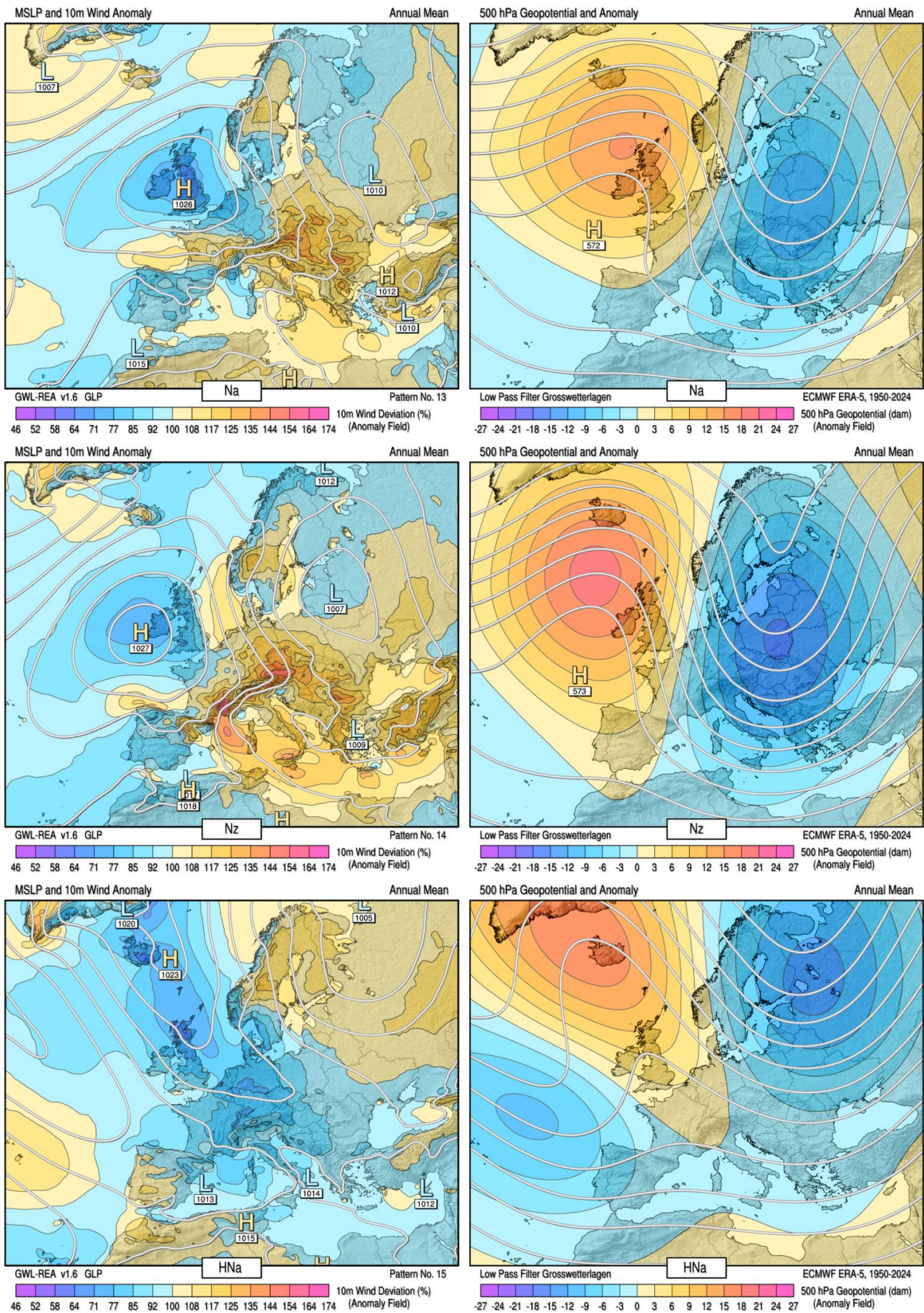


Fig. S56: Climatological GWL composites based on ECMWF ERA5 reanalyses, 1950-2024, for all times of the year, showing (left) mean sea-level pressure (contours, 3 hPa interval) and 10m-windspeed anomalies (colour-filled contours, %) and (right) 500 hPa geopotential height (interval 5 dam) and anomalies (colour-filled contours, interval 3 dam), for GWL nos. 13-15.

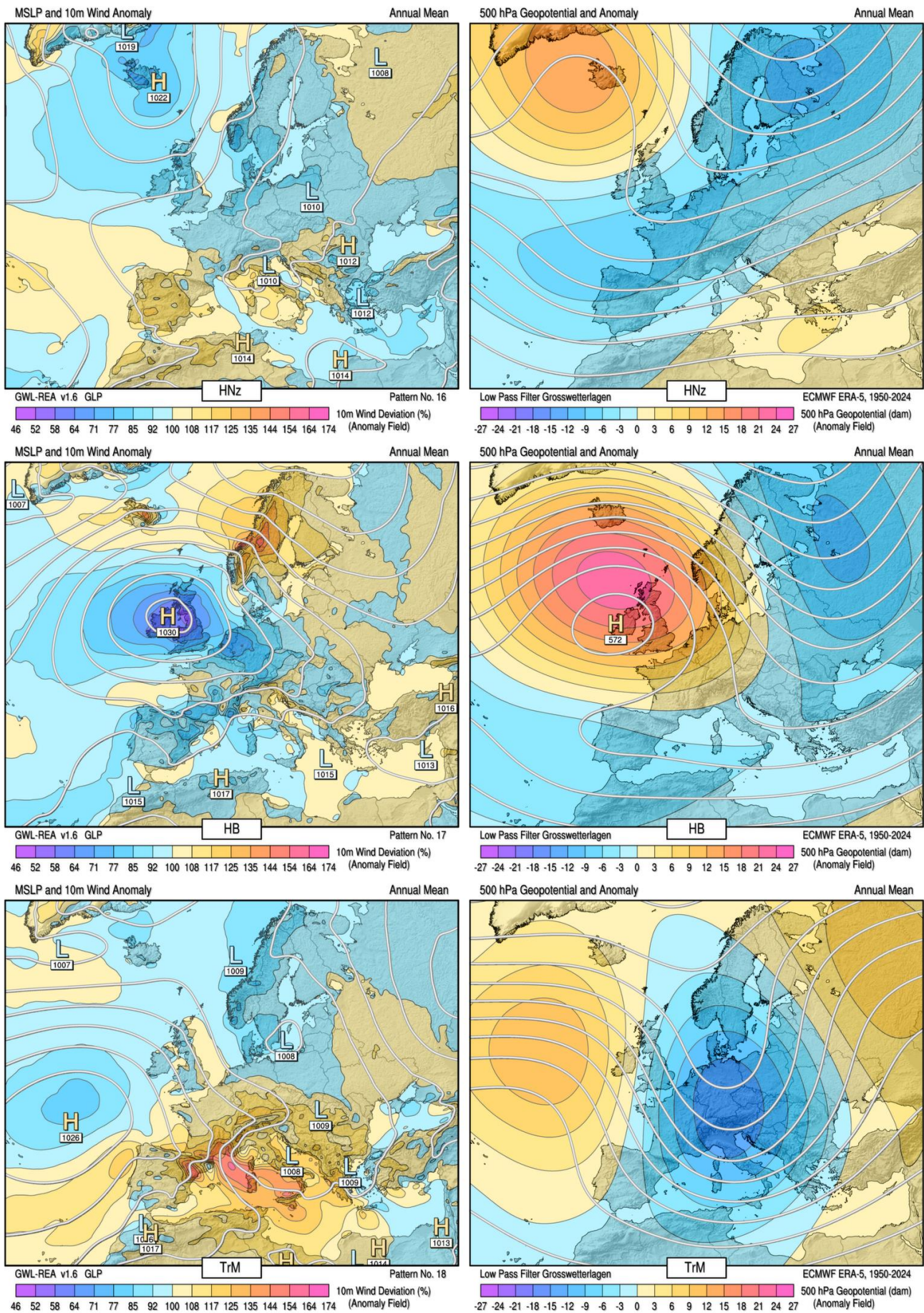


Fig. S57: Climatological GWL composites based on ECMWF ERA5 reanalyses, 1950-2024, for all times of the year, showing (left) mean sea-level pressure (contours, 3 hPa interval) and 10m-windspeed anomalies (colour-filled contours, %) and (right) 500 hPa geopotential height (interval 5 dam) and anomalies (colour-filled contours, interval 3 dam), for GWL nos. 16-18.

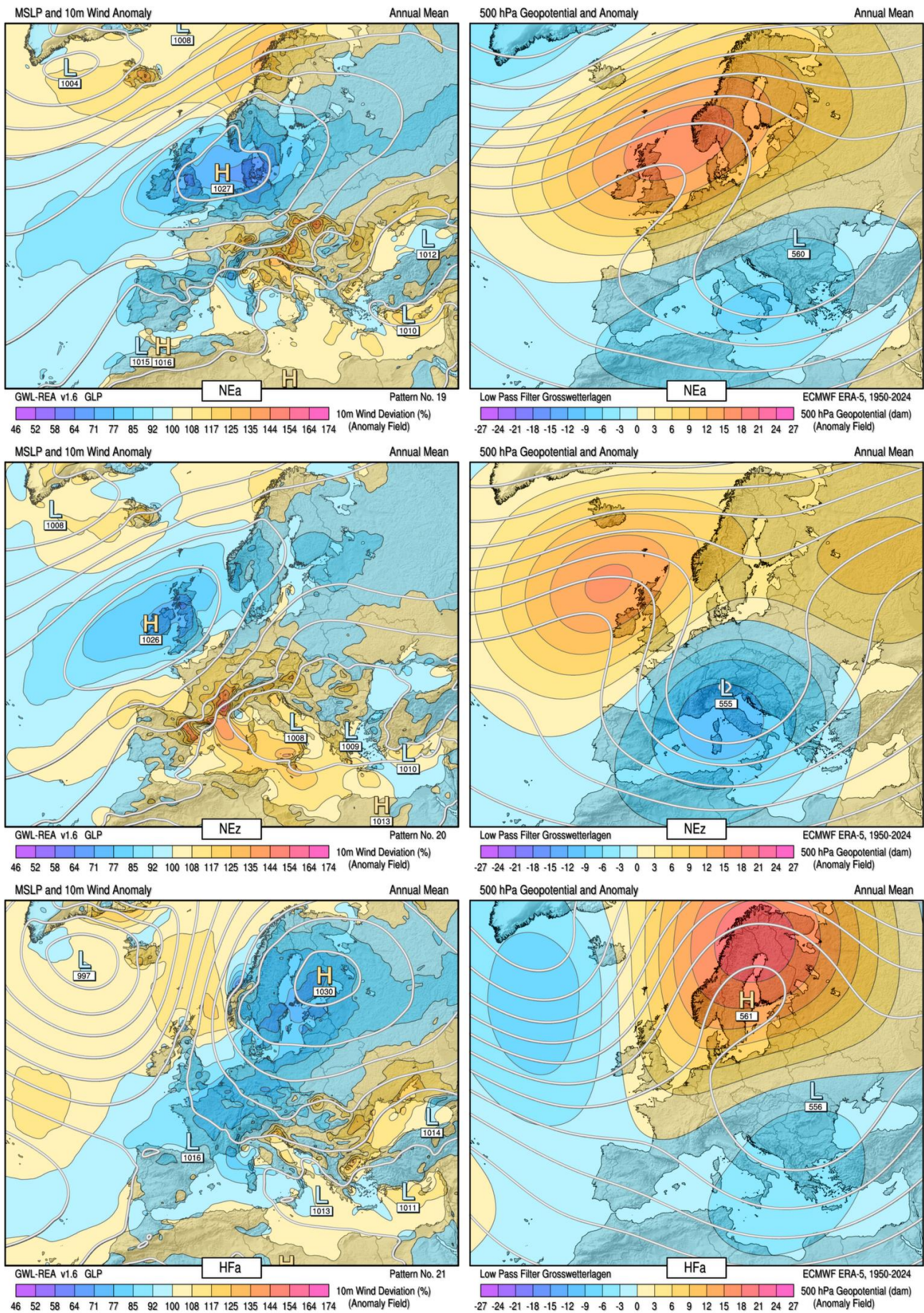


Fig. S58: Climatological GWL composites based on ECMWF ERA5 reanalyses, 1950-2024, for all times of the year, showing (left) mean sea-level pressure (contours, 3 hPa interval) and 10m-windspeed anomalies (colour-filled contours, %) and (right) 500 hPa geopotential height (interval 5 dam) and anomalies (colour-filled contours, interval 3 dam), for GWL nos. 19-21.

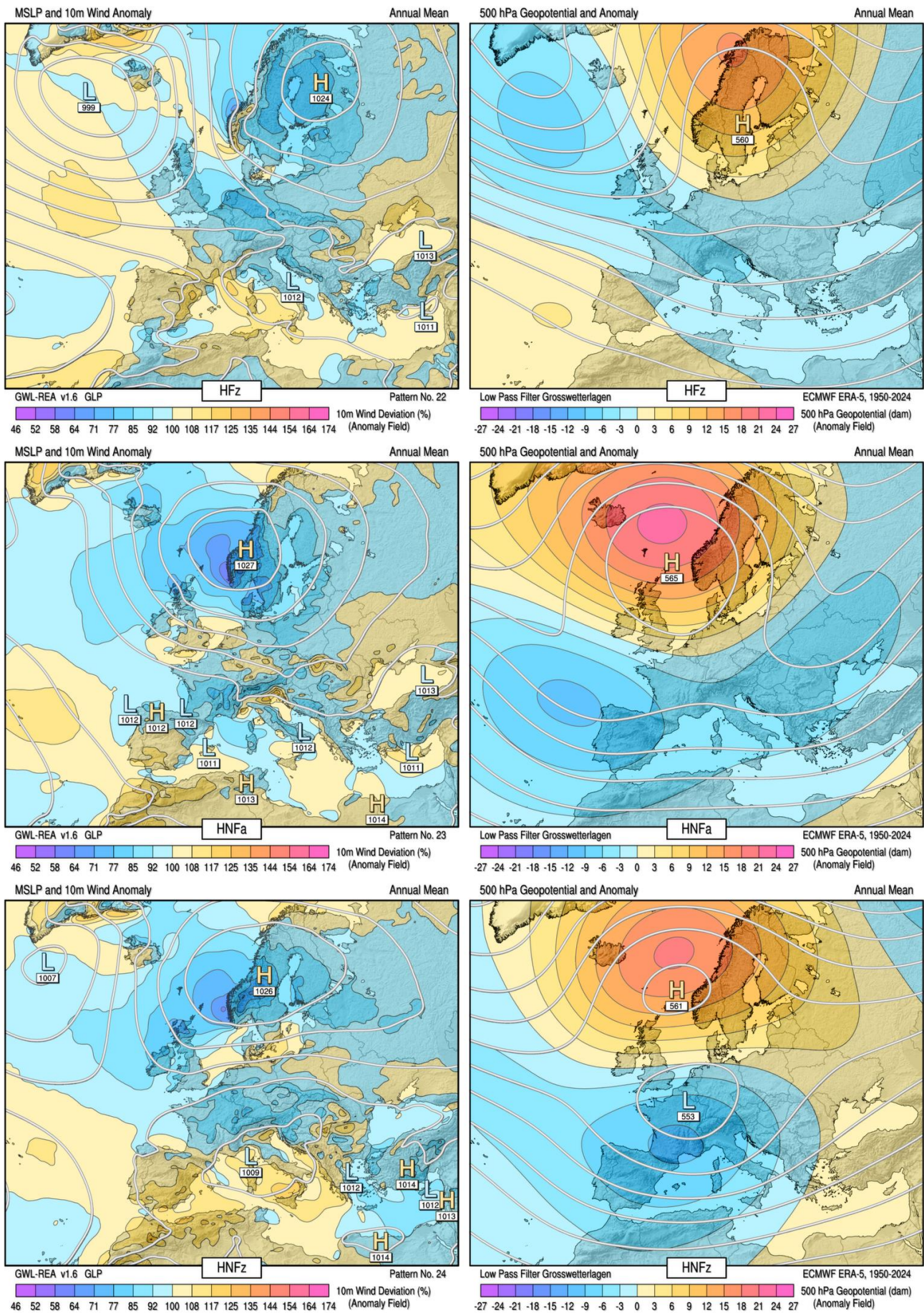


Fig. S59: Climatological GWL composites based on ECMWF ERA5 reanalyses, 1950-2024, for all times of the year, showing (left) mean sea-level pressure (contours, 3 hPa interval) and 10m-windspeed anomalies (colour-filled contours, %) and (right) 500 hPa geopotential height (interval 5 dam) and anomalies (colour-filled contours, interval 3 dam), for GWL nos. 22-24.

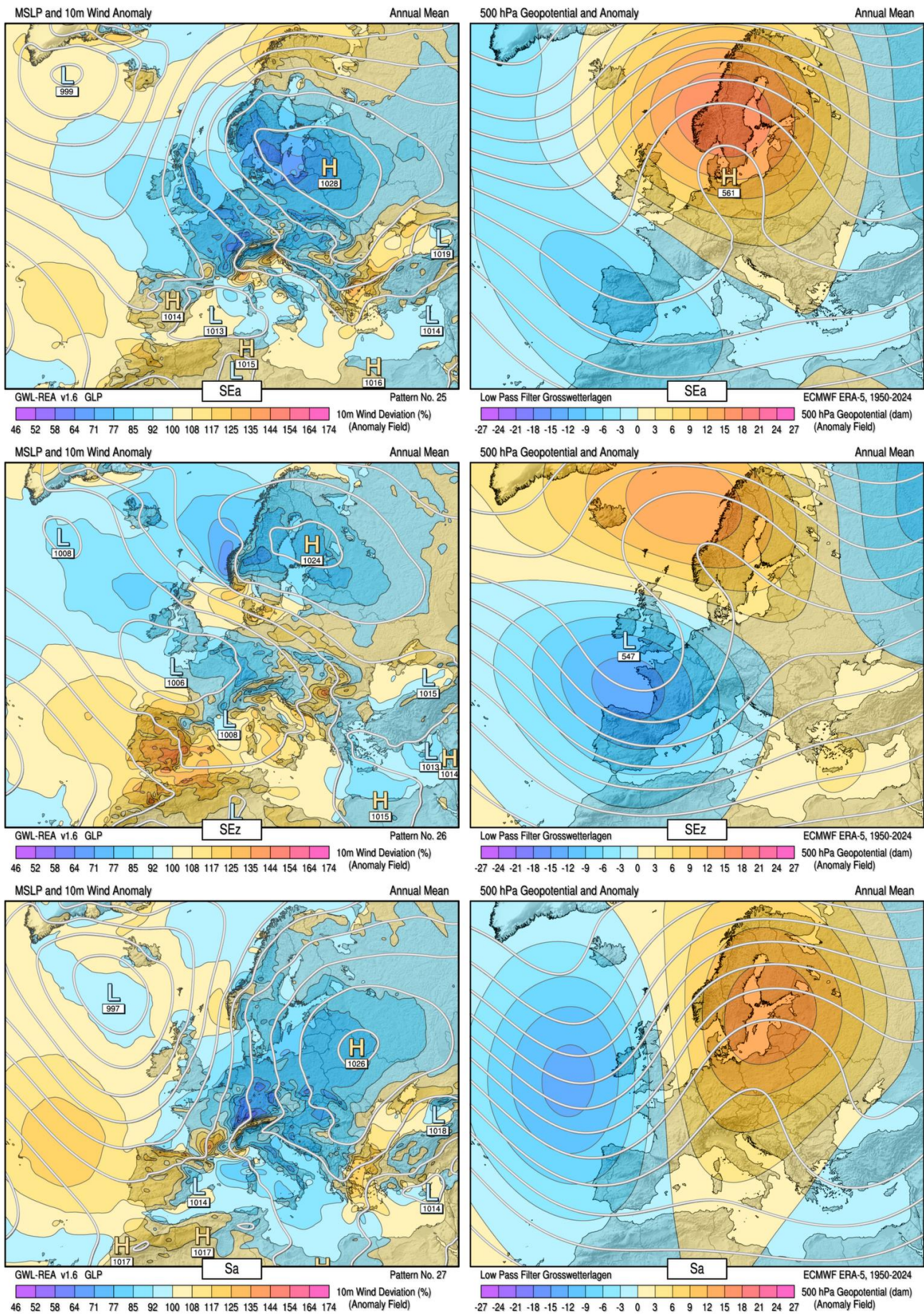


Fig. S60: Climatological GWL composites based on ECMWF ERA5 reanalyses, 1950-2024, for all times of the year, showing (left) mean sea-level pressure (contours, 3 hPa interval) and 10m-windspeed anomalies (colour-filled contours, %) and (right) 500 hPa geopotential height (interval 5 dam) and anomalies (colour-filled contours, interval 3 dam), for GWL nos. 25-27.

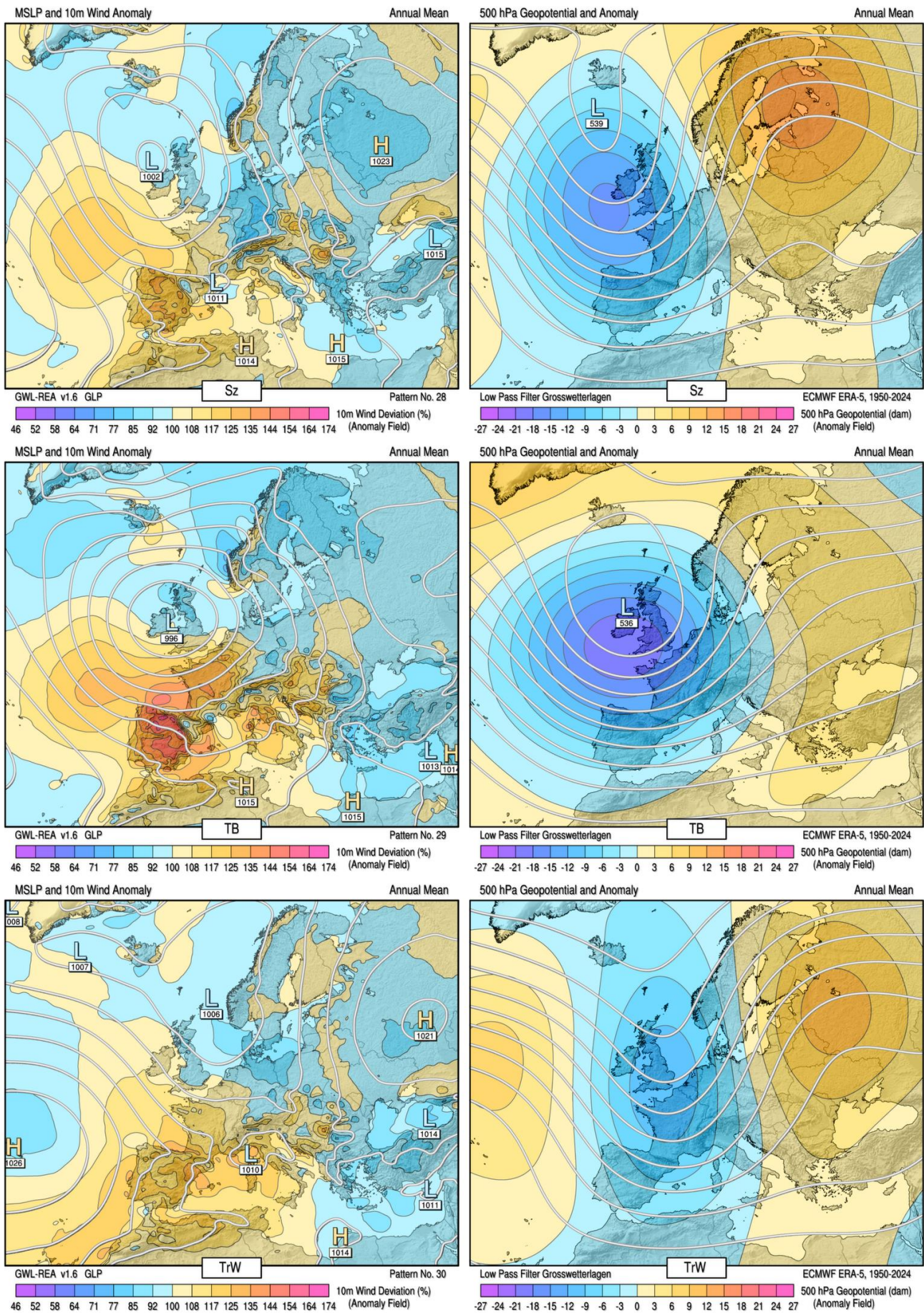


Fig. S61: Climatological GWL composites based on ECMWF ERA5 reanalyses, 1950-2024, for all times of the year, showing (left) mean sea-level pressure (contours, 3 hPa interval) and 10m-windspeed anomalies (colour-filled contours, %) and (right) 500 hPa geopotential height (interval 5 dam) and anomalies (colour-filled contours, interval 3 dam), for GWL nos. 28-30.

Author contributions

Paul James wrote the original draft of this supplement and created the visualizations. Jennifer Ostermöller contributed to its editing and finalization.

Competing interests

The authors declare that they have no conflict of interest.

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