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Klaus – an exceptional winter storm over northern Iberia and southern France

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Introduction

Extratropical cyclones are one of the most important features of the mid-latitude climate and represent a primary mechanism for poleward transport of heat and moisture. They typically develop as a result of the interaction between warm subtropical air and cold polar air masses over the mid-latitudes of both hemispheres. Over the North Atlantic (NA) extratropical cyclones (depressions) often undergo a strong intensification phase over the ocean, move eastwards and reach Europe where they are one of the main factors influencing local weather. Intense depressions are often associated with very strong winds and large precipitation totals (Raible *et al.*, 2007) and are among the most severe natural hazards affecting Europe.

Such systems appear less often over southern Europe (Trigo, 2006; Pinto *et al.*, 2009), but do occur sometimes when the jet stream pattern allows, and this paper describes an extreme example: storm *Klaus* (see Box 1 for storm names). On 21 January 2009 the jet stream extended across the NA Basin into Western Europe, and *Klaus* formed and moved, broadly, eastwards at a relatively low latitude (between 35°N and 45°N) on the edge of the dominant Atlantic storm-track identified in most climatological studies (e.g. Hoskins and Hodges, 2002; Pinto *et al.*, 2005; Trigo, 2006, and Figure 1). It swept by northern Iberia and southern France late on 23 January and during 24 January, and was considered the most damaging wind storm to affect these areas since the devastating storm *Martin* in late December 1999 (Ulbrich *et al.*, 2001).

Box 1. Naming of pressure systems

Since 1954, the Institute of Meteorology of the Freie Universität Berlin has named all pressure systems in Central Europe, with lows given female names and highs given male names. In 1998, following a discrimination discussion, names began to be assigned by giving the lows male names and the highs female names in odd years, and vice versa in even years. Since 2002, alphabetical lists are made from names suggested by the public. Source: http://www.met.fu-berlin.de/adopt-a-vortex/historie/

Data

Mean sea-level pressure (MSLP) charts from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Reanalyses (ERA-Int) (Dee and Uppala, 2009) are considered for the NA European sector (85°W to 50°E; 20–70°N) for January 2009, at the full temporal (six-hourly) and spatial (0.75° regular horizontal grid) resolutions available. Additionally, 500mbar geopotential height fields and 250mbar wind and divergence are considered so as to analyse large-scale conditions associated with the development of the storm. Maximum gust speeds observed at 75 stations located in northern Spain and southern France were retrieved from preliminary reports published

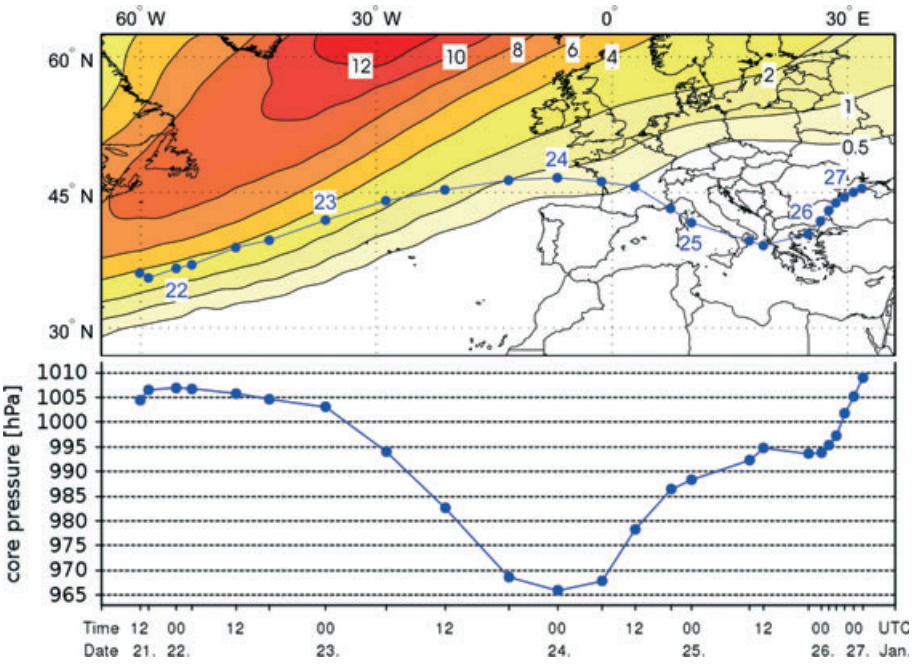

Figure 1. Surface track of Klaus. The position of the storm at six-hourly intervals is marked with a filled circle. The corresponding core MSLP data are shown in the bottom panel for the period 1200 UTC 21 January 2009 to 0600 UTC 27 January 2009. Contour lines represent the track density of the major (extreme) cyclones (cyclone days/winter) over the NA European sector (adapted from Pinto et al., 2009, their Fig. 4).

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by the corresponding Spanish[1] and French[2] Meteorological services. UK Met Office weather charts were analysed, and infrared channel METEOSAT satellite images provided by the Deutsch Wetterdienstweather service (DWD) were used for the analysis of cloud patterns and mid-level moisture transport.

Results

General description and impacts

Using an automatic cyclone tracking method (Murray and Simmonds, 1991; Pinto *et al.*, 2005), *Klaus* was first identified on 21 January 2009 as a small wave perturbation. The developing wave was embedded in the strong westerly flow and experienced a sharp intensification on 23 January around 21°W; it moved rapidly towards the Bay of Biscay, where it deepened further (Figures 1 and 2). At this stage severe storm force gusts of up to 55ms^{-1} (107kn) were measured at low-level stations, accompanied by heavy rain and attendant flooding, whilst snow fell across the Cantabrian Mountains and the Pyrenees. The strongest winds (and heaviest rain) were concentrated around the Pyrenees (Figure 3). Previous long-term records of wind speed were surpassed in several French cities as well as at other country stations. However, the impacts of the storm were felt over a wider area, including important urban sites in Spain (Santander, Bilbao, Barcelona) and France (Bordeaux, Narbonne, Perpignan) (Figure 4). The Spanish Oceanographic Institute (IEO) registered a new record of wave height within Spanish sea waters. According to data available from a buoy 22 miles north of Santander, two peak waves of 26.13m and 24.65m were registered between 0600 and 0700 on the morning of 24 January.[3] This magnitude of wave height was not foreseen when the buoy was designed and deployed, and the buoy drifted away (albeit still transmitting data) after the anchor cable broke. Thus, from this time on, the buoy data does not correspond exactly to the same location but from fairly close proximity. The readings from it show a peak of significant wave height during the morning of 24 January: 14.88m (Figure 5), the highest observed for this short-lived buoy (deployed in September 2007) and coincident with the lowest pressure observed (980mbar). In fact, this wave height is not

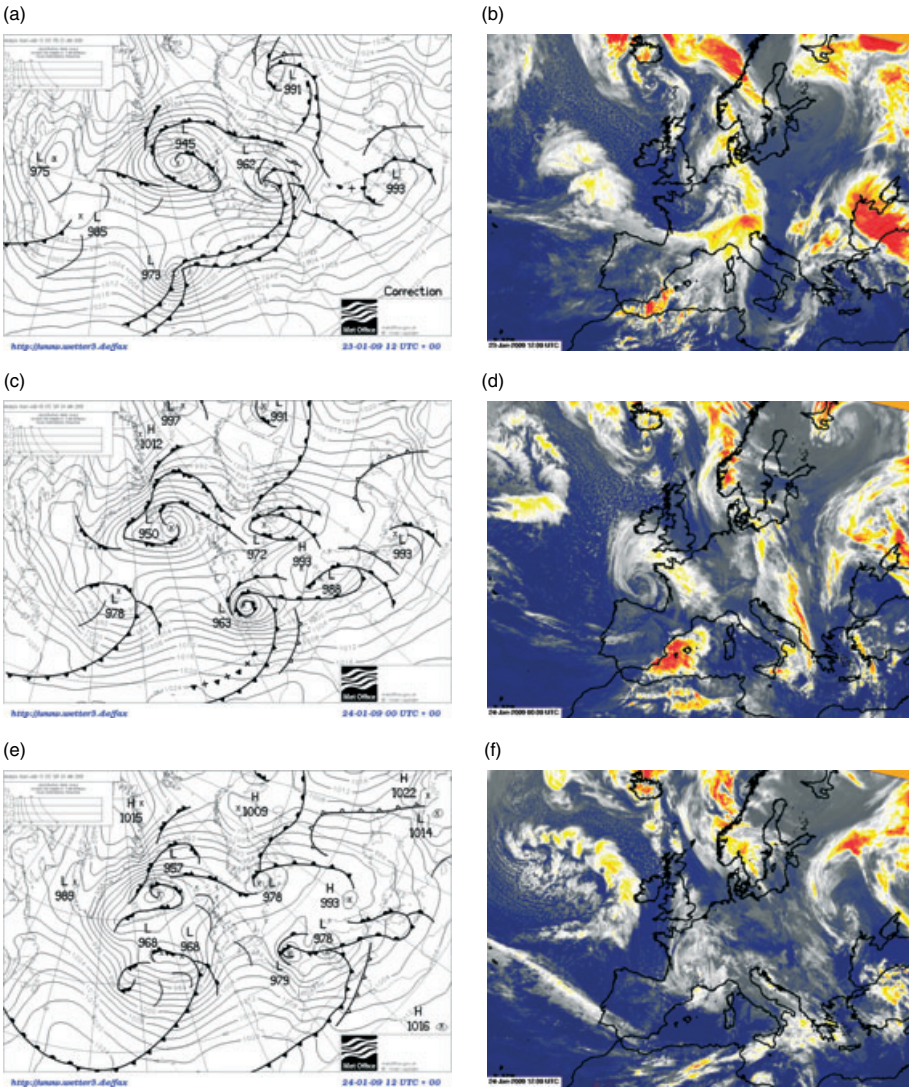

Figure 2. UK Met Office surface weather charts and infrared channel METEOSAT satellite images provided by the DWD for, (a) and (b) 1200 UTC on 23 January 2009; (c) and (d) 0000 UTC on 24 January 2009 and (e) and (f) 1200 UTC on 24 January 2009. (Crown copyright, the Met Office.)

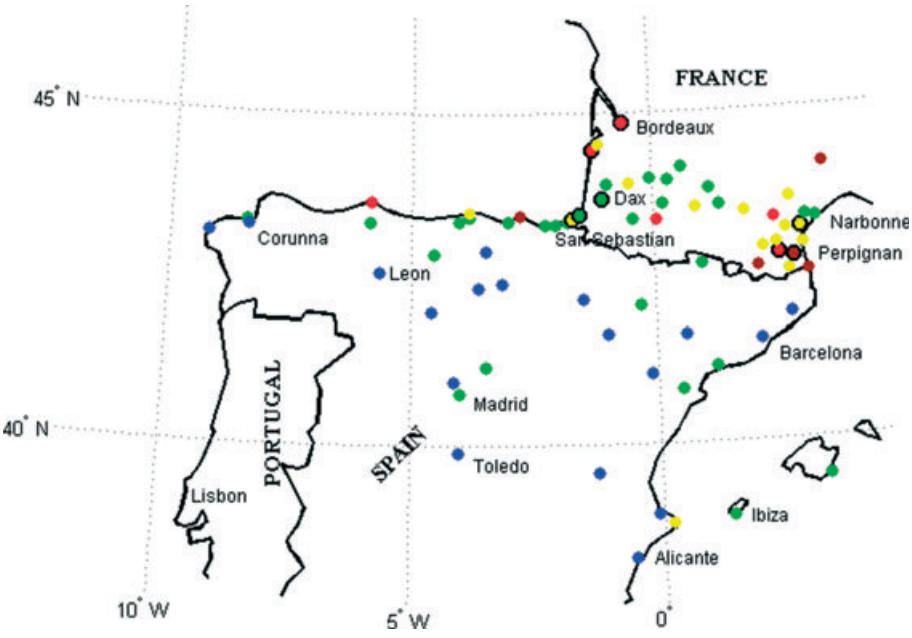

Figure 3. Maximum gusts measured at Spanish and French meteorological stations. Blue: 28–33ms^{-1} (54–65kn); green: 33–39ms^{-1} (65–76kn); yellow: 39–44ms^{-1} (76–86kn); red: 44–50ms^{-1} (86–97kn) and brown >50ms^{-1}. A black circumference is included around those stations where previous long-term records of wind speed were surpassed.

[1]Spanish weather service report: http://www.aemet.es/documentos/es/noticias/2009/03/ciclogenesisexplosiva_2325_01_2009_corr_V3.pdf (accessed on 18 November 2010).

[2]Meteofrance report: http://france.meteofrance.com/jsp/site/Portal.jsp?page_id=11330&page_id=10833 (accessed on 18 November 2010).

[3]Press release from IOE; http://www.ieo.es/prensa/NpOla26m.pdf (accessed on 18 November 2010).

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Figure 4. Example of damage associated with Klaus, near Corunna, northern Spain. (Photograph courtesy of Pablo Herrero Isasi.)

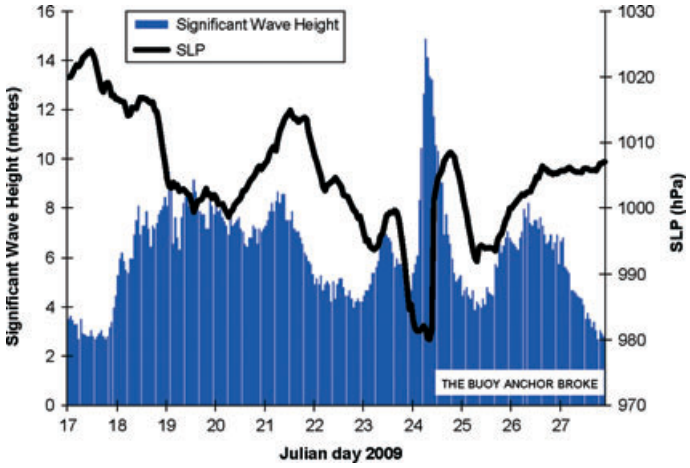

Figure 5. Hourly averages of significant wave height and sea-level pressure between 17 and 27 January 2009 from a buoy north of Santander. Missing readings (c. 10%) were linearly interpolated. Note that data from 24 to 27 January are from the drifting buoy (see text for details).

only the highest ever registered in this area but also within Spanish waters.

On 24 January the storm moved towards Italy and there were now two pressure minima: one over southern France and another over the Gulf of Genoa (Figure 2(e)). The latter (hereafter named *Klaus II*) developed at the occlusion point of *Klaus* and was apparent over the Gulf of Lion by 0600 UTC that day. From 25 January onwards, the cyclone track (Figure 1) follows *Klaus II* over the Adriatic Sea towards the Aegean and Black Seas, whilst the original system decays over southern France/northern Italy.

The French meteorological surveillance warning service issued (for the first time since 2001) the highest level of wind warnings for nine regions in the southwest of the country (Météo-France report). Unfortunately these were only issued at the height of the storm, not giving sufficient time to people and authorities to be prepared for such an event. Even though the Spanish Meteorological service had issued preliminary alerts as early as 22 January, the intensity of the storm was clearly underestimated. At least 26 people died in both countries as a direct consequence of *Klaus*. More than 1.7 million homes suffered power cuts (Aon-Benfield, 2010) as trees and power lines were brought down, and there was significant dislocation to all forms of transport with road and rail links blocked and airports closed. The reinsurance industry ranked the effects of *Klaus* as the most costly event of 2009 with over US$6 billion in losses being reported, mainly from France and Spain (Aon-Benfield, 2010). According to various insurers, insured losses were US$2.3 billion in France and US$1 billion in Spain after at least 715 000 claims were filed. It was described as the most damaging wind storm affecting northern Iberia, southern France and the western Mediterranean since storm *Martin* in December 1999 that killed 88 people and uprooted millions of trees (Ulbrich *et al.*, 2001).

Large-scale conditions associated with the explosive development

The occurrence of intense storms over the NA Ocean and Europe is favoured by a strong north-south temperature gradient in the low-to-mid troposphere, which contributes to stronger than average winds in the mid-to-upper troposphere across the region (e.g. Fink *et al.*, 2009). As pointed out by several authors (e.g. Uccellini and Johnson, 1979), the development of intense depressions occurs when the location of the initial perturbation with respect to the upper-level jet favours its amplification within enhanced low-level baroclinicity (Box 2). The incipient wave from which *Klaus* developed was some 800km to the eastnortheast of Bermuda on 21 January within an area of enhanced meridional temperature (θ_e, used as an indicator of the combined effect of latent and sensible heat) and developed downstream near the Azores (Figure 6(a)). The upper-level flow over the western NA was anomalously strong and oriented in a southwest-northeast direction (Figure 6(b)).

The cyclone path followed very closely the region characterized by the largest equivalent potential temperature gradient, within the transition between subtropical and polar air masses (Figure 6(c)). The comparison of the cyclone trajectory, 500mbar geopotential height and θ_e at 850mbar reveals a maximum of latent and sensible heat availability in the lower troposphere immediately downstream of the upper and surface disturbances (Pinto *et al.*, 2009). Thus, the lower troposphere θ_e and the vertical cross-sections of relative humidity indicate that

Box 2. Cyclone development and jet streaks

The links between cyclone development and jet streaks – regions with maximum upper air wind speed – have been studied for many years (e.g. Uccellini and Johnson, 1979; Reed and Albright, 1986). Extratropical cyclones typically intensify when they cross the polar jet stream, but this intensification is sensitive to the relative position between jet and cyclone. The intensification is particularly enhanced if the system is located at the south of the jet entrance or north of the jet exit (for the Northern Hemisphere). This effect is induced by ageostrophic winds associated with the wind speed acceleration and isobaric confluence at the entrance, and wind speed reduction and isobaric diffluence at the exit. Several jet streaks may contribute to the cyclone development simultaneously (as happened with *Klaus*).

the development was fed by very warm and moist air (Figure 6(e)). This assessment is supported by the meridional relative humidity vertical profile for 1200 UTC on 23 January from 25°W to 21°W (Figure 6(f)), which shows high relative humidity (>90%) in the warm air mass, embedded in the jet stream, moving from the southwest and suggesting its contribution to the baroclinic development.

To evaluate the source of the air mass and moisture associated with *Klaus*, backward trajectories were started from the location of the storm for various time steps. Results (not shown) indicate that many of the trajectories arrived from the subtropics and included a considerable amount of moisture. This assessment is in agreement with work by Knippertz and Wernli (2010: their Figure 4) who suggest *Klaus* as a possible example of 'tropical moisture export' (TME) influence on rapid extratropical cyclogenesis. Their analysis from 19 January to 24 January showed that the development of *Klaus* was embedded in a massive TME event which originated over the entire central and western tropical Atlantic and then converged into the genesis region of the cyclone.

An important factor in the development is the relative position of the storm and the upper-level jet. The surface depression first appeared to the south of the jet, then it was steered by the upper-level flow northeastward over the central NA, north of the Azores, where the explosive cyclogenesis began. During its maturing stage, rates of deepening exceeded 37mbar per 24 hours (1003.0–965.9mbar during 23 January), which

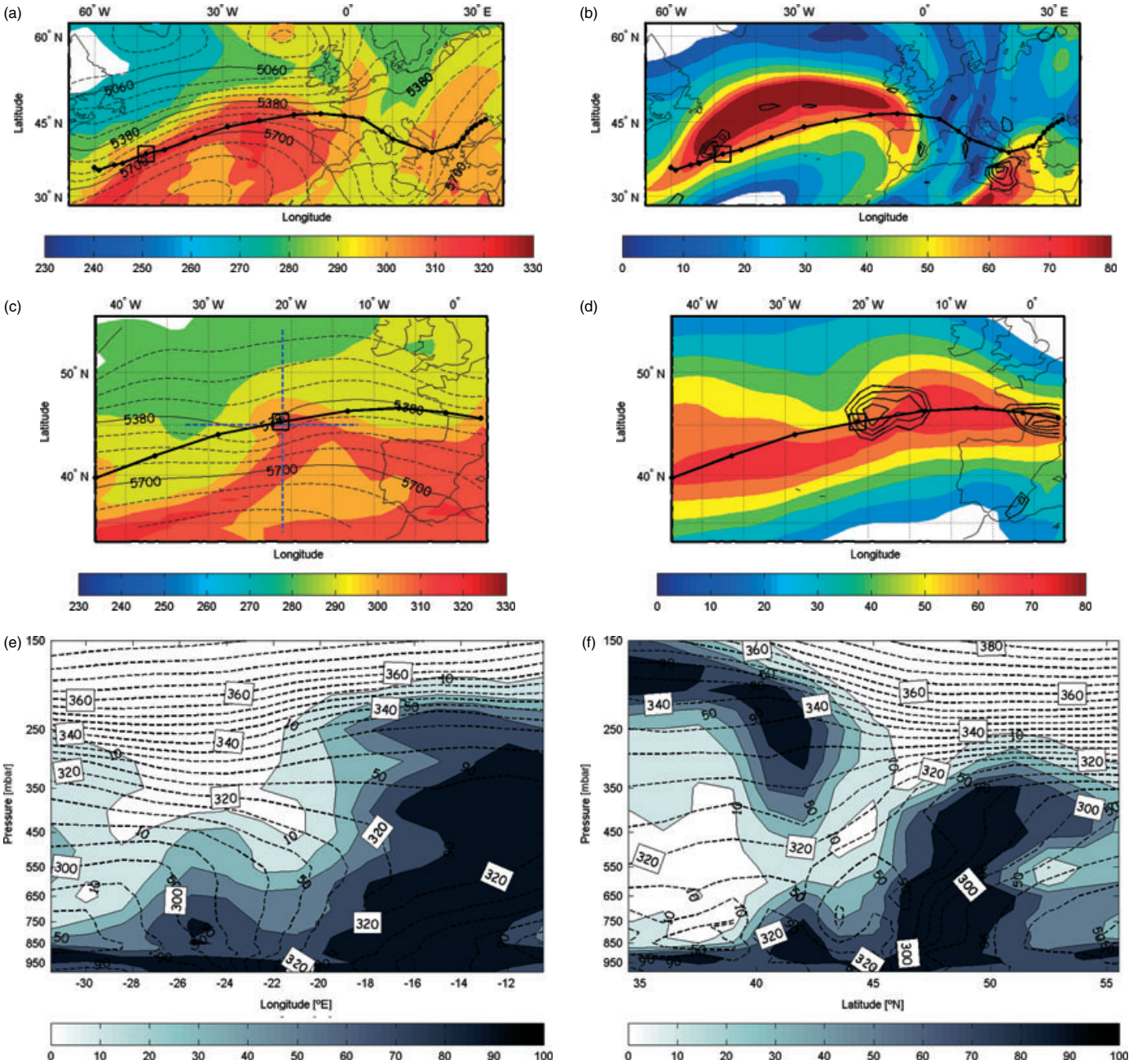

Figure 6. Large-scale conditions associated with the development of storm Klaus. (a) θ_e field at 850mbar (shaded: temperature in kelvins) and the 500mbar geopotential height (contours every 80gpm) for 1200 UTC on 22 January. (b) wind speed (shaded: ms^{-1}) and divergence (contours every $10 \times 10^{-6}s^{-1}$, delimiting areas above $30 \times 10^{-6}s^{-1}$) at the 250mbar level for 1200 UTC on 22 January. (c) as (a) but for 1200 UTC on 23 January. The dashed lines show the location of the vertical sections. (d) As (b) but for 1200 UTC on 23 January. (e) west-east oriented sections of the relative humidity field (shaded: %) and the θ_e field (dashed lines, contour interval 4K) at latitude 45°N. (f) As (e) for south-north oriented sections at longitude 21°W. Cyclone track is displayed in black and position at corresponding time is marked with a square.

after being geostrophically adjusted to the reference latitude of 60°N (Trigo, 2006), is equivalent to 44mbar per 24 hours, implying an exceptional event with 'bomb-characteristics'.[4] At 0600 UTC on 23 January the depression was positioned at the rear of the nearly zonal jet and was moving towards a region of stronger winds and higher divergence values (>30 × $10^{-6}s^{-1}$). During the next six hours the jet shifted southwards and became further elongated, developing two velocity maxima with the surface cyclone located in between (Figure 6(d)). During this phase *Klaus* crossed the jet to its poleward side, and its rapid development began as it exited the maximum velocity region. While such 'bombs' are not uncommon over the NA Basin (Sanders, 1986; Trigo, 2006), they are very rare this far south (Pinto *et al.*, 2009). The intensification of *Klaus* was also probably supported by the split jet streak and associated strong upper-air divergence between the two jets. Similar cases where split jets and enhanced upper-air divergence played an important role in storm development have been reported previously – for example, *Lothar* (Ulbrich *et al.*, 2001) and *Kyrill* (Fink *et al.*, 2009).

Summary and conclusion

We have presented a description of the synoptic evolution, impacts and the most relevant large-scale features associated with storm *Klaus*, the costliest weather hazard event in the world during 2009 with over US$6.0 billion in total losses reported (Aon-Benfield, 2010). The system underwent a rather typical mid-latitude explosive development, closely associated with the crossing of the polar jet, but this development occurred at an unusually low latitude, on the southern boundary of the NA main storm track climatological 'normal' envelope, due to the southerly displacement of the polar jet stream. *Klaus* underwent an explosive development with 'bomb' characteristics between the Azores and the Iberian Peninsula, with a deepening rate of 37mbar in 24 hours, unusually high for these latitudes. The development of *Klaus* was also apparently supported by an extraordinary tropical moisture export over the entire central and western tropical Atlantic converging into its genesis region, and then moving along with the storm towards Europe.

Unlike most intense winter cyclone events affecting Iberia and southern France, which are generally associated with moderate-to-strong precipitation, *Klaus* was primarily characterized by strong winds, and long-term records of wind speed were surpassed at several stations. Such storms are an increasingly important research topic: *Martin,* in December 1999*,* had a similar development, followed a very similar path and produced even stronger impacts and the recent storm *Xynthia* (28 February 2010) intensified strongly over the Bay of Biscay in association with a strong jet over south-western Europe, even though it followed a northeastward track thereafter.

In this paper, we have identified some of the mechanisms that were ultimately responsible for the unusual path and strength of *Klaus* and its associated impacts, but this peculiar system deserves a more in-depth study to seek to quantify the contribution from all the physical mechanisms involved (e.g. latent and sensible heats, energy transfer between planetary and synoptic scale atmospheric waves etc.) in order to improve both diagnosis studies and the accuracy of forecasts and warnings of severe weather.

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[4]'Bombs' are rapidly deepening extratropical surface cyclones with a pressure fall in the depression centre at sea level of at least (24*sinϕ/sin60°)mbar in 24 hours. This corresponds to 24mbar in 24 hours at latitude 60°N. The geostrophically-equivalent rate at 45°N is 19.6mbar in 24 hours.

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