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ADVECTION OF AIR MASSES RESPONSIBLE FOR EXTREME RAINFALL TOTALS IN POLAND, AS EXEMPLIFIED BY CATASTROPHIC FLOODS IN RACIBÓRZ (JULY 1997) AND DOBCZYCE (MAY 2010)

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Abstract. The paper analyses directions of advection of air masses responsible for extreme rainfall totals resulting in floods in Racibórz and Dobczyce in July 1997 and May 2010, respectively. The analysis was based on the HYSPLIT model available via the READY website of National Oceanic and Atmospheric Administration Air Resources Laboratory (NOAA ARL USA). The database used by the model (NCEP/NCAR reanalysis) contains global grid-based meteorological data updated every 3 hours. The ARL trajectories were used to compute archive trajectories, at 6-h intervals, of two cases of intensive rainfall. The first involved air masses advecting over Racibórz (50.1°N; 18.2°E) from 00.00 UTC 5 July 1997 through 06.00 UTC 9 July 1997, and of air massed advecting over Dobczyce (49.9°N; 20.1°E) from 0600 UTC 15 May 2010 through 0600 UTC 19 May 2010. The trajectories were computed for altitudes of 500, 2000, and 4000 m above ground level (a.g.l.). The analysis showed that, in both cases, the air at the highest level (4000 m a.g.l.) was advecting from the Mediterranean Sea basin. In contrast, the air at the lower altitudes advected from other directions, and the directions changed considerably during the periods analysed. The change made it possible for the air to draw moisture from different source areas. The extreme rainfall totals recorded were considerably affected by atmospheric fronts separating air masses differing in their temperature. The rainfall intensity resulted not only from the particular air circulation, but also from orographic conditions. The rainfall occurring in the frontal zone was locally intensifying due to storm cells developing during the day.

Keywords: archive trajectories, HYSPLIT model, extreme rainfall events, 1997 and 2010 floods in Poland

INTRODUCTION

Extreme rainfall may occur as a) storms, i.e. short-lived precipitation of small spatial range, high intensity, and duration of several minutes to a few hours; b) profuse rainfall covering large areas and lasting from several hours to a few days; and c) rainy seasons of several weeks-months duration (Chomicz 1951, Starkel 2011). The precipitation cases analysed in this paper involve profuse rainfall of high intensity and storm-like output (Prokop 2007).

Extremely high rainfall in Poland is dependent on the orography of an area, a passage of low pressure centres with frontal zones from the Mediterranean Sea and Italy towards north-east or with persistence of low atmospheric pressure with a centre over north-east Poland, resulting in advection of moist air masses from the north and their surge onto mountain slopes (Prokop 2007). The unusually severe rainfall events described in this paper resulted from both situations occurring in parallel. Air masses contributing to rainfall severity show a high specific volume and an exceptionally high water vapour content as well as atmospheric instability (Malinowska and Miętus 2010).

The paper describes circulation patterns which produced heavy rainfall in Racibórz and Dobczyce in July 1997 and May 2010, respectively. The two cases were selected due to exceptionally heavy rainfall episodes they involved, the rainfall contributing to the flooding of the two towns by the rivers Odra and Raba, respectively. The analysis will make it possible to elucidate the mechanisms responsible for the most profuse precipitation in Poland.

A number of authors have attempted to elucidate meteorological causes of floods, particularly the 1997 one. While some studies (Heino *et al.* 1999, Müller *et al.* 2009, Sobik and Błaś 2010, Wrona 2008) analysed and compared numerous flood events, other dealt with extremely heavy rainfall (Bokwa and Skowera 2009, Stach 2007) and were focused on individual floods (Klejnowski 1997, Stachý and Bogdanowicz 1997). Ustrnul and Czekierda (2001) described circulation-related causes of summer torrential rainfall episodes in Poland. Some authors (Kundzewicz 2005, Kundzewicz *et al.* 2005, Kyselý and Beranová 2009) ascribed the catastrophic floods in the Odra and the Elbe catchment in July 1997 and August 2002, respectively (as well as the 2001 flood in the Vistula catchment) to climate changes and anthropogenic effects on the terrain cover. A monograph edited by Dubicki *et al.* (1999) provides a detailed account of the course and causes of the 1997 flood in the Odra catchment; the 2010 flood in the Vistula catchment was described in depth in a monograph edited by Maciejewski *et al.* (2011). Causes of the rainfall contributing to the floods were in both monographs analysed by the Institute of Meteorology and Water Management from synoptic maps, radar images, and aerological diagrams. It was only Sobik and Błaś (2010) who addressed the direction of air mass advections by computing archived trajectories. With this method, circulation-related conditions of rainfall are rendered exceptionally lucid and easy to interpret so that areas generating the air masses which contribute to a heavy rainfall can be identified.

MATERIALS AND METHODS

The origins and directions of air mass advection over selected stations on days with exceptionally high rainfall totals were analysed with the aid of the HYSPLIT model developed by the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) in the US and by Australia's Bureau of Meteorology; it has been made available on-line by ARL. The model has been developed primarily to forecast movement of atmospheric pollutants, and thus to aid in the control of transport and transformation of gases and aerosols in the atmosphere and to predict their effects on the biotic components of the natural environment (Draxler and Rolph 2003). The model's structure makes it possible to reconstruct trajectories travelled by a portion of air during any time interval (starting from 1948) and in any part of space encompassing the Earth troposphere. The input data may be contained in graphic and text files containing geographic coordinates and altitudes of points marking out the advection trajectories as well as field characteristics of meteorological variables at those points. The trajectories track both the horizontal and vertical movement of the air portion modelled.

The HYSPLIT model is based on a world-wide grid of mean sea level pressure (MSLP), contained in databases derived from global modelling. In the present study, data produced by the National Centers for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) reanalysis are used. The NCEP/NCAR reanalysis is based on observational data and consists of global climatological information collected since 1948. The database is updated at 3-h intervals. The data are referred to a grid having a 2.5 degree longitude and latitude resolution (Kalnay *et al.* 1996).

As the global modelling produces a rather poor reconstruction of true precipitation totals at the measuring stations in the area of concern for this study (Pilarski *et al.* 2010), no concrete rainfall totals or intensities are referred to, although the NCEP/NCAR reanalysis database does contain such values. The rainfall information produced by the NCEP/NCAR reanalysis was used here exclusively to determine approximate dates of the onset and termination of the rainfall, i.e., the periods for which the trajectories were computed.

The archived trajectories were generated at 6-h time intervals. The first trajectory illustrates an air mass advection immediately prior to the onset of the rainfall, the last trajectory reflecting the advection after the rainfall terminated. The air was advecting over Racibórz from 0000 UTC 5 July 1997 through 0600 UTC 9 July 1997 and over Dobczyce from 0600 UTC 15 May 2010 through 0600 UTC 19 May 2010, and a continuous rainfall was observed during periods between the time points indicated.

RESULTS

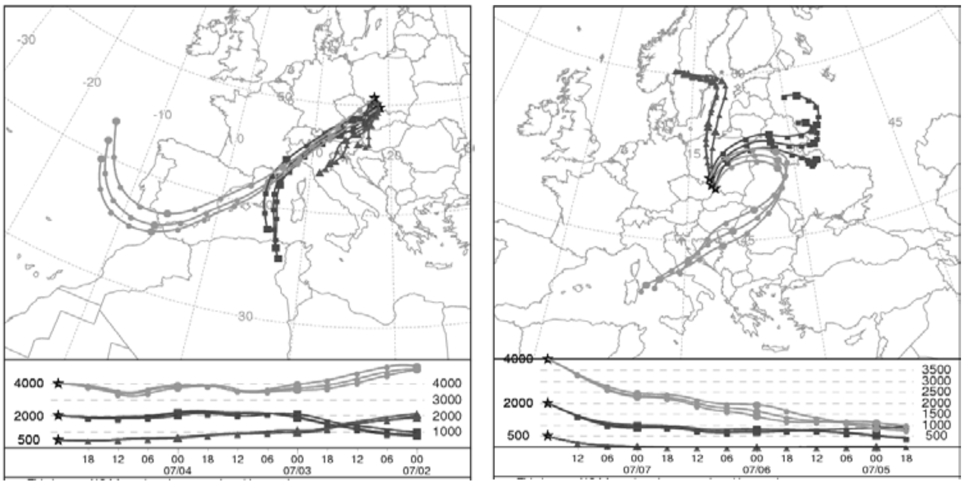
Advection of air masses generating flood-producing rainfall in Racibórz (1997)

According to the Institute of Meteorology and Water Management (IMWM) data, over 5-9 July 1997, Racibórz received as much as 235.4 mm rainfall. The heaviest precipitation (92.9 mm) was recorded on 7 July. It should be added that the threatening rainfall is that with total precipitation exceeding 30 mm (Szalińska and Otop 2012), the flood-producing rainfall having a total exceeding 70 mm (Kosierb 2011) or 50 mm (Szalińska *et al.* 2008). The annual mean rainfall in Racibórz (1951-2000) is 646 mm (Woś 2010), i.e., it is only 2.65 times higher than that experienced during the few days mentioned. According to Dubicki *et al.* (1999), the rainfall total over 5-9 July 1997 was as much as 265.5% of the multi-annual (1961-1990) mean July precipitation total. The rainfall episode contributed to the generation of a huge flood wave which culminated at 1045 cm, the flow rate at culmination amounting to 3260 $m^3 s^{-1}$. It is noteworthy that the flow rate of 1% exceedence probability, estimated from the 1921-1990 data, was 1680 $m^3 s^{-1}$ (Stachý and Bogdanowicz 1997), i.e., approximately half of the value actually recorded.

The points on the trajectories shown in graphs (Figs 1 – 4) were determined at 6-h intervals. The curves beneath the maps depict the vertical transport of the air mass. The time and dates (month/day) are provided beneath, whereas altitudes (metres) above the ground level (a.g.l.) are indicated on both sides of the curves.

The three-day archived trajectories terminating directly before the rainfall (Fig. 1a) as well as those in the initial hours of the precipitation episode, indicate the air mass, throughout the vertical profile, to have been advecting from the south-east, i.e., from over the Mediterranean Sea basin. The air advecting from that area is particularly water-laden and produces exceptionally heavy floods in Poland (Alpert *et al.* 1990, Bartoszek 2006, Morozowska 1987). This air mass was responsible also for the heavy rainfall in July 1997 (Wrona 2008). According to Bogdanowicz and Stachý (1998), as many as 88% of heavy floods in Poland are a result of air pressure lows moving along the van Berber trajectory Vb from over the Mediterranean Sea.

The pronounced differences in length of the trajectories shown in Fig. 1 evidence differences in the advection rate at different altitudes, the advection rate increasing with altitude. The trajectories are indicative of the advection of cool polar-maritime air from the north in the entire vertical profile analysed. When the advection reaches southern Europe (the Mediterranean Sea), it frequently results in cyclogenesis producing shallow lows moving towards central Europe (including Poland; Sobik and Błaś 2010).



a) b)

Fig. 1. Three-day archived trajectories of air mass advection over Racibórz and over Skoczów and Opole (meteorological basis: NCEP/NCAR reanalysis). Times: a) 0000 UTC 5 July 1997; b) 1800 UTC 7 July 1997

Important information is provided by the archived trajectories determined for 1800 UTC on 7 July. They illustrate advection of tropical (very warm and humid) air mass from the Mediterranean Sea at 4000 m a.g.l. The trajectories of air mass movement at 2000 m a.g.l are indicative of continental air advection from Eastern Europe. The lowest level (at 500 m a.g.l. in Racibórz) shows advection of cool, maritime polar air travelling from the north and north-west (Fig. 1b).

Both the tropical and the maritime polar air masses, separated by a quasi-stationary atmospheric front, were exceptionally moist (Kundzewicz *et al.* 1999, Stachý and Bogdanowicz 1997). On 5 July, at an altitude higher than 3 km, the air above Poland was still relatively dry. In turn, on 6 July, advection of very warm and very moist tropical air resulted in the difference between the actual temperature and the dew point temperature for 850-500 hPa being reduced to as low as 1.7^{o}C. As a consequence, the 400-10,000 m a.g.l. layer was highly labile as a result of air stream convergence in the lower and middle troposphere. This led to the extremely high precipitation recorded in the Lower Silesia on 5-9 July 1997 (Sobik and Błaś 2010); this precipitation exceeded the precipitable water in the air colum (30-40 mm) many times.

A similar situation occurred in Lower Silesia in July 2001 when a cold front was separating two basically different air masses: a hot tropical air advecting from the south and a moist maritime polar air, colder by about 10^{o}C. Moreover, the front was blocked by a high from the eastern part of Europe. As a result, the front was quasi-stationary, and the extended period of the rainfall induced the water level of rivers in mid-length of the Odra catchment to rise and to exceed the alarm state by more than 200 cm (Wrona 2003).

Although Racibórz lies at a relatively low absolute altitude (205 m a.g.l.), the amount of rainfall the station received was affected also by orographic factors. The descent of the air mass from the northern sector resulted in warm and moist air masses being lifted upward (a dynamic-stationary lifting effect; Kwiatkowski 1984) already at the foot of the Sudeten Mountains. The effect involves a slow lifting of an air mass upward against an orographic barrier. When the air mass crosses the barrier on gorges and wide intra-montane depressions, a considerable part of the air locally changes the direction of its passage and moves along the mountain foreland. Under such circumstances, a very extensive zone of precipitation is formed at the windward side of the barrier (extending to 100 km away from it), the rainfall being continuous (Kwiatkowski 1984).

The example shown in Figure 1b makes it clear that advection of an air mass in the zone of convergence has to be presented at different altitudes. It also shows that it is possible to draw erroneous conclusions as to the origin of the air masses responsible for intensive precipitation. This is particularly evident with respect to trajectories, defining the origin and direction of air mass advection, developed for the 500 and 2000 m a.g.l. level over Racibórz. Application of 6-h time intervals made it possible to observe the diverse advection dynamics and altitude-dependent direction during the four consecutive days (from 0600 UTS 5 July to 0500 UTS 9 July) when the intensive rainfall took place.

The graph illustrating movement of air mass portions in the vertical dimension shows that the air mass is being gradually lifted up, primarily in its top part (curves beneath the map; Fig. 1). The air portions which reached Racibórz at 4000 m a.g.l. 3 days previously were, according to the model, at the level as low as 760 m a.g.l. The air mass which appeared in Racibórz at the level of 2000 m a.g.l. 3 days earlier was at 399 m a.g.l. The changes are associated with the intensive forced ascending movement of the warm air from the south which became superimposed on a cooler air mass present within the convergence zone.

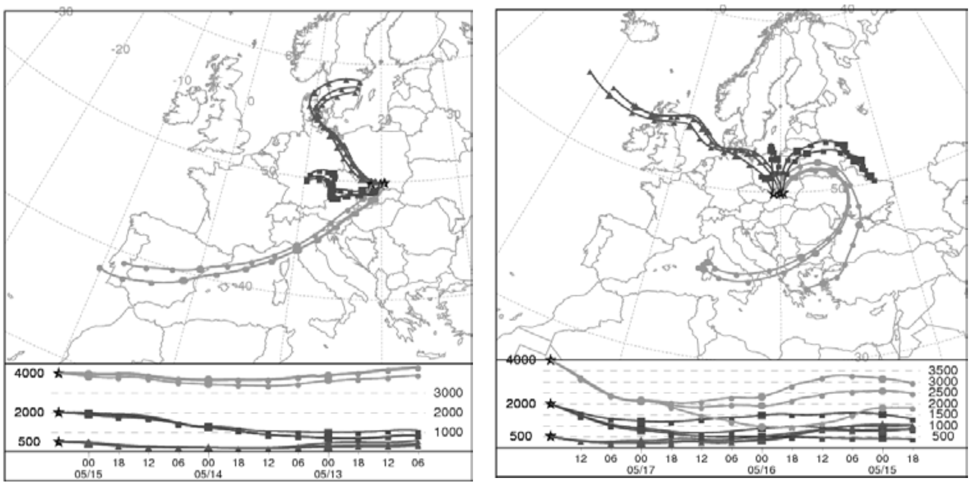
Trajectories (not shown) describing the situation shortly after the precipitation subsided, i.e. at 0600 UTC 9 July 1997, depict advection, at all the levels, from the northern sector. The air advecting over Racibórz was then much less thermally diversified than was the case in previous situations of heavy rainfall.

Advection of air producing precipitation inducing flood in Dobczyce in 2010

A period of extremely heavy rainfall producing flood events occurred in Poland in May 2010 as well. At numerous sites, the riverine water level exceeded that recorded in July 1997. Particularly high rainfall totals in May 2010 were observed in the Małopolska Province (as much as 352% of the monthly mean) (Jakóbik 2011). An exceptionally dangerous situation emerged in the River Raba catchment. The rainfall total over four days, 15-19 May, was 232.1 mm. The heaviest precipitation (totalling as much as 126 mm) occurred on 16 May. For comparison, the annual mean rainfall total in the area amounts to about 800 mm (Obrębska-Starklowa *et al.* 1995). Paszkiewicz (2009) assumed the corrected annual precipitation total to be 939 mm, but admitted that this value was arrived at by augmenting the measured precipitation by as much as 21.3%. The hydrological situation in the Raba catchment was made worse by the fact that intensive rainfall had occurred there as early as in the first half of May (the rainfall total over 1-14 May 2010 in Dobczyce was 151.8 mm) and in late May-early June (the rainfall total over 30 May-4 June 2010 was 155 mm; Maciejewski *et al.* 2011).

Trajectories of air advection over Bielsko-Biała (49.8^{o}N; 18.7^{o}E) and Bochnia (49.9^{o}N; 20.4^{o}E) were used as reference to routes of air advection over Dobczyce (49.9^{o}N; 20.1^{o}E). The 3-day archived trajectories developed for pre-determined altitudes illustrate advection of air from different directions. During the initial several hours of rainfall (the trajectories drawn for one of the moments in time are shown in Fig. 2a), very warm masses of tropical air from northern Algeria, relatively warm air from northern Italy, and cool maritime polar air the northern sector were advecting simultaneously. At the foot of the Carpathians, in the convergence zone, the warm air masses were gradually lifting above the surrounding colder air. This is most clearly seen in the trajectories developed for 4000 and 2000 m a.g.l. The air advecting from the North West, cooler and heavier, remained at the lowest level all the time.

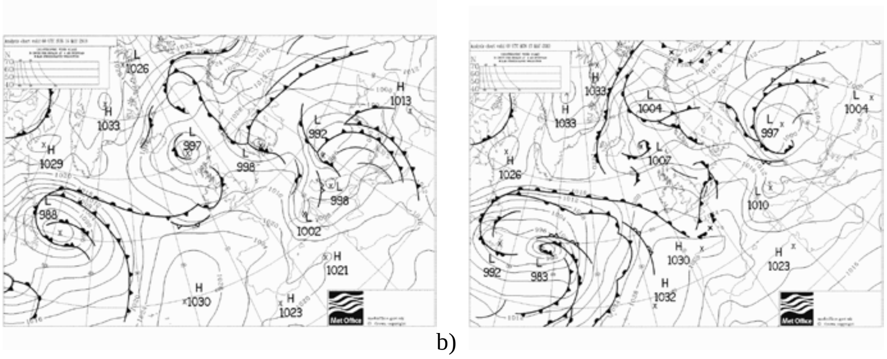
As confirmed by aerological surveys, the day of 15 May was characterised by constant equilibrium. The air advecting at the level of the lower and middle troposphere was relatively warmer, its vapour content increasing continuously (Maciejewski *et al.* 2011). On 16 May, in turn, with constant equilibrium persisting, the air was saturated with water vapour throughout the troposphere. Therefore, the clouds observed were represented primarily by stratified clouds, mostly the Nimbostratus, of a substantial thickness. Subsequently, on 17 May, most part of Poland experienced advection of clearly cooler maritime polar air in the lower part of the vertical profile, which resulted in a distinct horizontal temperature gradient: the noon temperature in the north-east and in the south of Poland was 22 and as little as 7-10^{o}C, respectively. The atmospheric pressure distribution over central Europe on 18 May was conducive to intensified advection of the cool air over the south-west of Poland and enhanced advection of warm air over the north-east of the country. The lower troposphere experienced a strong NE wind which intensified the uplift of the cool air mass on the orographic barrier, which enhanced the rainfall persisting until noon of 19 May. From that time on, advection of the cool air mass was observed to gradually weaken, the air mass humidity being reduced as well, which is documented on the aerological diagrams (Maciejewski *et al*. 2011).



a) b)

Fig. 2. Three-day archived trajectories of air advection over Dobczyce, Bielsko-Biała, and Bochnia (meteorological reference: NCEP/NCAR reanalysis); times: a) 1800 UTC 15 May 2010; b) 1800 UTC 17 May 2010

Similarly to the 1997 event, advection of moist air masses from different source areas was one of the major causes of the exceptionally heavy and, more importantly, long-lasting precipitation. Of key importance was the advection of tropical air from the Mediterranean basin, the precipitable water (PWAT) of which considerably exceeded 30 mm. This air mass was responsible for generating the rainfall in the convergence zone throughout the four days of the rainfall. On the other hand, the cool maritime polar air advecting from the northern sector was responsible for intensification of the convergence itself. This is confirmed by the archived trajectories developed (Figs 2a, 2b, 3) which show how intensive was the convergence during the consecutive days and at the different layers analysed. The convergence covered an area much smaller than that affected by the 7 July 1997 event (Fig. 1b). The heavy rainfall was enhanced by the atmospheric low being blocked and the accompanying longitudinal frontal zone which moved very slowly over the southern part of Poland (Fig. 3).



a) b)

Fig. 3. Surface synoptic charts: a) 16 V 2010 and b) 17 V 2010

In both cases, important was also the topography of the area affected. During advection of humid air masses, when the condensation level lies in a zone of air stream deformation over a mountain barrier, the humid air becomes lifted up and an orographic cloud emerges. Although Dobczyce is located at a relatively low absolute altitude (306 m a.g.l.), it was located on the windward of the orographic barrier, that is in the area where orographic processes are intensified and the precipitable water is considerable (Trepińska 2002). Consequently, the highest rainfall totals generally occur on the western, north-western and northern slopes of the Western Carpathians (Hess 1965).

A similar synoptic situation occurred, under similar orographic conditions, in the Ciężkowice Piedmont (230-280 m a.g.l.) in July 2005, resulting in a high water level rise in the Wątok Stream several kilometres east of Tarnów (Bryndal *et al.* 2010). Then, too, an atmospheric front was separating two thermally different air masses: hot tropical air on the eastern side of the cyclone and a humid maritime polar air mass prevailing on the western side of the front (Bryndal *et al.* 2010).

DISCUSSION

Effects similar to those presented here have been discussed by other authors. Synoptic conditions of extremely heavy precipitation resulting in floods were described by, i.a., Řezáčova *et al.* (2005). In their opinion, the extremely heavy precipitation is enhanced by: a) a long-lasting air stream uplift on a frontal area associated with the low centre moving NE from over north Italy; b) an atmospheric low with a centre moving very slowly over an area experiencing the extremely heavy rainfall; c) substantial horizontal pressure gradients contributing to intensified precipitation due to orographic forcing during air mass advection from the northern sector. All those conditions were fulfilled in the cases analysed in this paper. Ustrnul and Czekierda (2001), too, found the heaviest rainfall in Poland to occur during the N-NE-E circulation and when a low pressure lobe or centre lies over central Europe. Numerous authors pointed to the importance of air mass advection along the van Bebber Vb trajectory (Kundzewicz *et al.* 2005) for generation of heavy rainfall and violent floods (Kundzewicz 2005). Such advection routes were presented in this paper by reconstructing advection trajectories at 4000 m a.g.l. The importance of lows advecting from the Mediterranean Sea was noticed also in the eastern part of the Czech Republic, particularly in the River Odra catchment (Kyselý and Beranová 2009).

CONCLUSIONS

1. Application of the HYSPLIT model to analyse advection of air masses on days with exceptionally heavy rainfall in Racibórz in July 1997 and in Dobczyce in May 2010 was very helpful in the description of the advection level-dependent differences in both directions and rates of air mass advection in the vertical profile. The origin areas of individual air masses were determined and the thermal and humidity-related characteristics of the air masses advecting simultaneously over the areas under study were described. The HYSPLIT model allowed to identify those air masses at various altitudes.
2. Analyses of air mass trajectories during both rainfall episodes described confirmed a strong effect of the Mediterranean air masses on the emergence of flood-producing rainfall. The analyses showed that, in both cases, tropical air masses could be identified at 4000 m a.g.l., the lower part of the profile showing the presence of the cold maritime polar air advecting from the northern sector.
3. Very important for the occurrence of heavy rainfall was the dynamic converged in the zone of atmospheric fronts separating thermally different air masses. The peculiar nature of those fronts, resulting in high precipitation totals, was caused by advection of very moist and warm air mass from the Mediterranean basins. Important was also the fact that the atmospheric low was blocked by high pressure systems situated east and north of Poland (Klejnowski 1997, Maciejewski *et al.* 2011).
4. The rainfall intensity and magnitude was affected also by the location of the precipitation on the windward side of the mountains. Thus, rainfall intensity was related not only to circulation, but also to orographic conditions. The precipitation occurring in the front zone increased locally on account of storm cells developing during the day (Klejnowski 1997).
5. The analysis allow to list the following conditions associated with the extremely high precipitation in Poland:

- the appearance of a quasi-stationary low moving over Central Europe from the northern sector;
- advection of very warm and humid tropical air mass from the Mediterranean basin (advection from S, followed by advection from E and NE);
- simultaneous advection of cool and moist maritime polar air (advection from the northern sector);
- intensive convergence in the front zone (uplift of warmer and more humid southern air over the cooler air advecting from the north).

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ADWEKCJA MAS POWIETRZA WARUNKUJĄCA FORMOWANIE SIĘ WYDAJNEGO OPADU ATMOSFERYCZNEGO W POLSCE NA PRZYKŁADZIE KATASTROFALNYCH POWODZI W RACIBORZU W LIPCU 1997 ORAZ W DOBCZYCACH W MAJU 2010

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Streszczenie. Cel pracy stanowi analiza kierunków napływu mas powietrza warunkujących wystąpienie opadów o bardzo dużych sumach wywołujących w konsekwencji wezbrania powodziowe w Raciborzu w lipcu 1997r. oraz w Dobczycach w maju 2010r. Analiza została przeprowadzona w oparciu o trajektorie wsteczne wygenerowane z modelu HYSPLIT. Model ten funkcjonuje w internecie w ramach systemu READY na stronie ARL (USA). Baza danych wykorzystana w modelu (Reanaliza NCEP/NCAR) zawiera w formie gridowej wartości pola meteorologicznego z powierzchni całej kuli ziemskiej, które są uaktualniane co trzy godziny. Model opracowany przez ARL został wykorzystany do wygenerowania trajektorii wstecznych w okresie od godziny 0.00 UTC 5. lipca do 6.00 UTC 9. lipca 1997r. (w interwałach czasowych 6. godzinnych) kończących się w Raciborzu (50,1^{o}N, 18,2^{o}E) oraz od godziny 6.00 UTC 15. maja do 6.00 UTC 19. maja 2010r. (w tych samych interwałach) kończących się w Dobczycach (49,9^{o}N, 20,1^{o}E). Trajektorie zostały wyznaczone na poziomach 500, 2000 oraz 4000 metrów nad poziomem gruntu. Przeprowadzone analizy wykazały, ze w obydwóch przypadkach na najwyższym poziomie (4000 m) powietrze napływało znad basenu Morza Śródziemnego. Na niższych poziomach powietrze napływało z szeroko rozumianego sektora północnego. Umożliwiało to adwekcję wilgotnych mas powietrznych z różnych obszarów zasilania. Bardzo duży wpływ na wystąpienie znacznych sum opadów miała intensywna konwergencja w strefie frontów atmosferycznych rozdzielających odmienne pod względem termicznym masy powietrza. Intensywność opadów spowodowana była nie tylko względami cyrkulacyjnymi ale również uwarunkowaniami orograficznymi. Wiązało się to z położeniem zarówno Raciborza, jak i Dobczyc w strefie pogórza.

Słowa kluczowe: trajektorie wsteczne, model HYSPLIT, nawalne i wydajne opady atmosferyczne, powodzie w Polsce w 1997 i 2010 r.