

İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

MESOSCALE ANALYSIS OF A SEVERE CONVECTION EVENT

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ŞİDDETLİ BİR KONVEKSİYON OLAYININ ORTA ÖLÇEKLİ ANALİZİ

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EYLÜL 2009

FOREWORD

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ABBREVIATIONS

ARW	: Advanced Research WRF
CAPE	: Convective Available Potential Energy
CCL	: Cumulative Condensation Level
CT	: Cross Total Index
DMC	: Deep Moist Convection
EL	: Equilibrium Level
LCL	: Lifting Condensation Level
LI	: Lifted Index
LFC	: Level of Free Convection
LSM	: Land Surface Model
MCC	: Mesoscale Convective Complex
MCS	: Mesoscale Convective System
NWP	: Numerical Weather Prediction
RH	: Relative Humidity
SREH	: Storm Relative Helicity
TT	: Total Total Index
VT	: Vertical Total Index
WPS	: WRF Preprocessing System
WRF	: Weather Research and Forecasting Modelling System

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MESOSCALE ANALYSIS OF A SEVERE CONVECTION EVENT

SUMMARY

Severe weather events are usually related with deep moist convection (DMC), and must be studied with mesoscale processes that favor them. Cloud resolving models are used to analyse severe convection, as well as high resolution observational networks. In this study, a severe convection case of 15 August 2004 in Marmara Region is analysed with WRF-ARW atmospheric model results, from synoptic scale to mesoscale, initialized with GFS data.

A broad investigation on the sensitivity of the model is tested before the simulation. Three domains with horizontal resolutions of 24 km (time step: 72 seconds), 8 km and 2.67 km with 45 vertical levels are used, creating the boundary conditions by two-way nesting procedure. After validation with observational data, cumulus scheme is chosen as Kain-Fritsch, WRF single moment 3-class-scheme is used for microphysics, NOAH land surface model is used with 4 layers, Monin-Obukhov with Zilitinkevich thermal roughness length scheme is used for surface physics, Mellor-Yamada-Janjic scheme is used for planetary boundary layer, and full diffusion dynamic option is used.

The model results are verified with traditional observations, as well as remote sensing data. The convection was very well forecasted by the model in synoptic scale. However, location and time of the tornadic supercell was not perfectly predicted, though success in creating the DMC cell with its severe features was satisfying.

The reasons of the severe convection are analysed with an ingredients-based methodology, namely the conditional instability, existence of LFC, and a lifting mechanism to make the parcel reach the LFC. In this case, synoptic and mesoscale effects played a role together to create a tornadic supercell. Conditional instability was existing with moderate CAPE values, and the moisture content was high enough due to the Black Sea. Frontal surface was a triggering factor for the convection. There was a convergence on the surface due to low level winds, favoring the updraft. Strong vertical wind shear was also a key factor for the severity of the supercell storm.

BİR ŞİDDETLİ KONVEKSİYON OLAYININ ORTA ÖLÇEKLİ ANALİZİ

ÖZET

Şiddetli hava olayları genel olarak derin nem konveksiyonu ile ilişkili olduklarından, orta ölçekli yaklaşımlarla incelenmelidirler. Şiddetli konveksiyon analizi için yüksek çözünürlüklü atmosfer modelleri kullanılmakta, yine radar, uydu vb yüksek çözünürlüklü gözlem verisi ile çalışmalar yapılmaktadır. Bu çalışmada 15 Ağustos 2004'te Marmara Bölgesi'nde meydana gelen bir şiddetli konveksiyon hadisesi ele alınmış, NCEP GFS verisi kullanılarak WRF-ARW atmosfer modeli ile elde edilen sonuçlar sinoptik ve orta ölçekte değerlendirilmiştir.

Çalışmadan önce modelleme için büyük çapta bir hassaslık analizi gerçekleştirilmiştir. 24 km (zaman adımı: 72 saniye), 8 km ve 2.67 km'lik yatay çözünürlüğe sahip üç domain, 45 düşey seviye ile çift-yön-nesting yöntemiyle çalıştırılmıştır. Yapılan verifikasyon sonucunda, Kain-Fritsch konvektif parametrisasyonu, WRF single moment 3-sınıf mikrofizik yaklaşımı, 4 seviyeli NOAH yer-yüzey modeli, Monin-Obukhov ve Zilitinkevich yüzey parametrisasyonu, Mellor-Yamada-Janjic atmosferik sınır tabaka modeli, ve tam difüzyon dinamik opsiyonu başarılı bulunmuştur.

Model sonuçları geleneksel gözlemlerin yanısıra uydu verileri ile de karşılaştırılmış, ve sinoptik ölçekte konveksiyonun gayet başarılı bir şekilde simüle edilebildiği görülmüştür. Öte yandan, tornado üreten super-hücreli fırtınanın tahmininde konum ve zaman olarak sapma gerçekleşmiş, ancak hücrenin pek çok özellikleriyle modellenebilmesi de tatmin edici bulunmuştur.

Şiddetli konveksiyonun nedenleri içerik-bazlı metodoloji ile incelenmiştir. Bu metodolojiye göre gerekli olan üç içerik, koşullu kararsızlık, LFC'nin mevcudiyeti, ve parseli LFC'ye taşıyacak bir kaldırma mekanizmasıdır. Konveksiyonun şiddetinde sinoptik ve orta ölçekli süreçlerin birlikte rol oynadığı tespit edilmiştir. Bölgede orta seviyedeki CAPE değerleri ile koşullu kararsızlık ve Karadeniz'den kaynaklanan yüksek nem mevcuttur. Cephesel yüzey, konveksiyonu tetikleyen bir mekanizma olmuştur. Alçak seviye rüzgarlarının neden olduğu yüzey konverjansı yükselişi desteklemiş, yüksek düşey rüzgar şiri de süper-hücreli fırtınanın şiddetinde anahtar bir rol oynamıştır.

1. INTRODUCTION

Although there are not many studies done in region, convective storms can cause severe weather and significant damage in Turkey. On 15.08.2004, parts of Marmara Region and western Black Sea were effected by severe convection that produced a tornadic supercell near Yalova. The F1 tornado caused no casualties since it was not over the urban area, but the farms and fields of 455 people in 10 villages were substantially damaged. Furthermore, high precipitation including hail with 3-4 cm diameter occurred over the area, according to the newspapers. Meteorologists have forecasted severe convection and related phenomena more than 3 days before the event and issued early warnings on time. However, no specific warnings about the small supercell or tornado could be done due to lack of a working meteorological radar and unpredictability.

One of the objectives of this study is to create a scientific awareness on severe weather occurrence over Turkey. Due to the fact that severe convection usually occurs over smaller scales of areas than the conventional observational network, voluntary reporters are essential for a database of such phenomena. In Turkey, this consciousness has yet started to appear. Since there is not reliable data about the severe convection storms in Turkey, there is also not any scientific study about the climatology of such storms done. In second chapter, a background over the area and related studies done in Europe are examined.

The main purpose of the thesis is applying a mesoscale modelling approach to a severe convection case in Turkey. This study can help improving the predictability of similar future events. In third chapter, the case is studied with a state-of-the-art mesoscale model, WRF-ARW, after a broad sensitivity analysis. Using the model results, an ingredients-based methodology is used to understand the phenomena, and reasons of severe convection are discussed as synoptic and mesoscale features.

Fourth chapter states the conclusion and recommendations.

2. SEVERE CONVECTION AND RECENT STUDIES IN EUROPE

2.1 Convection and Deep Moist Convection (DMC)

Convection is the transport of some property by fluid movement (Doswell, 2001, p. 1). This term is generally used for expressing heat transport, in addition to the other two processes conduction and radiation.

Atmospheric convection is the heat transport in the atmosphere by the vertical component of the flow associated with buoyancy. Advection, either vertical or horizontal, refers to the transport of heat (or another property) by the nonbuoyant flow. Buoyancy is defined as follows:

$$B = g \frac{T - T'}{T'} \quad 1.1$$

where g is the gravitational acceleration, T is the temperature of an air parcel, and T' is the environmental temperature. When the temperature of the air parcel is higher than that of the environment, buoyancy is positive, where lower parcel temperature makes the buoyancy negative.

Integration of buoyancy from the Level of Free Convection (LFC) to Equilibrium Level (EL) gives the Convective Available Potential Energy (CAPE), which is frequently used in analysing and forecasting severe convection.

$$CAPE = \int_{z_{LFC}}^{z_{EL}} g \frac{T - T'}{T'} dz \quad 2.2$$

Sometimes, hazardous weather can be associated with convection without thunder. That is why the term “Deep, Moist Convection” (DMC) is preferred instead of the term “thunderstorm”, by some scientists.

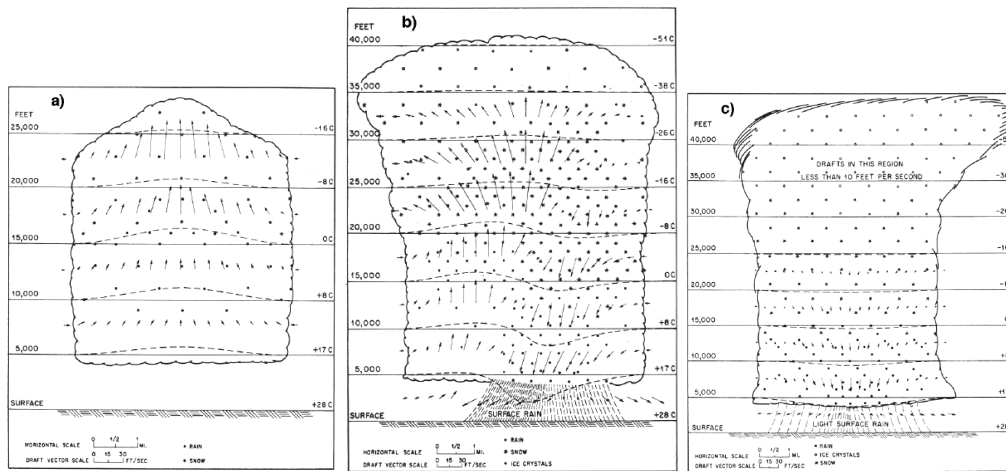


Figure 2.1 : Classic thunderstorm cell schematics from Byers and Braham (1949) showing the (a) the cumulus stage, (b) the mature stage, and (c) the dissipating stage.

The origin of modern concepts of DMC is the famous Thunderstorm Project and Byers and Braham's report (1949). Other projects followed the path of this study, like the mesonetwork used by Fujita (1955), the NSSL mesonetworks analyzed by Barnes (1978), the National Hail Research Experiment described by Foote and Knight (1979) and the Florida Area Cumulus Experiment described by Barnston et al. (1983). Doswell states this as "a key concept grew out of this project: the thunderstorm cell" (2001). As depicted in Byers and Braham (1949), the cell is the basic organizational structure of all thunderstorms (Fig. 1.1.a, Fig. 1.1.b, Fig. 1.1.c) and this notion became the fundamental paradigm for deep moist convection (Doswell, 2001). Browning (1964) created the idea of supercell, using the thunderstorm cell paradigm as a basis for his ideas. This concept was also used for a taxonomy of severe hailstorms developed by Marwitz (1972a,b,c). Warner 1970, 1972; Simpson 1971, 1972; and Newton 1963 worked on how the entrainment was occurring in thunderstorms. Stommel's (1947), Scorer and Ludlam's (1953), Squires and Turner's (1962) ideas on entrainment of environmental air to be occurring along the lateral boundaries of the cloud was criticized by them, like penetrative downdrafts within the cloud might have been contributing substantially to entrainment. Levine's (1959) bubble theory for entrainment was rediscovered by Blyth (1993) with a modification, proposing that the major form of entrainment for convection is via the "toroidal" circulation like a smoke ring, associated with the "thermal" model of a convective cloud.

Doswell states that our perceptions of convective structure are highly dependent on the observing system being employed. Classifications based on radar are not necessarily equivalent to those developed from satellite imagery, and so on. The most intense severe convective weather is associated with organized DMC (2001). The term “organized” refers to squall lines, mesoscale convective systems (MCS) and supercells. The details of these DMC structures will not be reviewed here.

2.2 Recent Studies About Severe Weather in Europe

There are many studies done about severe storms and tornadoes not only in USA, but also in whole world. Here, some of the recent significant studies in Europe will be cited.

Tornado climatologies of Austria and Portugal can be some examples for creating one for Turkey. Holzer performed a tornado climatology of Austria in 2001, using a database of 89 tornadoes, one landspout and 6 waterspouts. Leita0 (2003) also made a tornado climatology of Portugal, using 30 tornadoes that occurred from 1936 to 2002.

Garcia-Herrera et al (2005) studied on the characterization of mesoscale convective systems over Spain with a 3-year database. Rigo and Llasat (2007) worked on a climatology of mesoscale convective systems in the northeast of the Iberian Peninsula, on the basis of meteorological radar observations, using the period of 1996 to 2000. Sanches et al (2003) presented an analysis based on a classification of METEOSAT images for hail events in the Ebro Valley over Northeastern Spain. A logistic regressive analysis has been applied in the study and the results showed the difficulties encountered in forecasting the formation of MCSs on the basis of preconvective variables.

In addition to general studies, there are also many case studies performed. Lopez (2007) performed a case study for a derecho over Catalonia using a high resolution observation network and radar data. Takemi (2007) studied on the sensitivity of squall-line intensity to environmental static stability under various shear and moisture conditions. Putsay and friends (2008) made a case study of mesoscale convective systems over Hungary on 29 June 2006 with satellite, radar and lightning

data. Furthermore, Kaspar et al (2008) studied a severe storm in Bavaria, the Czech Republic and Poland on 12–13 July 1984. They performed a statistic- and model-based analysis. Aran et al (2008) made a synoptic and mesoscale analysis of an F2 tornado event over Catalonia, and Kaltenböck (2004) studied a mesoscale analysis of a case study of a MCS over northeast of the Alps. These high resolution observation network based studies are maybe the most objective way to examine such phenomena.

The most popular way of studying severe weather is numerical modelling. Modern atmospheric models have the capability of simulating mesoscale meteorological features with high accuracy, when used with a good initial condition and proper physics / dynamics packages. Some of the studies done with models are given here. Knupp et al (1998) described a mini-supercell storm over northern Alabama through a combined observational analysis and numerical modelling study. RAMS was used as the modelling tool. Martin et al (2006)'s case study on a heavy precipitation event was performed with MM5 simulations. Ortega and friends (2008) worked on a sensitivity study of two severe storm cases in the Southeastern Andes using MM5. Keil and Hagen (2000) evaluated high resolution simulations with radar data, using two models; Deutschland Model and Canadian MC2 Research model. Krichak and friends (2000) studied a severe convection case of 02.11.1994 in the southeastern Mediterranean using MM5. Horvath et al (2008) wrote a paper on numerical modeling of severe convective storms occurring in the Carpathian Basin. They examined two case studies, one pre-frontal squall line and one frontal convective line, using MM5. Garcia-Ortega et al (2007) made a sensitivity study of a severe hailstorm in northeastern Spain using MM5. Bechtold and Bazile (2001) worked on a case study of a flash flood over southern France using ALADIN with ARPEGE input. The methodology such studies follow is to simulate the atmospheric conditions accurately, verified by observations, and perform synoptic to mesoscale analysis subjectively. The case study in third chapter also follows this path.

3. CASE STUDY OF A SEVERE CONVECTION EVENT IN TURKEY

3.1 Objective

Main objective of this case study is to analyse a severe convection event with respect to its mesoscale properties, to define a severe weather phase on the region. As the number of such studies will increase, operational forecasting of severe weather events and early warnings will be able to be performed accurately.

3.2 Methodology

An ingredients-based methodology is used within this study. Doswell's three ingredients for deep moist convection are basically known as the conditional instability, a moisture source and a lifting mechanism. The question is, how these three ingredients occurred and came together at our case. As the physical reasons of these ingredients will be able to be explained, the analysis will be done.

In order to see how the three ingredients come together, we must have a mesoscale analysis of the meteorological conditions of the case. Mostly, meteorological stations are not dense enough with respect to horizontal resolution, to analyse a convection case which requires a fine scale observation network in terms of space and time. To create a satisfactory high resolution analysis, mesoscale models can be used to dynamically downscale coarse resolution data. In this study, this approach is used to investigate the mesoscale analysis of the severe weather case.

3.2.1 Mesoscale modelling with WRF-ARW

The Weather Research and Forecasting (WRF) model is known as a replacement of MM5, a numerical weather prediction (NWP) and atmospheric simulation system designed for both research and operational applications. The development of WRF has been a multi-agency effort to build a next-generation mesoscale forecast model

and data assimilation system to advance the understanding and prediction of mesoscale weather and accelerate the transfer of research advances into operations. The WRF effort has been a collaborative one among the National Center for Atmospheric Research's (NCAR) Mesoscale and Microscale Meteorology (MMM) Division, the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Prediction (NCEP) and Earth System Research Laboratory (ESRL), the Department of Defense's Air Force Weather Agency (AFWA) and Naval Research Laboratory (NRL), the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma, and the Federal Aviation Administration (FAA), with the participation of university scientists in USA (Skamarock et al., 2008).

WRF has a wide physics and dynamics options, as well as a data assimilation and chemistry modelling tool.

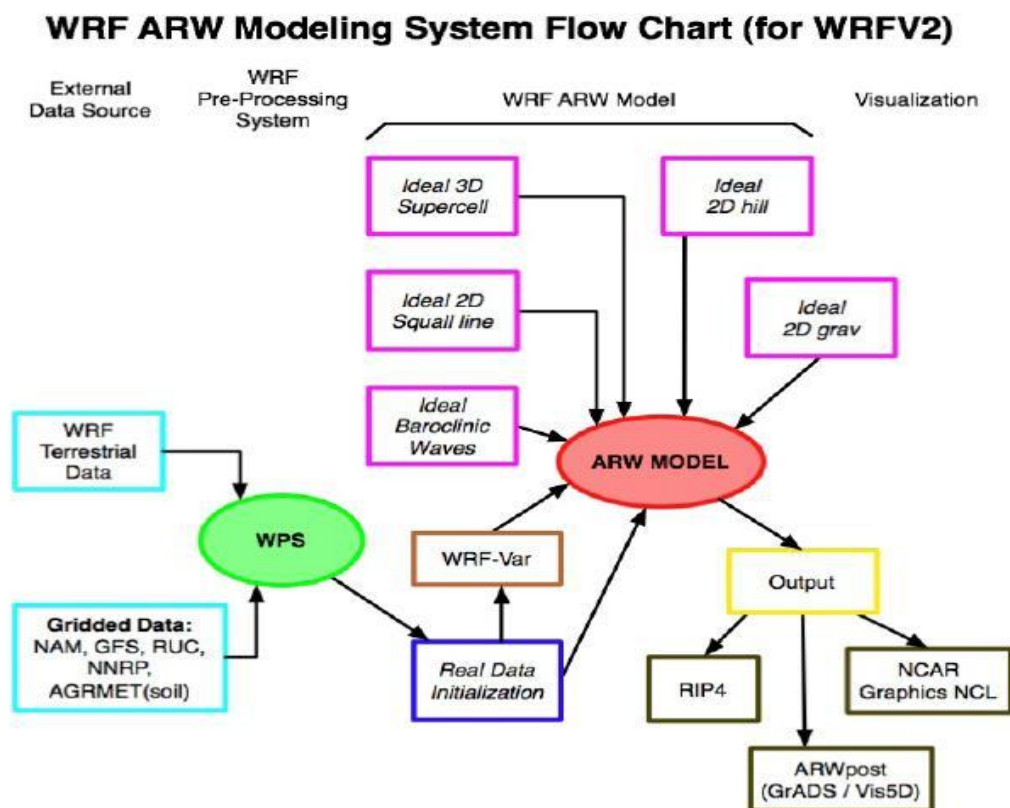


Figure 3.1: Flow Chart for WRF-ARW.

The model uses terrain-following, hydrostatic-pressure vertical coordinate (Figure 3.2) with the top of the model being a constant pressure surface. The horizontal grid WRF uses is the Arakawa-C grid. The time integration scheme in the model uses the third-order Runge-Kutta scheme, and the spatial discretization employs 2nd to 6th order schemes. Lamber Comformal, Polar Stereographic and Mercator are the three projections WRF supports.

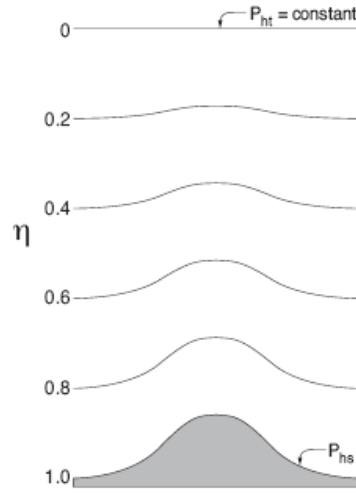


Figure 3.2: ARW sigma coordinate

To make a real data forecast with WRF-ARW, three steps are followed. First is the preprocessing, second is the model run, and the last is the visualisation part. In figure 3.1, flow chart of WRF-ARW can be seen.

Preprocessing system of WRF has three stages; geogrid, ungrib and metgrid. Geogrid is a program which creates the domain according to the WPS namelist and TBL files. The static data including topography, terrains, land use etc are processed at this stage per domain. Ungrib performs degribbing the gribbed atmospheric variables data. Finally, metgrid puts the output of the geogrid and ungrib together on new netcdf files, ready for the real.exe.

After the completion of preprocessing, met_em files for the whole time of the simulation must be ready for the ARW model. These files are used as input to real.exe, which is a program interpolating the fields to the vertical levels defined by the namelist.input file of the WRF. After the real.exe process is successfully completed, the model solver starts its calculation and performs the simulation.

Output of the model can be visualised with tools like RIP, NCL, GrADS, PyNGL, Vis5D, VAPOR, etc.

3.3 Description of Study Area

The area of the case study is The Marmara Region of Turkey, which is the most populized and industrialized part of the country. Including the historical Istanbul, where is also the heart of the business and culture in Turkey, surrounded by Black Sea, Eagean Sea, Balkans, Anatolia, and including an inland sea –Marmara-, the area has been always important throughout the ages.

With its mid-latitude geography and complex topography, Eastern Mediterranean is an area which has very interesting climatological features. Marmara Region lays down on the path of polar fronts, even sometimes arctic fronts visit the area. In addition to such frontal phases, it also receives the Asor and Siberia Highs' effects, with a seasonal variability. Dry air from high mountains of Balkans and Anatolia, as well as moist air from Marmara, Black Sea and Eagean have different aspects in weather conditions in whole region.

Figure 3.3 shows a map of the area studied.

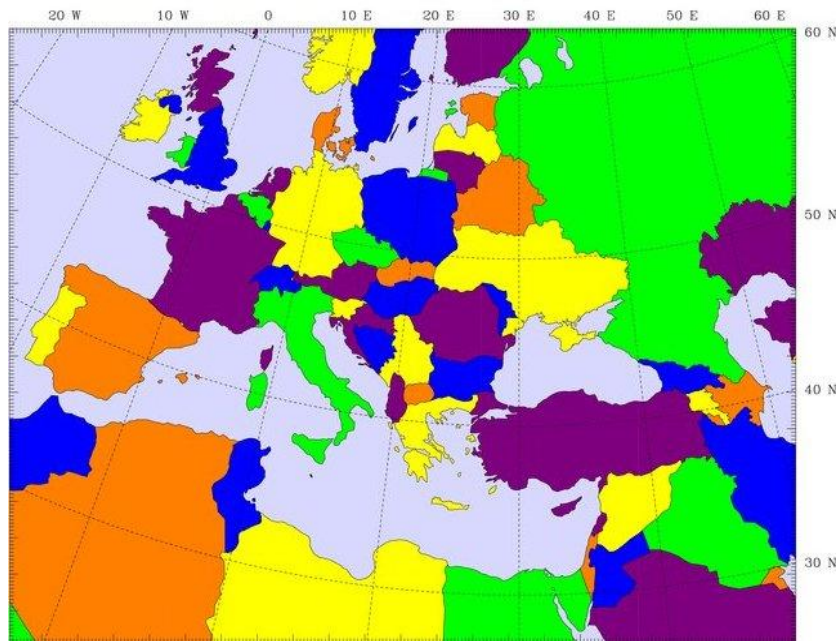


Figure 3.3: Map of the area studied.

3.4 Data

The data used in the model is of two types: The static data and the variable data.

The static data includes the geographical features like terrain height, land use, soil categories, provided by the WRF model. Four different resolutions can be chosen according to the resolution interest for the studies. The resolutions are 10', 5', 2' and 30". Within this study, 10' data is used for the first domain (24 km horizontal resolution), 5' data is used for the second domain (8 km horizontal resolution) and 30" data is used for the third domain (2.7 km horizontal resolution). All static fields are used as an input for geogrid, which is a WPS program interpolating and locating the data into the selected domain's grid points. Table 3.1 is the table of the land use, and Table 3.2 is of the soil categories defined within the static data. Figure 3.4 shows how the land use is described in the first domain.

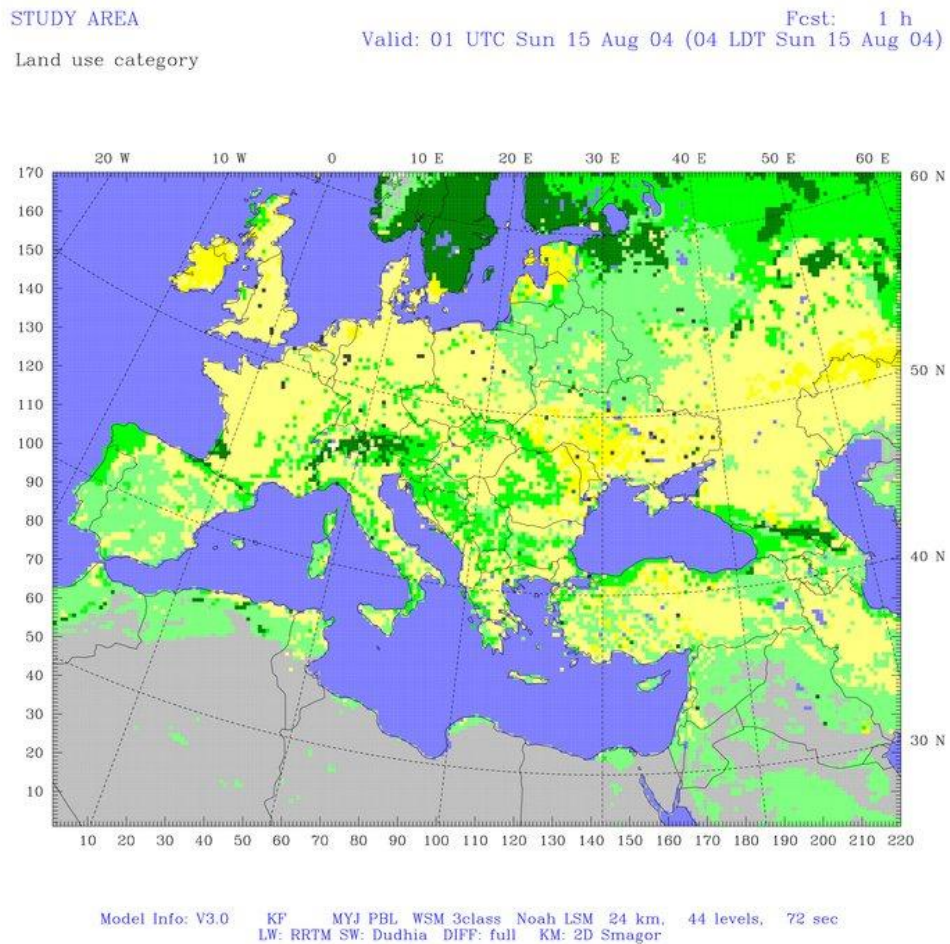


Figure 3.4: Land use category for the first domain with 24 km horizontal resolution.

Table 3.1: USGS 24-category Land Use Categories

Land Use Category	Land Use Description
1	Urban and Built-up Land
2	Dryland Cropland and Pasture
3	Irrigated Cropland and Pasture
4	Mixed Dryland/Irrigated Cropland and Pasture
5	Cropland/Grassland Mosaic
6	Cropland/Woodland Mosaic
7	Grassland
8	Shrubland
9	Mixed Shrubland/Grassland
10	Savanna
11	Deciduous Broadleaf Forest
12	Deciduous Needleleaf Forest
13	Evergreen Broadleaf
14	Evergreen Needleleaf
15	Mixed Forest
16	Water Bodies
17	Herbaceous Wetland
18	Wooden Wetland
19	Barren or Sparsely Vegetated
20	Herbaceous Tundra
21	Wooded Tundra
22	Mixed Tundra
23	Bare Ground Tundra
24	Snow or Ice

Table 3.2: 16-category Soil Categories

Soil Category	Soil Description
1	Sand
2	Loamy Sand
3	Sandy Loam
4	Silt Loam
5	Silt
6	Loam
7	Sandy Clay Loam
8	Silty Clay Loam
9	Clay Loam
10	Sandy Clay
11	Silty Clay
12	Clay
13	Organic Material
14	Water
15	Bedrock
16	Other (land-ice)

The variable data includes the variables of the atmosphere, oceans and lands. NCEP final operational analysis data is used as the variable-input to the model. The data are on 1.0x1.0 degree grids continuously at every six hours. This product is from the Global Forecast System (GFS) that is operationally run four times a day in near-real time at NCEP. The analyses are available on the surface, at 26 mandatory (and other pressure) levels from 1000mb to 10mb, in the surface boundary layer and at some sigma layers, the tropopause and a few others. Data is in GRIB format, which is converted into another raw format by the ungrib tool inside the WPS. Tables 3.3 and 3.4 show the variables included in this dataset.

Table 3.3 : 28 parameters from NCEP Parameter Code Table 1 included in NCEP final operational analysis dataset.

Parameter Code	Short Name	Description	Units
1	PRES	Pressure	Pa
2	PRMSL	Pressure reduced to MSL	Pa
7	HGT	Geopotential height	gpm
10	TOZNE	Total ozone	Dobson
11	TMP	Temperature	K
13	POT	Potential temperature	K
27	GPA	Geopotential height anomaly	gpm
33	U GRD	u-component of wind	m s ⁻¹
34	V GRD	v-component of wind	m s ⁻¹
39	V VEL	Pressure vertical velocity	Pa s ⁻¹
41	ABS V	Absolute vorticity	s ⁻¹
51	SPF H	Specific humidity	kg kg ⁻¹
52	R H	Relative humidity	%
54	P WAT	Precipitable water	kg m ⁻²
65	WEASD	Water equivalent of accumulated snow depth	kg m ⁻²
71	T CDC	Total cloud cover	%
81	LAND	Land cover	fraction
91	ICE C	Ice concentration	fraction
131	LFT X	Surface lifted index	K
132	4LFTX	Best (4 layer) lifted index	K
136	VW SH	Vertical speed shear	s ⁻¹
144	SOILW	Volumetric soil moisture content	fraction
154	O3MR	Ozone mixing ratio	kg kg ⁻¹
156	CIN	Convective inhibition	J kg ⁻¹
157	CAPE	Convective available potential energy	J kg ⁻¹
221	HPBL	Planetary boundary layer height	m
222	5WAVH	5-wave geopotential height	gpm
230	5WAVA	5-wave geopotential height anomaly	

Table 3.4 : 32 parameters from NCEP Parameter Code Table 2 included in NCEP final operational analysis dataset.

Parameter Code	Short Name	Description	Units
1	PRES	Pressure	Pa
2	PRMSL	Pressure reduced to MSL	Pa
7	HGT	Geopotential height	gpm
10	TOZNE	Total ozone	Dobson
11	TMP	Temperature	K
13	POT	Potential temperature	K
15	TMAX	Maximum temperature	K
16	TMIN	Minimum temperature	K
27	GPA	Geopotential height anomaly	gpm
33	UGRD	u-component of wind	m s ⁻¹
34	VGRD	v-component of wind	m s ⁻¹
39	VVEL	Pressure vertical velocity	Pa s ⁻¹
41	ABSV	Absolute vorticity	s ⁻¹
51	SPFH	Specific humidity	kg kg ⁻¹
52	RH	Relative humidity	%
54	PWAT	Precipitable water	kg m ⁻²
65	WEASD	Water equivalent of accumulated snow depth	kg m ⁻²
71	TCDC	Total cloud cover	%
76	C WAT	Cloud water	kg m ⁻²
81	LAND	Land cover	fraction
91	ICEC	Ice cover	fraction
131	LFTX	Surface lifted index	K
132	4LFTX	Best (4 layer) lifted index	K
136	VSSH	Vertical speed shear	s ⁻¹
144	SOILW	Volumetric soil moisture content	fraction
153	CLWMR	Cloud water mixing ratio	kg kg ⁻¹
154	O3MR	Ozone mixing ratio	kg kg ⁻¹
156	CIN	Convective inhibition	J kg ⁻¹
157	CAPE	Convective available potential energy	J kg ⁻¹
221	HPBL	Planetary boundary layer height	m
222	5WAVH	5-wave geopotential height	gpm
230	5WAVA	5-wave geopotential height anomaly	

In addition to the model input data, satellite images of METEOSAT-7 supplied by Turkish State Meteorological Service and TRMM data retrieved from NASA are used for verification.

3.5 Sensitivity Analysis

In order to understand the sensitivity of the model to the lateral boundaries, physical parameterizations, dynamical approaches, horizontal resolution, number of vertical levels, time step and other parameters, several simulations have been performed before the experiment. Table 3.1 shows the elements of the tests and namelist variables.

The first aim of the tests was to determine the lateral boundaries for the simulation. Lateral boundaries of a selected domain has a very important role in simulation, because lateral boundary conditions depend on this. If the observations at the lateral boundaries do not represent the “real” weather conditions, then the regional model will create “unreal” patterns in whole domain. To adjust the best lateral boundaries, one must choose topographically homogeneous and uniform areas as the edges of the domain. This helps the possibility of the topography of the model domain to be more similar to that of the global model output or observation data used, as well as calculations of the relaxation zone to be more “natural”. That’s why three different domains are tested as the first experiments, with all other parameters being constant.

Figure 3.5 shows the first two domains used in sensitivity analysis elements 1 and 2. The first domain was found to be too large for a mesoscale model run due to the planetary scale facts and also with respect to computational time. The final study is performed with a domain smaller than both these domains.

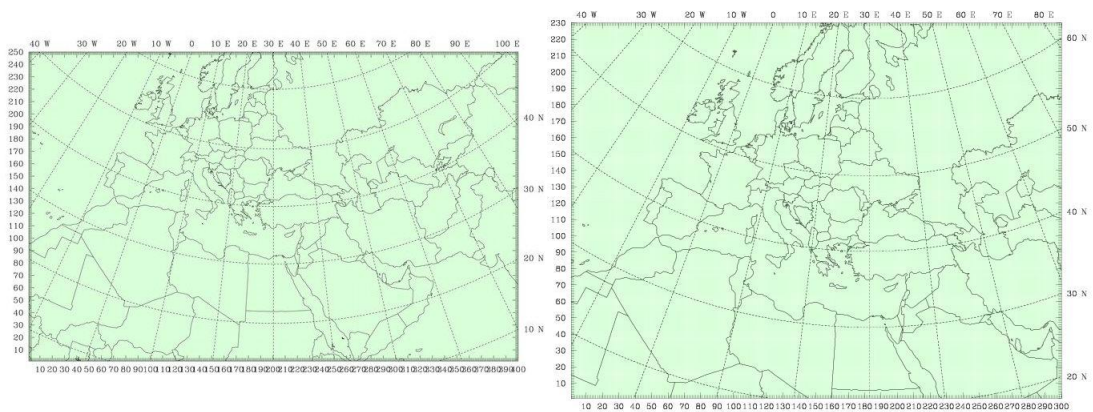


Figure 3.5: Domains of the sensitivity analysis test elements 1 and 2, named as (a) and (b). Horizontal resolutions of both domains are 24 km.

Table 3.5. Sensitivity Analysis Elements.

RUN	domain	cu	mp	radiation	initalization	lsm	layer	time step
1	a	1	3	1	14.08, 00:00	1	5	120
2	b	1	3	1	14.08, 00:00	1	5	120
3	c	1	3	1	14.08, 00:00	1	5	120
4	b 1: 3: 5	1,1,0	3,3,3	1,1,1	14.08, 00:00	1,1,1	5,5,5	120
5	b 1: 3: 5	5,5,5	3,3,3	1,1,1	14.08, 00:00	1,1,1	5,5,5	120
6	b 1: 3: 5	2,2,2	3,3,3	1,1,1	14.08, 00:00	1,1,1	5,5,5	120
7	d 1	1	3	1	14.08, 00:00	1	5	120
8	d 1: 3: 5	1,1,0	3,3,3	1,1,1	14.08, 00:00	1,1,1	5,5,5	120
9	d 1: 3: 5	5,5,5	3,3,3	1,1,1	14.08, 00:00	1,1,1	5,5,5	120
10	d 1: 3: 5	2,2,2	3,3,3	1,1,1	14.08, 00:00	1,1,1	5,5,5	120
11	d 1: 3: 5	1,1,0	5,5,5	1,1,1	14.08, 00:00	1,1,1	5,5,5	120
12	d 1: 3: 5	1,1,0	5,5,5	99,99,99	14.08, 00:00	1,1,1	5,5,5	120
13	d 1: 3: 5	1,1,0	3,3,3	1,1,1	15.08, 00:00	1,1,1	5,5,5	120
14	d 1: 3: 5	5,5,5	3,3,3	1,1,1	15.08, 00:00	1,1,1	5,5,5	120
15	last 1: 3: 3	1,1,1	3,3,3	1,1,1	15.08, 00:00	1,1,1	5,5,5	120
16	last 1: 3: 3	5,5,5	3,3,3	1,1,1	15.08, 00:00	1,1,1	5,5,5	120
17	last 1: 3: 3	2,2,2	3,3,3	1,1,1	15.08, 00:00	1,1,1	5,5,5	120
18	last 1: 3: 3	1,1,1	3,3,3	1,1,1	15.08, 00:00	2,2,2	4	75
19	last 1: 3: 3	1,1,1	3,3,3	1,1,1	15.08, 00:00	1,1,1	5,5,5	120
20	last 1: 3: 3	1,1,1	5,5,5	1,1,1	15.08, 00:00	1,1,1	5,5,5	120
21	last 1: 3: 3	1,1,1	5,5,5	99,99,99	15.08, 00:00	1,1,1	5,5,5	120
22	last 1: 3: 3	1,1,1	3,3,3	1,1,1	15.08, 00:00	1,1,1	5,5,5	120
23	last 1: 3: 3	1,1,1	3,3,3	1,1,1	15.08, 00:00	1,1,1	5,5,5	120
24	last 1: 3: 3	3,3,3	3,3,3	1,1,1	15.08, 00:00	1,1,1	5,5,5	120
25	last 1: 3: 3	1,1,1	3,3,3	1,1,1	15.08, 00:00	1,1,1	5,5,5	120
26	last 1: 3: 3	1,1,1	3,3,3	1,1,1	15.08, 00:00	1,1,1	5,5,5	120
27	last 1: 3: 3	99,99,99	3,3,3	1,1,1	15.08, 00:00	1,1,1	5,5,5	120
28	last 1: 3: 3	1,1,1	3,3,3	1,1,1	15.08, 00:00	1,1,1	5,5,5	72
29	last 1: 3: 3	1,1,1	3,3,3	1,1,1	14.08, 12:00	1,1,1	5,5,5	120
30	last 1: 3: 3	1,1,1	3,3,3	1,1,1	15.08, 00:00	2,2,2	4	72
31	last 1: 3: 3	1,1,1	3,3,3	1,1,1	14.08, 18:00	1,1,1	5,5,5	120
32	last 1: 3: 3	1,1,1	3,3,3	1,1,1	15.08, 00:00	1,1,1	5,5,5	120
33	last 1: 3: 3	1,1,1	3,3,3	1,1,1	15.08, 00:00	2,2,2	4	72

Table 3.5. Sensitivity Analysis Elements (continued).

sfclay	pbl	co2tf	rk_ord	diff_6th_opt	hydrostatic	vertical levels	spec_ bdy_width	relax	diff_opt	data
1	1			2	non-h	27		4	1	GFS
1	1			2	non-h	27		4	1	GFS
1	1			2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1			2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
2	2			2,2,2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1	1		2,2,2	non-h	27		4	1	GFS
1	1		3	1,1,1	non-h	27		4	1	GFS
1	1			2,2,2	hydrostatic	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	45,45,45		4	1	GFS
1	1			2,2,2	non-h	27	1	0	1	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	2	GFS
1	1			2,2,2	non-h	27		4	1	GFS
2	2			2,2,2	non-h	45,45,45		4	2	GFS
1	1			2,2,2	non-h	27		4	1	GFS
1	1			2,2,2	non-h	27		4	1	ECMWF
2	2			2,2,2	non-h	45,45,45		4	2	ECMWF

Experiments 4, 5 and 6 are performed with three domains using two-way nesting procedure with the domain b as the mother domain, to test three cumulus parameterization schemes (Kein Fritsch, Grell 3d ensemble, Betts-Miller-Janjic), holding all other parameters fixed. Second domain had a horizontal resolution of 8 km, where third had 1.6 km. Since the this is fine enough with respect to horizontal resolution, no cumulus parameterization is used at 4th experiment's third domain. Grell-3d ensemble scheme is designed for a high resolution run according to the users guide of the model, so it is used in all domains of 5th experiment. BMJ is also used in all three domains.

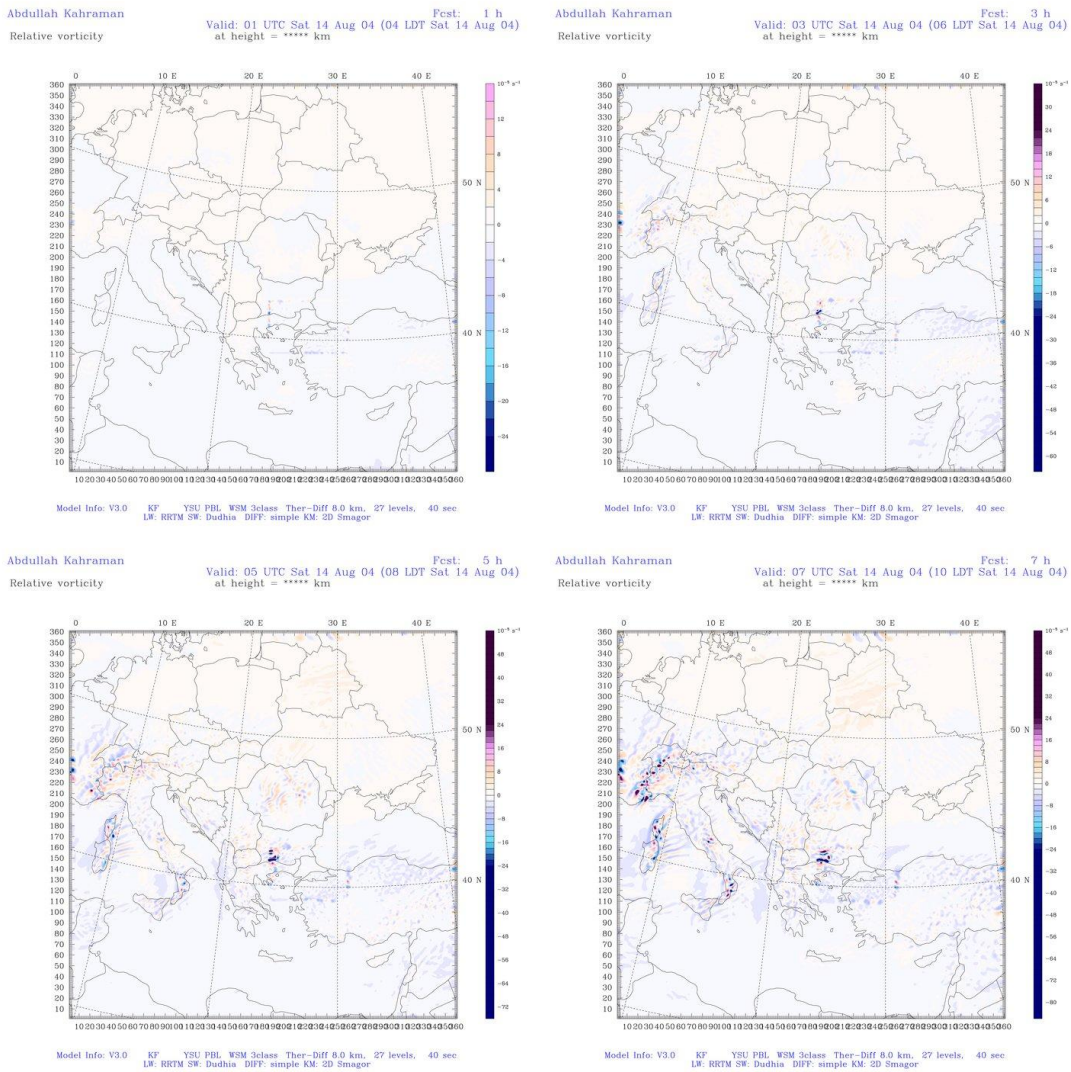


Figure 3.6: 1500 m relative vorticity plots of the second domain of 4th experiment. The boundaries of the third domain (surrounding the Marmara Region) create unnatural waves.

While these tests were performed to see the difference of precipitation patterns of three cumulus parameterization schemes, one other fact about the importance of domain choice appeared. Especially the relative vorticity plots showed clearly that there was something wrong at the edges of the very-fine-resolution third domain. Figure 3.6 shows the evolution of “unnatural” waves related to the lateral boundaries of this domain. Such patterns occurred also with the 5th and 6th experiments, so the reason of these patterns was not the cumulus parameterization scheme, but something different. Then the topography of the third domain is plotted, and the high mountains at the edges were thought to be the reason of these waves. Figure 3.7 shows the terrain height of the third domain used at 4th, 5th and 6th experiments.

Abdullah Kahraman

Valid: 00 UTC Sat 14 Aug 04 (03 LDT Sat 14 Aug 04) Fcst: 0 h

Terrain height AMSL

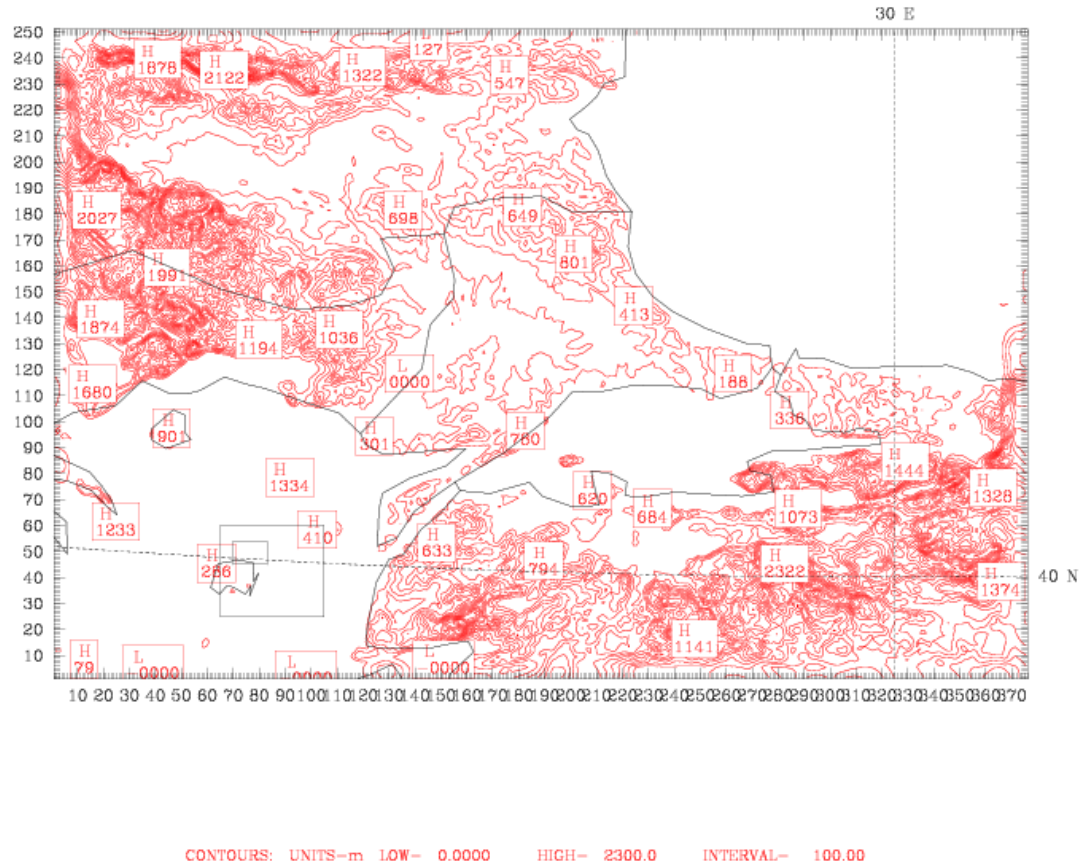


Figure 3.7: Third domain’s terrain height above mean sea level, used at 4th, 5th and 6th experiments. The mountainous zone at the northwest is significant.

At seventh experiment, a new main domain is tested. 8th, 9th and 10th experiments are performed with this main domain and additional two nested domains to test the cumulus parameterization schemes again. Eta microphysics parameterization is used with 11th experiment, instead of WRF Single-Moment-3 class scheme. With 12nd experiment, GFDL (Eta operational scheme) radiation schemes (both for shortwave and longwave radations) are used with Eta microphysics. 13rd and 14th experiments were performed to see how different initial conditions effect the simulation results.

Although this bunch of experiments (from 7th to 14th) showed how some main physical parameterizations effect the simulations, they have not been found accurate

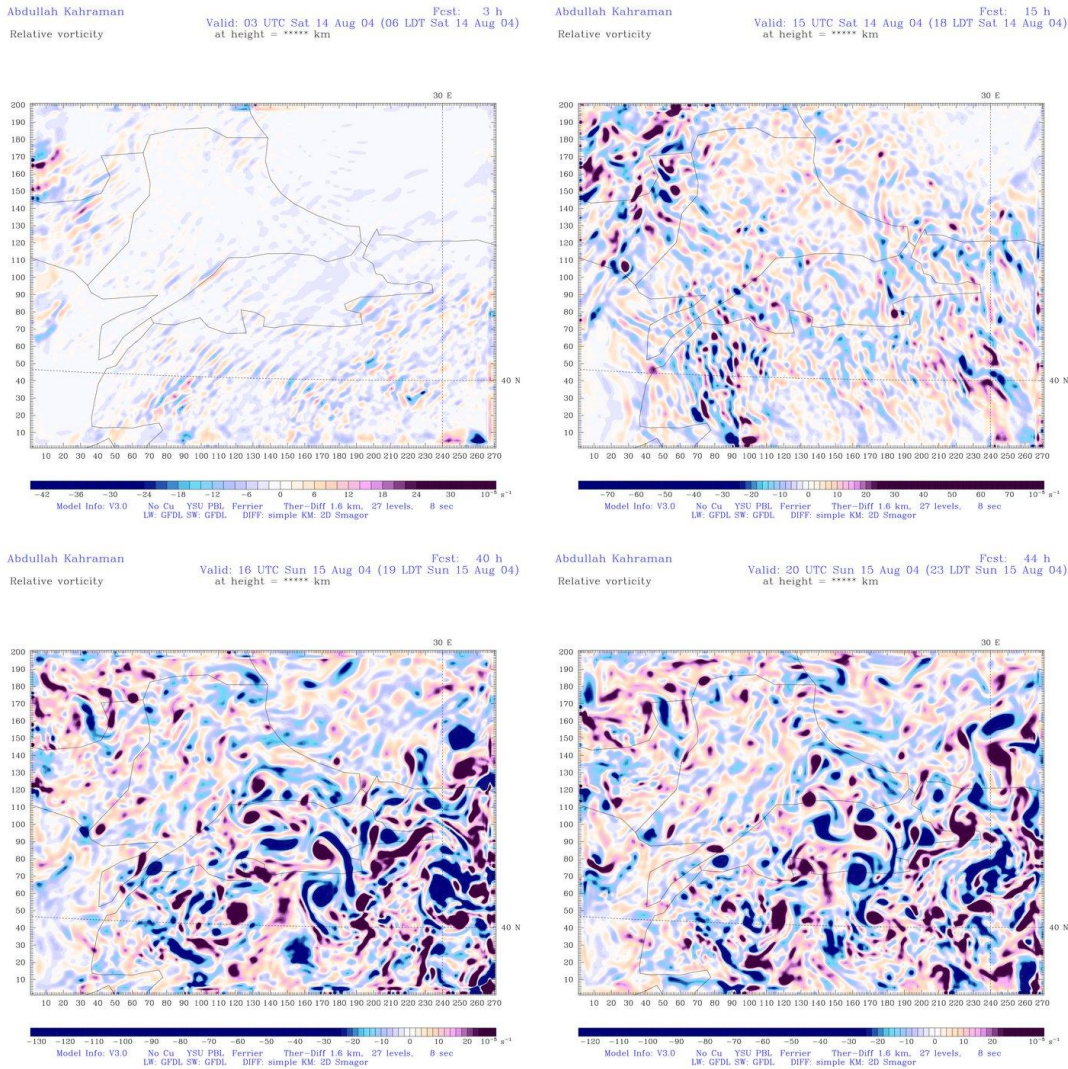


Figure 3.8: 1500 m relative vorticity plots of the third domain of experiment 12 for t+3, t+15, t+40 and t+44. See the topography at western lateral boundary creating unnatural waves in all plots.

enough. The problem with the third domain's lateral boundaries was not as bad as the 4th, 5th and 6th experiment's one, but still remained at different points of the edges. Figure 3.8 shows some of the 1500 m level relative vorticity plots of the third domain of the 12nd run. At the western boundary, near the 170th grid point, a source of an “unnatural” wave is occurring. After these results, it is understood that the topography of the Balkans were too steep to be a boundary of a 1:5 aspect ratio nesting. That's why, the aspect ratio between second and third domain is determined to be 1:3 like it is, between the first and second domain. All of the next experiments are performed with 1:3:3 aspect ratio domains, called as “last” domain choice. The details of the last domain can be found at the namelist.wps file, printed on page 40.

15th, 16th, 17th, 24th and 27th experiments are the cumulus parameterizations tests for the “last” domain choice. All five available schemes of the model could be tested with these runs. Results are compared with a script which calculates the RMSE and BIAS statistics of some main parameters of the whole output. Tables 3.6 to 3.10 show these statistics for cumulus parameterization tests.

18th experiment is performed with the Noah Land Surface Model and gave better results than the default 5-layer thermal diffusion as LSM, according to the RMSE and BIAS scores, which are shown at Table 3.7. Compared to the Table 3.6, it is obvious that forecasts of almost all parameteres are improved with this LSM.

Table 3.6: RMSE and BIAS statistics for the second domain of 15th experiment.

parameter	RMSE	BIAS
T	-0.41980010	1.34151399
QVAPOR	-0.00002452	0.00072632
QCLOUD	0.00000075	0.00001301
QRAIN	0.00000063	0.00001672
U	-0.13463899	1.73248506
V	-0.29448953	1.81327438
W	-0.00246523	0.05883734
PH	-16.09216309	70.96009827
PHB	0.02366149	127.23658752
MUB	-0.28473541	180.04959106
U10	0.00305741	1.71484196
V10	-0.75020468	1.77986085

Table 3.7: RMSE and BIAS statistics for the second domain of 16th experiment.

parameter	RMSE	BIAS
T	-0.44989517	1.35609746
QVAPOR	-0.00001589	0.00073180
QCLOUD	0.00000130	0.00001892
QRAIN	0.00000018	0.00000434
U	-0.13126636	1.72015059
V	-0.30209583	1.80025303
W	-0.00253718	0.05822026
PH	-19.00615120	71.08341980
PHB	0.02366149	127.23658752
MUB	-0.28473541	180.04959106
U10	-0.02382110	1.70702112
V10	-0.73529977	1.78133678

Table 3.8: RMSE and BIAS statistics for the second domain of 17th experiment.

parameter	RMSE	BIAS
T	-0.42610377	1.35205960
QVAPOR	-0.00002982	0.00073044
QCLOUD	0.00000088	0.00001564
QRAIN	0.00000077	0.00001742
U	-0.13172835	1.77840269
V	-0.29324630	1.85239935
W	-0.00250439	0.05898664
PH	-18.55657005	73.32422638
PHB	0.02366149	127.23658752
MUB	-0.28473541	180.04959106
U10	0.00720553	1.72295427
V10	-0.74605560	1.78405702

Table 3.9: RMSE and BIAS statistics for the second domain of 24th experiment.

parameter	RMSE	BIAS
T	-0.44126621	1.35820508
QVAPOR	-0.00001782	0.00073187
QCLOUD	0.00000124	0.00001838
QRAIN	0.00000014	0.00000328
U	-0.12867534	1.72293091
V	-0.29637909	1.79107964
W	-0.00261242	0.05949474
PH	-17.13443375	71.49693298
PHB	0.02366149	127.23658752
MUB	-0.28473541	180.04959106
U10	-0.00837070	1.70468199
V10	-0.71741563	1.76612532

Table 3.10: RMSE and BIAS statistics for the second domain of 27th experiment.

parameter	RMSE	BIAS
T	-0.46403620	1.37078536
QVAPOR	-0.00001840	0.00072533
QCLOUD	0.00000126	0.00001880
QRAIN	0.00000077	0.00002711
U	-0.12704837	1.75677311
V	-0.30051172	1.80252326
W	-0.00254363	0.05933808
PH	-19.02210426	70.72624969
PHB	0.02366149	127.23658752
MUB	-0.28473541	180.04959106
U10	0.00684567	1.71931839
V10	-0.70963013	1.76146841

Table 3.11: RMSE and BIAS statistics for the second domain of 18th experiment.

parameter	RMSE	BIAS
T	-0.43328232	1.32718968
QVAPOR	0.00000253	0.00065834
QCLOUD	0.00000074	0.00001284
QRAIN	0.00000058	0.00001456
U	-0.10519053	1.71023738
V	-0.23071042	1.79039860
W	-0.00253149	0.05793478
PH	-14.72518635	69.38451385
PHB	0.02366149	127.23658752
MUB	-0.28473541	180.04959106
U10	0.07234187	1.65581787
V10	-0.60270309	1.68508255

Mellor-Yamada-Janjic scheme for planetary boundary layer (PBL) is tested with Monin-Obukhov with Zilitinkevich surface layer scheme option at 19th experiment. RMSE and BIAS scores of this test is shown at Table 3.12.

Experiment 20 and 21 have the Eta microphysics instead of WRF-Single-Moment-3 class scheme. 21 is performed with Eta radiation schemes for both shortwave and longwave. Statistics for these runs, which can be seen at Tables 3.13 and 3.14 indicate that these physical parameterizations are not better than the default ones.

Table 3.12: RMSE and BIAS statistics for the second domain of 19th experiment.

parameter	RMSE	BIAS
T	-0.57406127	1.47866547
QVAPOR	0.00012830	0.00097297
QCLOUD	0.00000065	0.00001384
QRain	0.00000060	0.00001492
U	-0.17349011	1.77619600
V	-0.25964779	1.80933619
W	-0.00302824	0.05015026
PH	-23.34939194	76.33452606
PHB	0.02366149	127.23658752
MUB	-0.28473541	180.04959106
U10	0.08273333	1.97083759
V10	-0.80356473	1.97025681

Table 3.13: RMSE and BIAS statistics for the second domain of 20th experiment.

parameter	RMSE	BIAS
T	-0.34011883	1.33145094
QVAPOR	-0.00004322	0.00073977
QCLOUD	0.00000057	0.00001398
QRain	0.00000013	0.00000546
U	-0.13871635	1.74422026
V	-0.28871560	1.83372617
W	-0.00239768	0.05914829
PH	-7.58681059	71.19757843
PHB	0.02366149	127.23658752
MUB	-0.28473541	180.04959106
U10	0.03498381	1.74826205
V10	-0.72759897	1.78250623

Table 3.14: RMSE and BIAS statistics for the second domain of 21st experiment.

parameter	RMSE	BIAS
T	-0.15759936	1.20540357
QVAPOR	-0.00003912	0.00074395
QCLOUD	0.00000066	0.00001474
QRain	0.00000009	0.00000326
U	-0.14336081	1.73450089
V	-0.30870369	1.80103719
W	-0.00223211	0.05793579
PH	9.97217274	70.98815155
PHB	0.02366149	127.23658752
MUB	-0.28473541	180.04959106
U10	0.02296653	1.72466338
V10	-0.73885560	1.75841856

Instead of the default 2nd order, recommended 3rd order Runge-Kutta dynamics is used at experiment 22. diff_6th_opt parameter was also chosen as 1. However, as seen at Table 3.15, almost no improvement could be gained with this option, where the test was more expensive with respect to computation time.

23rd experiment was performed to see how accurate the results would be, when the model is run with hydrostatic option. The simulation was a bit faster, but scores were not so much satisfactory. The RMSE and BIAS scores are calculated according to the second domain, which has a 8 km horizontal resolution, and almost all parameters are forecasted worse than non-hydrostatic run. So it is clear that with higher resolutions, this option will make the forecast just less accurate. Table 3.16 shows the statistics of hydrostatic run.

Table 3.15: RMSE and BIAS statistics for the second domain of 22nd experiment.

parameter	RMSE	BIAS
T	-0.43502462	1.34549725
QVAPOR	-0.00002176	0.00071989
QCLOUD	0.00000080	0.00001271
QRAIN	0.00000057	0.00001478
U	-0.12689239	1.71436620
V	-0.29390034	1.79741037
W	-0.00256617	0.05229823
PH	-18.11697960	70.93245697
PHB	0.02366149	127.23658752
MUB	-0.28473541	180.04959106
U10	0.01191605	1.69555211
V10	-0.74891400	1.76443696

Table 3.16: RMSE and BIAS statistics for the second domain of 23rd experiment.

parameter	RMSE	BIAS
T	-0.46731880	1.37395537
QVAPOR	-0.00000522	0.00074576
QCLOUD	0.00000161	0.00002241
QRAIN	0.00000103	0.00002429
U	-0.19031216	1.75898802
V	-0.29910493	1.80942643
W	0.00054295	0.01059786
PH	-26.68663979	73.68075562
PHB	0.02366149	127.23658752
MUB	-0.28473541	180.04959106
U10	-0.15205720	1.72201800
V10	-0.77430010	1.74610722

25th experiment is performed to see the effect of number of vertical levels. Instead of default value 27, 45 levels are used with this run. Although the computational time takes longer, this brings out a better forecast especially with convection cases.

The lateral boundaries can be used with or without relaxation at a regional model. Default WRF relaxation zone has 4 points. With 26th experiment, no relaxation is tested. No significant change was observed with this experiment.

28th experiment is the test of the diffusion term taken as 2, instead of 1. As model documentation didn't recommend this option, it gave worse results than the default one. Also due to the halt of the run, time step had to be decreased while using this option.

Initialization was at 00z with all experiments until experiment 29. With this experiment, 12z of 14 August 2004, and with 31st experiment, 18z of the same day are taken as initial times. Probably due to the fact that these are more unstable times of the day at the domain area, the scores were worse than those of 00z initializations.

With all “good” options, a final experiment, number 30 is performed as a member of the sensitivity analysis and gave the best results though. Table 3.17 shows the RMSE and BIAS statistics for this run. All analysis are done according to this simulation.

Table 3.17: RMSE and BIAS statistics for the second domain of 30th experiment.

parameter	RMSE	BIAS
T	-0.31079173	1.19597328
QVAPOR	0.00001821	0.00070228
QCLOUD	0.00000045	0.00001093
QRAIN	0.00000050	0.00001273
U	-0.11205843	1.75780678
V	-0.18146902	1.79373264
W	-0.00375682	0.05371501
PH	-5.92352057	71.40837860
PHB	0.02681876	120.20515442
MUB	-0.28473541	180.04959106
U10	0.23694731	1.98098481
V10	-0.81036532	1.97479606

Experiments 31 and 32 were done with ECMWF data as input, instead of GFS data. Although these runs had better results at middle and higher levels of the troposphere, there was a problem with the surface level temperatures and humidity, so that convection was not successfully created at the boundary layer. To overcome this problem, instead of using the surface fields, interpolation from 1000 hPa level can be tried with next studies.

Furthermore, CHAMP data from COSMIC system was assimilated to create better initial conditions. However, due to the small number of data available, the results did not bring any improvement.

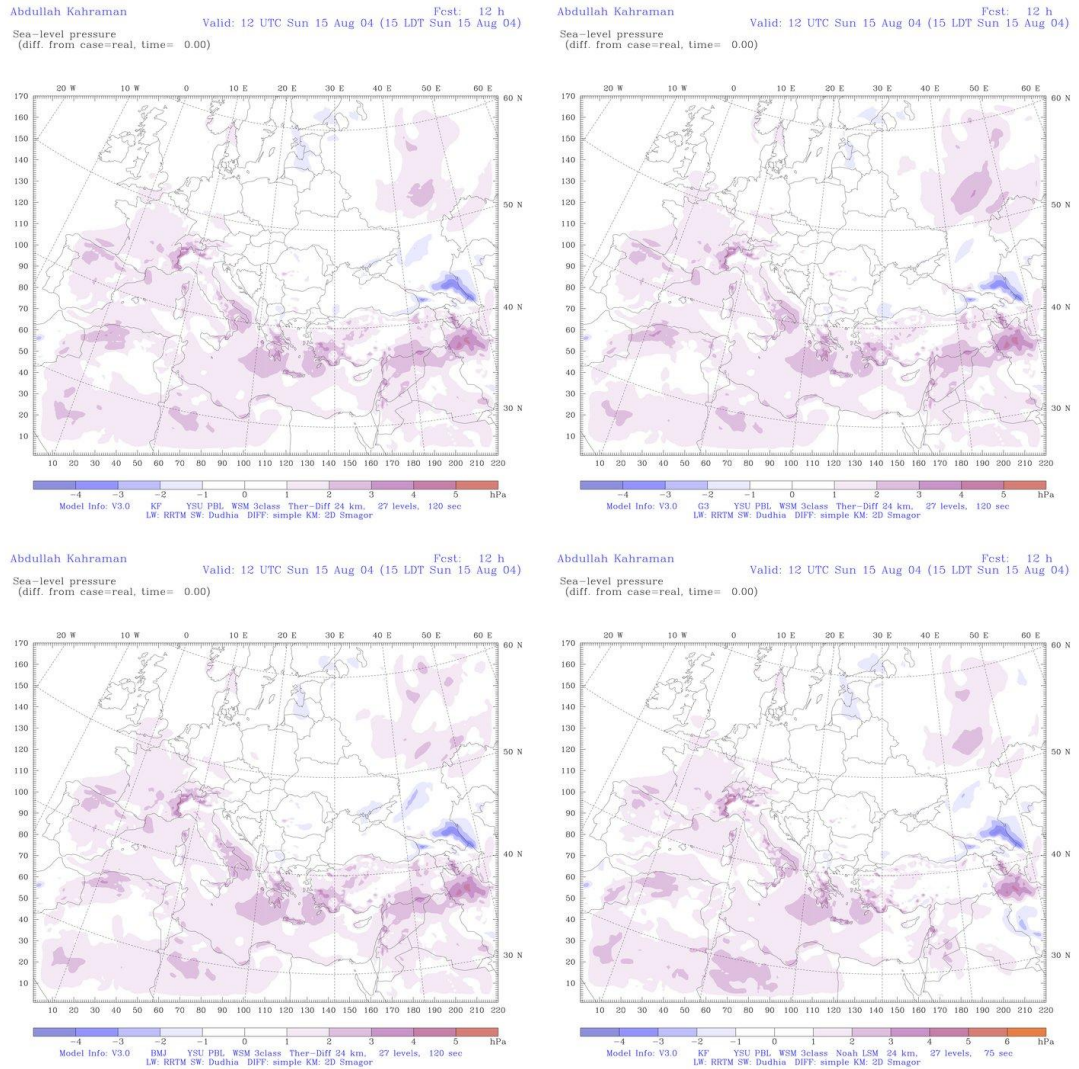
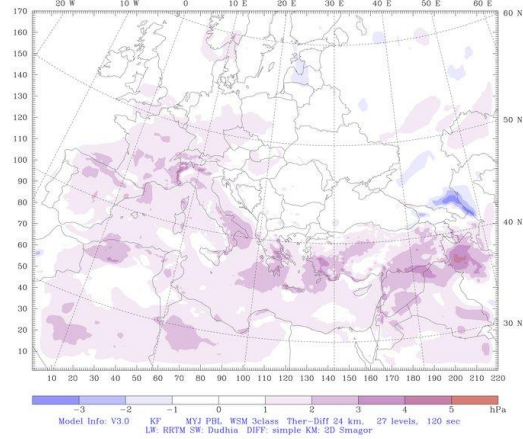
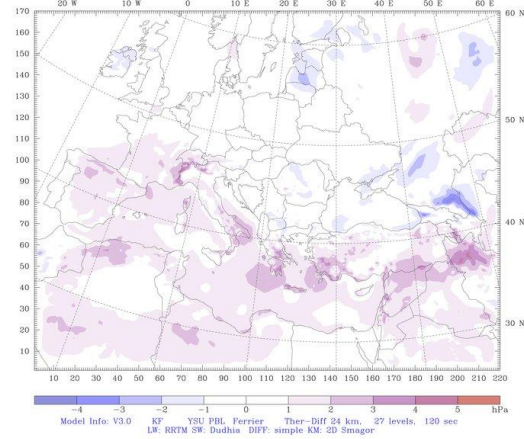


Figure 3.9: Mean sea level pressure difference of the forecast and the observation at 12z on 15.08.2004, according to the sensitivity test elements 15, 16, 17 and 18.

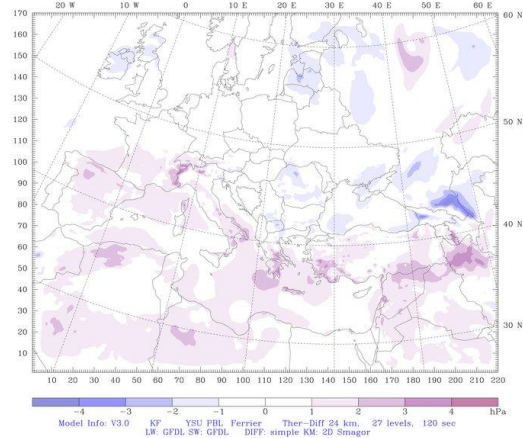
Abdullah Kahraman Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04) Fcst: 12 h
Sea-level pressure
(diff. from case=real, time= 0.00)



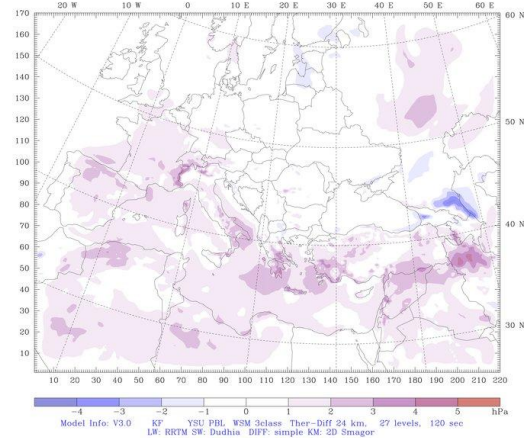
Abdullah Kahraman Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04) Fcst: 12 h
Sea-level pressure
(diff. from case=real, time= 0.00)



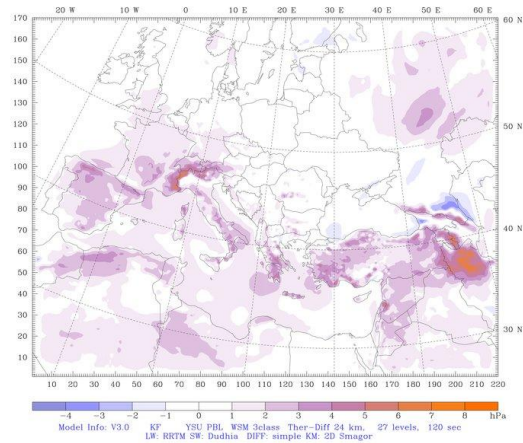
Abdullah Kahraman Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04) Fcst: 12 h
Sea-level pressure
(diff. from case=real, time= 0.00)



Abdullah Kahraman Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04) Fcst: 12 h
Sea-level pressure
(diff. from case=real, time= 0.00)



Abdullah Kahraman Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04) Fcst: 12 h
Sea-level pressure
(diff. from case=real, time= 0.00)



Abdullah Kahraman Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04) Fcst: 12 h
Sea-level pressure
(diff. from case=real, time= 0.00)

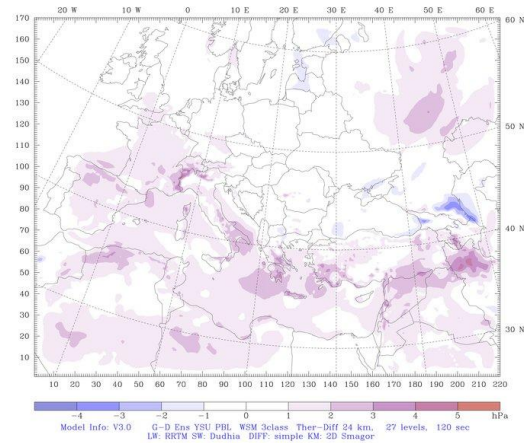


Figure 3.9 (cont.): Mean sea level pressure difference of the forecast and the observation at 12z on 15.08.2004, according to the sensitivity test elements 19, 20, 21, 22, 23 and 24.

Figure 3.9 shows the mean sea level pressure difference between the forecasts of the sensitivity test elements and the observations for the coarse domain, on 15.08.2004 12UTC, when the convection is playing a major role at the area. With a general look, model seems to be overestimating the mean sea level pressure over Mediterranean and lower latitudes. A negative bias can be seen near Caspian Sea, Baltic Sea and

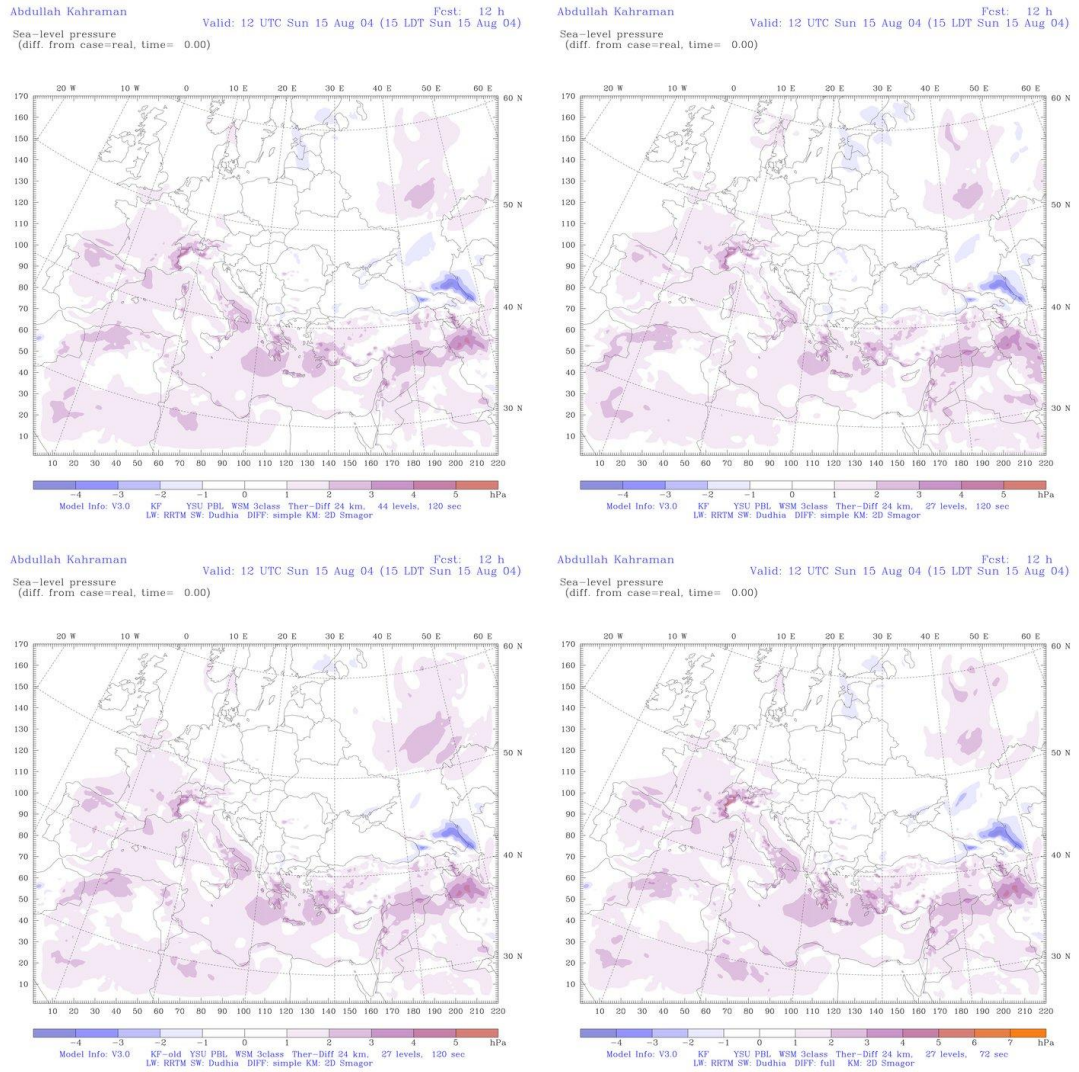


Figure 3.9 (cont.): Mean sea level pressure difference of the forecast and the observation at 12z on 15.08.2004, according to the sensitivity test elements 25, 26, 27, 28.

Sea-level pressure
(diff. from case=real, time= 0.00)

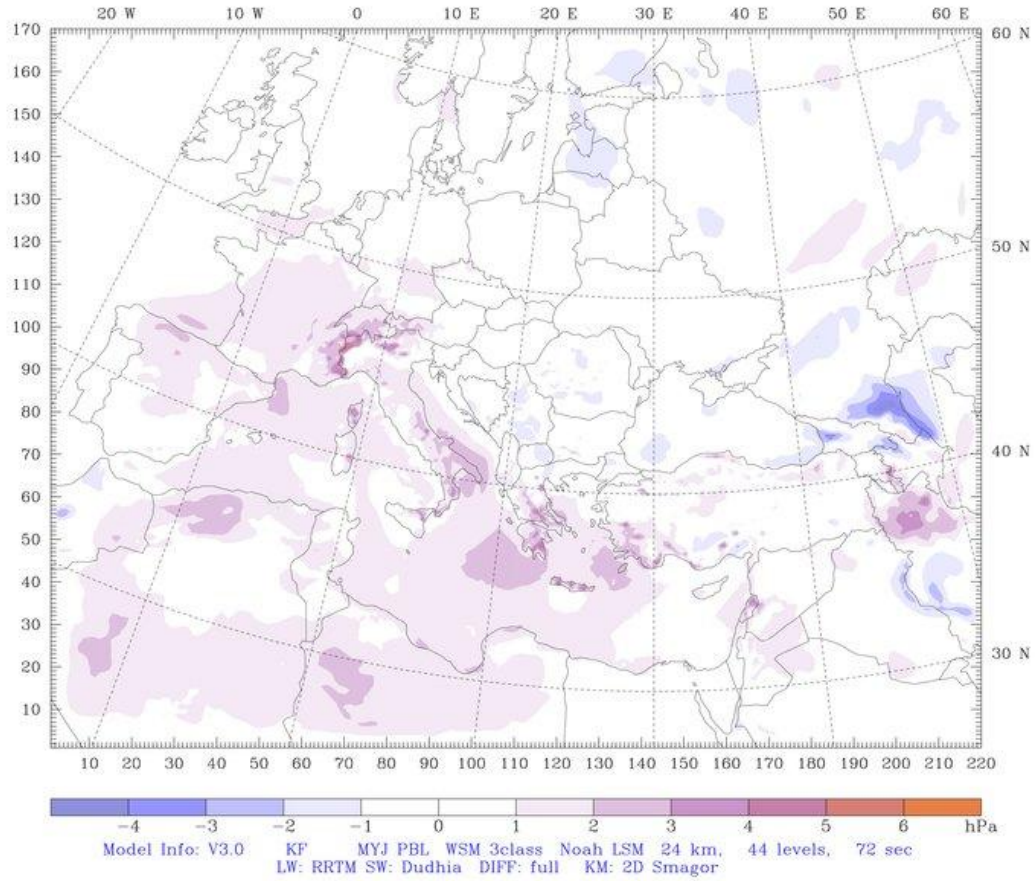


Figure 3.9 (cont.): Mean sea level pressure difference of the forecast and the observation at 12z on 15.08.2004, according to the sensitivity test element 30.

north part of the Black Sea where the low pressure is effecting. It is obvious that the 23rd run, which was a test for seeing how hydrostatic approach works, has important problems forecasting the mean sea level pressure, especially on mountainous regions like Northern Iran, Anatolia and Alps. The most succesful run according to an overall look at these plots can be analysed as 30th run, which also gave the best numerical results in RMSE and BIAS statistics.

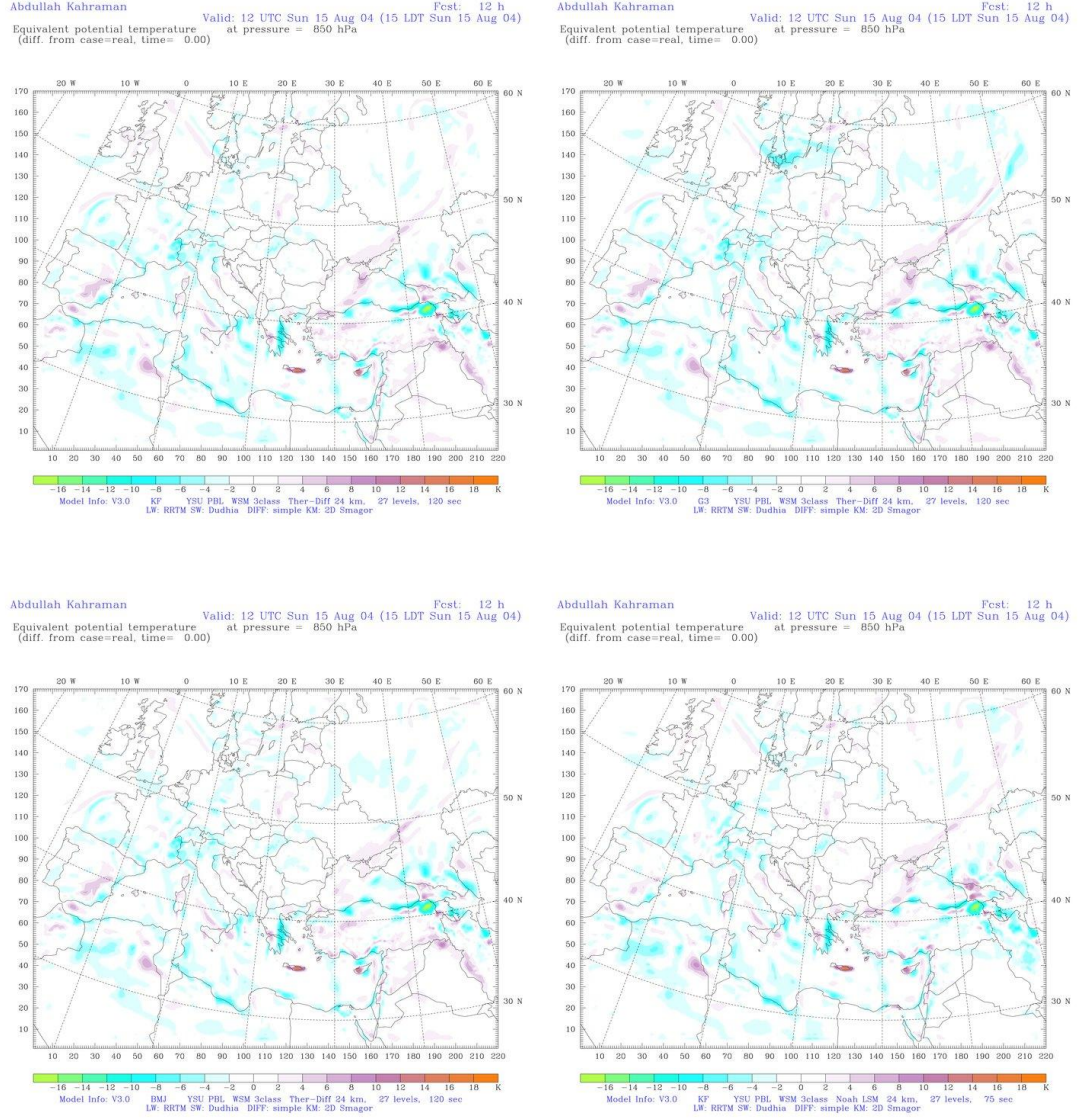
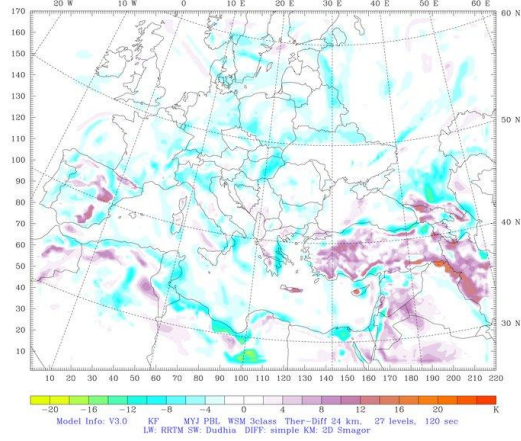


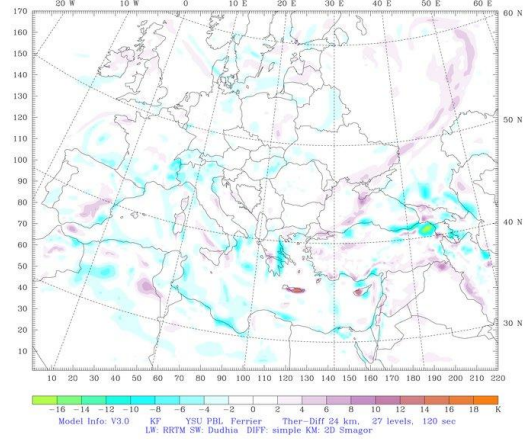
Figure 3.10: 850 hPa level equivalent potential temperature difference of the forecast and the observation at 12z on 15.08.2004, according to the sensitivity test elements 15, 16, 17 and 18.

Figure 3.10 shows the equivalent potential temperature differences of the forecasts and the observations at 850 hPa level, for 15.08.2004 12UTC. It can be commented that the model works fine in general, noting that there are negative and positive bias areas in the domain. The planetary boundary layer scheme test, 19th run features an overestimate over the southeast regions of the domain.

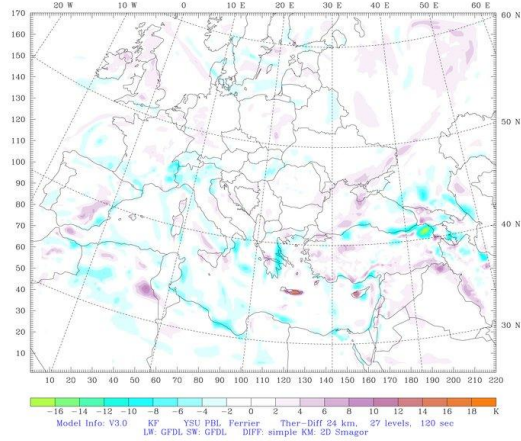
Abdullah Kahraman Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04) Fcst: 12 h
Equivalent potential temperature at pressure = 850 hPa
(diff. from case=real, time= 0.00)



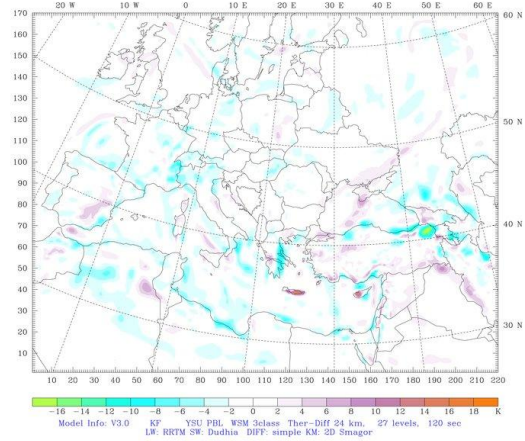
Abdullah Kahraman Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04) Fcst: 12 h
Equivalent potential temperature at pressure = 850 hPa
(diff. from case=real, time= 0.00)



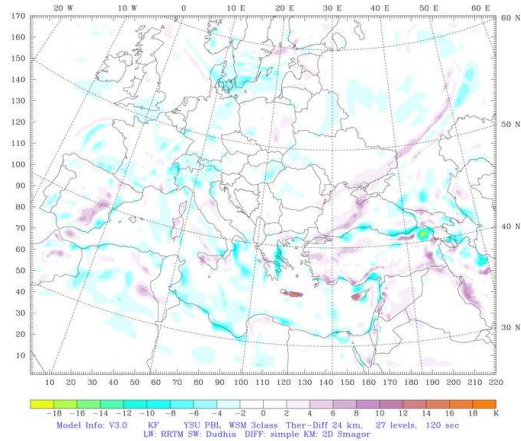
Abdullah Kahraman Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04) Fcst: 12 h
Equivalent potential temperature at pressure = 850 hPa
(diff. from case=real, time= 0.00)



Abdullah Kahraman Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04) Fcst: 12 h
Equivalent potential temperature at pressure = 850 hPa
(diff. from case=real, time= 0.00)



Abdullah Kahraman Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04) Fcst: 12 h
Equivalent potential temperature at pressure = 850 hPa
(diff. from case=real, time= 0.00)



Abdullah Kahraman Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04) Fcst: 12 h
Equivalent potential temperature at pressure = 850 hPa
(diff. from case=real, time= 0.00)

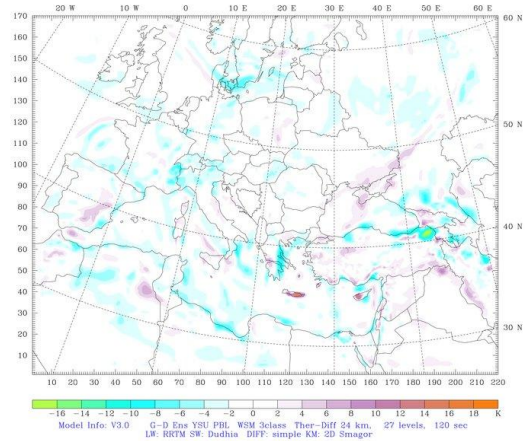


Figure 3.10 (cont.): 850 hPa level equivalent potential temperature difference of the forecast and the observation at 12z on 15.08.2004, according to the sensitivity test elements 19, 20, 21, 22, 23 and 24.

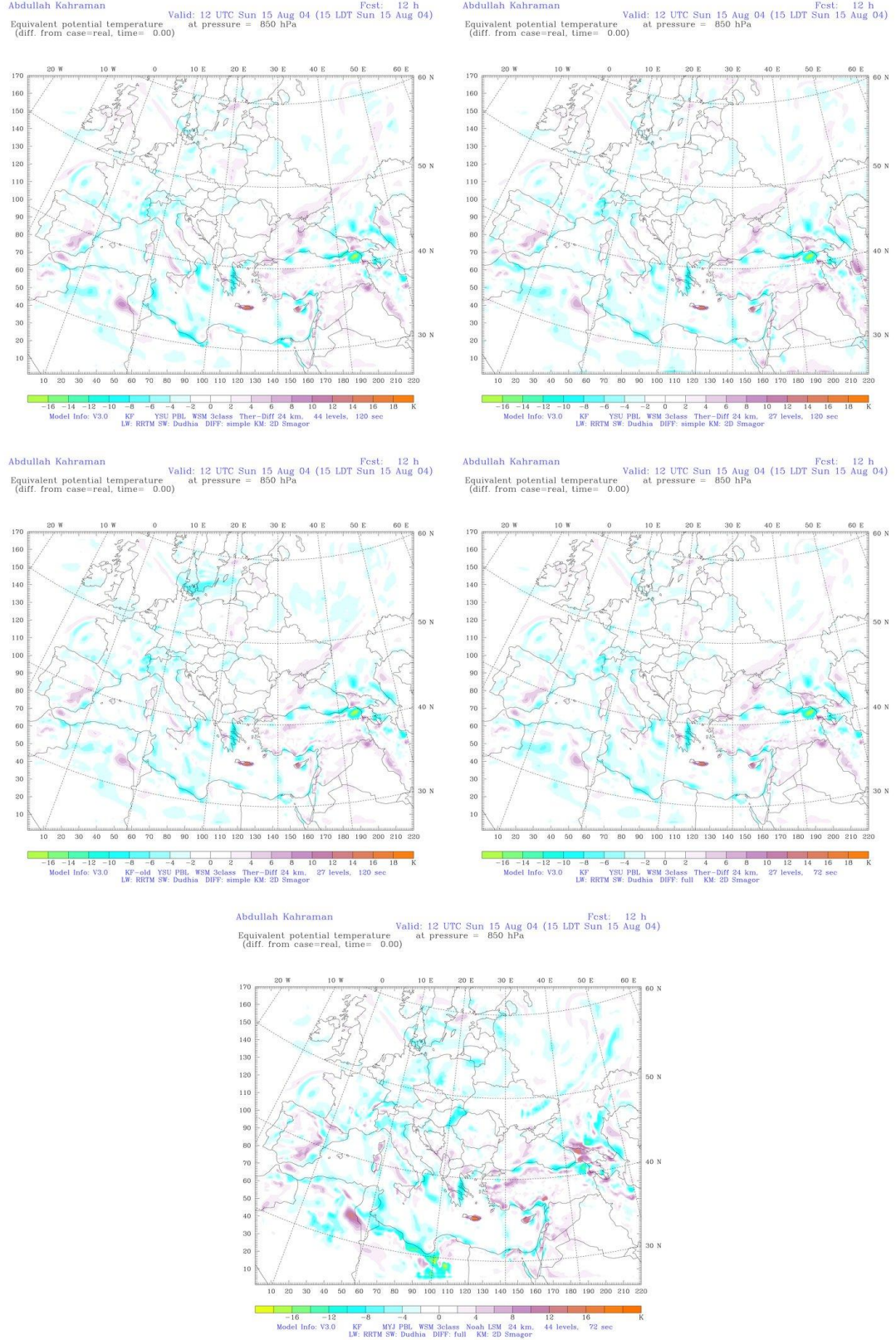


Figure 3.10 (cont.): 850 hPa level equivalent potential temperature difference of the forecast and the observation at 12z on 15.08.2004, according to the sensitivity test elements 25, 26, 27, 28 and 30.

Appendix A.4 is given for a clear look how the parameterization choice effects the forecast with respect to the total precipitation amount, a parameter which can be said to be effected by all other parameters used in the model. The figures show the fine-scale forecast of precipitation between 05UTC and 06UTC of 15.08.2004, including the rainfall from the severe storm studied. These results can be compared to the TRMM rainfall estimations, given at Appendix A.5.

The most important parameterization is the cumulus parameterization, which is tested by the 15th, 16th, 17th, 24th and 27th runs. It is seen that Grell 3-d ensemble cumulus scheme (16th run) creates additional rainfall over eastern Thracen region and on Marmara Sea, according to Kein-Fritsch scheme. Location of the storm and amount of precipitation from the storm also differs from those of the default scheme.

Betts-Miller-Janjic scheme (17th run) can be said to be giving the most different pattern in precipitation prediction. It creates a homogeneous area with mild amounts of rainfall over the region of the storm. Unfortunately, according to the verification data, this is not the case happened.

Result of the Grell-Devenyi ensemble cumulus scheme can be seen on 24th run's plot, and is also distuingishably different from the other runs. Precipitation seems to be scattered in a wider area over Black Sea, compared to other schemes. Amount of precipitation doesn't give cell-like higher spots, but can be said to be a better prediction than Betts-Miller-Janjic scheme's one.

27th run was the test of the Old-Kein-Fritsch scheme. This scheme creates the storm cell shifted a bit northeast from its place in other runs, which is a bit more far away from the real location. Amount of precipitation does not indicate huge difference from the new Kein Fristch scheme.

The precipitation pattern and amount is not only effected by the cumulus parameterization, but also the other physics and dynamics options, as seen from the other plots not mentioned. Since it is the most difficult parameter to forecast, a succesful run can be defined as the one which gives a higher accuracy over this. But verification of the precipitation is also difficult, due to the lack of high resolution observational network. Although Kein-Fritsch was chosen at this study, Grell-Devenyi ensemble and Grell 3-d ensemble schemes are also found succesful.

Additionally, some other forecast-observation difference plots for the “successful” 30th run are included as Figure 3.9, 3.10, 3.11, 3.12, 3.13, 3.14, 3.15 and 3.16.

Figure 3.11 shows the lowest sigma level temperature difference of the forecast and the observation. The forecast over the coasts seem underpredicted, where there is a positive bias over northern inlands.

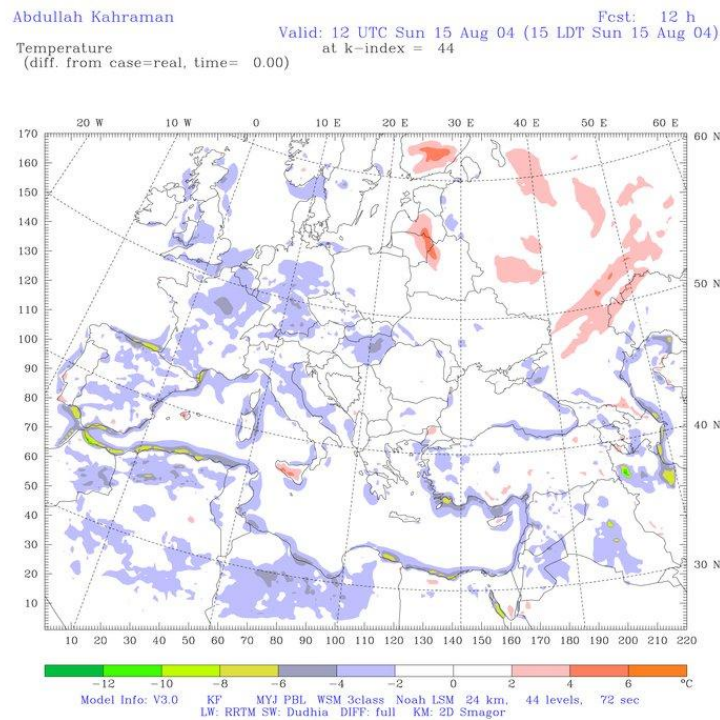


Figure 3.11 : Lowest sigma level temperature difference of the forecast and the observation at 12z on 15.08.2004, according to the sensitivity test element 30.

At figure 3.12, 1500 m relative vorticity difference is plotted. There seems no problem on forecast of this field, in general. Lateral boundaries create imaginary vorticity patterns.

Figure 3.13 shows the 850 hPa level temperature difference. Forecast of this field seems quite succesful, but there is a slightly negative bias over Alps, Caucasus, northern Iran , northern Algeria and mountaionus regions of Spain.

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Relative vorticity
(diff. from case=real, time= 0.00)

Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04)
at height = ***** km

Fcst: 12 h

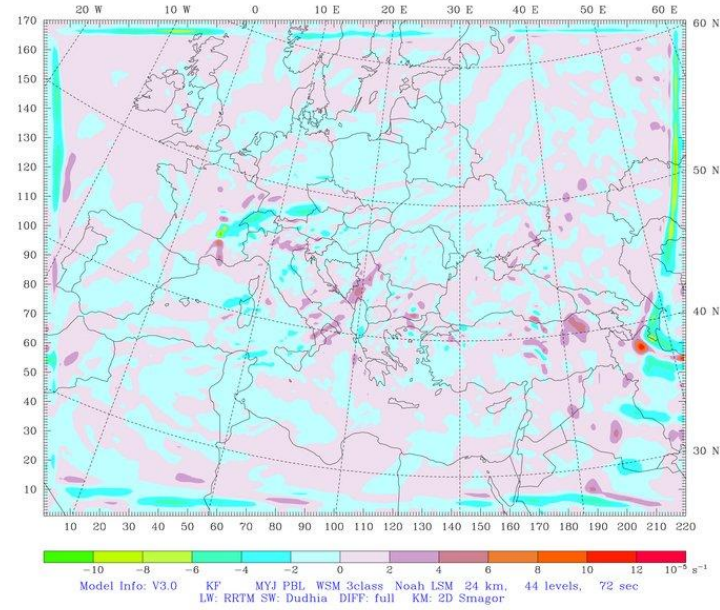


Figure 3.12 : 1500 m relative vorticity difference of the forecast and the observation at 12z on 15.08.2004, according to the sensitivity test element 30.

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Temperature
(diff. from case=real, time= 0.00)

Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04)
at pressure = 850 hPa

Fcst: 12 h

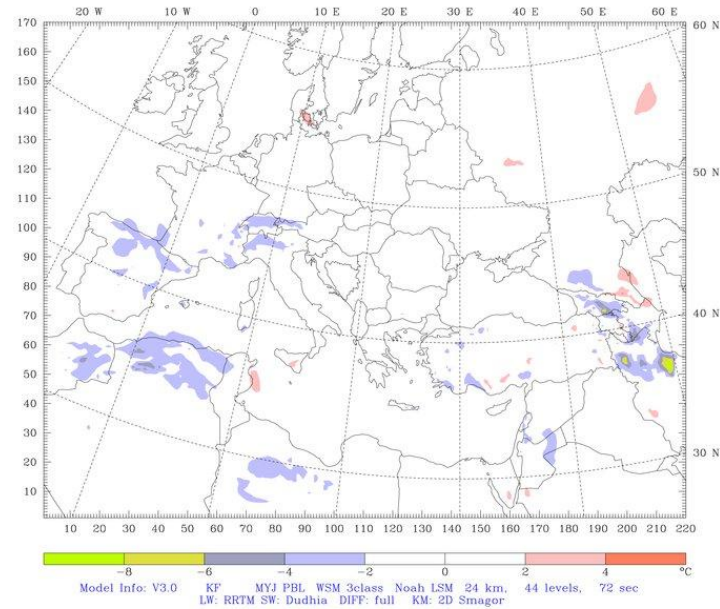


Figure 3.13 : 850 hPa level temperature difference of the forecast and the observation at 12z on 15.08.2004, according to the sensitivity test element 30.

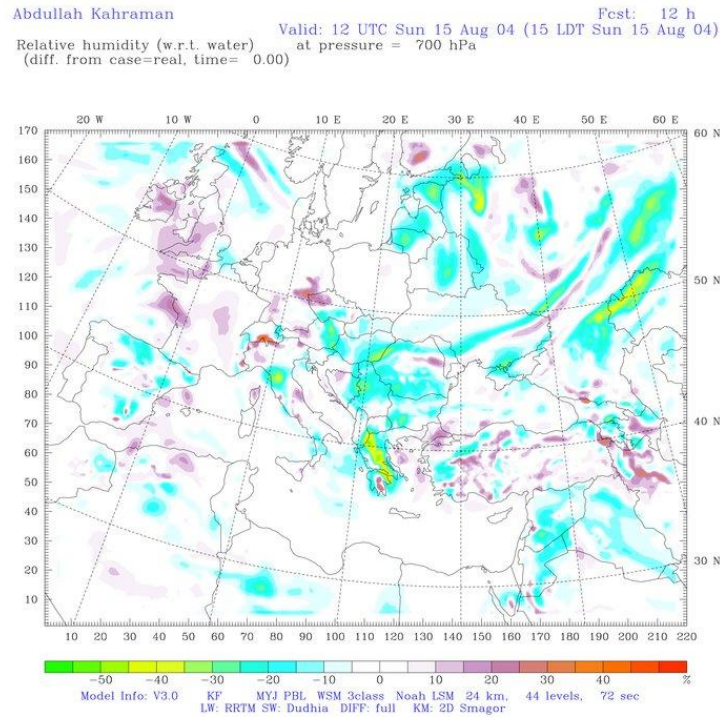


Figure 3.14 : 700 hPa level relative humidity difference of the forecast and the observation at 12z on 15.08.2004, according to the sensitivity test element 30.

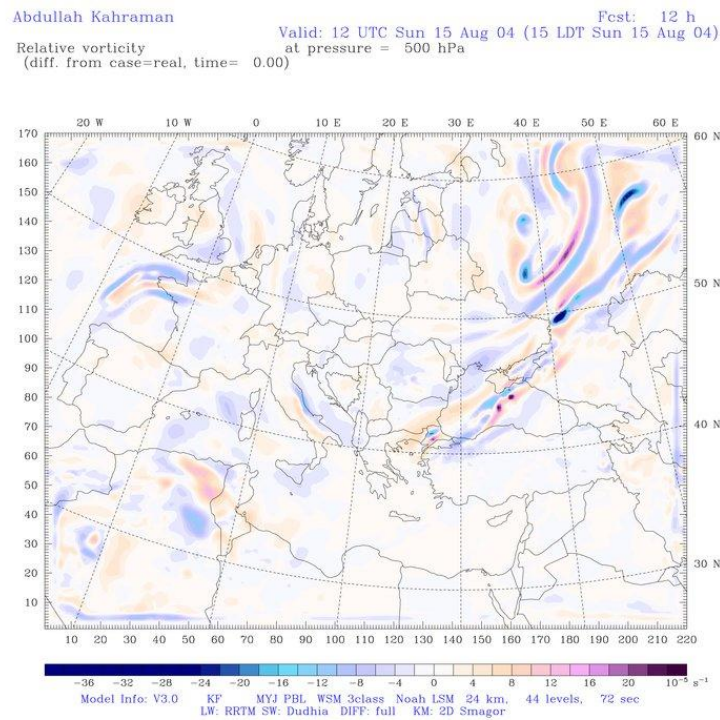


Figure 3.15 : 500 hPa relative vorticity difference of the forecast and the observation at 12z on 15.08.2004, according to the sensitivity test element 30.

700 hPa level relative humidity difference is plotted on Figure 3.14. The model is capable to forecast the humidity field in general, but there is an important underestimate over Greece.

Figure 3.15 shows the 500 hPa relative vorticity difference between the forecast and the observations. The anomaly occurs near the low center and the cold front.

500 hPa temperature is maybe the most succesful field forecasted by the model. Except a very small area over Alps, the anomaly is smaller than 2 C. Figure 3.16 shows the difference map.

Figure 3.17 shows the 925 hPa equivalent potential temperature difference. There are more errors at this level when compared to that of 850 hPa, because of land-atmosphere interactions and boundary layer effects. There seems an underestimate over seas and positive bias over lands near the coasts.

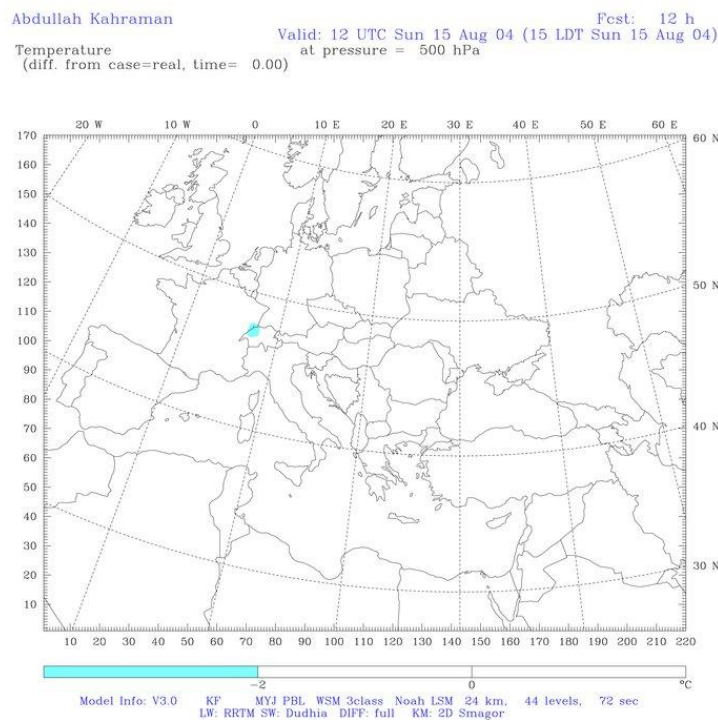


Figure 3.16 : 500 hPa temperature difference of the forecast and the observation at 12z on 15.08.2004, according to the sensitivity test element 30.

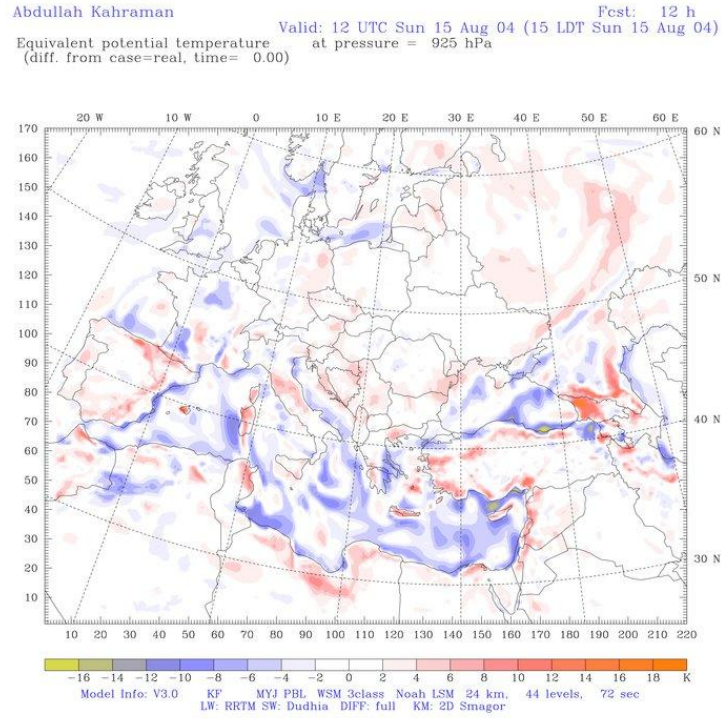


Figure 3.17 : 925 hPa equivalent potential temperature difference of the forecast and the observation at 12z on 15.08.2004, according to the sensitivity test element 30.

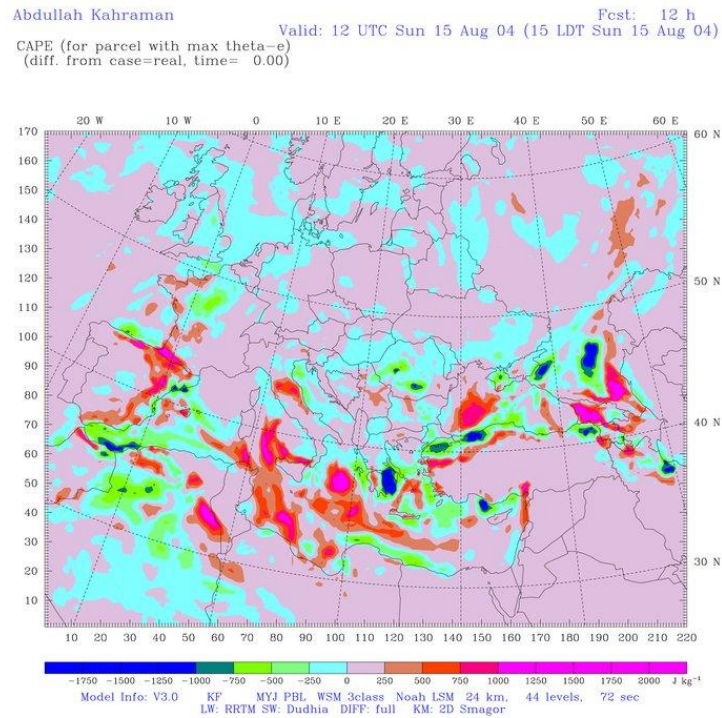


Figure 3.18 : CAPE difference of the forecast and the observation at 12z on 15.08.2004, according to the sensitivity test element 30.

At last, CAPE difference is plotted and shown as Figure 3.18. There seems important biases of this field. When looked at the study area, Marmara Region, it can be seen that there is an overestimate over Black Sea, and underestimate over Southern and Eastern Marmara. This is the place where severe convection occurred. This plot shows that the model is able to forecast the severe convection, but the location of the forecast is shifted to Black Sea. Though the real tornado and supercell occurred over Yalova, where model predicts the cell over a northern part of Istanbul.

As a conclusion to sensitivity analysis, Kein-Fritsch scheme is used as cumulus parameterization, noting the two Grell schemes are also succesful. WRF Single-Moment 3-class scheme is chosen as microphysics parameterization instead of Eta microphysics. Shortwave radiation scheme Dudhia, and longwave radiation scheme RRTM were preferred instead of Eta radiation schemes. Surface physics is changed into Noah Land Surface Model with 4 layers, from 5-layer thermal diffusion. Surface layer parameterization is switched into Eta similarity scheme, from the default MM5 similarity scheme. For planetary boundary layer, again Eta similarity (Mellor-Yamada-Janjic scheme) found to be better than the default Yonsei University scheme. 6th-order horizontal hyper diffusion option is used as 2, relaxation at the boundaries were done with 4 points, and the run is performed nonhydrostatically with full diffusion option, instead of simple diffusion.

The horizontal resolution of the first domain was 24 km, and the inner domains had 8 and 2.67 km resolution, with 1:3:3 aspect ratio. Number of vertical levels for each domain was 45. Time step is chosen as 72 seconds, and for the inner domains it became 24 seconds and 8 seconds respectively. Runs are performed with 14.08.2004 00UTC and 15.08.2004 00UTC initialization.

Before coming to the meteorological analysis of the case, the namelist variables of 30th run will be given here.

The namelist.wps file is as follows:

```
&share  
wrf_core = 'ARW',  
max_dom = 3,  
start_date = '2004-08-15_00:00:00','2004-08-15_00:00:00','2004-08-15_00:00:00'
```

```

end_date = '2004-08-16_00:00:00','2004-08-16_00:00:00','2004-08-16_00:00:00'
interval_seconds = 21600
io_form_geogrid = 2,
/

```

```

&geogrid
parent_id      = 1, 1, 2,
parent_grid_ratio = 1, 3, 3,
i_parent_start  = 1, 60, 202,
j_parent_start  = 1, 20, 115,
e_we           = 220, 340, 163,
e_sn           = 170, 340, 121,
geog_data_res   = '10m','2m','30s'
dx = 24000,
dy = 24000,
map_proj = 'lambert',
ref_lat = 45.00,
ref_lon = 20.00,
truelat1 = 35.0,
truelat2 = 50.0,
stand_lon = 30.0,
geog_data_path = '/home/kahraman/WRF/geog'
/

```

```

&ungrib
out_format = 'WPS',
prefix = 'FILE',
/

```

```

&metgrid
fg_name = 'FILE'
io_form_metgrid = 2,
/

```

```

&mod_levs
press_pa = 201300 , 200100 , 100000 ,
          95000 , 90000 ,
          85000 , 80000 ,
          75000 , 70000 ,
          65000 , 60000 ,
          55000 , 50000 ,
          45000 , 40000 ,
          35000 , 30000 ,
          25000 , 20000 ,
          15000 , 10000 ,
          5000 , 1000
/

```

The namelist.input file for the model run is as follows:

```

&time_control
run_days           = 1,
run_hours          = 0,
run_minutes        = 0,
run_seconds        = 0,
start_year         = 2004, 2004, 2004,
start_month        = 08, 08, 08,
start_day          = 15, 15, 15,
start_hour         = 00, 00, 00,
start_minute       = 00, 00, 00,
start_second       = 00, 00, 00,
end_year           = 2004, 2004, 2004,
end_month          = 08, 08, 08,
end_day            = 16, 16, 16,
end_hour           = 00, 00, 00,
end_minute         = 00, 00, 00,
end_second         = 00, 00, 00,
interval_seconds   = 21600
input_from_file    = .true.,.true.,.true.,
history_interval    = 60, 60, 30,
frames_per_outfile = 1000, 1000, 1000,
restart            = .false.,
restart_interval   = 5000,
io_form_history    = 2
io_form_restart    = 2
io_form_input      = 2
io_form_boundary   = 2
debug_level        = 0
/

&domains
time_step          = 72,
time_step_fract_num = 0,
time_step_fract_den = 1,
max_dom            = 3,
s_we               = 1, 1, 1,
e_we               = 220, 340, 163,
s_sn               = 1, 1, 1,
e_sn               = 170, 340, 121,
s_vert             = 1, 1, 1,
e_vert             = 45, 45, 45,
num_metgrid_levels = 27
dx                 = 24000, 8000, 2666.667,
dy                 = 24000, 8000, 2666.667,
grid_id            = 1, 2, 3,
parent_id          = 0, 1, 2,
i_parent_start     = 1, 60, 202,
j_parent_start     = 1, 20, 115,

```

```

parent_grid_ratio      = 1, 3, 3,
parent_time_step_ratio = 1, 3, 3,
feedback               = 1,
smooth_option          = 0
/

```

```

&physics
mp_physics              = 3, 3, 3,
ra_lw_physics           = 1, 1, 1,
ra_sw_physics           = 1, 1, 1,
radt                   = 24, 24, 24,
sf_sfclay_physics       = 2, 2, 2,
sf_surface_physics      = 2, 2, 2,
bl_pbl_physics          = 2, 2, 2,
bldt                   = 0, 0, 0,
cu_physics              = 1, 1, 1,
cudt                   = 5, 5, 5,
isfflx                  = 1,
ifsnow                  = 0,
icloud                  = 1,
surface_input_source    = 1,
num_soil_layers         = 4,
ucmcall                 = 0,
mp_zero_out             = 0,
maxiens                 = 1,
maxens                  = 3,
maxens2                 = 3,
maxens3                 = 16,
ensdim                  = 144,
slope_rad               = 0,
topo_shading            = 0,
/

```

```

&fdda
/

```

```

&dynamics
w_damping               = 0,
diff_opt                = 2,
km_opt                  = 4,
diff_6th_opt            = 0,
diff_6th_factor         = 0.12,
base_temp               = 290.
damp_opt                = 0,
zdamp                   = 5000., 5000., 5000.,
dampcoef                = 0.01, 0.01, 0.01
khdif                   = 0, 0, 0,
kvdif                   = 0, 0, 0,
non_hydrostatic         = .true., .true., .true.,
pd_moist                 = .true., .true., .true.,

```

```
pd_scalar      = .true., .true., .true.,
/
```

```
&bdy_control
spec_bdy_width      = 5,
spec_zone           = 1,
relax_zone          = 4,
specified           = .true., .false., .false.,
nested              = .false., .true., .true.,
/
```

```
&grib2
/
```

```
&namelist_quilt
nio_tasks_per_group = 0,
nio_groups = 1,
/
```

Abdullah Kahraman

Valid: 00 UTC Sat 14 Aug 04 (03 LDT Sat 14 Aug 04) Fcst: 0 h
 at pressure = 500 hPa
 at pressure = 500 hPa
 at pressure = 500 hPa

Temperature
 Geopotential height
 Horizontal wind vectors

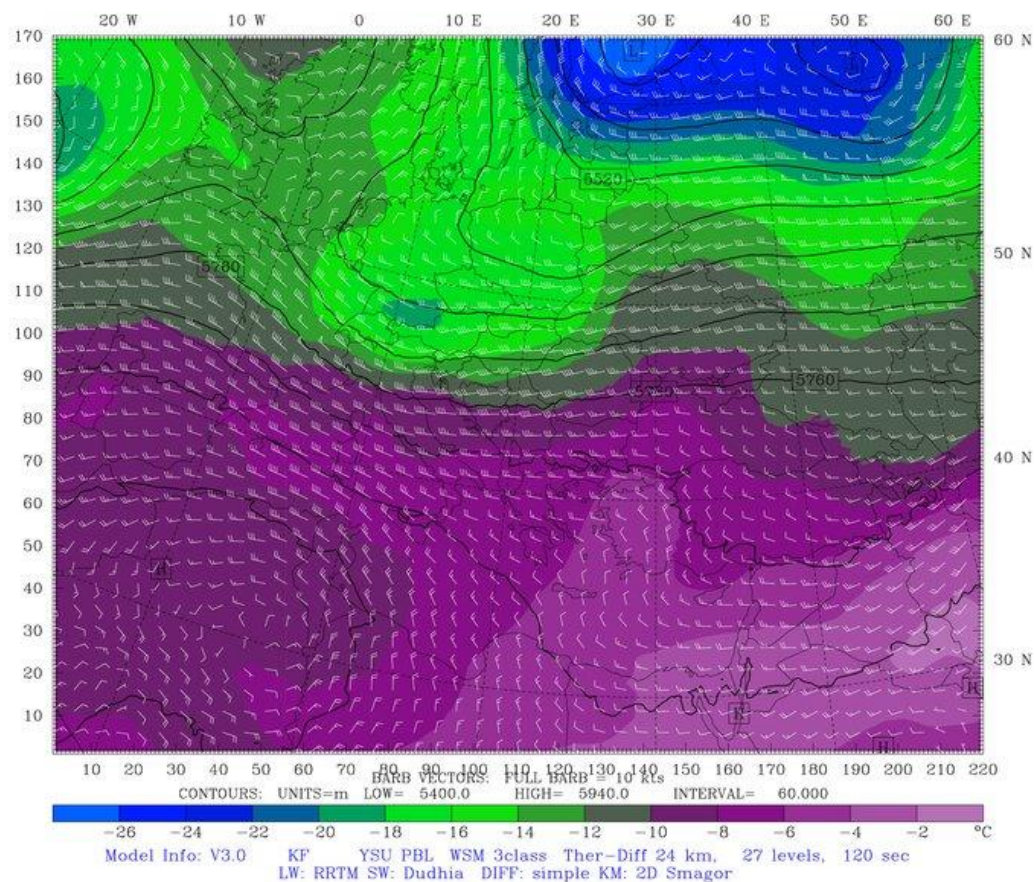


Figure 3.19 : 14.08.2004 00UTC 500 hPa chart.

3.6. Synoptic Analysis

Before the mesoscale approach, a synoptic analysis is performed with the weather charts supplied by the model.

On 14.08.2004 00UTC, there seem two low centres on north, one near Finland and one over Siberia at 500 hPa level (see Figure 3.19). These lows have troughs, especially the trough of the western low over Europe is sharp and long, with a high pressure gradient in front, creating strong western winds over southern Europe. Looking at the temperature field, it is clear that the trough has an impressive cold tongue, even less than -18 C temperatures could be seen over Southern Germany,

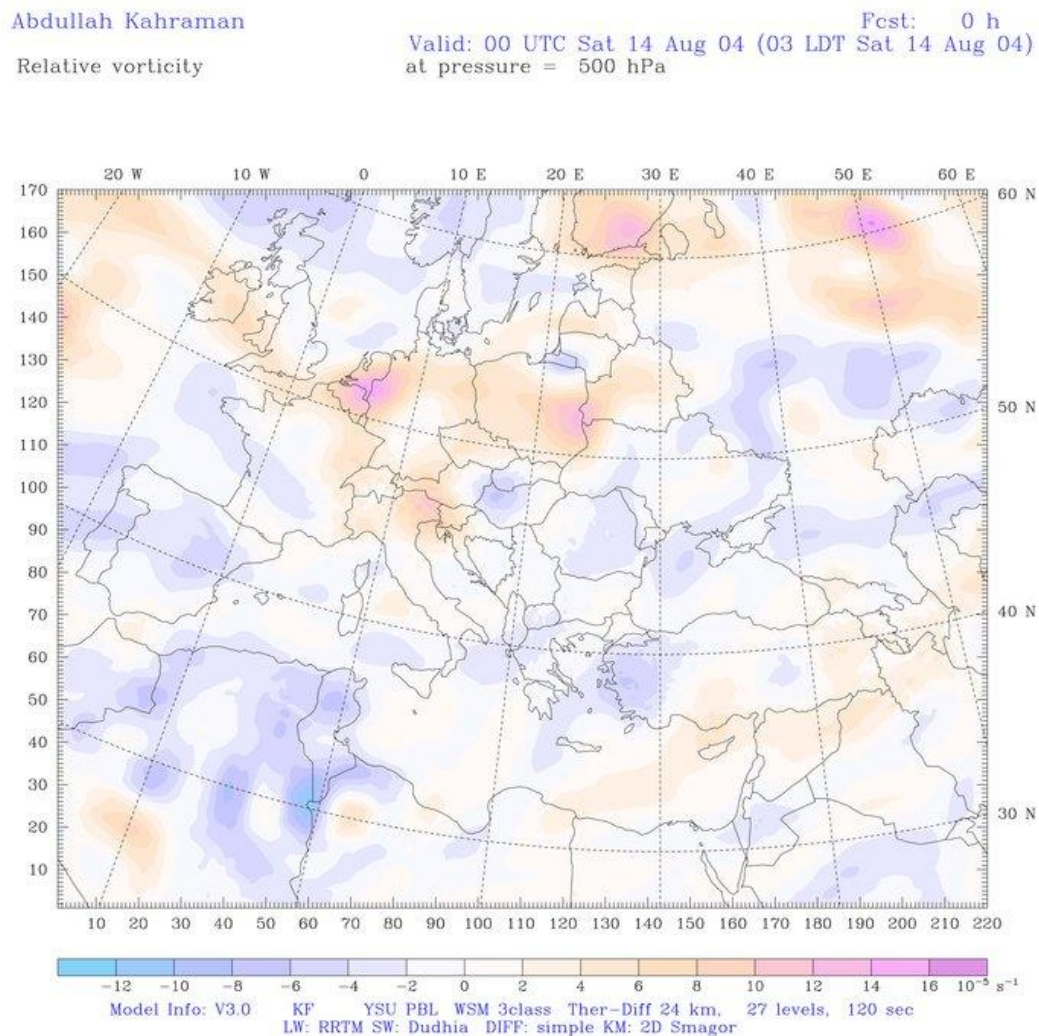


Figure 3.20 : 14.08.2004 00UTC 500 hPa relative vorticity.

which is not so common in mid-August. This cold cell results a huge temperature

gradient over the area near 45th latitude and between southern France to Balkans. As seen at the relative vorticity map of the same level, important positive vorticity areas can be seen over central Europe (Figure 3.20).

There is also a high centre over Western Sahara, which creates a ridge to the northwards (see Figure 3.19) and negative vorticity on the area (see Figure 3.20). Even a high centre has occurred over northern England, with deformation of the ridge. Another ridge with very low contour gradient goes over Mediterranean to

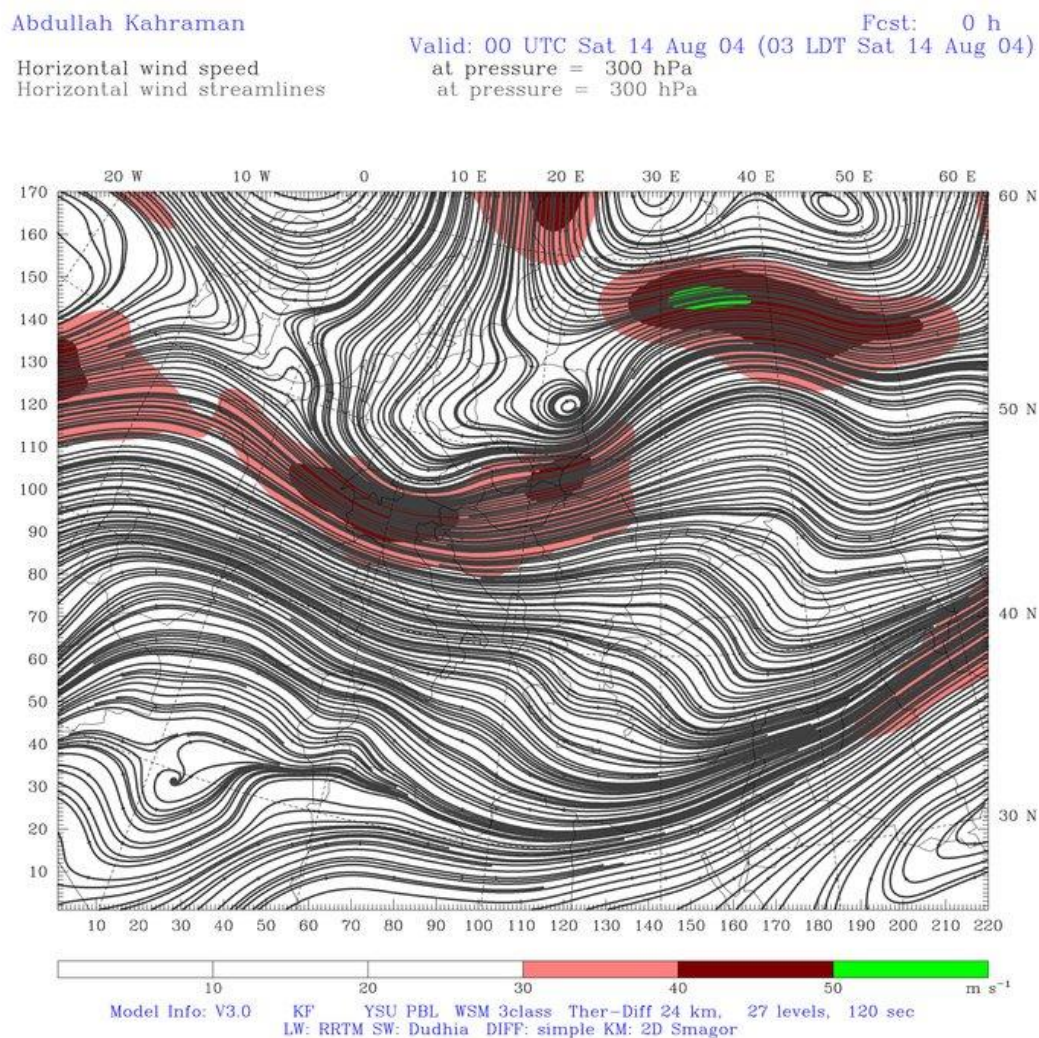


Figure 3.21 : 14.08.2004 00UTC 300 hPa chart.

Figure 3.21 shows the 300 hPa streamlines of the same time. According to the plot, the western flow is strong over southern Europe, wind speed reaching 40 to 50 ms^{-1} . There seems a closed centre over Eastern Poland, in addition to the two lows at the same places of them at 500 hPa. The flow in south of these lows are as strong as 50 to 60 ms^{-1} . These two important flows are obviously polar jets, separating cool polar air mass and hot tropical air mass. Tail of subtropical jet starting from north of Iran



and subtropical high in Southern Iraq are also visible at the right edge of the plot. At this season of the year, they would be expected to be stronger over the area at mid-latitudes.

The flows at higher levels of the troposphere effect the lower troposphere directly. In figure 3.22, 14.08.2004 00UTC 700 hPa relative humidity and horizontal wind vectors can be seen. High humidity over mid-Europe and near Balkans are recognisable. One other important feature at this plot is the sharp wind direction

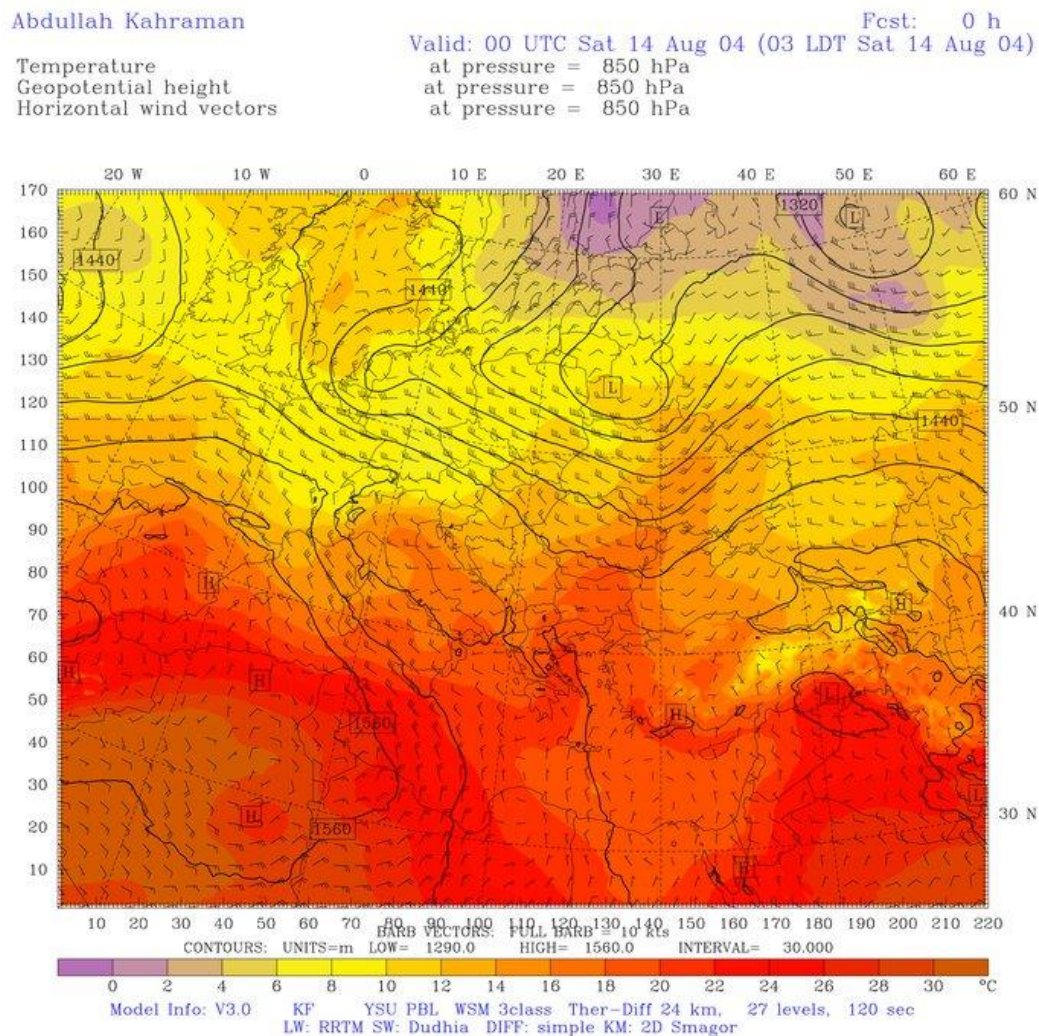


Figure 3.23 : 14.08.2004 00UTC 850 hPa chart.

change at the high humidity areas over northern Poland. This figure shows a nice representation of a cold frontal cloudiness zone. In addition to these comments, the very dry air over Egypt and the area going as north as mid-Black Sea must be noted. Humidity gradient is also a very important factor for severe weather studies.

850 hPa level chart for the same time can be seen at Figure 3.23. According to the figure, the lows of 500 hPa are on their locations at this level also, but a more important low is centred over Western Belarus. This low centre has strong contour

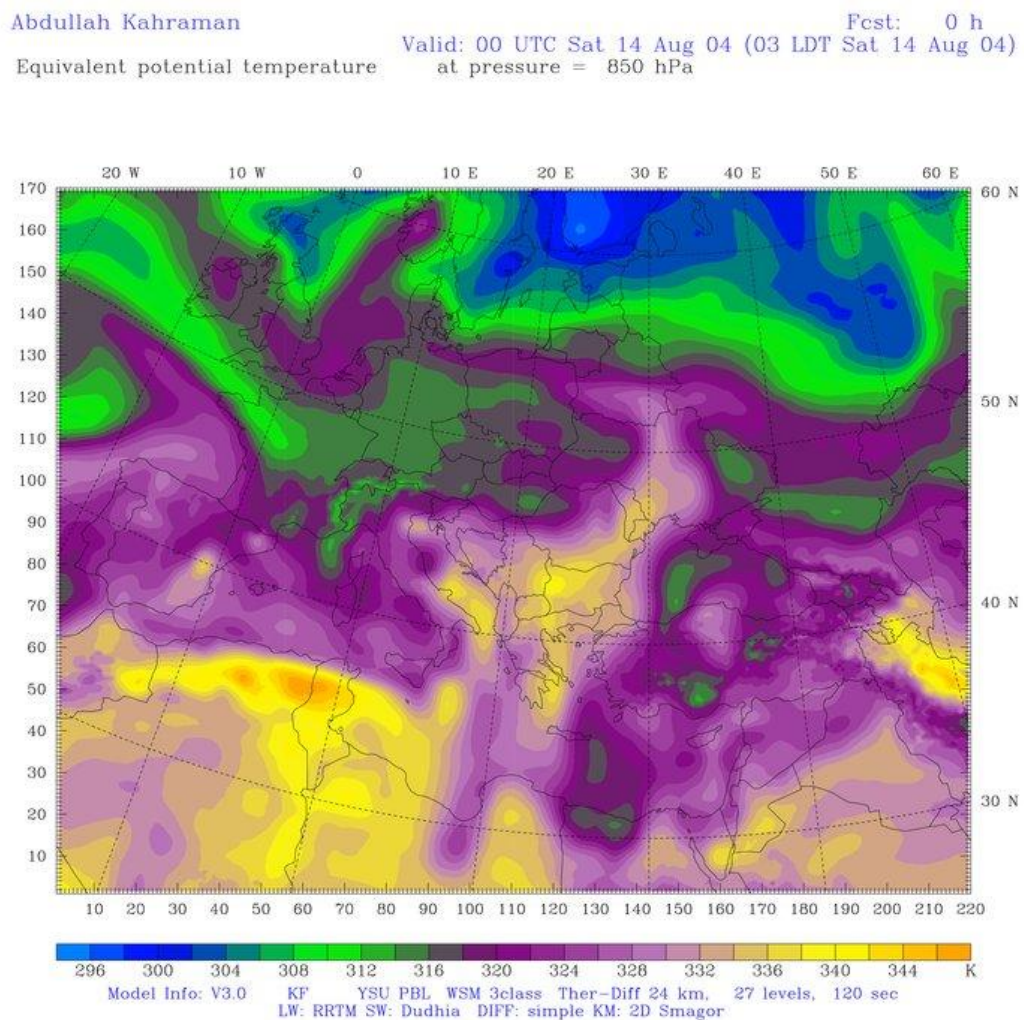


Figure 3.24 : 14.08.2004 00UTC 850 hPa equivalent potential temperature.

gradients around, as well as sharp troughs one to the south until western Black sea border and one to the west following the Baltic Sea border, going further away. The western trough seems to be creating another low at the edge, over Netherlands. On the other side, the isotherm pattern in front of the southern trough indicate a clear frontal look, pulling a warm tongue to the northwards, with strong southwestern winds. 14 C isotherm reaches 50N latitude with this warm advection. Two cold tongues are important at this map, one over continental Europe and one over northern Caucasus. To develop a better understanding of the properties of these patterns,

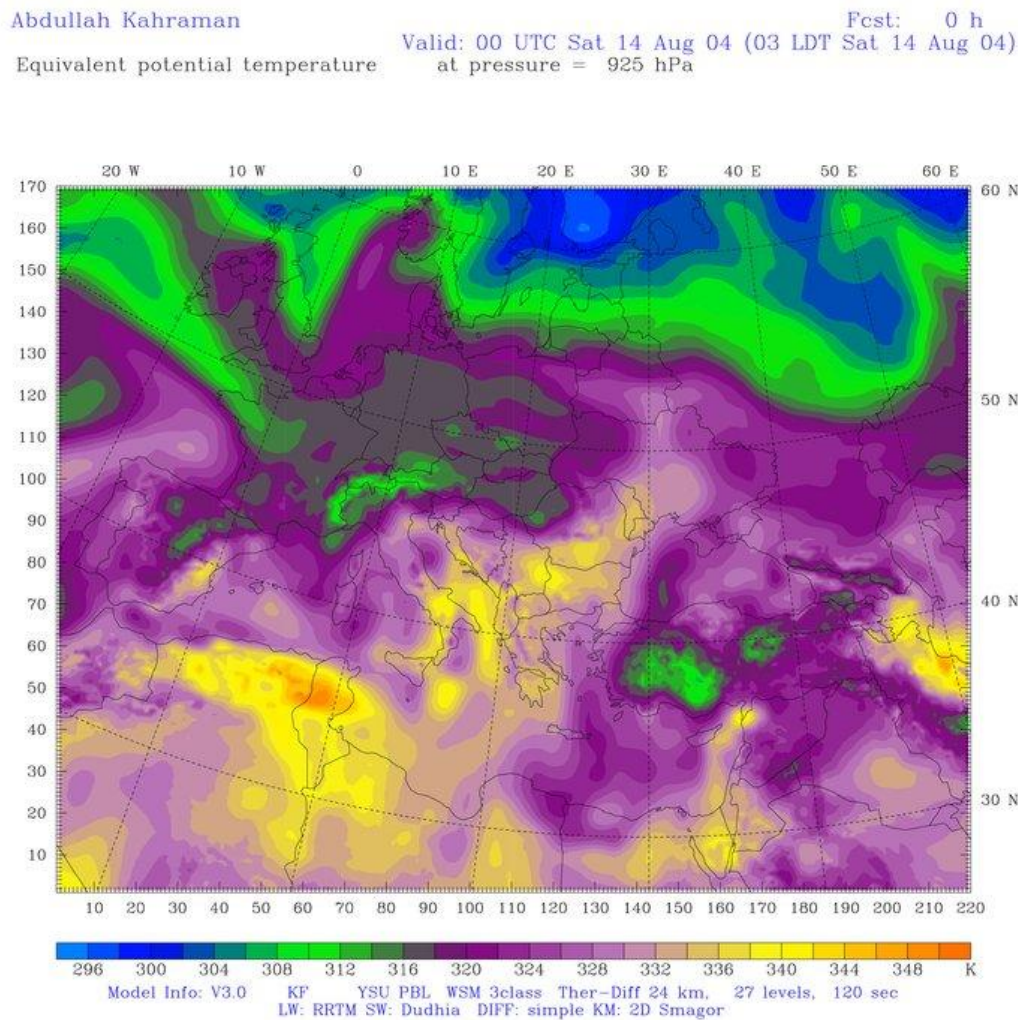


Figure 3.25 : 14.08.2004 00UTC 925 hPa equivalent potential temperature.

equivalent potential temperature of this level is also plotted and shown at Figure 3.24. Defeating the humidity and pressure level effects, the warm flow over southeastern Europe is very effective and respectively colder rest of the continental Europe and Anatolia show moderate feature for the season. However, the difference between Figure 3.23 and Figure 3.24 isotherms of southern Baltic border is important. The “warm” line going into the west at Figure 3.24 does not exist at Figure 3.23. This is because of the high humidity reasoned by the occluded front over that area. It can be said that cold north also seems more clear with equivalent potential temperature plot.

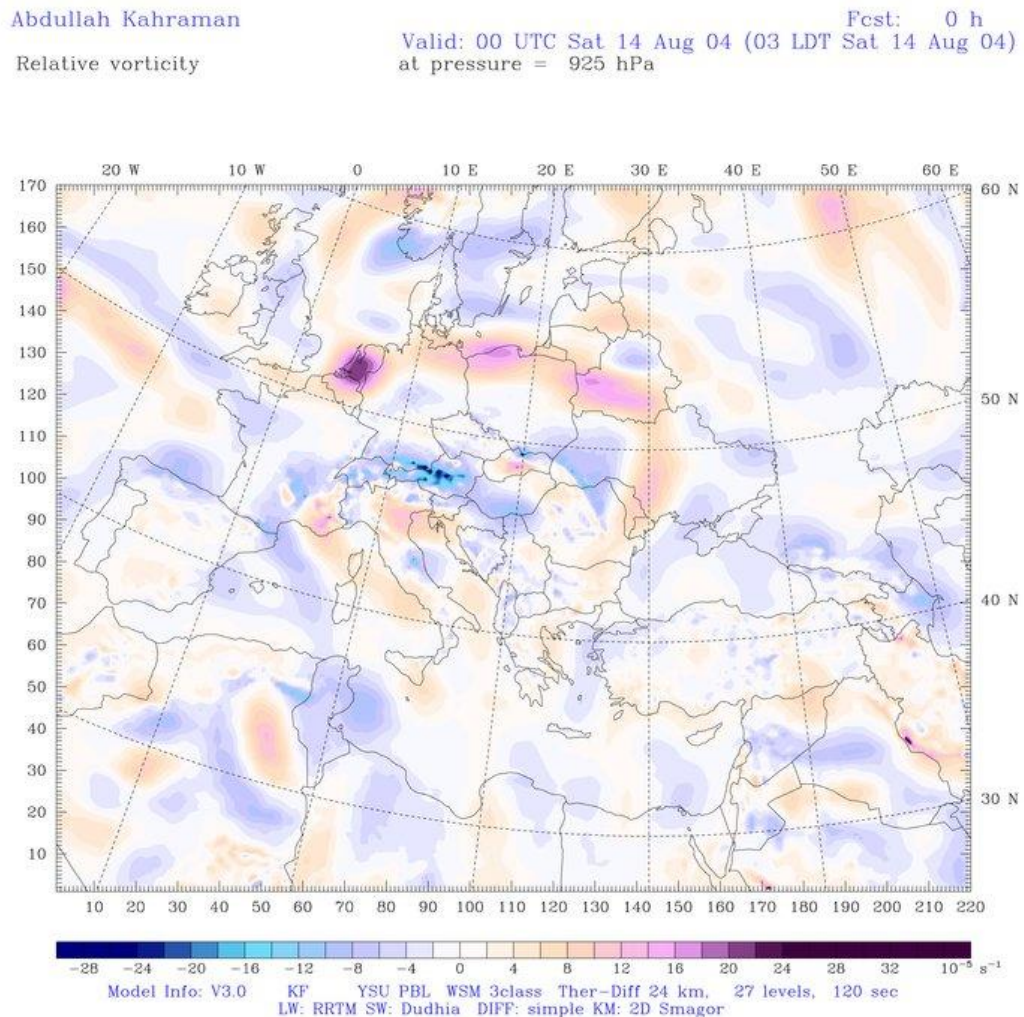


Figure 3.26 : 14.08.2004 00UTC 925 hPa relative vorticity.

Figure 3.25 is plotted for seeing the equivalent potential temperature at 925 hPa level. Since the low level conditions are very important for convection, this level must be analysed with respect to the features of the planetary boundary layer. Here the general patterns seem similar to the 850 hPa level map in general, although some local differences exist. The cold areas over and around Black Sea seem weaker at 925 hPa level, where the ones over Anatolia and Alps show a strong feature. When these mountainous areas are thought to be over 925 hPa level, one may not take these values into account, but the difference over and northeastern Black Sea are

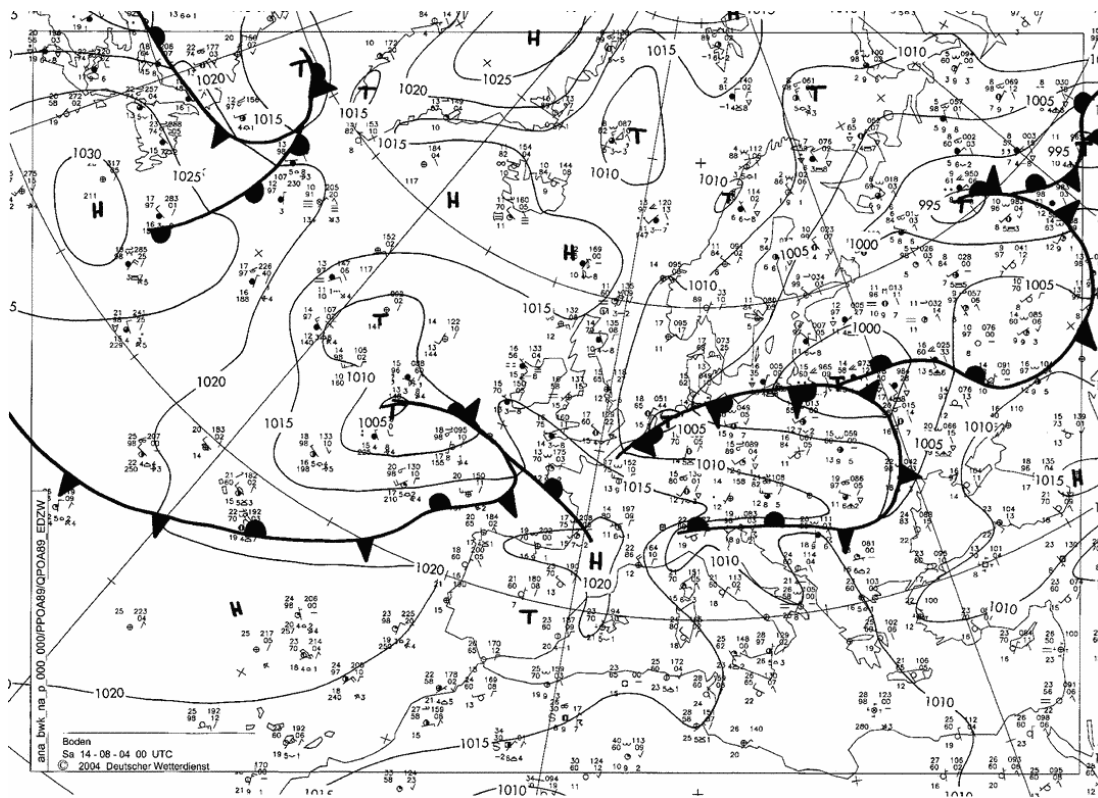


Figure 3.27 : 14.08.2004 00UTC surface weather chart, analysed by DWD.

Abdullah Kahraman

Temperature
Horizontal wind vectors

Valid: 01 UTC Sat 14 Aug 04 (04 LDT Sat 14 Aug 04)
Fest: 1 h
at k-index = 27
at height = 0.01 km

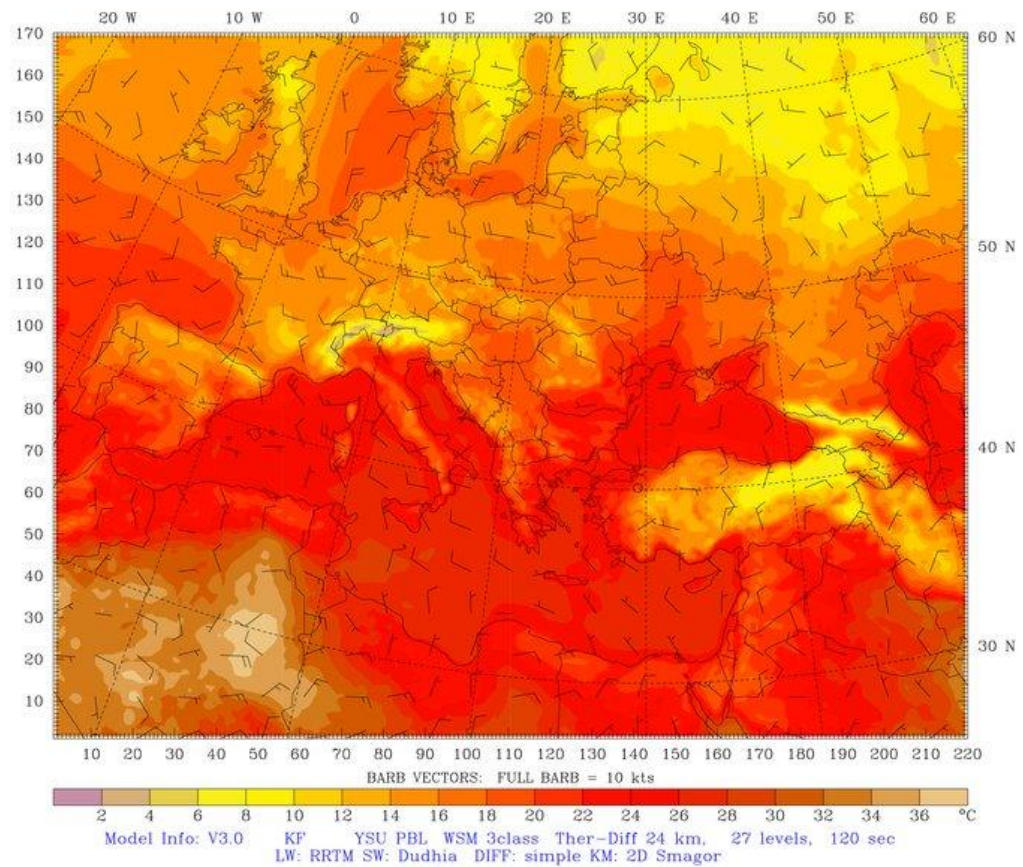


Figure 3.28 : 14.08.2004 01UTC lowest level temperature and 10 m wind.

important. This 4-8 C degrees of difference between these close levels make a vertical equivalent potential temperature gradient, which will reason a strong instability over the area. Relative vorticity of 925 hPa can be taken as a sense of vorticity on the ground layer, which somehow means the location of the fronts. Figure 3.26 shows this chart, indicating a very accurate similarity to the analysed

surface chart of German Weather Service (DWD) (Figure 3.27). There is a positive vorticity region starting from Netherlands, going on the coast of northern Germany and Poland, curving southwards by Belarus and mid-Ukraine, reaching Balkans. Another positive vorticity region over Urals and Atlantic also exist. Noting the difference of map projections and scales, it is obvious that the surface level fronts of DWD agree with this plot.

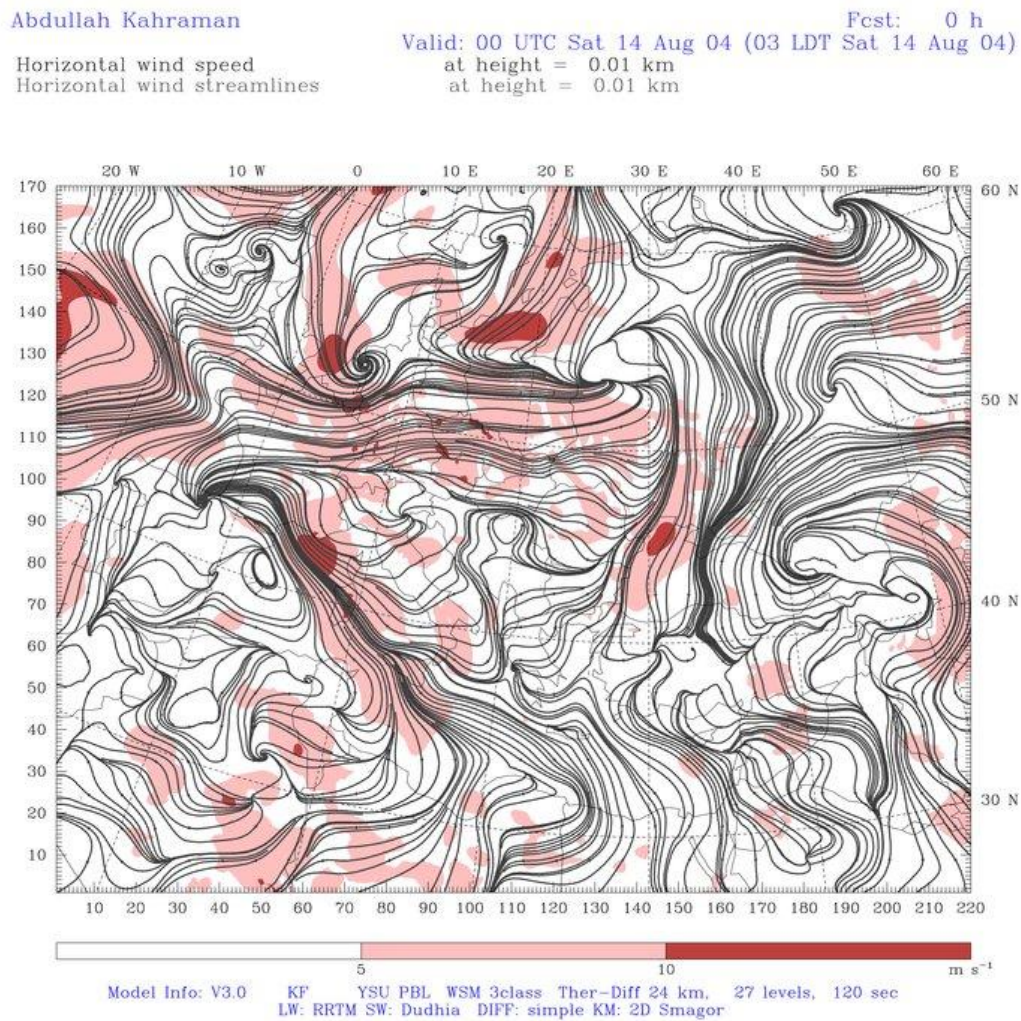


Figure 3.29: 14.08.2004 00UTC streamlines at 10 m.

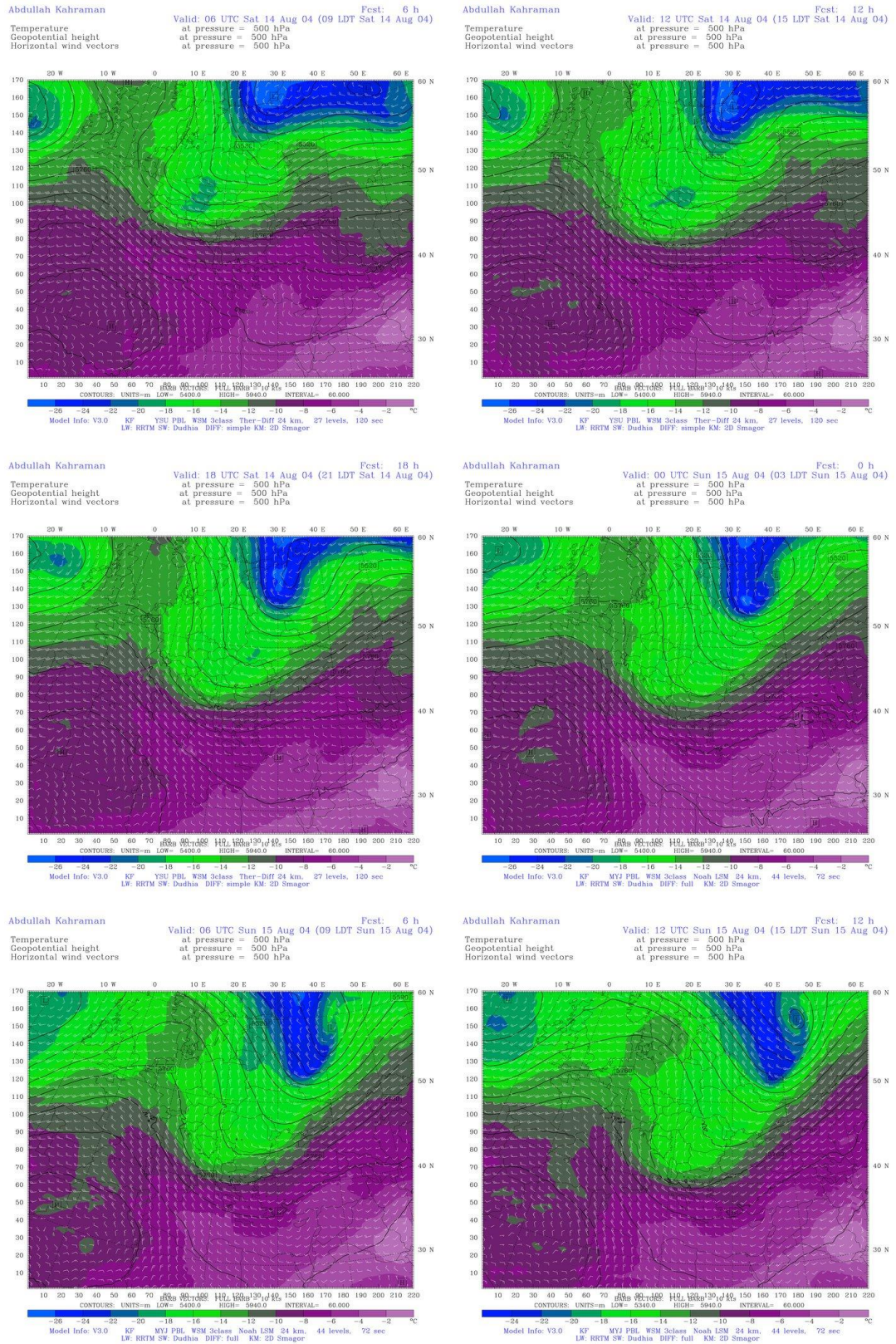
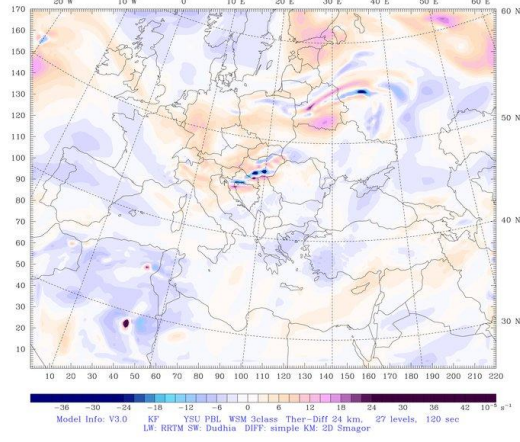


Figure 3.30 : 500 hPa plots between 14.08.2004 06UTC to 15.08.2004 12UTC, with 6 hours interval.

Abdullah Kahraman
Relative vorticity

Valid: 06 UTC Sat 14 Aug 04 (09 LDT Sat 14 Aug 04)
at pressure = 500 hPa

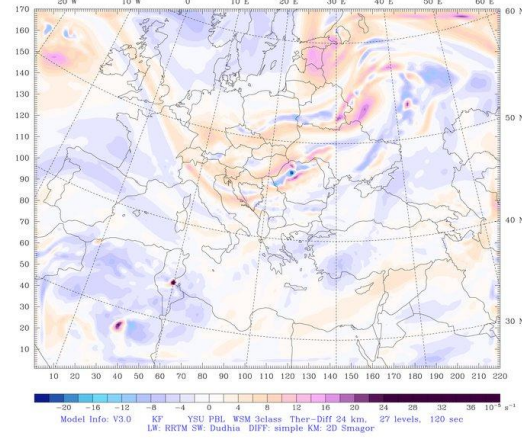
Fcst: 6 h



Abdullah Kahraman
Relative vorticity

Valid: 12 UTC Sat 14 Aug 04 (15 LDT Sat 14 Aug 04)
at pressure = 500 hPa

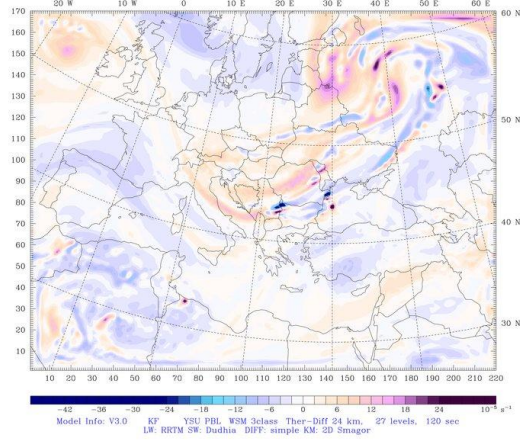
Fcst: 12 h



Abdullah Kahraman
Relative vorticity

Valid: 18 UTC Sat 14 Aug 04 (21 LDT Sat 14 Aug 04)
at pressure = 500 hPa

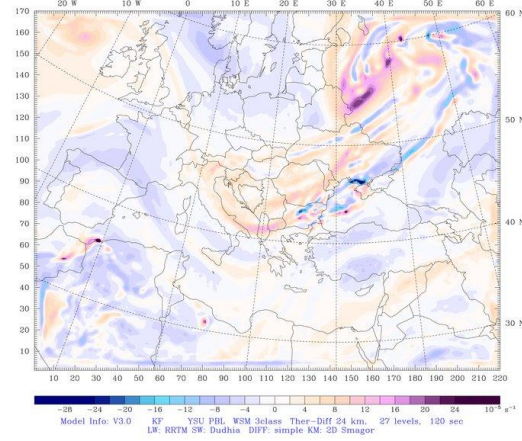
Fcst: 18 h



Abdullah Kahraman
Relative vorticity

Valid: 00 UTC Sun 15 Aug 04 (03 LDT Sun 15 Aug 04)
at pressure = 500 hPa

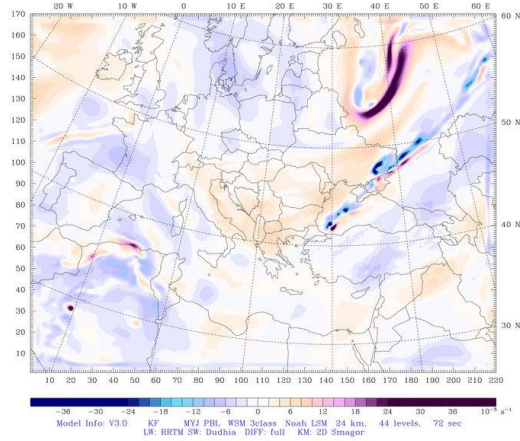
Fcst: 24 h



Abdullah Kahraman
Relative vorticity

Valid: 06 UTC Sun 15 Aug 04 (09 LDT Sun 15 Aug 04)
at pressure = 500 hPa

Fcst: 6 h



Abdullah Kahraman
Relative vorticity

Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04)
at pressure = 500 hPa

Fcst: 12 h

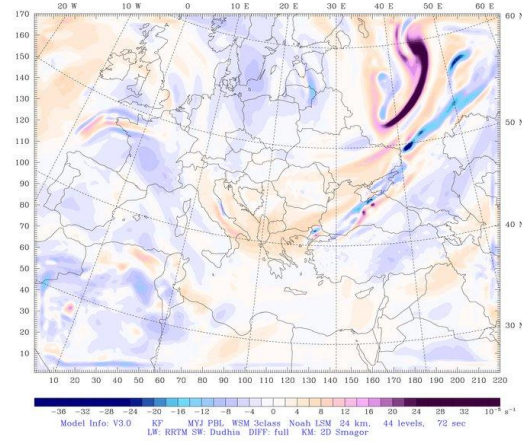


Figure 3.31 : 500 hPa relative vorticity plots between 14.08.2004 06UTC to 15.08.2004 12UTC, with 6 hours interval.

For the surface analysis, not only the chart analysed by DWD (Figure 3.27), but also the model output showing the temperature and wind fields (Figure 3.28) and 10 m streamlines (Figure 3.29) can be used. The low pressure centre with 1000 hPa value over Belarus has a sharp occluded front exactly following the northern coast of continental Europe, as the 500 hPa and 850 hPa troughs, as well as low level equivalent potential temperature patterns and 700 hPa humidity field do. This is an active occlusion, which produces rainshowers around the area.

The cold front of this low pressure centre goes southwards, and from the southern Romania curves to west, until Alps. These two frontal paths show a very good agreement with the jet of 300 hPa. In addition, the warm tongue of 850 hPa just fits to the sector, as the warm front follows a way to southeast. The surface winds from the model output show 20 knots of western flow over Central Europe, where the southern winds in sector also reaches that value. The Baltic winds behind the occlusion are also strong, showing the impact of the whole low pressure system.

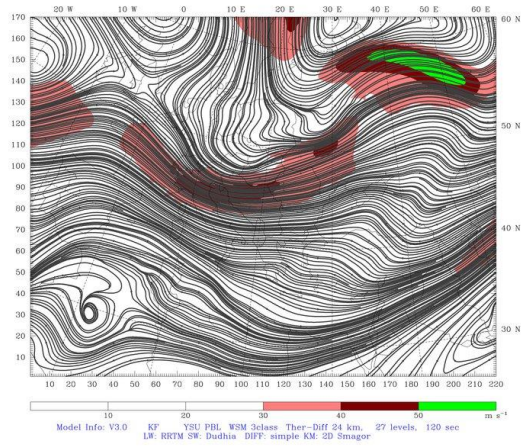
To conclude the overlook at the synoptic features of the area on 14.08.2004 00UTC, it can be said that the most important factor effecting is the cold low system over central Europe. Especially the cold front and the occlusion right behind it impact the whole region respectively. The warm air pushed northwards in front of the cold front is remarkable, as well as the strong winds pushing the cold tongue behind the front southwards. These two main paths make a convergence at the ground, which can be easily seen by streamlines as plotted at Figure 3.29. (The other strong flow over Mediterranean is because of the Asor High, and the magnitude is comparable to that of the frontal winds just because of the less friction over sea.)

As the evolution of the low pressure system will be evaluated, the synoptic forcing mechanism of severe convection will be seen. For a continuous look, the plots of 500 hPa between 14.08.2004 06UTC and 16.08.2004 00UTC are shown on figure 3.30. With 06UTC and 12 UTC on 14.08.2004, the cold air on far north seems enlarging,

Abdullah Kahraman
Horizontal wind speed
Horizontal wind streamlines

Valid: 06 UTC Sat 14 Aug 04 (09 LDT Sat 14 Aug 04)
at pressure = 300 hPa
at pressure = 300 hPa

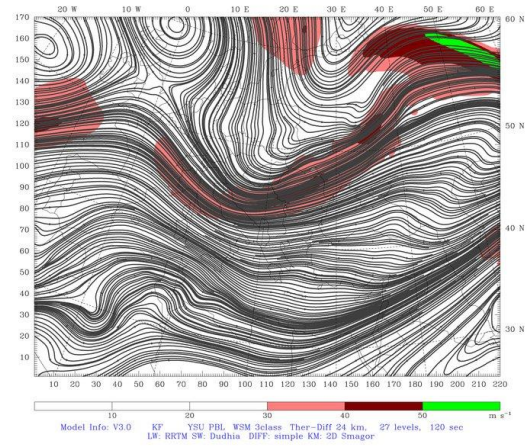
Fcst: 6 h



Abdullah Kahraman
Horizontal wind speed
Horizontal wind streamlines

Valid: 12 UTC Sat 14 Aug 04 (15 LDT Sat 14 Aug 04)
at pressure = 300 hPa
at pressure = 300 hPa

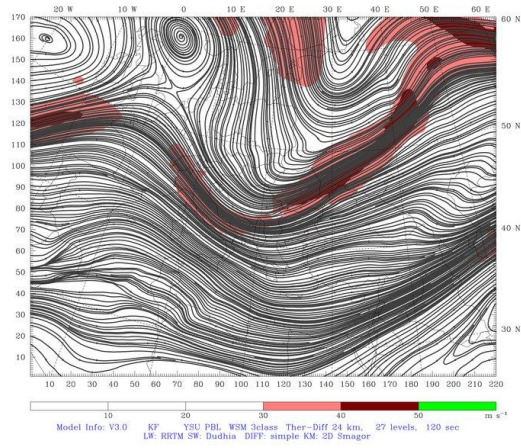
Fcst: 12 h



Abdullah Kahraman
Horizontal wind speed
Horizontal wind streamlines

Valid: 18 UTC Sat 14 Aug 04 (21 LDT Sat 14 Aug 04)
at pressure = 300 hPa
at pressure = 300 hPa

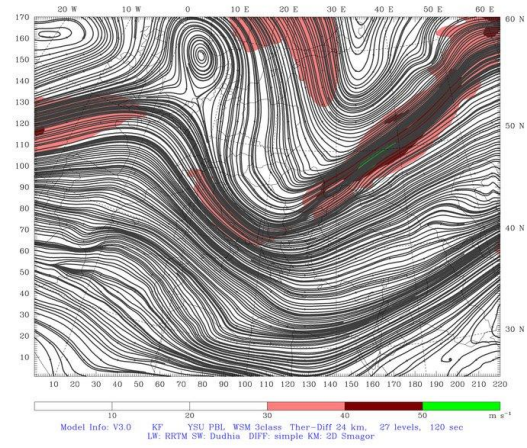
Fcst: 18 h



Abdullah Kahraman
Horizontal wind speed
Horizontal wind streamlines

Valid: 00 UTC Sun 15 Aug 04 (03 LDT Sun 15 Aug 04)
at pressure = 300 hPa
at pressure = 300 hPa

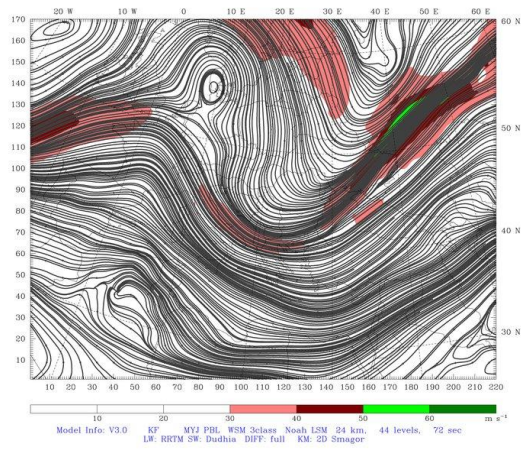
Fcst: 24 h



Abdullah Kahraman
Horizontal wind speed
Horizontal wind streamlines

Valid: 06 UTC Sun 15 Aug 04 (09 LDT Sun 15 Aug 04)
at pressure = 300 hPa
at pressure = 300 hPa

Fcst: 6 h



Abdullah Kahraman
Horizontal wind speed
Horizontal wind streamlines

Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04)
at pressure = 300 hPa
at pressure = 300 hPa

Fcst: 12 h

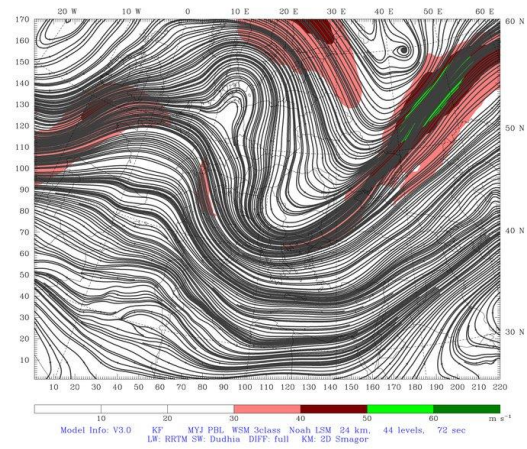


Figure 3.32 : 300 hPa streamlines and jets between 14.08.2004 06UTC to 15.08.2004 12UTC, with 6 hours interval.

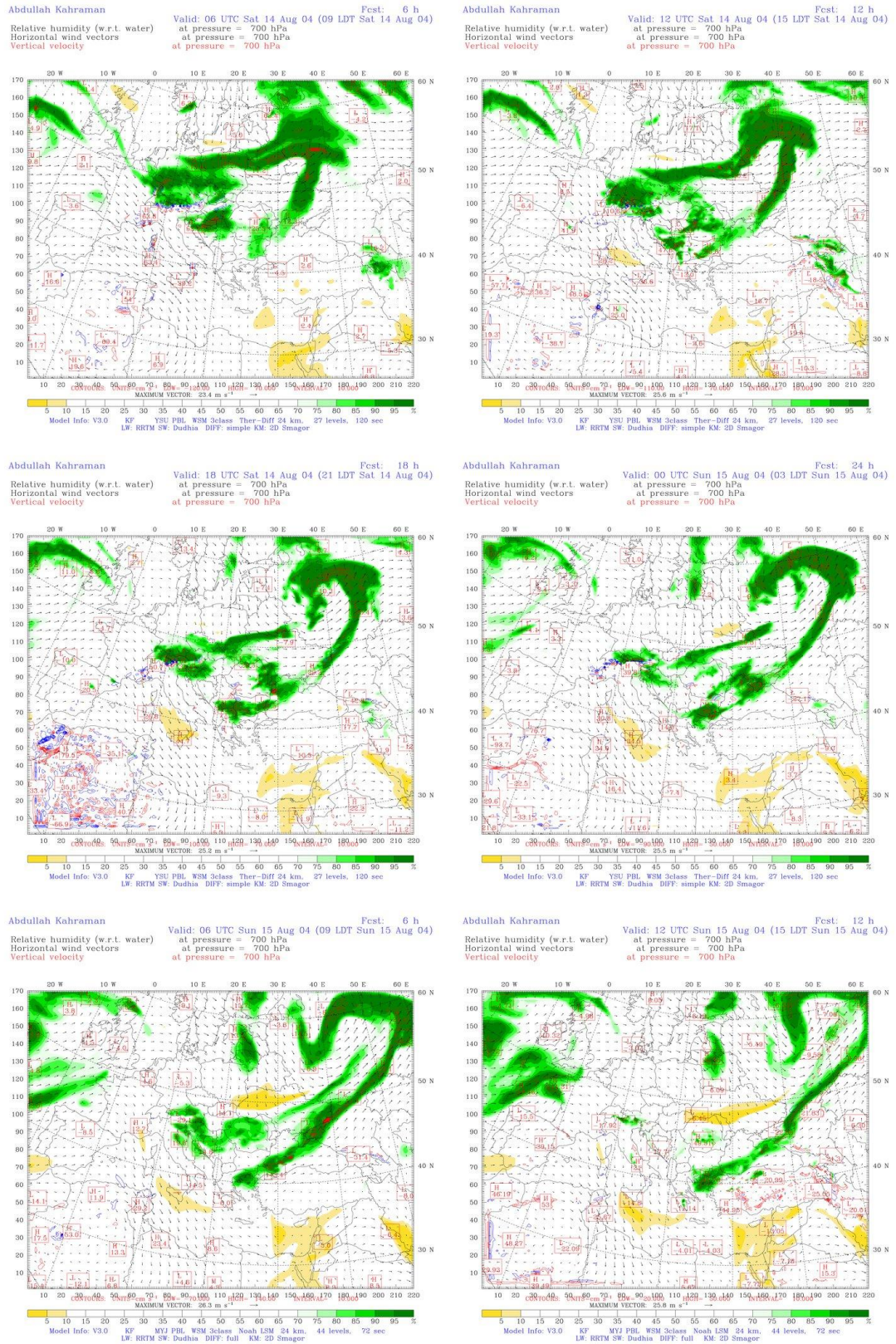


Figure 3.33 : 700 hPa relative humidity, horizontal wind and vertical velocity plots between 14.08.2004 06UTC to 15.08.2004 12UTC, with 6 hours interval.

while it changes its pattern recessing the area but curving itself southwards creating a sharp tongue at the next charts. But the most important pattern to be talked about is the very impressive evolution of the through over Europe and the winds strengthening the temperature gradient between the cold air over continental Europe and warmer Mediterranean air flowing northeastwards, over Black Sea. On 15.08.2004 12UTC, there is the -12 C isotherm over Istanbul, where is inside a strong gradient. The flows are southwesterly, tail of the sharp through is approaching right ahead.

Figure 3.31 shows the relative vorticity maps of the same level, for the same times. The quantity of the positive (and negative) vorticity fields show a remarkable increase on 15.08.2004. It must be noted by now that the vorticity path in front of the through is the strongest at 06UTC, at the moment when the model created the severe convective cell near Istanbul in the innermost domain. Even with this scale, 24 km horizontal resolution, the flow around the convection zone is visible with positive vorticity in front, and negative vorticity behind the vertical movement of air.

300 hPa streamlines and jets for the same timeline are shown at Figure 3.32. Evolution of the polar jet, which is related with the frontal system discussed strengthens itself on 15.08.2004 maps, exceeding 60 ms^{-1} . This is a very high value for a summer polar jet, at these latitudes. As the tail of upper jet results a divergence at that level, the convergence will occur on the ground, as a triggering (or feeding) mechanism of convection.

Figure 3.33 shows the relative humidity, horizontal wind and vertical velocity at 700 hPa level between 14.08.2004 06UTC to 15.08.2004 12UTC, with 6 hours interval. It is obvious that as the time passes, the humid area related to the occluded front over continental Europe weakens where the cold front does not. Especially when the tail of the front reaches Macedonia and Thracia, air becomes richer in moisture. On 15.08.2004 12UTC, the second moisture curve behind the cold front disappears and a

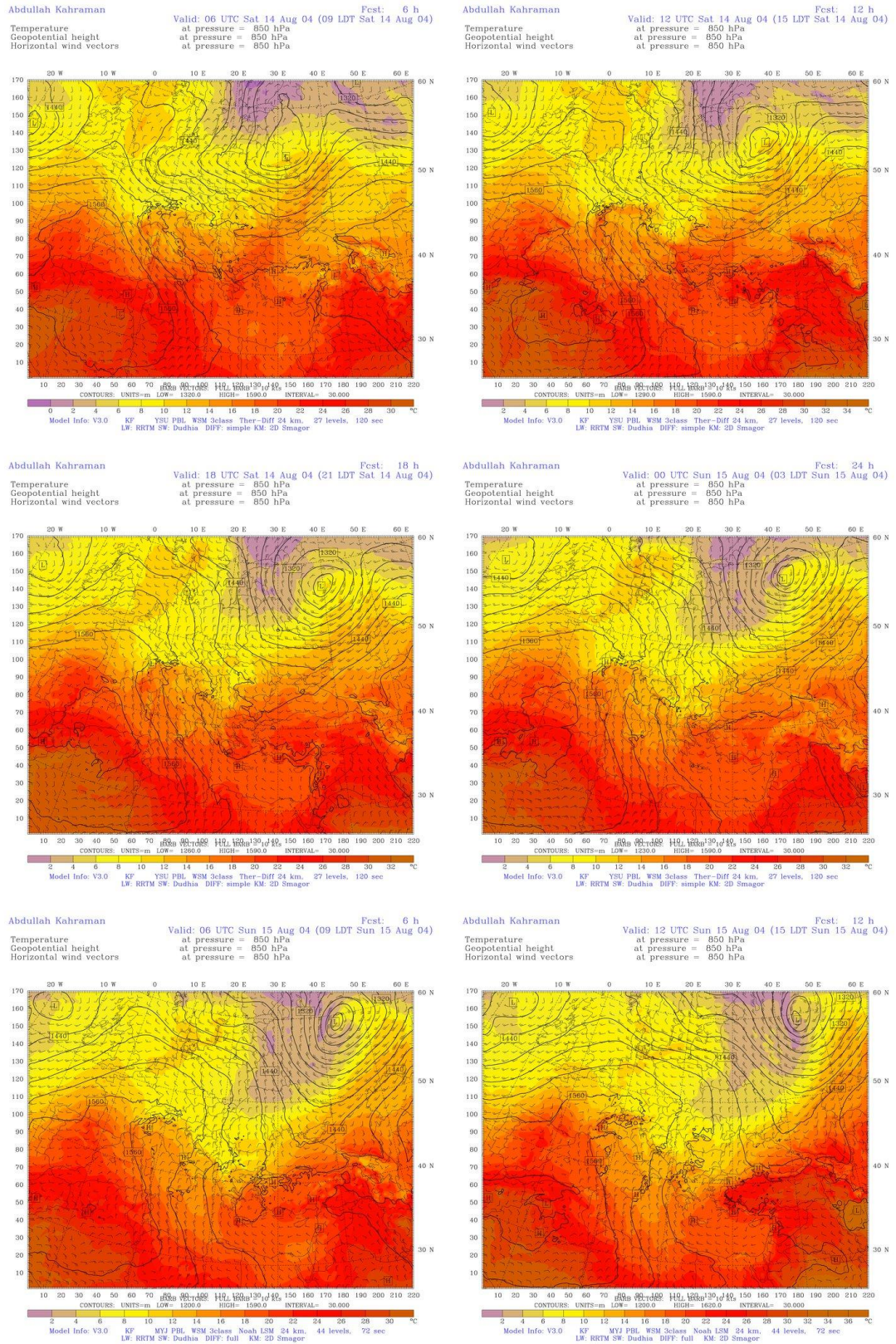
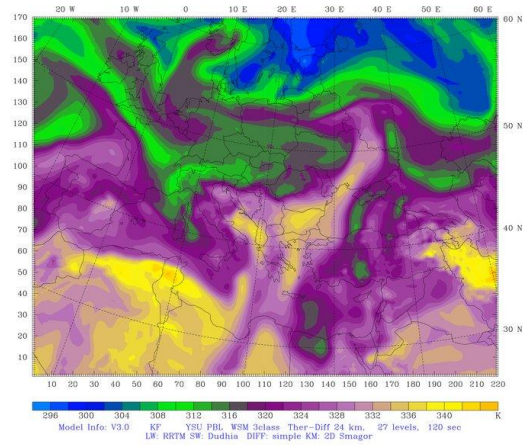
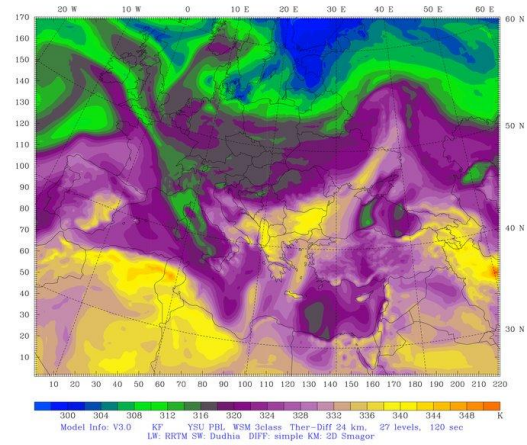


Figure 3.34 : 850 hPa charts between 14.08.2004 06UTC to 15.08.2004 12UTC, with 6 hours interval.

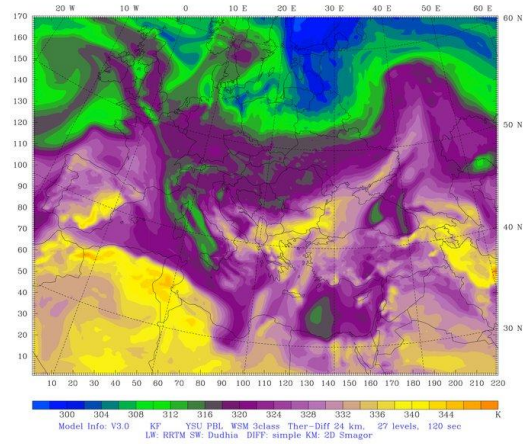
Abdullah Kahraman Fcst: 6 h
Valid: 06 UTC Sat 14 Aug 04 (09 LDT Sat 14 Aug 04)
Equivalent potential temperature at pressure = 850 hPa



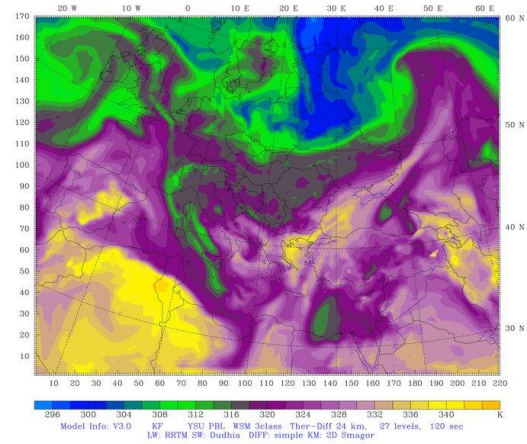
Abdullah Kahraman Fcst: 12 h
Valid: 12 UTC Sat 14 Aug 04 (15 LDT Sat 14 Aug 04)
Equivalent potential temperature at pressure = 850 hPa



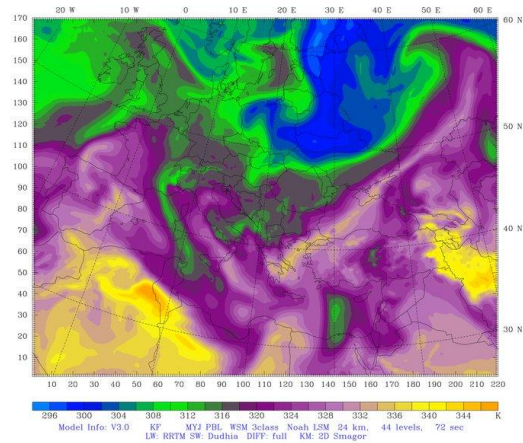
Abdullah Kahraman Fcst: 18 h
Valid: 18 UTC Sat 14 Aug 04 (21 LDT Sat 14 Aug 04)
Equivalent potential temperature at pressure = 850 hPa



Abdullah Kahraman Fcst: 24 h
Valid: 00 UTC Sun 15 Aug 04 (03 LDT Sun 15 Aug 04)
Equivalent potential temperature at pressure = 850 hPa



Abdullah Kahraman Fcst: 6 h
Valid: 06 UTC Sun 15 Aug 04 (09 LDT Sun 15 Aug 04)
Equivalent potential temperature at pressure = 850 hPa



Abdullah Kahraman Fcst: 12 h
Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04)
Equivalent potential temperature at pressure = 850 hPa

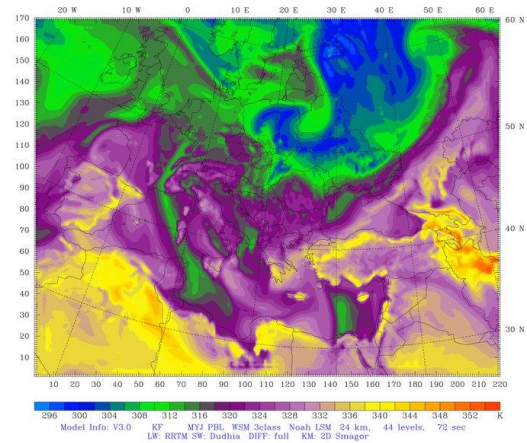


Figure 3.35 : 850 hPa equivalent potential temperature plots between 14.08.2004 06UTC to 15.08.2004 12UTC, with 6 hours interval.

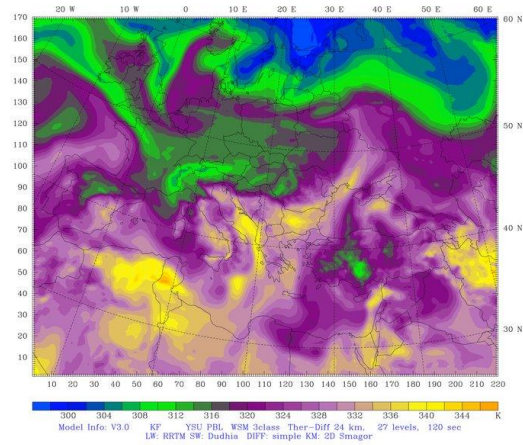
very dry air takes place. This is a result of the precipitation taking all the moisture to the ground, leaving dry air behind with subsidence. Eastern Mediterranean dry air and positive vertical velocity values as spots over Anatolia are also recognisable at this level on 15.08.2004 12UTC.

850 hPa plots are given as figures 3.34 and 3.35. Evolution of the low centre at this level shows why the system was more effective at the studied area. The sharper through to the east weakens by time, where the southern through gets sharpened. High wind speeds reaching 50 knots (see 14.08.2004 18UTC plot, 55N 45E coordinates) take the warm and moist Mediterranean air northwards at the east, as well as the cold air from north reaches Balkans, with 2 C isotherm on Romania borders on 15.08.2004 06UTC. The through is the sharpest at this moment.

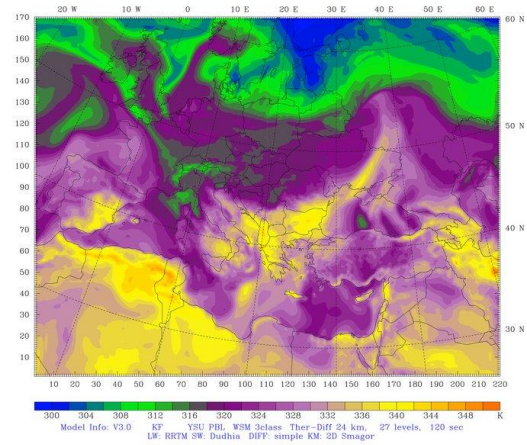
Equivalent potential temperature plots give another clue about the mixing of the air parcels at the area. There is a warm area over Bulgaria on 06UTC 14.08.2004, between the cold mid-Europe and cool Anatolia. Due to the radiative heating during the day, the area gets larger and warmer, reaching 342 K. However, as there are strong blocking winds over high terrains of Anatolia, synoptic mechanisms force the northern cold air suppress this warm parcel at that area and a support for lifting occurs. This warm air could just find a thin way in front of the through, going northeastwards on 15.08.2004. This suppression of warm air parcel is also visible at

925 hPa plots, given at Figure 3.36. Comparing this pattern with the relative vorticity maps at the same level (Figure 3.37), it will be seen that the small-scale vorticity “bubble” regarding the severe convection cell being analysed (see the 06UTC 15.08.2004 plot at figure 3.37, over Istanbul) will be tearing out of this jammed warm air.

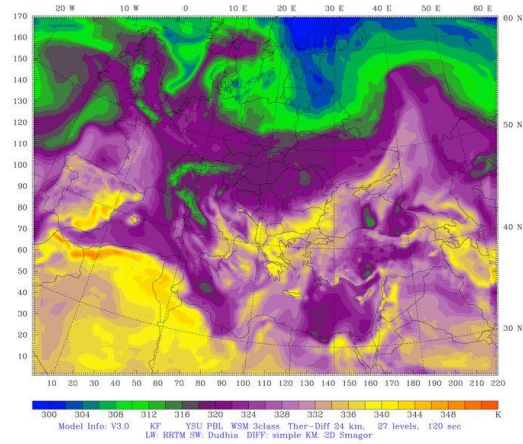
Abdullah Kahraman Fcst: 6 h
Valid: 06 UTC Sat 14 Aug 04 (09 LDT Sat 14 Aug 04)
Equivalent potential temperature at pressure = 925 hPa



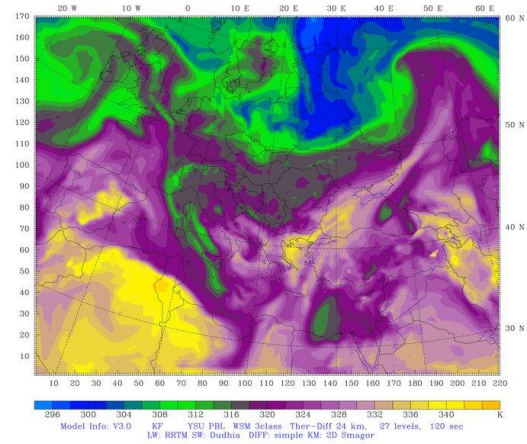
Abdullah Kahraman Fcst: 12 h
Valid: 12 UTC Sat 14 Aug 04 (15 LDT Sat 14 Aug 04)
Equivalent potential temperature at pressure = 925 hPa



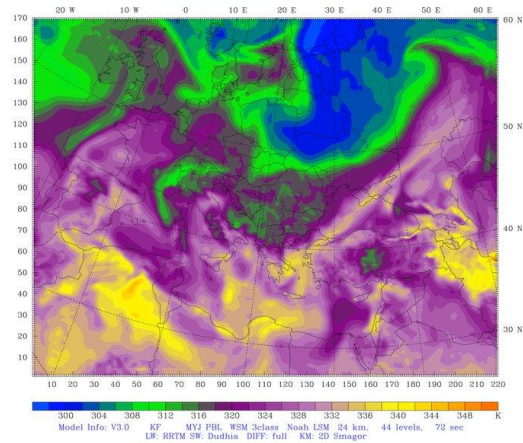
Abdullah Kahraman Fcst: 18 h
Valid: 18 UTC Sat 14 Aug 04 (21 LDT Sat 14 Aug 04)
Equivalent potential temperature at pressure = 925 hPa



Abdullah Kahraman Fcst: 24 h
Valid: 00 UTC Sun 15 Aug 04 (03 LDT Sun 15 Aug 04)
Equivalent potential temperature at pressure = 850 hPa



Abdullah Kahraman Fcst: 6 h
Valid: 06 UTC Sun 15 Aug 04 (09 LDT Sun 15 Aug 04)
Equivalent potential temperature at pressure = 925 hPa



Abdullah Kahraman Fcst: 12 h
Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04)
Equivalent potential temperature at pressure = 925 hPa

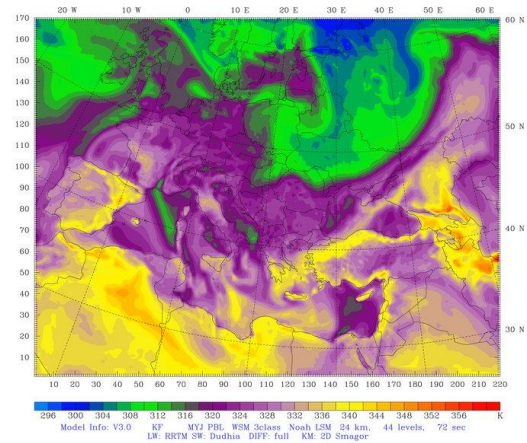
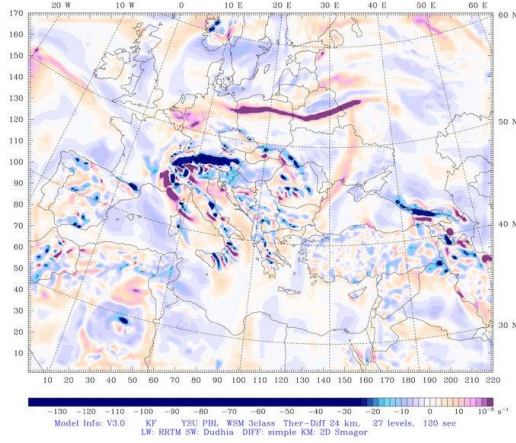


Figure 3.36 : 925 hPa equivalent potential temperature plots between 14.08.2004 06UTC to 15.08.2004 12UTC, with 6 hours interval.

Abdullah Kahraman
Relative vorticity

Valid: 06 UTC Sat 14 Aug 04 (09 LDT Sat 14 Aug 04)
at pressure = 925 hPa

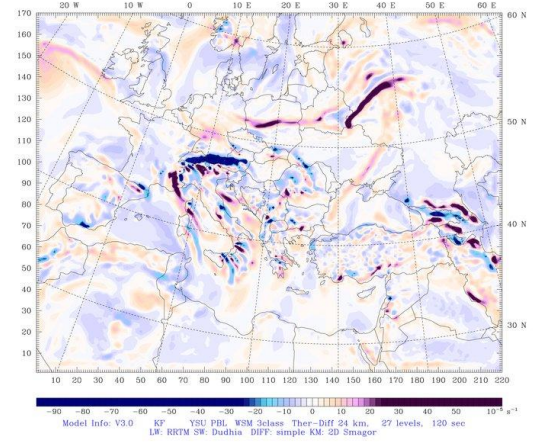
Fcst: 6 h



Abdullah Kahraman
Relative vorticity

Valid: 12 UTC Sat 14 Aug 04 (15 LDT Sat 14 Aug 04)
at pressure = 925 hPa

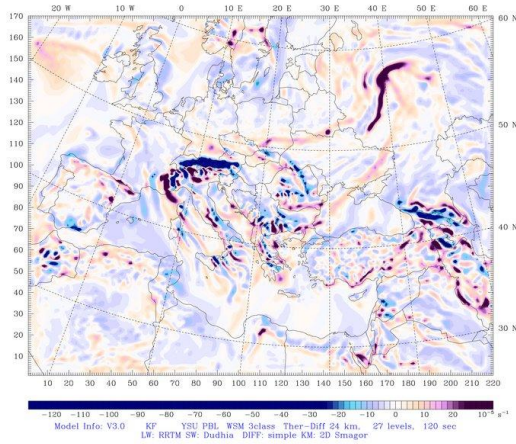
Fcst: 12 h



Abdullah Kahraman
Relative vorticity

Valid: 18 UTC Sat 14 Aug 04 (21 LDT Sat 14 Aug 04)
at pressure = 925 hPa

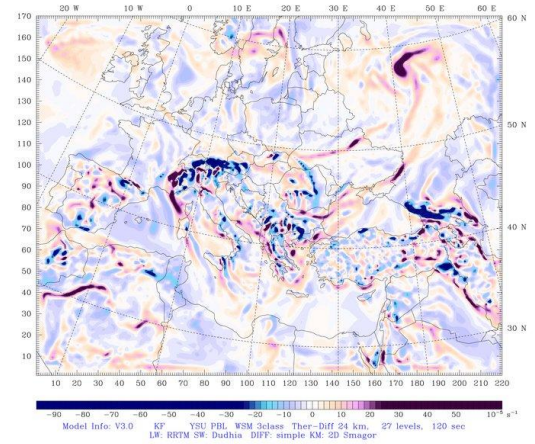
Fcst: 18 h



Abdullah Kahraman
Relative vorticity

Valid: 00 UTC Sun 15 Aug 04 (03 LDT Sun 15 Aug 04)
at pressure = 925 hPa

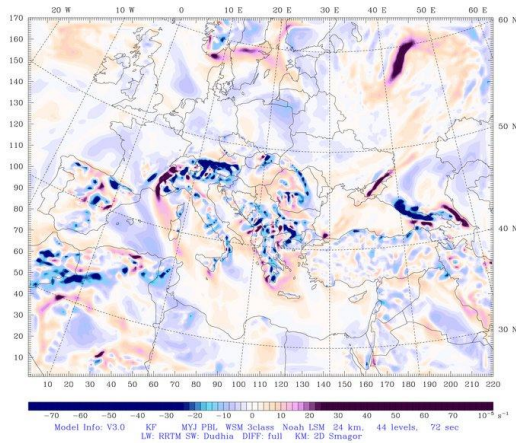
Fcst: 24 h



Abdullah Kahraman
Relative vorticity

Valid: 06 UTC Sun 15 Aug 04 (09 LDT Sun 15 Aug 04)
at pressure = 925 hPa

Fcst: 6 h



Abdullah Kahraman
Relative vorticity

Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04)
at pressure = 925 hPa

Fcst: 12 h

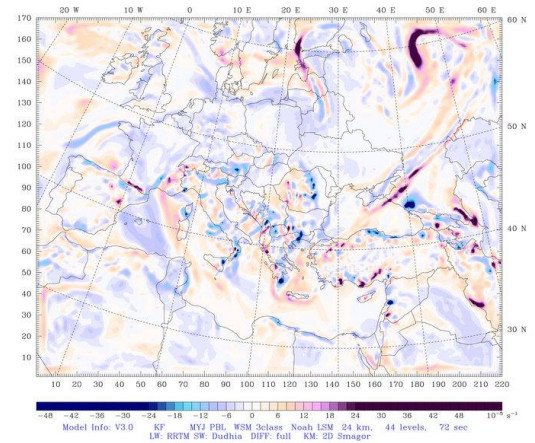


Figure 3.37 : 925 hPa relative vorticity plots between 14.08.2004 06UTC to 15.08.2004 12UTC, with 6 hours interval.

Analysed surface maps also show that there is a local modification of the system over the area (Figure 3.38). Local low centres occur at 18UTC on 14.08.2004, thunderstorms being started to be observed behind the frontal zone. The cold front passes over Istanbul at 06UTC on 15.08.2004.

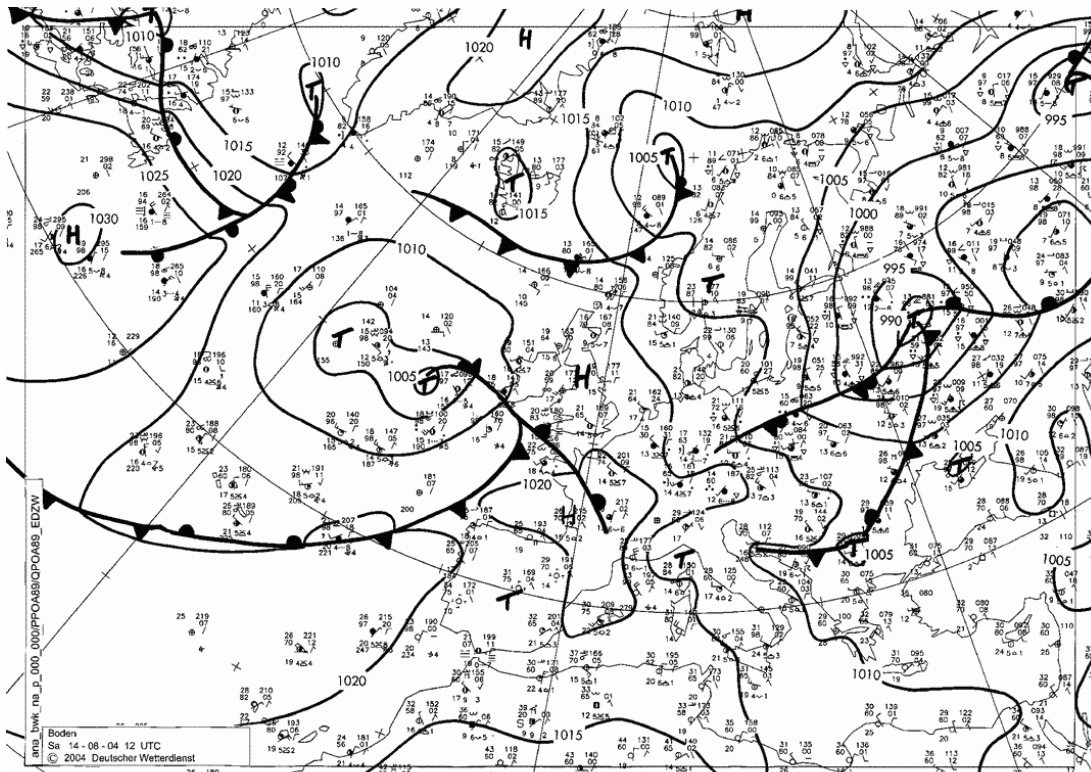


Figure 3.38 : Surface analysis charts from 06UTC on 14.08.2004 to 12UTC on 15.08.2004, issued by DWD.

With an overall look, the synoptic situation with the case is that a strong baroclinic area is situated over Eastern Europe, and the related cold front with a very strong wind shear and temperature gradient is passing over the region. This front triggers convection as a line, but it is not the onliest reason of the severe convective storm itself. Mesoscale features also play a magnificent role in creating the supercell. Detailed IR satellite images of the day can be seen in Appendix 2. For a comparison, Appendix 1 also includes some of the model output.

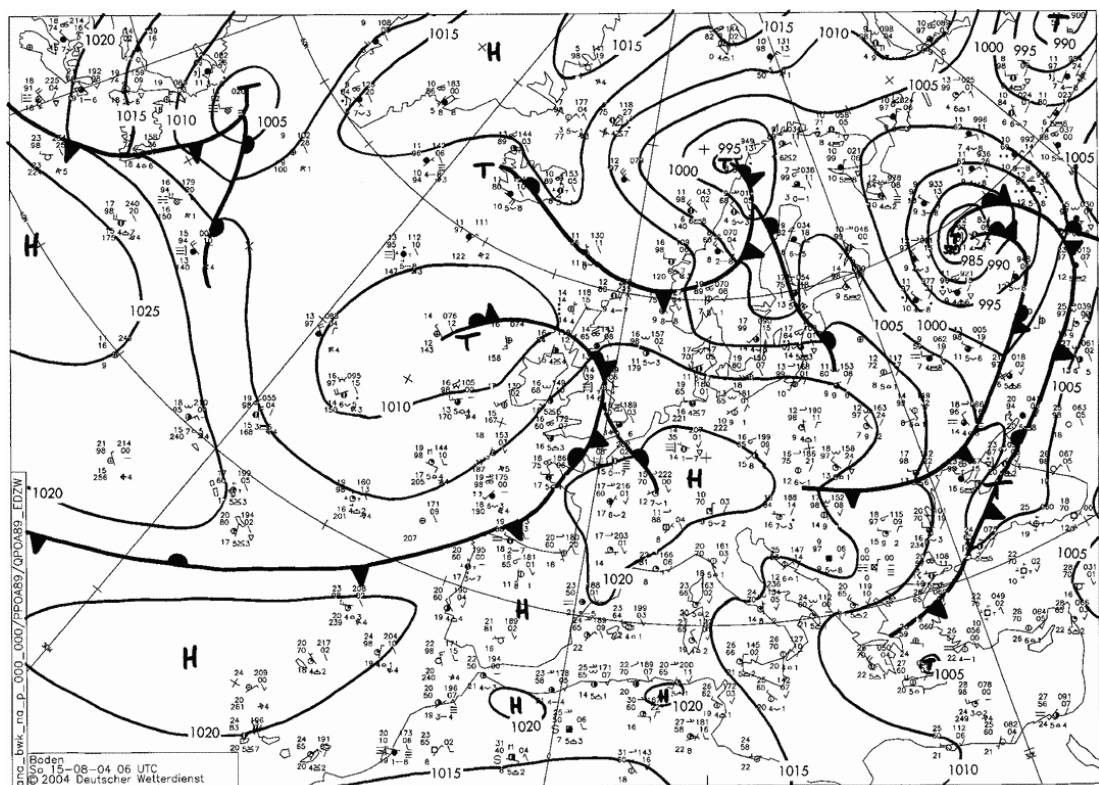
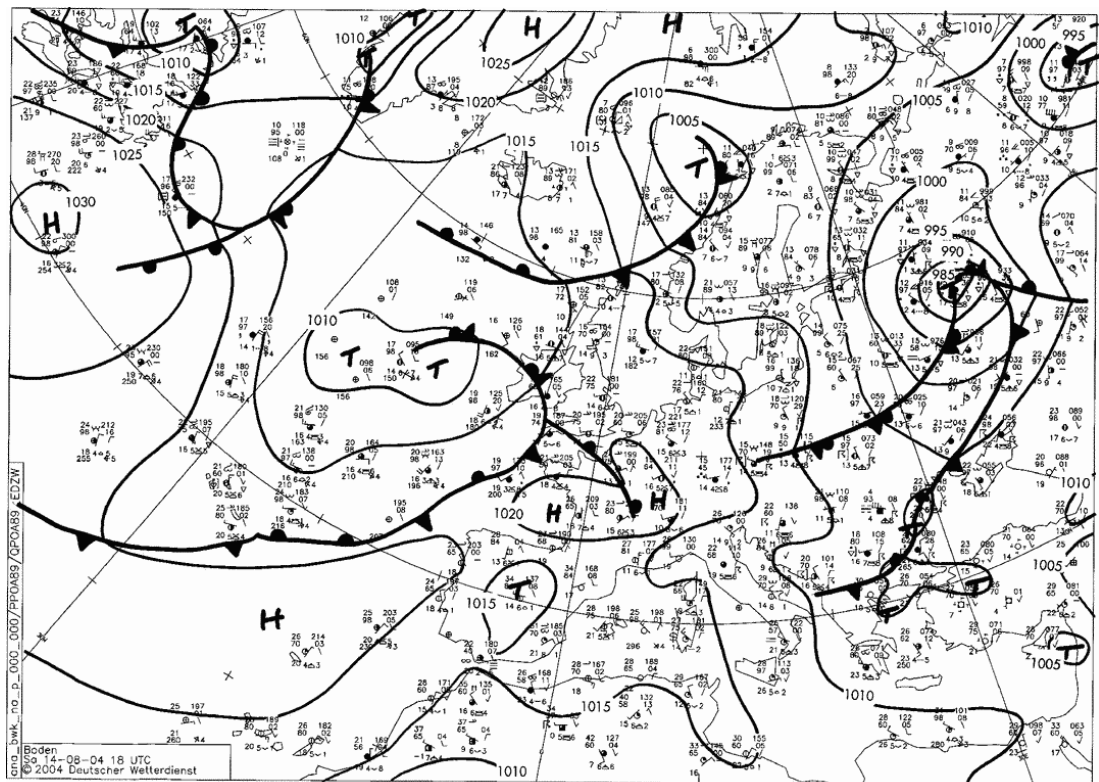


Figure 3.38 (cont) : Surface analysis charts from 06UTC on 14.08.2004 to 12UTC on 15.08.2004, issued by DWD.

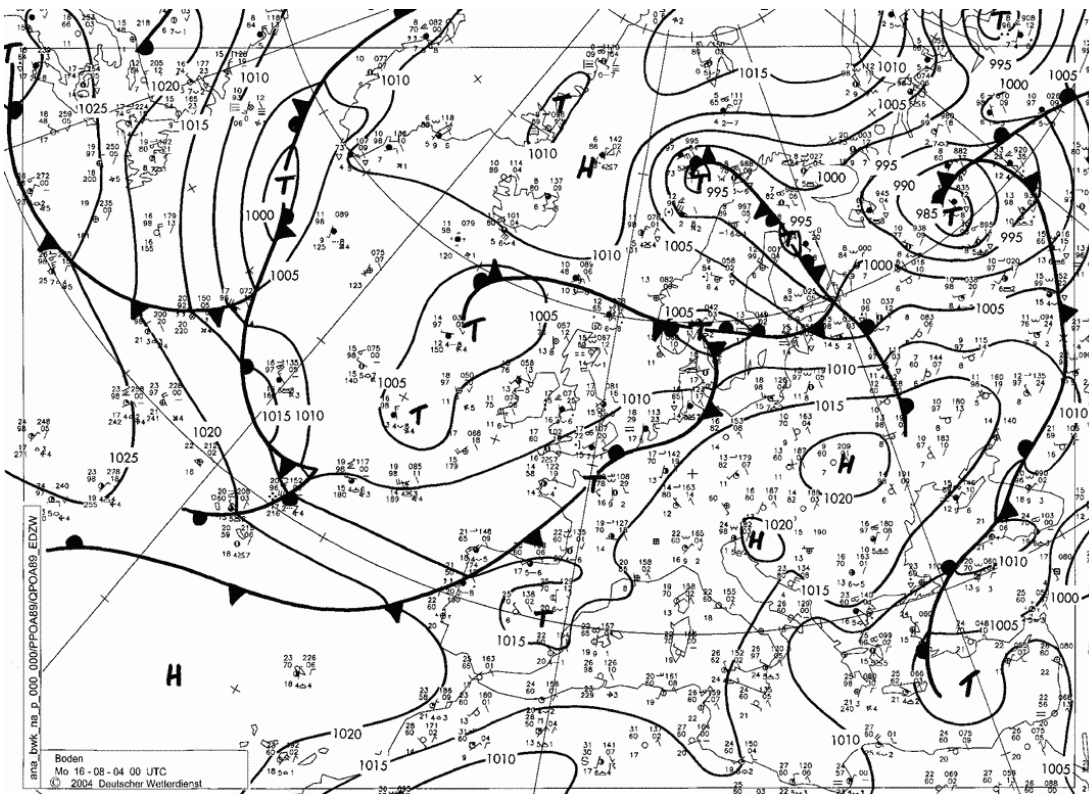
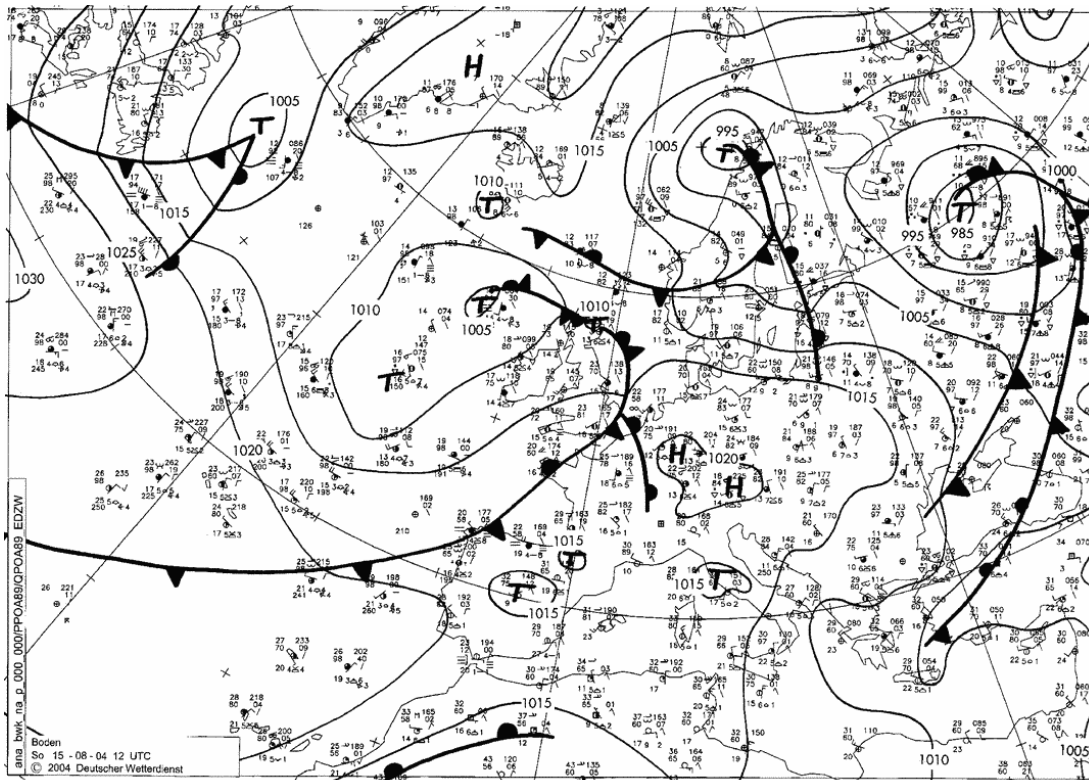


Figure 3.38 (cont) : Surface analysis charts from 06UTC on 14.08.2004 to 12UTC on 15.08.2004, issued by DWD.

3.7. Mesoscale Analysis

The mesoscale analysis will be focused on the cell over Northeastern Istanbul, 06UTC seen at the output of the numerical simulation. The location of the cell is not exactly at the place and time observed, but this will be taken as a modelling error. Fortunately, the cell the model creates shows the aspects of tornadic supercells, and for this reason the run can be suggested as a succesful one. The three ingredients for the severe weather, conditional instability, moisture content and a lifting mechanism will be discussed within the mesoscale analysis.

To investigate the instability, CAPE is a good starting point, in severe weather studies. CAPE and SREH values at 05UTC are plotted on Figure 3.39 for domain 2,

Abdullah Kahraman Fcst: 5 h
Valid: 05 UTC Sun 15 Aug 04 (08 LDT Sun 15 Aug 04)
CAPE (for parcel with max theta-e)
Sfc-3 km Storm-Rel Helicity 75%:30R

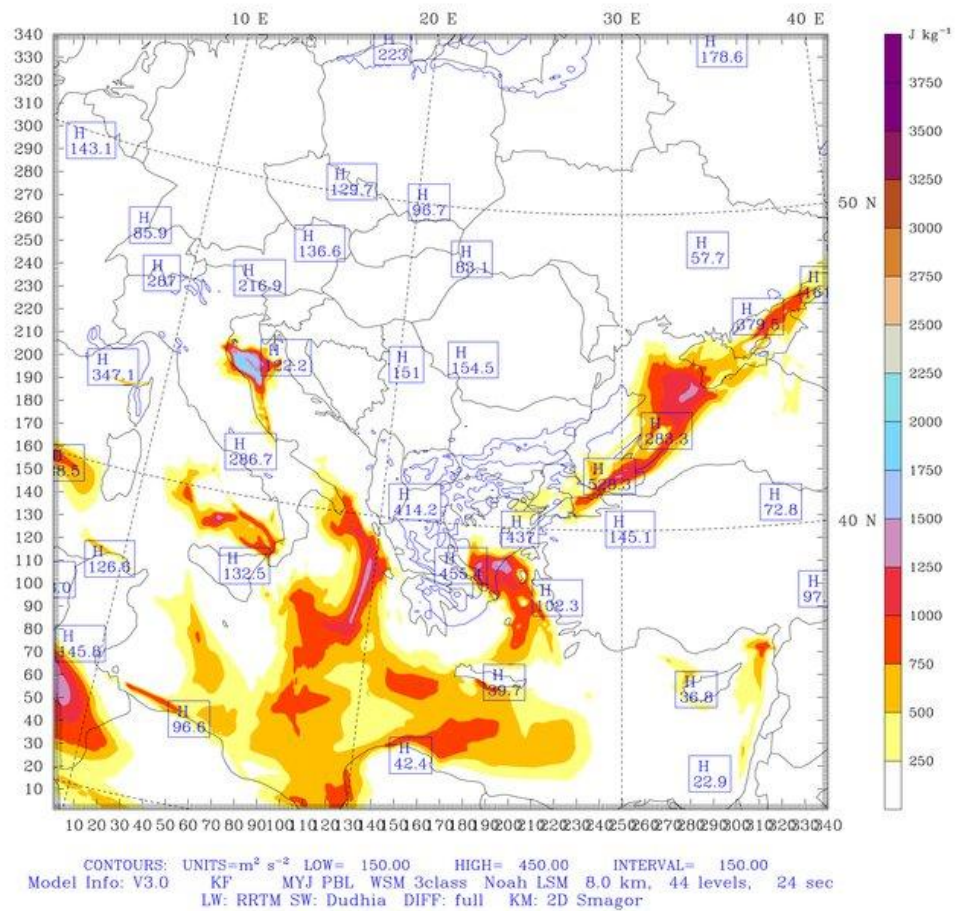


Figure 3.39 : Domain 1, CAPE & SREH at 05UTC, 15.08.2004.

and on Figure 3.40 for domain 3. CAPE values around the area do not look too high, but exist anyhow in moderate values reaching 1250 to 1500 j/kg. These values can be enough for tornadogenesis, if other conditions approve. On the same plots, SREH gives a clue about the other conditions: a maxima of 528 m^2s^{-2} at domain 2 and 838.2 m^2s^{-2} at domain 3. These are high values, indicating the dynamic conditions to be suitable for a severe storm. The locations of the maxima of CAPE and SREH fit well.

Instability indexes also show moderate to high values; CT 22, VT 25, TT 47, S 38, TQ 27, SWEAT 189, LI -1.9, K 34, Kahraman Index 37; according to the threshold values for Istanbul (Kahraman, 2008).

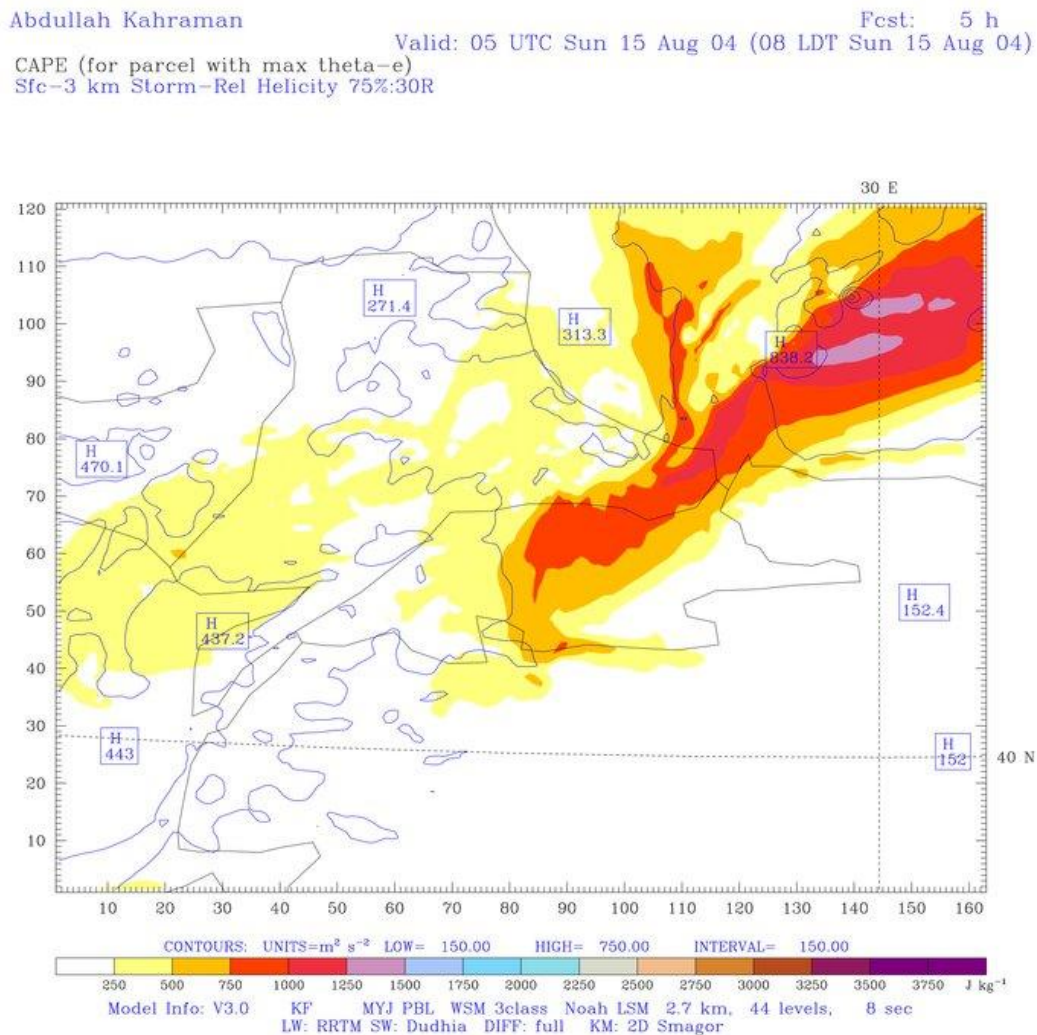


Figure 3.40 : Domain 3, CAPE & SREH at 05UTC, 15.08.2004.

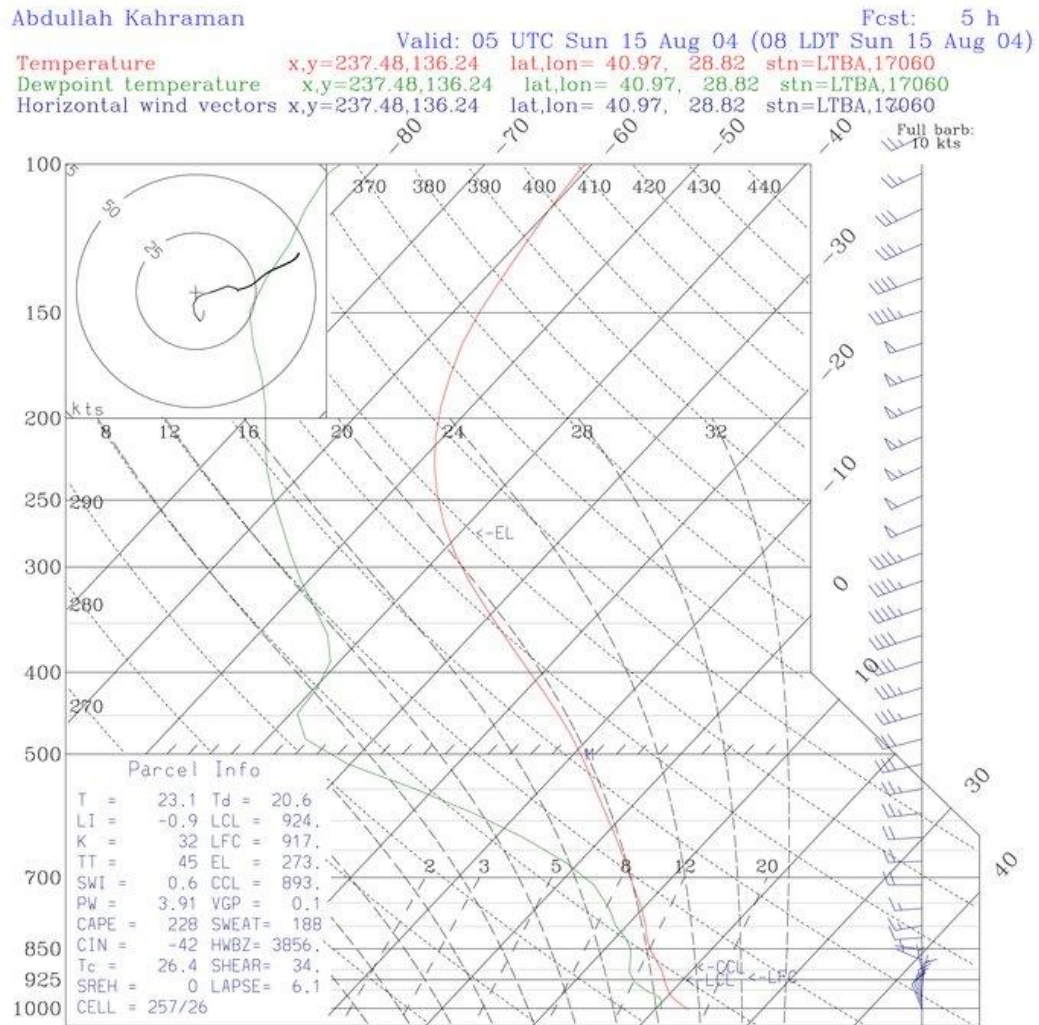


Figure 3.41 : Skew-T log-p diagram and hodograph of Istanbul for 05UTC on 15.08.2004.

Figure 3.41 is the skew-T log-p diagram for Istanbul at 05UTC on 15.08.2004. The environmental temperature is parallel to the moist adiabat from low level to about 300 hPa level, which means that the air is conditionally unstable until tropopause. There is a high moisture under 700 hPa level, but above is very dry. LCL, CCL and LFC are around 925 hPa, very close to the ground. Low level LFC is a key feature at this point. The wind profile at planetary boundary layer has a strong shear, although easterly flows can not be seen from this diagram, due to the location of the grid point. Hodograph has a hook style revealing a kink, which shows a pattern of tornadogenesis.

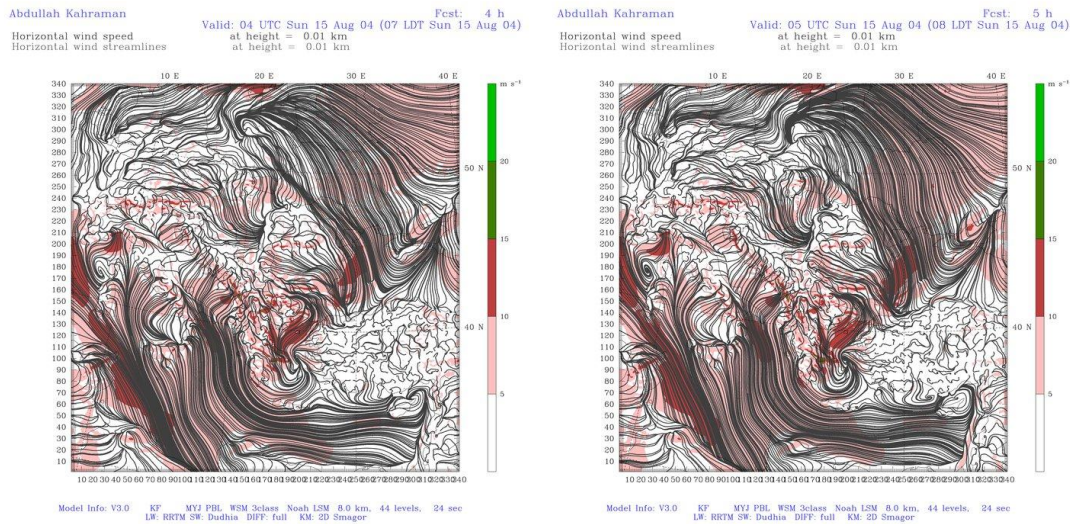


Figure 3.42 : Streamlines at 10 m above surface, for 04UTC and 05UTC, 15.08.2004.

As seen from Figure 3.42, a ground level convergence exist over northeastern Istanbul coasts on 04 UTC and 05UTC streamline plots. The strong flow carrying moisture from Black Sea is cut by a northwesterly wind parallel to the north coasts of Istanbul. This pattern dynamically forces the air parcel to rise at this area, no matter the parcel is eager to be lifted. Figure 3.43 indicate a 90 degrees of shear in wind direction (15 kt velocity) near Istanbul's north coast.

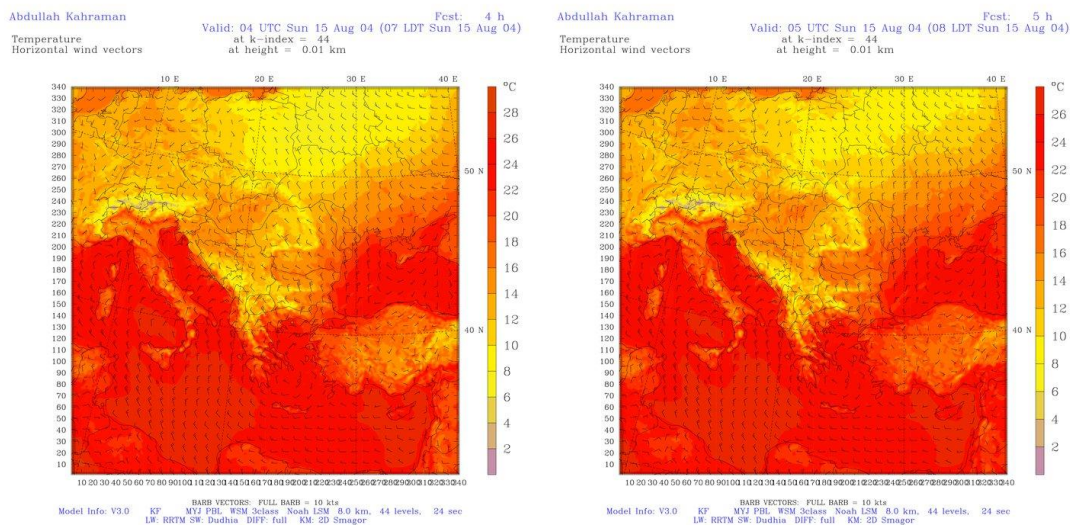


Figure 3.43 : 10 m wind barbs and ground level temperature, for 04UTC and 05UTC, 15.08.2004.

Given that the three ingredients exist over the storm area, a closer look to the model output of domain 3 would be useful. As known, low level jet is one of the important indicators for severe storms. 850 hPa level winds are shown at Figure 3.44, for 04UTC, 05 UTC and 06 UTC.

As seen from the plots, the low level jet exist as 25 knots at 05UTC. As a supercell feature, the cyclonic turn of the barbs indicate a mesocyclone at all three charts. A warm air is prisoned inside the vortex.

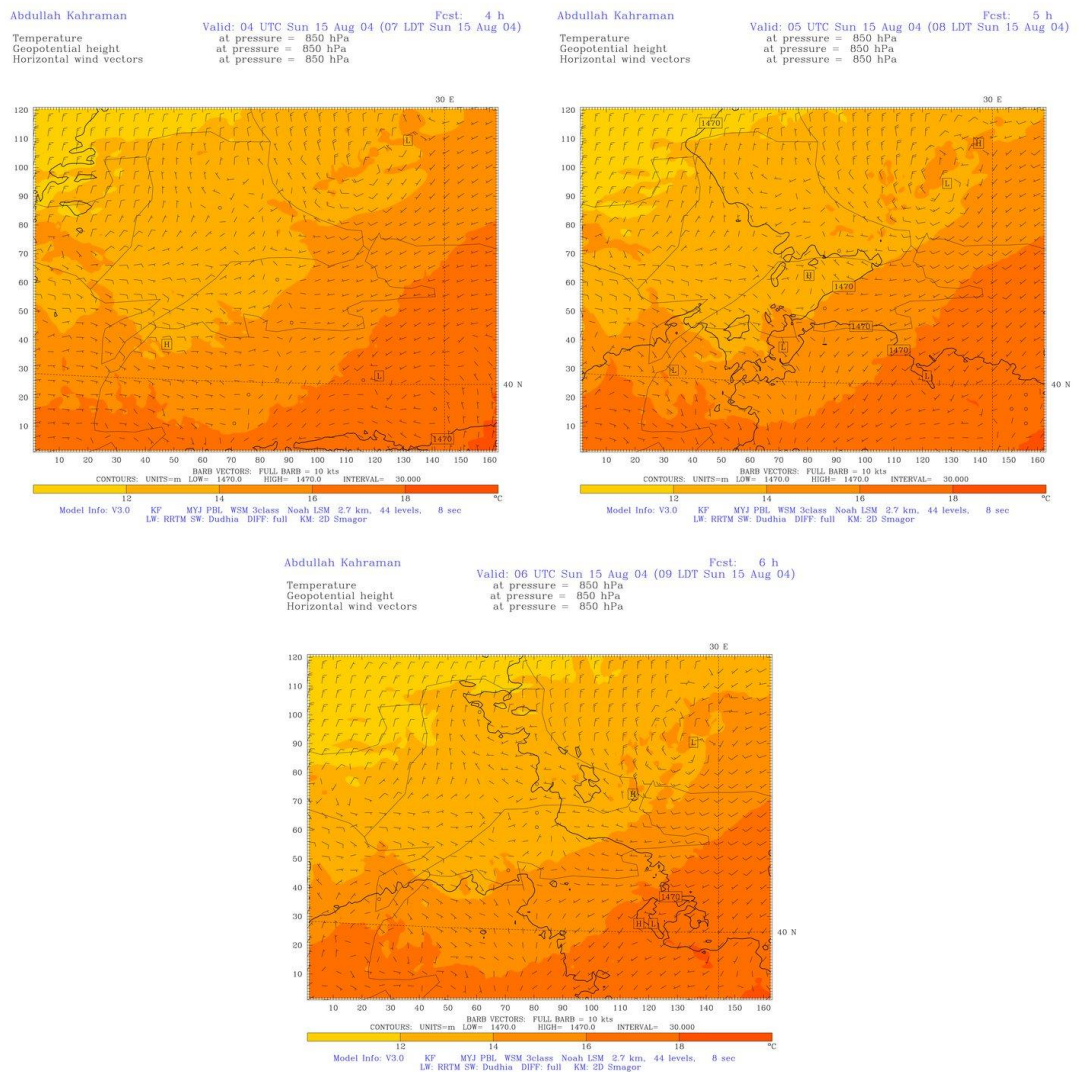


Figure 3.44 : 850 hPa wind and temperature, for 04UTC, 05UTC and 06 UTC, 15.08.2004.

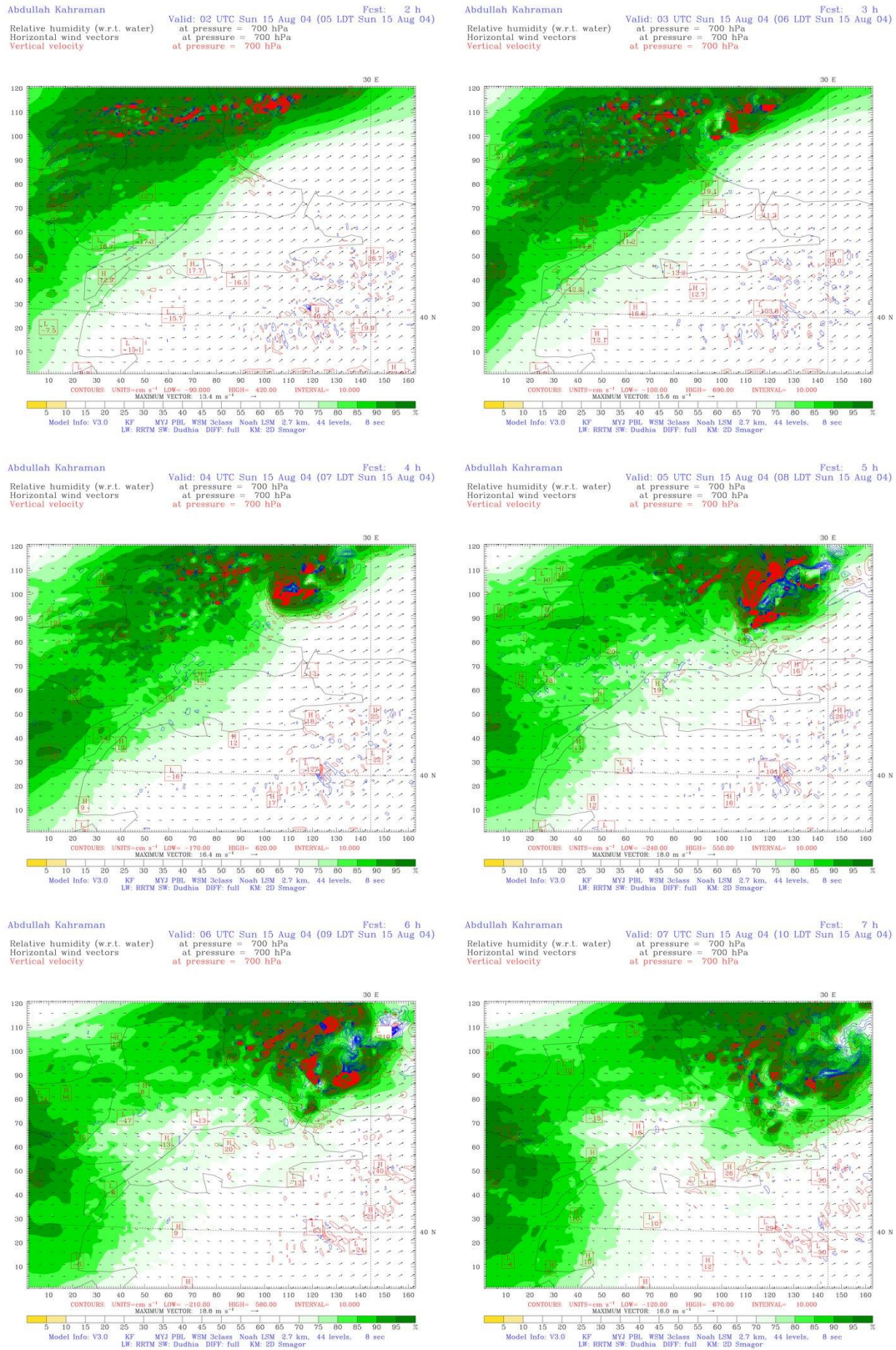


Figure 3.45 : 700 hPa humidity, wind and vertical velocity for 02UTC, 03UTC, 04UTC, 05UTC, 06 UTC and 07UTC on 15.08.2004.

Figure 3.45 gives a nice overview on the evolution of the DMC cell. These are the 700 hPa plots, showing the relative humidity, wind vectors and vertical velocity. On 02UTC and 03 UTC, a red area indicating updraft on north appears. On 03UTC, the highest vertical velocity value reaches 746.9 cm/s and the moisture pattern takes a cell form around the updraft. These two plots can be thought as the initial stage of the storm cell.

On 04 UTC, the cell becomes larger, letting a blue zone inside the updraft, which means that the vertical movement is downwards. This can be taken as a downdraft with precipitation, which corresponds to the beginning of the mature stage. 05UTC plot makes the updraft and downdraft zones become equal, with a maximum of 240 cm/s downwards movement at northeastern part of the cell.

06UTC and 07UTC can be taken as the dissipating stage, as the updraft starts to disappear and the relative humidity values also decrease, due to the precipitation. At 05UTC plot, even rear flank downdraft is visible, which is important in tornadogenesis.

Likewise 700 hPa plots, on 500 hPa plots can also be seen that the horizontal flow makes a curve around the convective cell (Figure 3.46). Strong wind shear exist in mid-troposphere.

After seeing the upper charts, the surface streamlines make more sense to see. Figure 3.47 shows 05UTC streamlines for 10 m above ground. The convergence is clear and the horizontal wind exceeds 15 m/s near the centre of the mesocyclone.

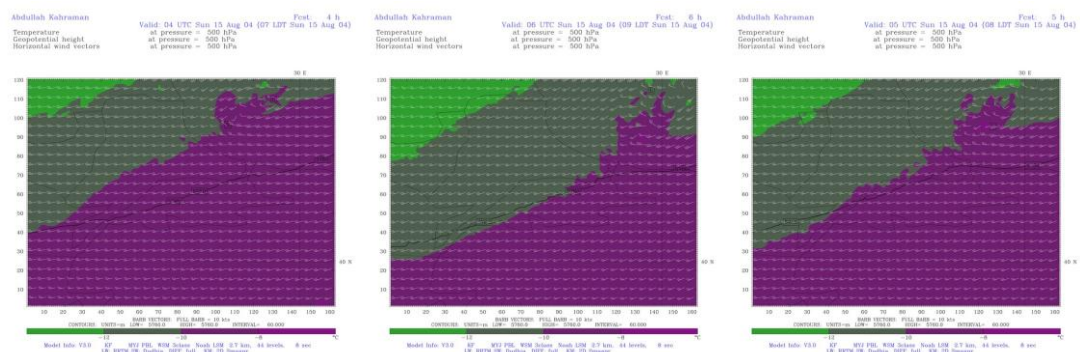


Figure 3.46 : 500 hPa geopotential height, temperature and wind for 04UTC, 05UTC and 06 UTC on 15.08.2004.

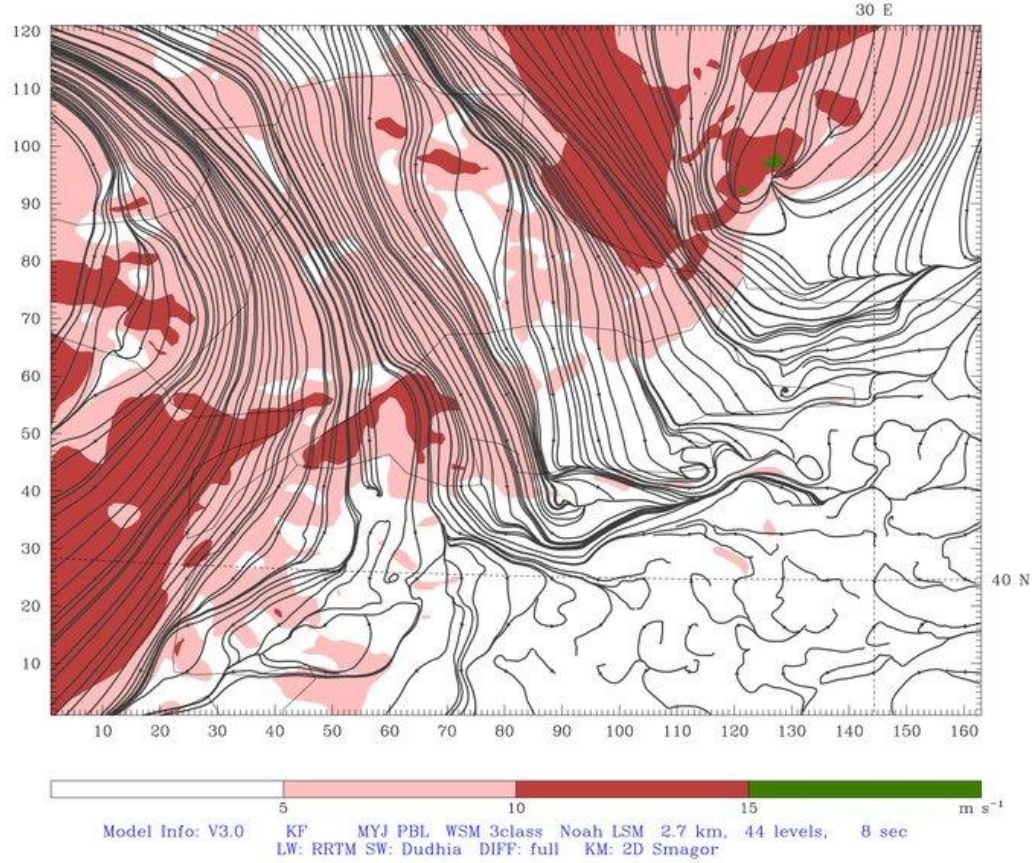


Figure 3.47 : 10 m streamlines for 05 UTC on 15.08.2004.

Finally, vertical cross sections from southwest (coordinates of grids 20, 20) to northeast (coordinates 150, 100) of the domain 3 are shown at Figure 3.48. The mountainous area at the left is the area of Çanakkale province, the middle refer to the Marmara Sea, the low terrain from 240 to 290 is Istanbul, and the right side is the Black Sea, where the severe storm is simulated. The vectors show the circulation, red lines are equivalent potential temperature, and the shaded field is the potential vorticity. From the 00UTC, it is clear that there is a vertical windshear between the low level and above 900 hPa level. According to the equivalent potential temperature

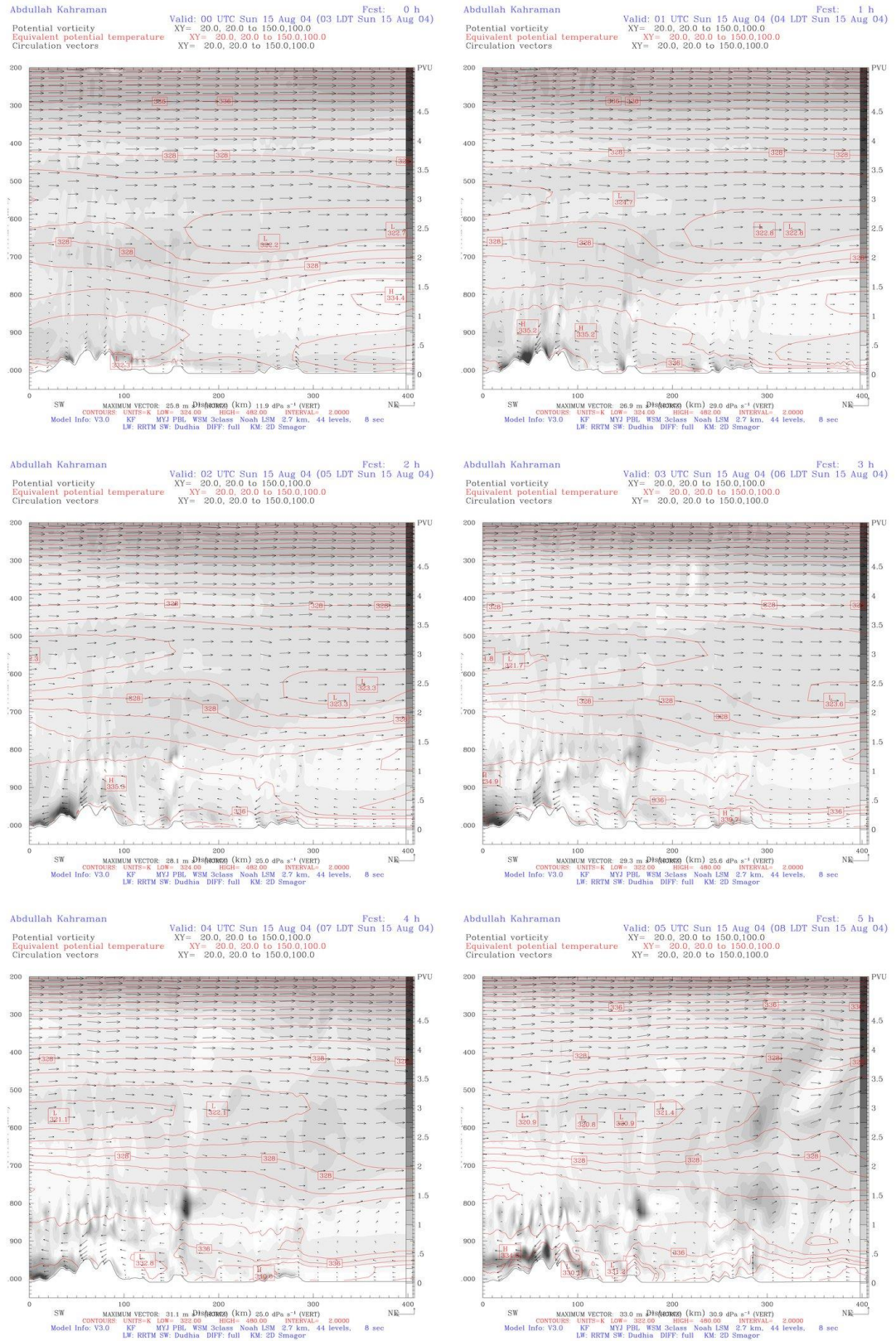


Figure 3.48 : Vertical cross sections from SW to NE of the domain 3. From 00UTC to 05UTC on 15.08.2004.

isotherms, there is a moderate lapse rate over Black Sea, near the ground. As the time passes, the vertical movement gets mature over the area and at 06UTC, 19.23 hPa/s value is reached. This image is an impressive view of the supercell storm, in terms of potential vorticity.

As a result, a composite chart for the severe convection is pictured on WV image of METEOSAT-7 (Figure 3.49). Important synoptic and mesoscale features can be seen together on such a chart. The 500 hPa through is drawn with brown, 300 hPa polar jet is blue, and low level jet is drawn with magenta colors. The red rings with crosses represent the maximum vorticity centers. The cold front is drawn with black, and the significant isotherm at 500 hPa level is shown with dashed green line.

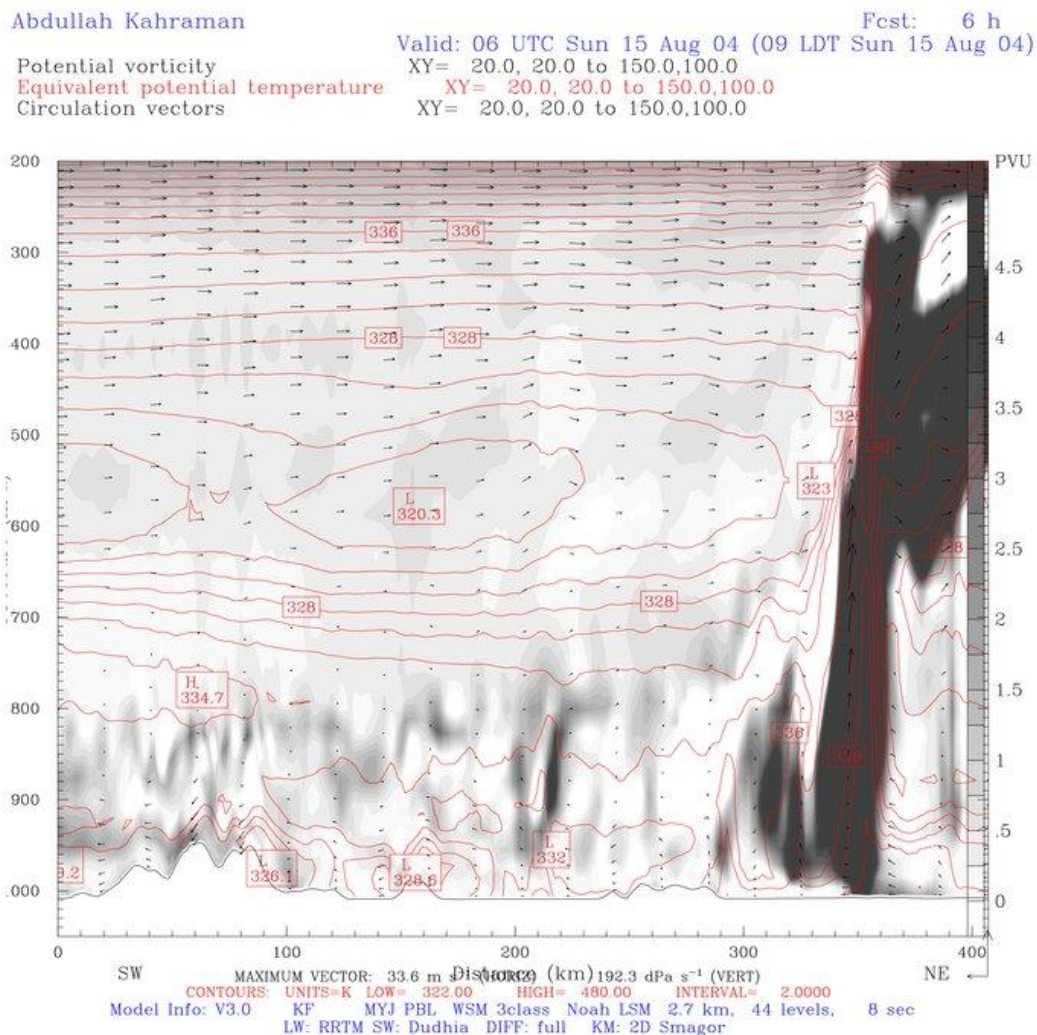


Figure 3.48 (cont.) : Vertical cross section from SW to NE of the domain 3. 06UTC on 15.08.2004.

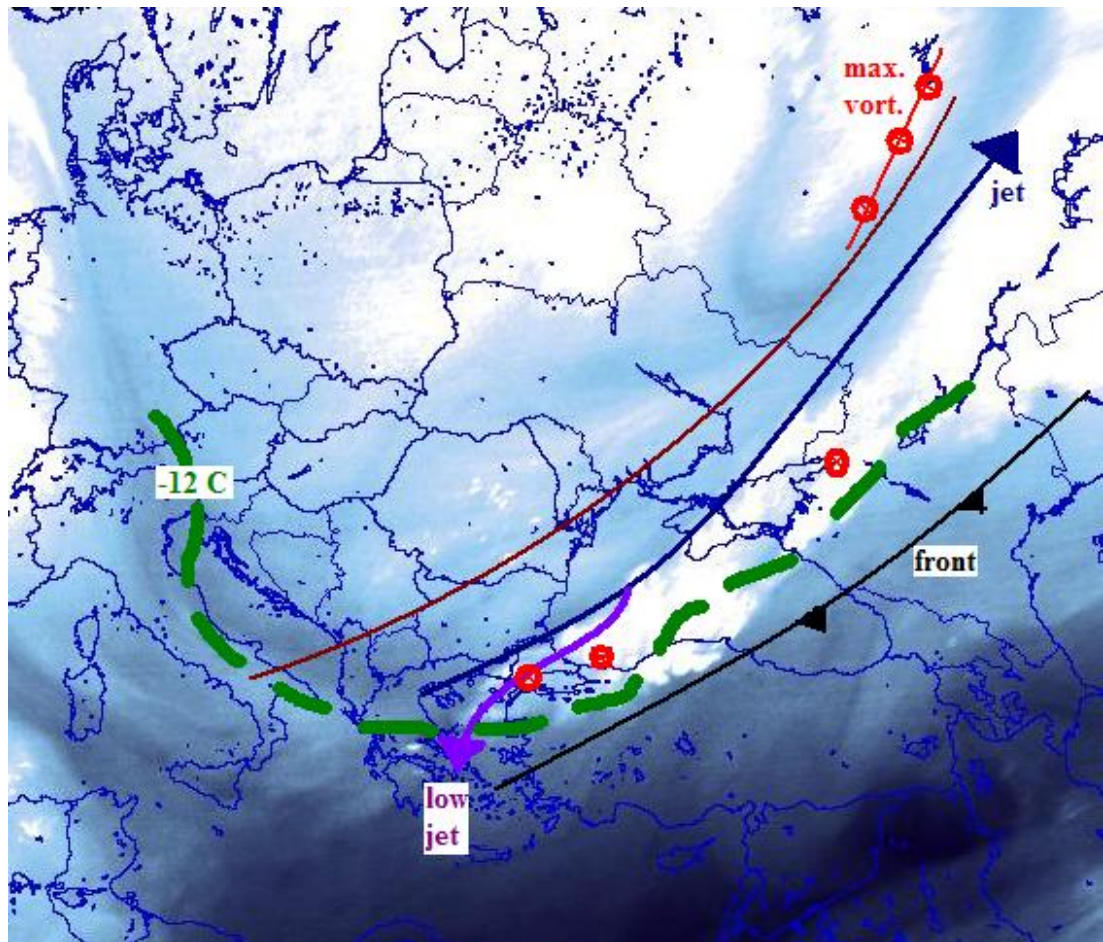


Figure 3.49 : Composite chart of the case at 12UTC 15.08.2004, on METEOSAT-7 WV image. Brown line is the 500 hPa through, blue line is the 300 hPa jet, magenta line is the low-level jet, red crosses are the maximum vorticity areas, black line is the cold front on surface and dashed green line is the significant isotherm (-12 C) at 500 hPa.

4. CONCLUSION AND RECOMMENDATIONS

The major purpose of this research was to analyse a severe convection case in Turkey. In this study, numerical simulation of the severe convection on 15.08.2004 is performed after a broad sensitivity analysis. Results show that in addition to synoptic scale forcings, mesoscale features also played an important role on the severity of the convection. There was enough moisture for whole system, as it occurred on Black Sea, on a cold front line. The warm air jammed over Bulgaria was pushed by strong winds over Marmara and a strong convergence created the phenomena. The CAPE and other instability thresholds were not extreme, but the very low LFC was enough for the severe convection, as well as the strong vertical and horizontal wind shear.

Mesoscale models are capable of predicting the convection and relevant phenomena, on the other hand, capturing the cells from mesoscale to microscale is usually not possible. This is due to the resolution and errors of the analysis data, as well as physical approaches and parameterizations used in the model. While investigating the severe weather events, especially when working with fine resolution, model parameters must be chosen very carefully. In this study, absence of radar data prevented a better validation of model results and deeper analysis of each convective cells. However, satellite images and TRMM data could give an idea of the success of the simulations.

A Doppler radar is the most important necessity for the research and forecasting of these mesoscale events. All the country must be under radar coverage as soon as possible. Severe weather reports must be issued properly by the stations, as well as the public consciousness must be set for a good database of such phenomena. A climatology must be performed on these severe weather events as well.

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APPENDICES

APPENDIX A.1 : Output of Run 30: Synoptic conditions that favor the convection.

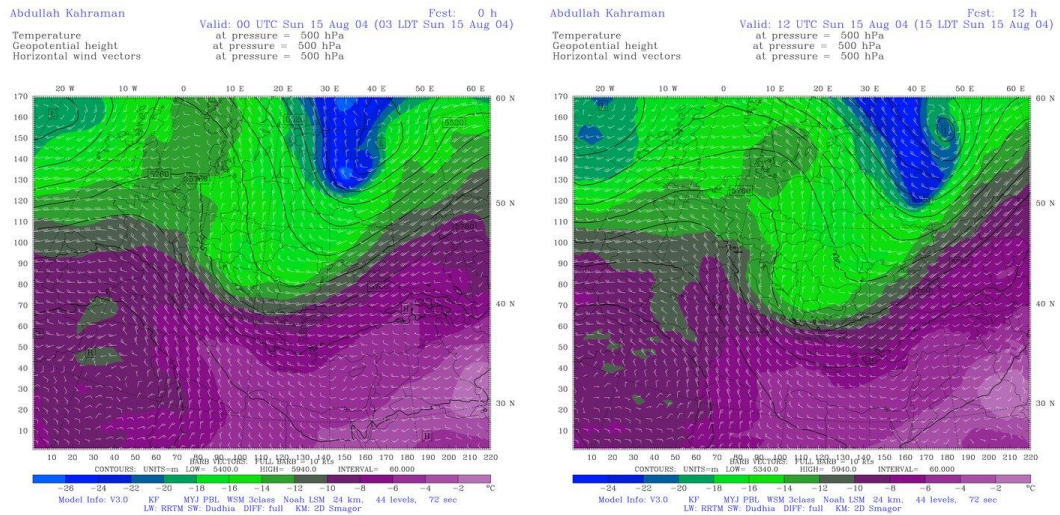


Figure A.1.1: 500 hPa geopotential height, temperature and wind on 15.08.2004 analysis at 00:00GMT (a), and forecast at 12:00GMT (b).

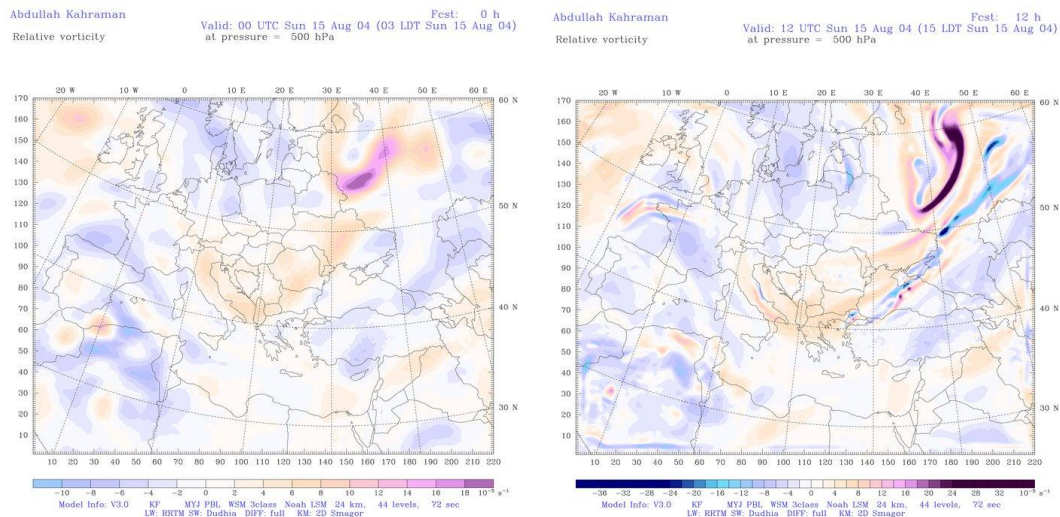


Figure A.1.2: 500 hPa relative vorticity on 15.08.2004 analysis at 00:00GMT (a), and forecast at 12:00GMT (b).

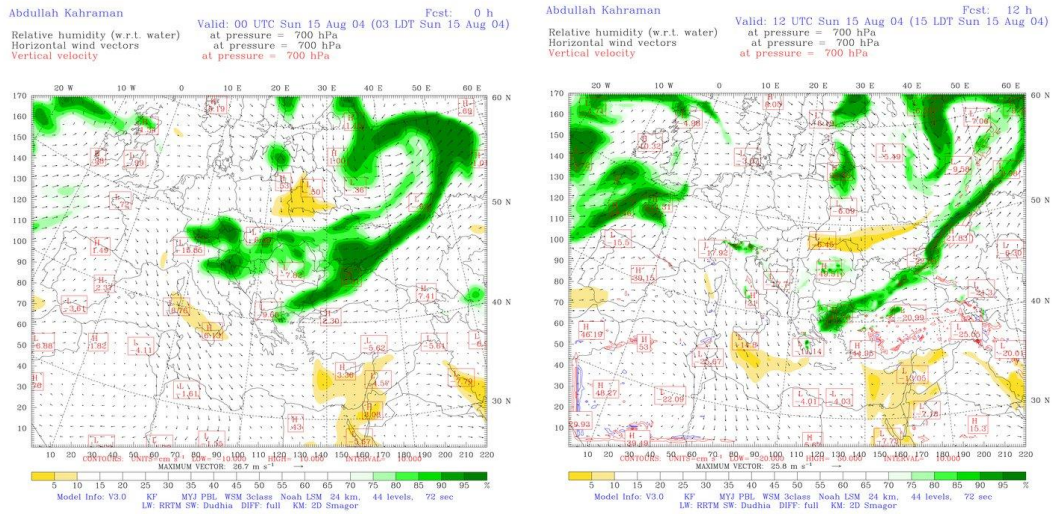


Figure A.1.3: 700 hPa relative humidity, horizontal wind and vertical velocity on 15.08.2004 analysis at 00:00GMT (a), and forecast at 12:00GMT (b).

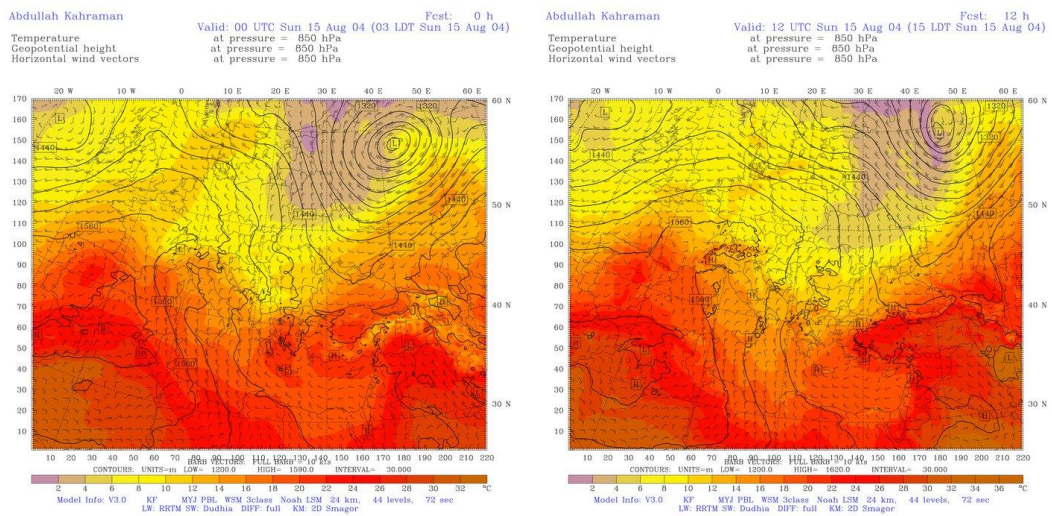


Figure A.1.4: 850 hPa temperature, geopotential height and wind on 15.08.2004 analysis at 00:00GMT (a), and forecast at 12:00GMT (b).

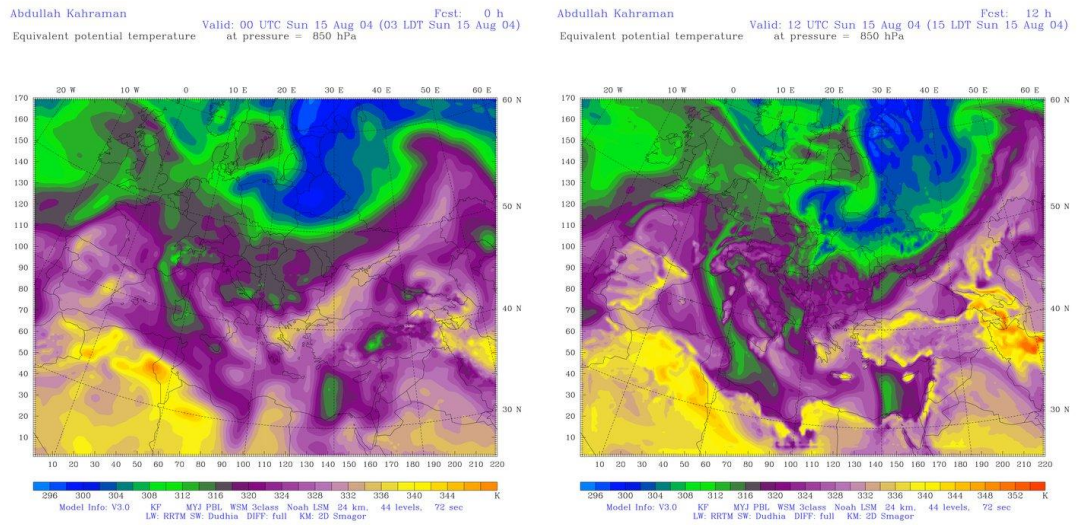


Figure A.1.5: 850 hPa equivalent potential temperature on 15.08.2004 analysis at 00:00GMT (a), and forecast at 12:00GMT (b).

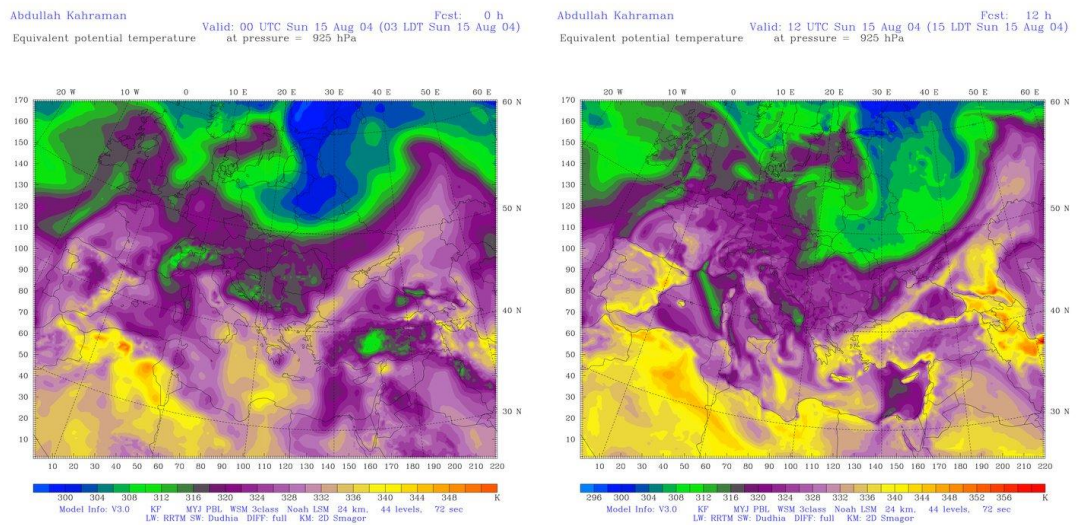


Figure A.1.6: 925 hPa equivalent potential temperature on 15.08.2004 analysis at 00:00GMT (a), and forecast at 12:00GMT (b).

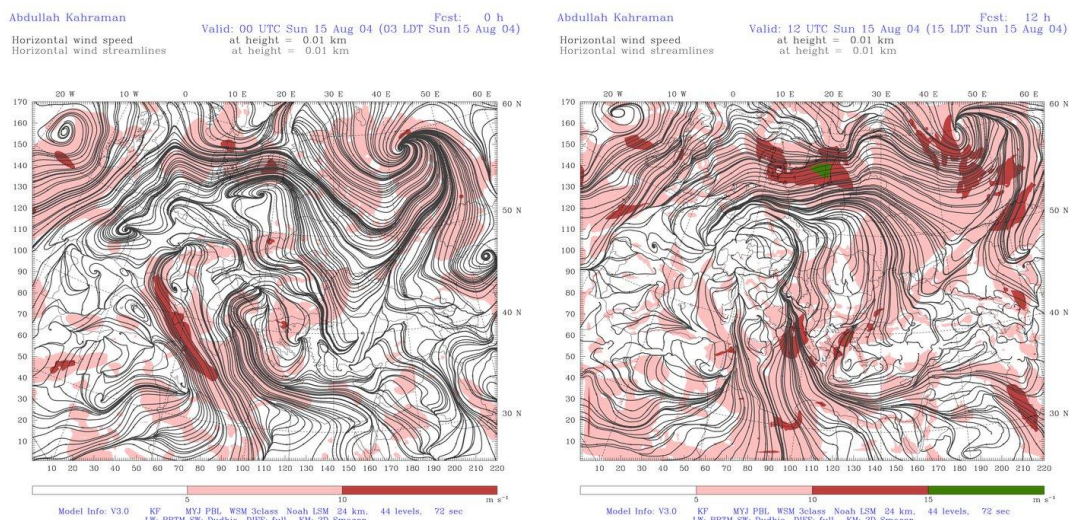


Figure A.1.7: 10 meters horizontal wind streamlines on 15.08.2004 analysis at 00:00GMT (a), and forecast at 12:00GMT (b).

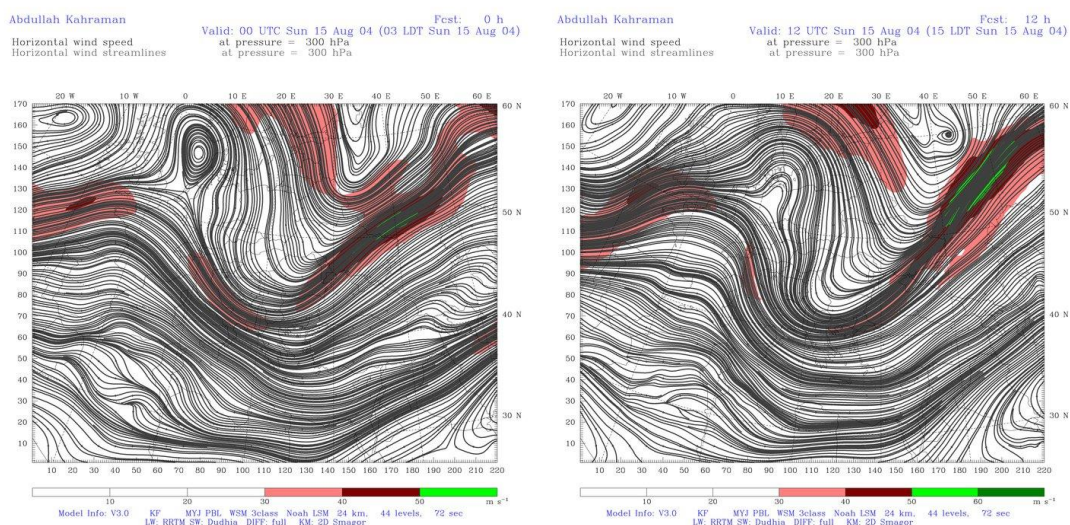
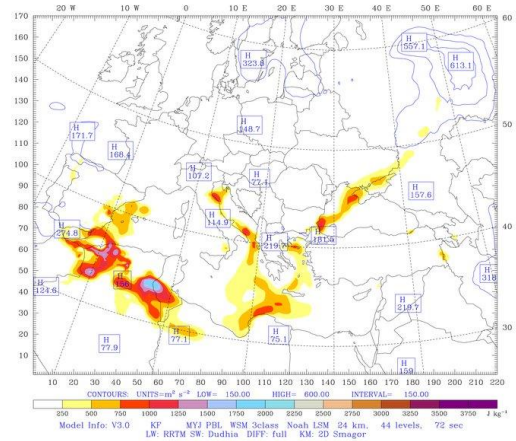


Figure A.1.8: 300 hPa horizontal wind streamlines on 15.08.2004 analysis at 00:00GMT (a), and forecast at 12:00GMT (b).

Abdullah Kahraman Valid: 00 UTC Sun 15 Aug 04 (03 LDT Sun 15 Aug 04) Fcst: 0 h
CAPE (for parcel with max theta-e)
Sfc-3 km Storm-Rel Helicity 75%-30R



Abdullah Kahraman Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04) Fcst: 12 h
CAPE (for parcel with max theta-e)
Sfc-3 km Storm-Rel Helicity 75%-30R

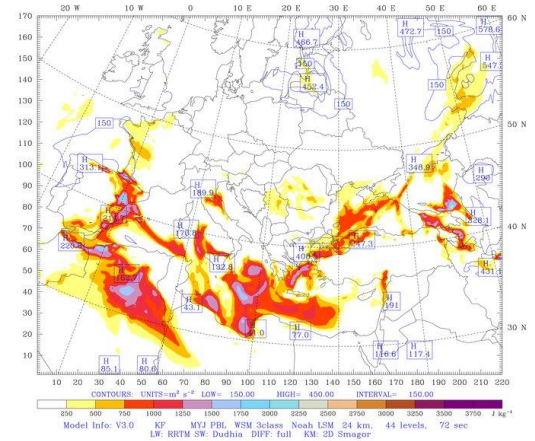
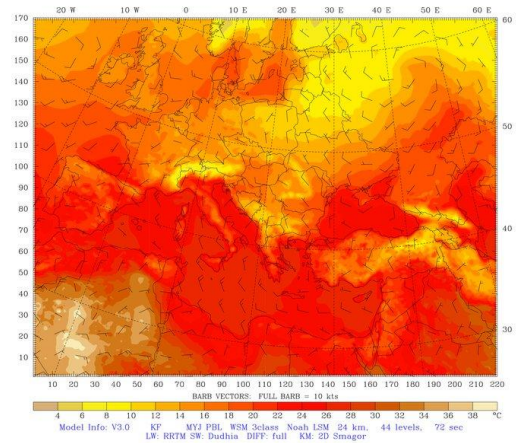


Figure A.1.9: CAPE and SREH on 15.08.2004 analysis at 00:00GMT (a), and forecast at 12:00GMT (b).

Abdullah Kahraman Valid: 00 UTC Sun 15 Aug 04 (03 LDT Sun 15 Aug 04) Fcst: 0 h
Temperature
Horizontal wind vectors
at k-index = 44
at height = 0.01 km



Abdullah Kahraman Valid: 12 UTC Sun 15 Aug 04 (15 LDT Sun 15 Aug 04) Fcst: 12 h
Temperature
Horizontal wind vectors
at k-index = 44
at height = 0.01 km

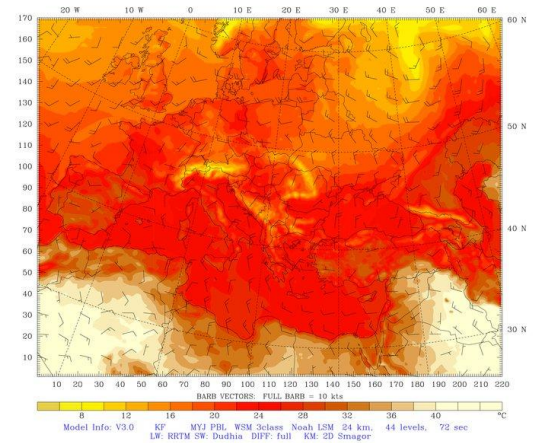


Figure A.1.10: Surface wind and temperature on 15.08.2004 analysis at 00:00GMT (a), and forecast at 12:00GMT (b).

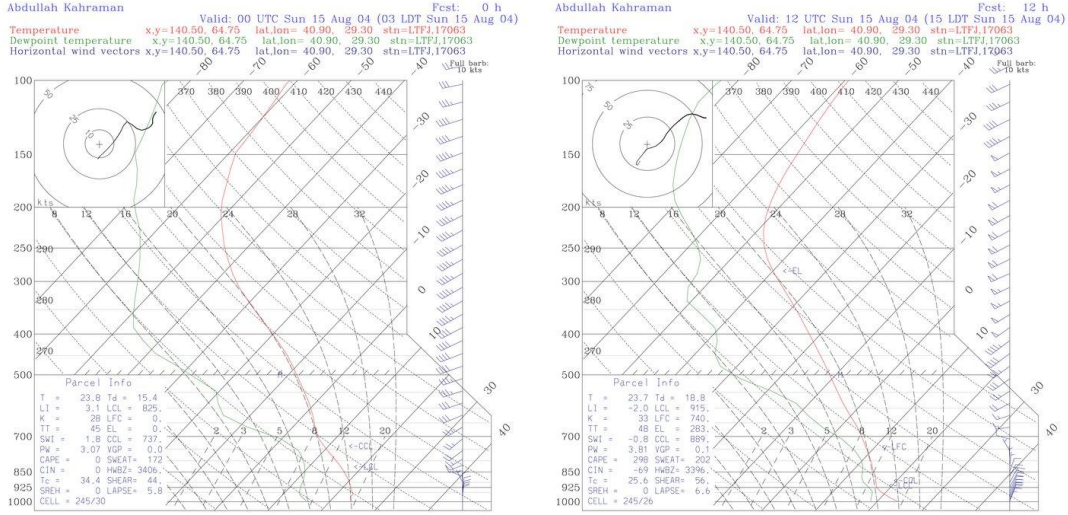


Figure A.1.11: Skew-T log-p diagram of Sabiha Gokcen Airport on 15.08.2004 analysis at 00:00GMT (a), and forecast at 12:00GMT (b).

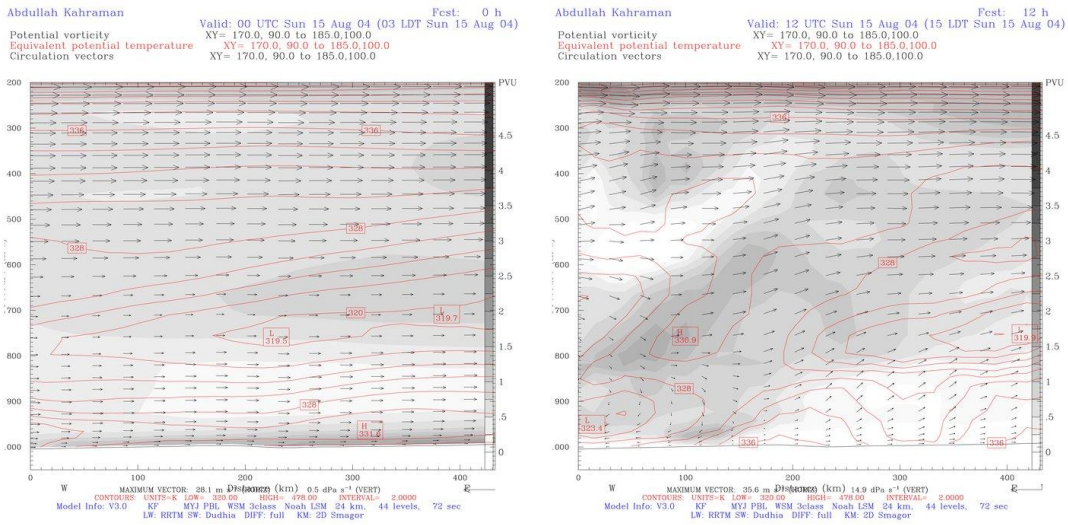


Figure A.1.12: Vertical cross-section over Black Sea on 15.08.2004 analysis at 00:00GMT (a), and forecast at 12:00GMT (b).

APPENDIX A.2 : Infrared Satellite images of METEOSAT-7 for 15. 08. 2004

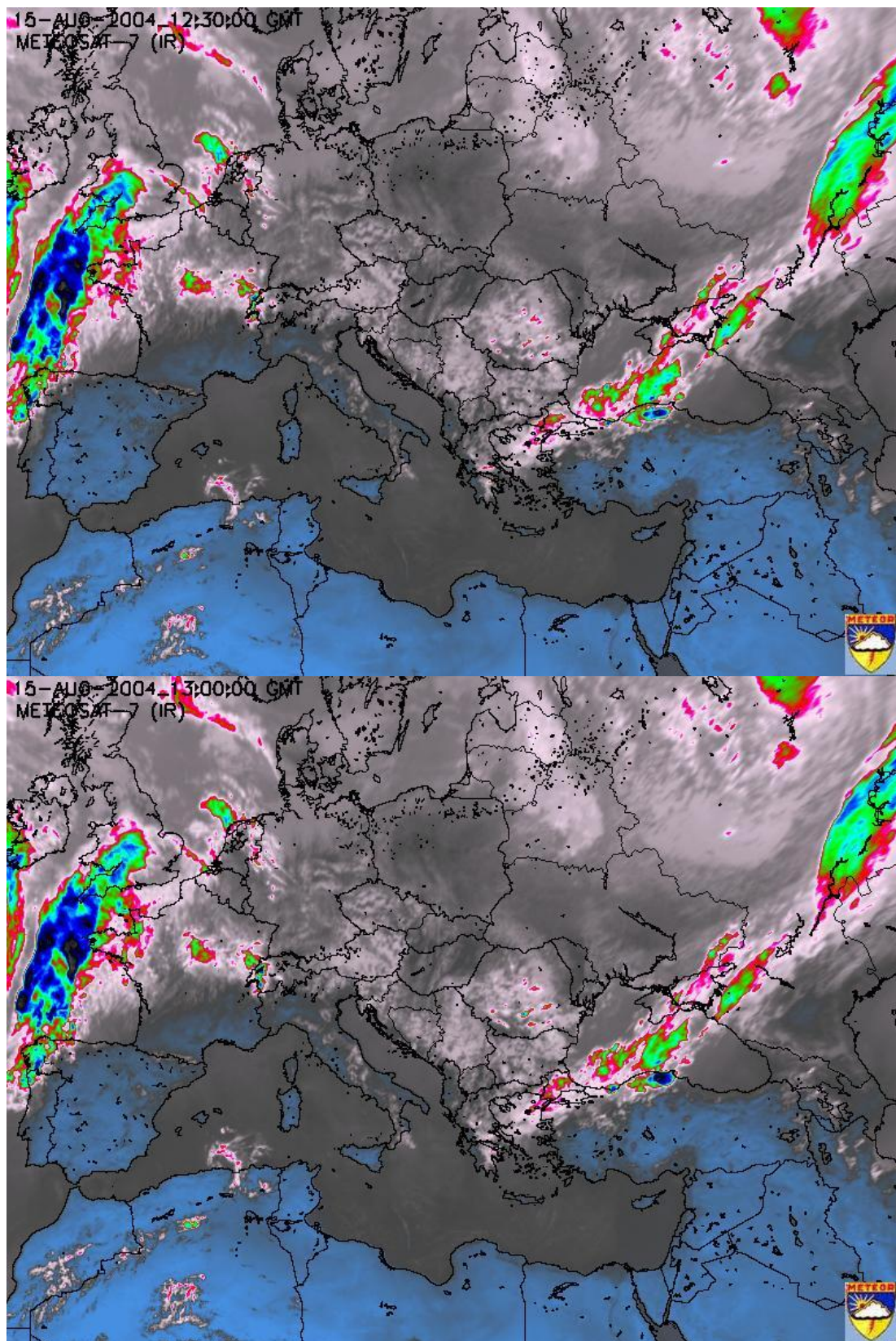


Figure A.2 : Infrared Satellite images of METEOSAT-7 for 15. 08. 2004

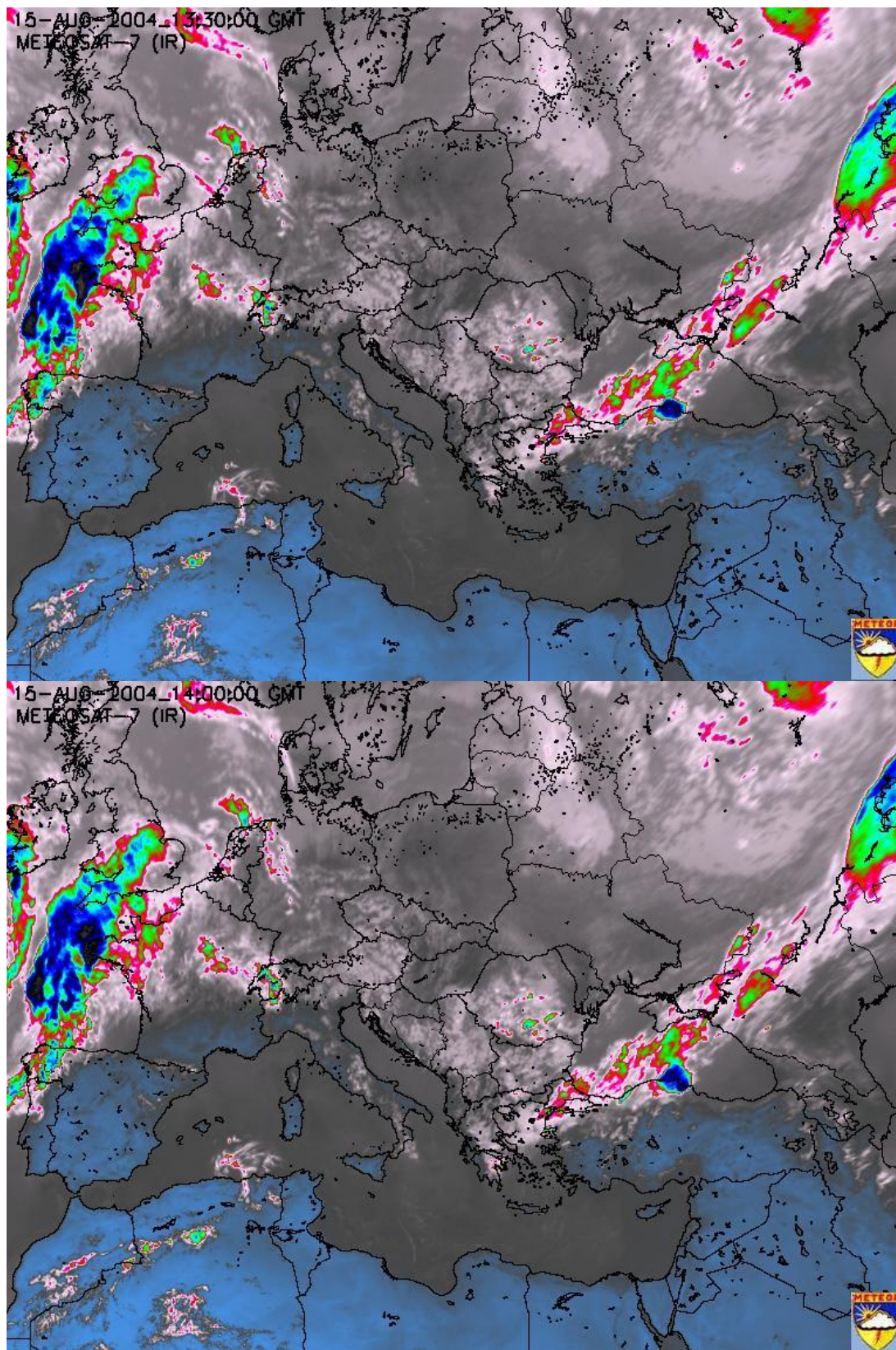


Figure A.2 : Infrared Satellite images of METEOSAT-7 for 15. 08. 2004

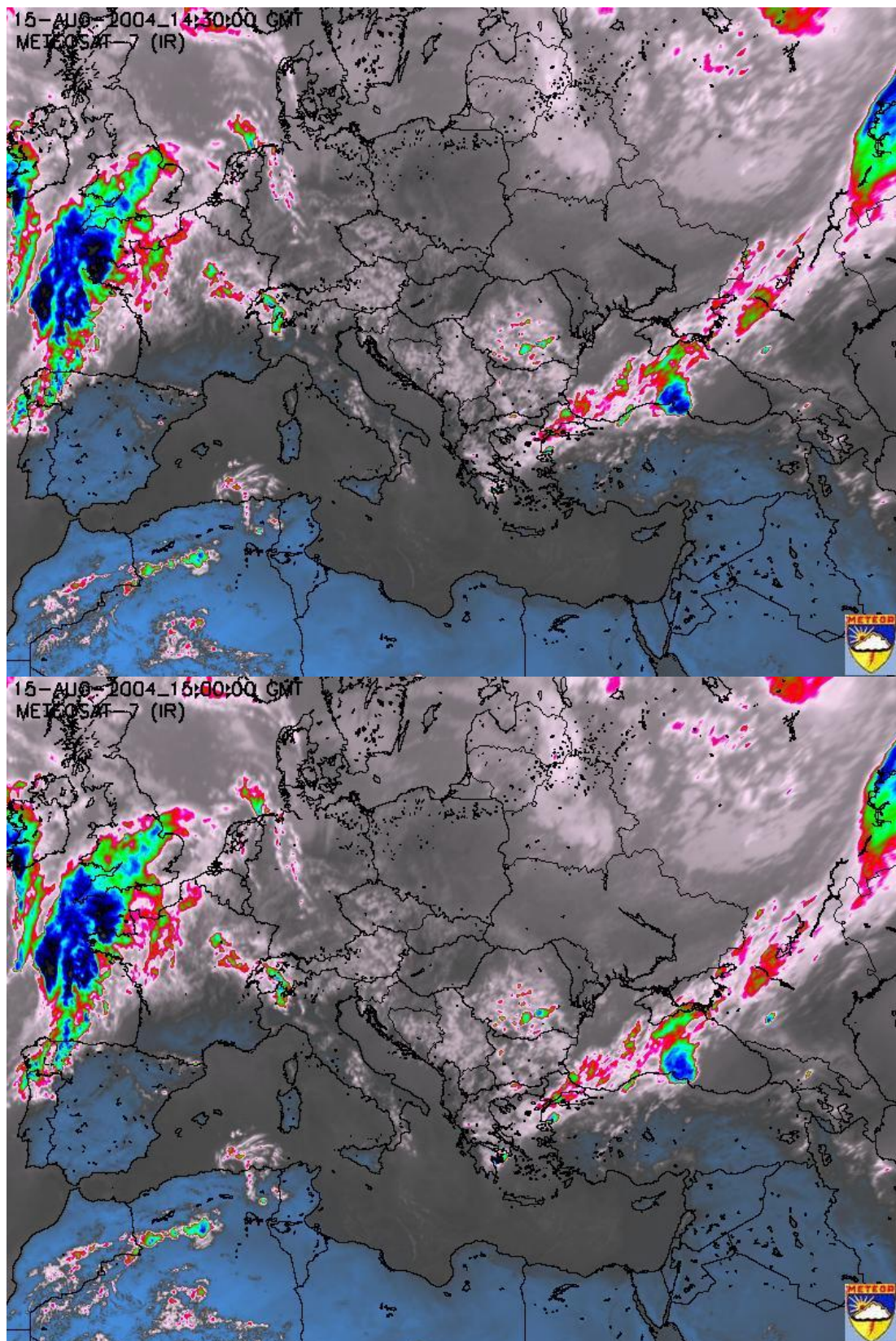


Figure A.2 : Infrared Satellite images of METEOSAT-7 for 15. 08. 2004

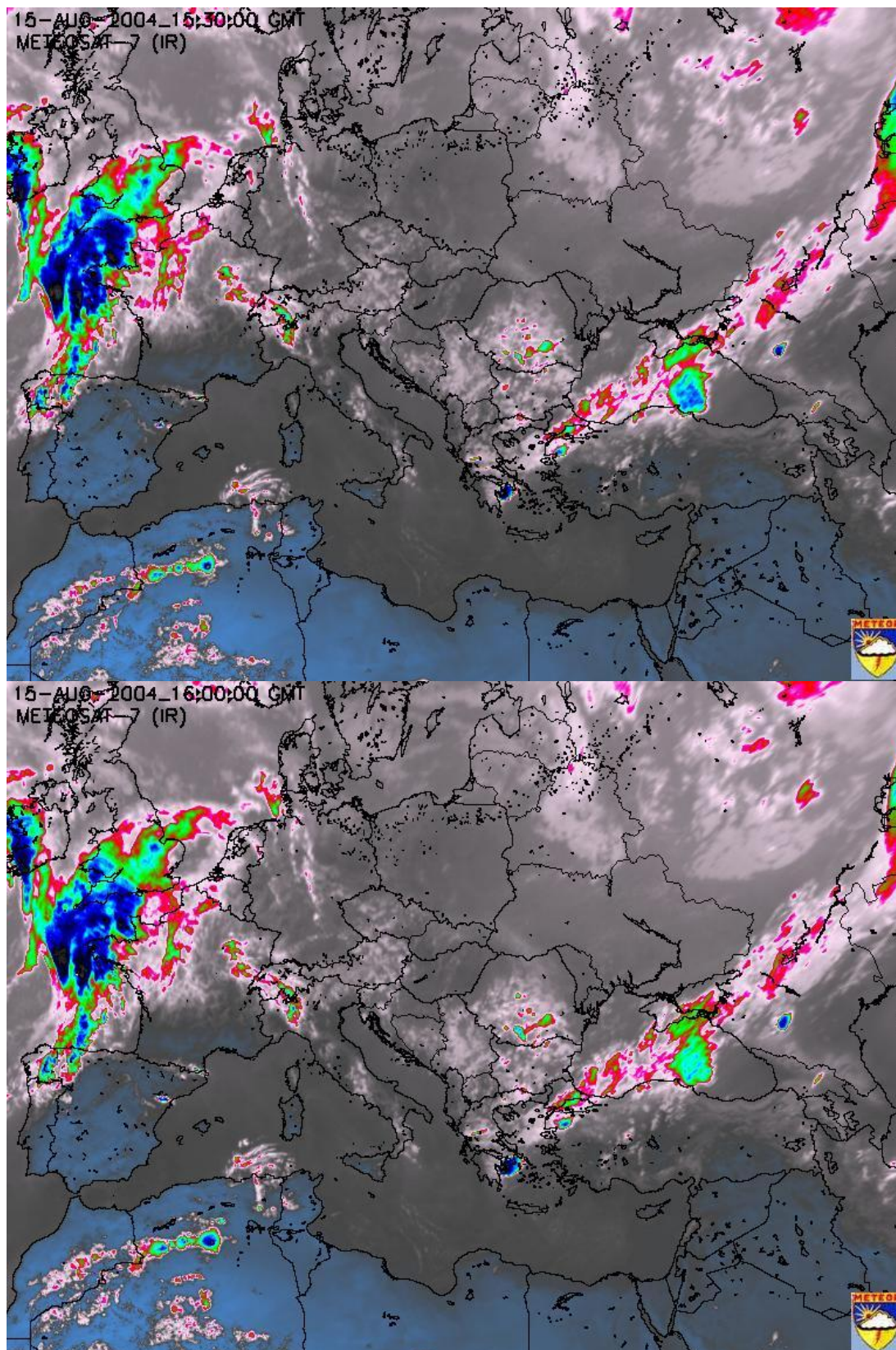


Figure A.2 : Infrared Satellite images of METEOSAT-7 for 15. 08. 2004

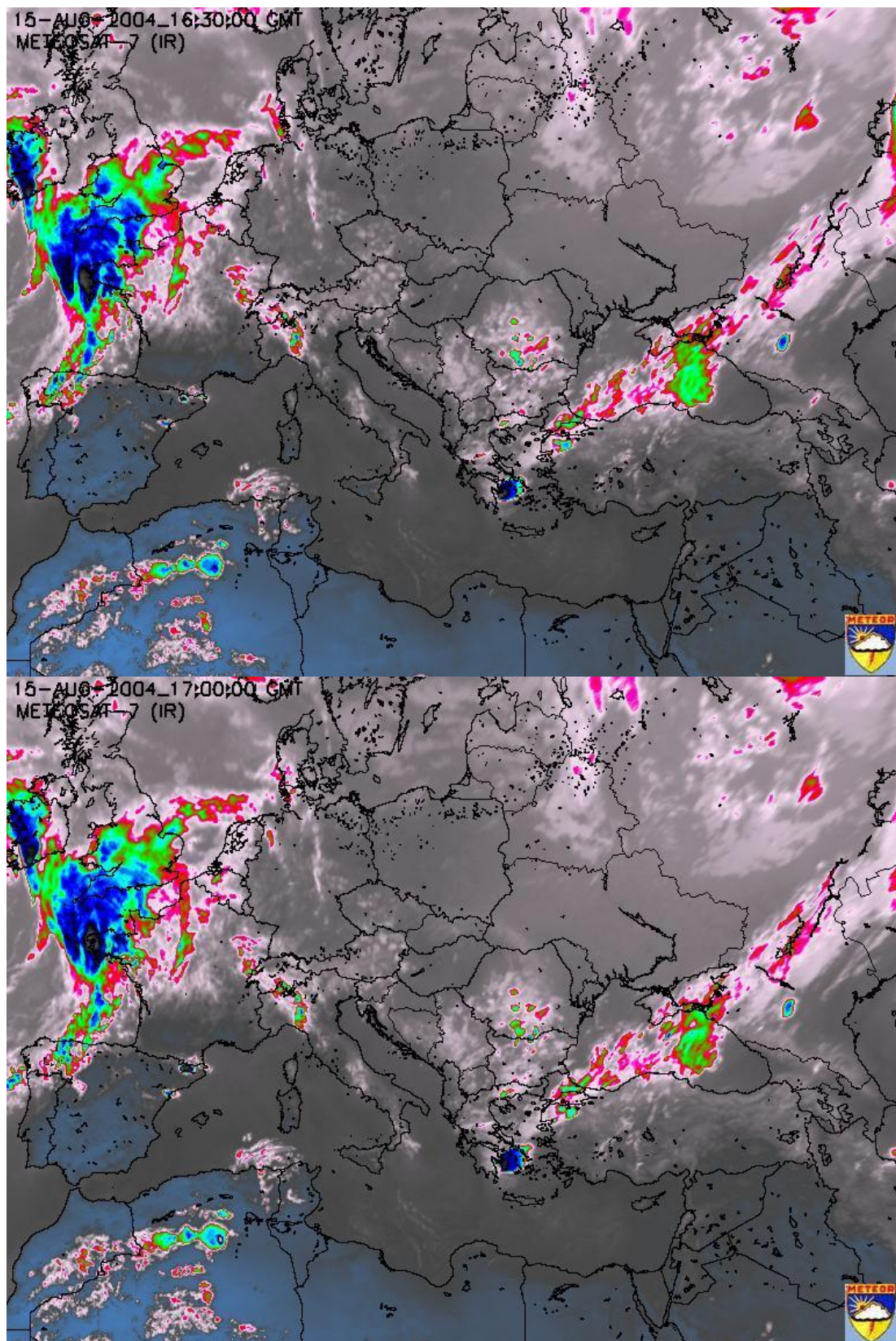


Figure A.2 : Infrared Satellite images of METEOSAT-7 for 15. 08. 2004

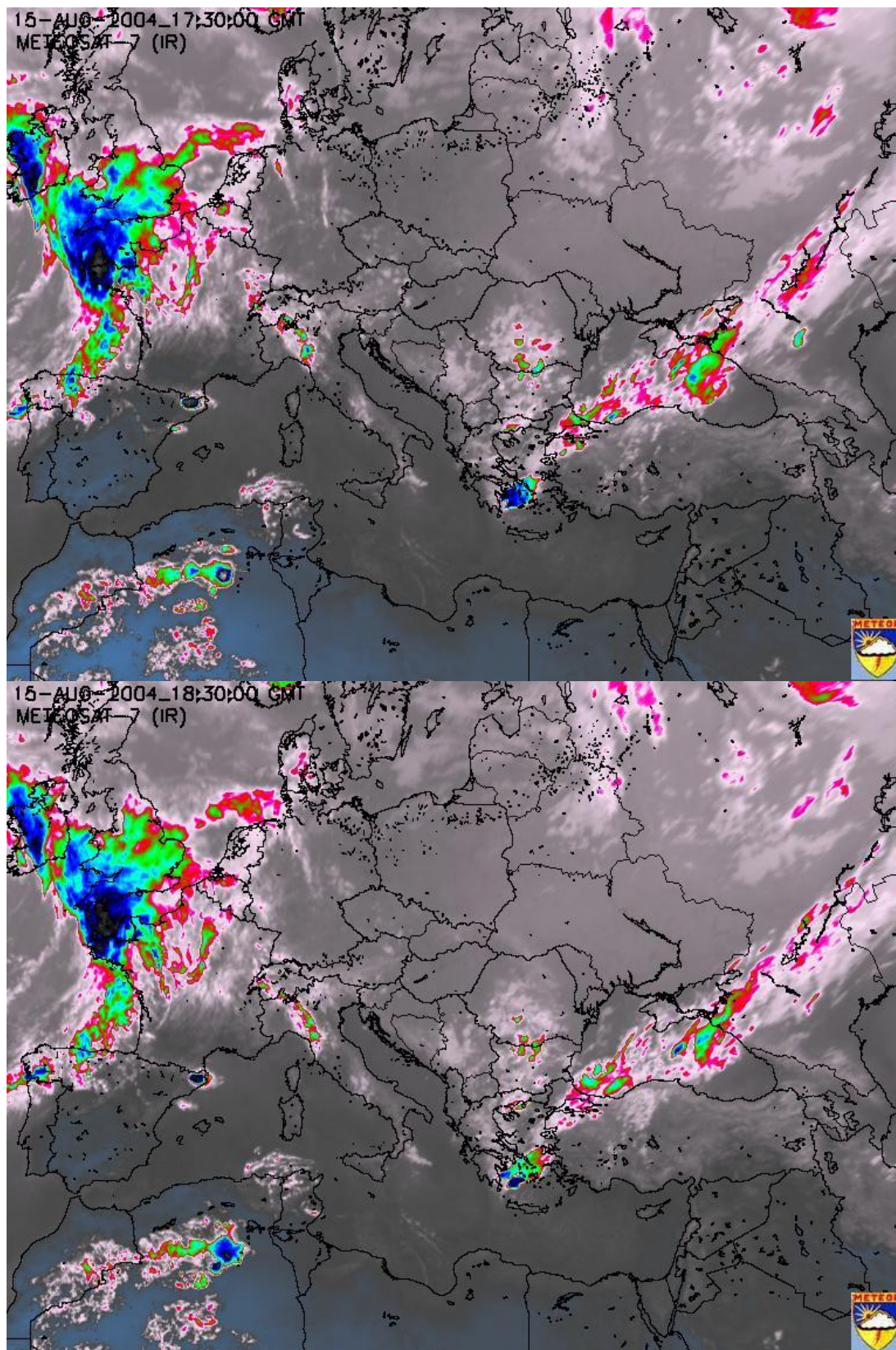


Figure A.2 : Infrared Satellite images of METEOSAT-7 for 15. 08. 2004

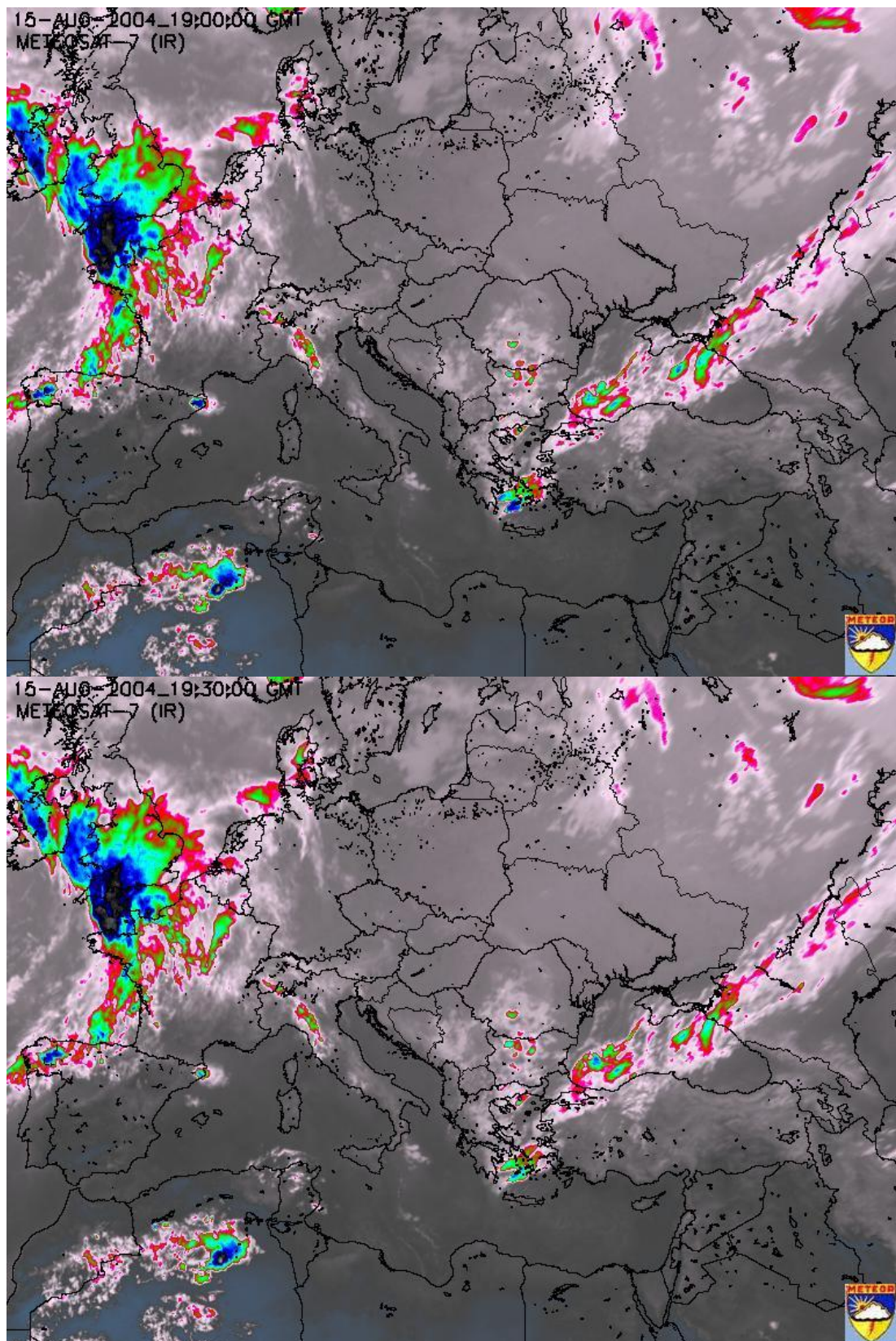


Figure A.2 : Infrared Satellite images of METEOSAT-7 for 15. 08. 2004

APPENDIX A.3 : NCEP Reanalysis plots for 14.08.2004 and 15.08.2004.

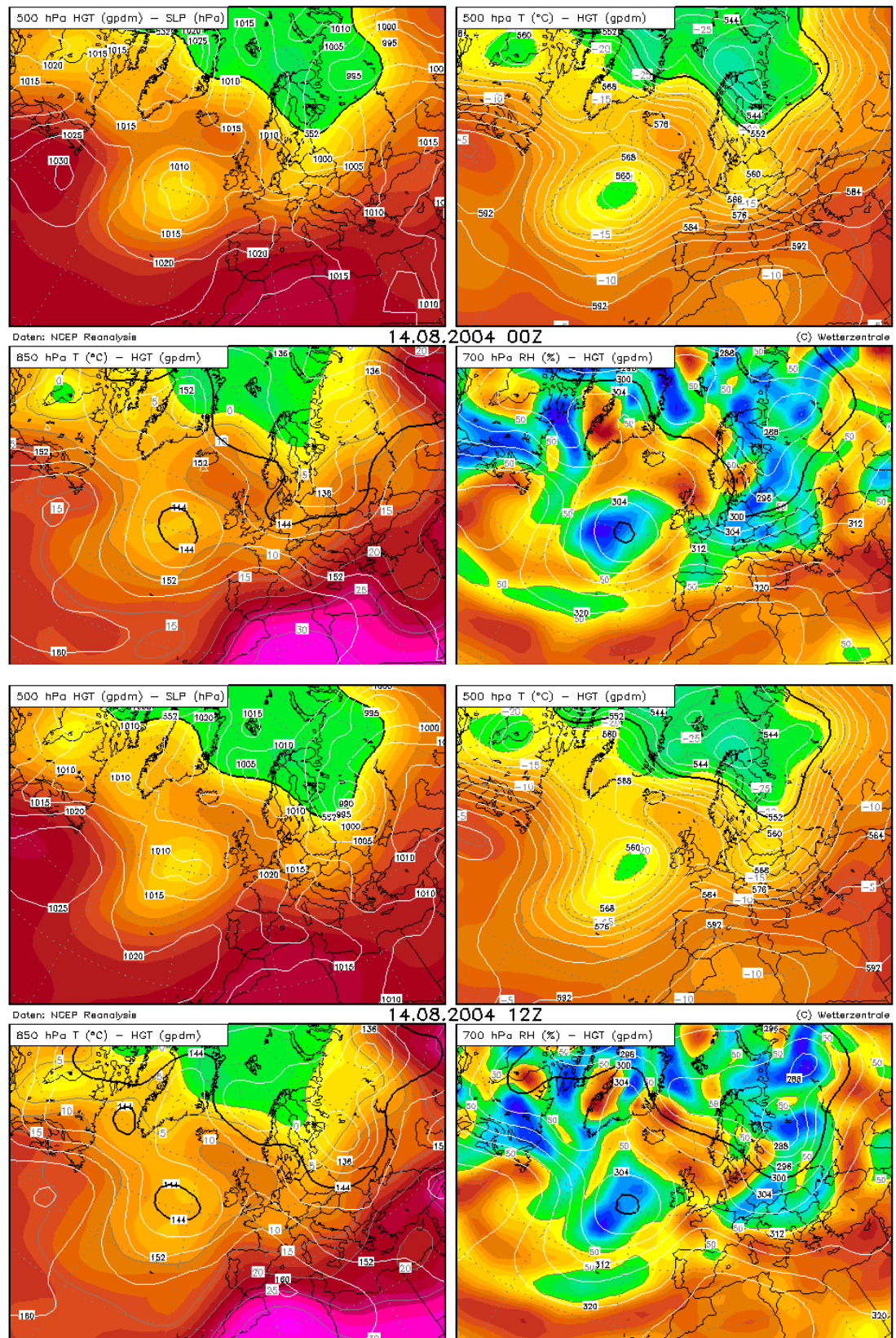


Figure A.3 : NCEP Reanalysis plots for 14.08.2004 and 15.08.2004.

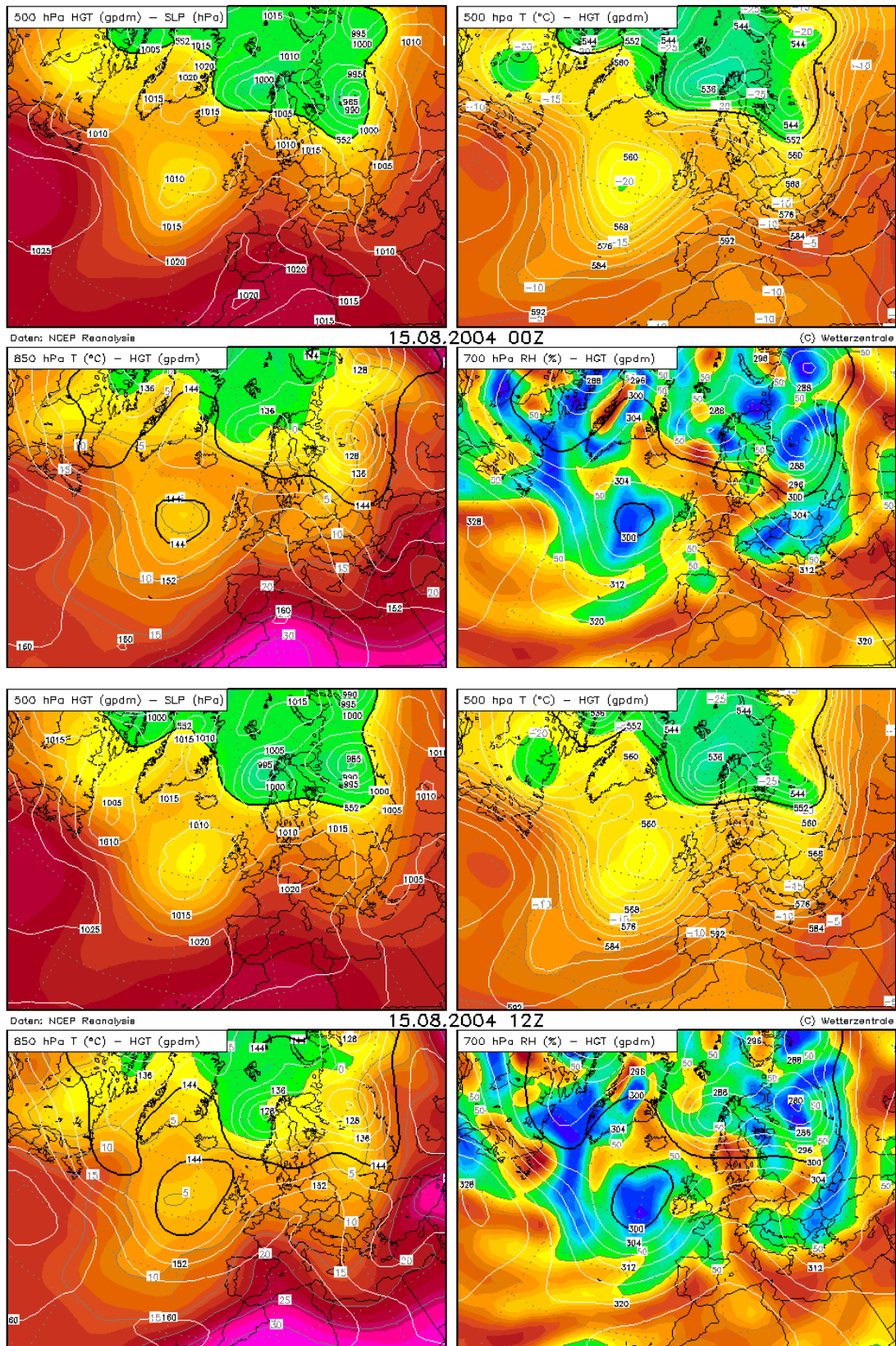


Figure A.3 : NCEP Reanalysis plots for 14.08.2004 and 15.08.2004.

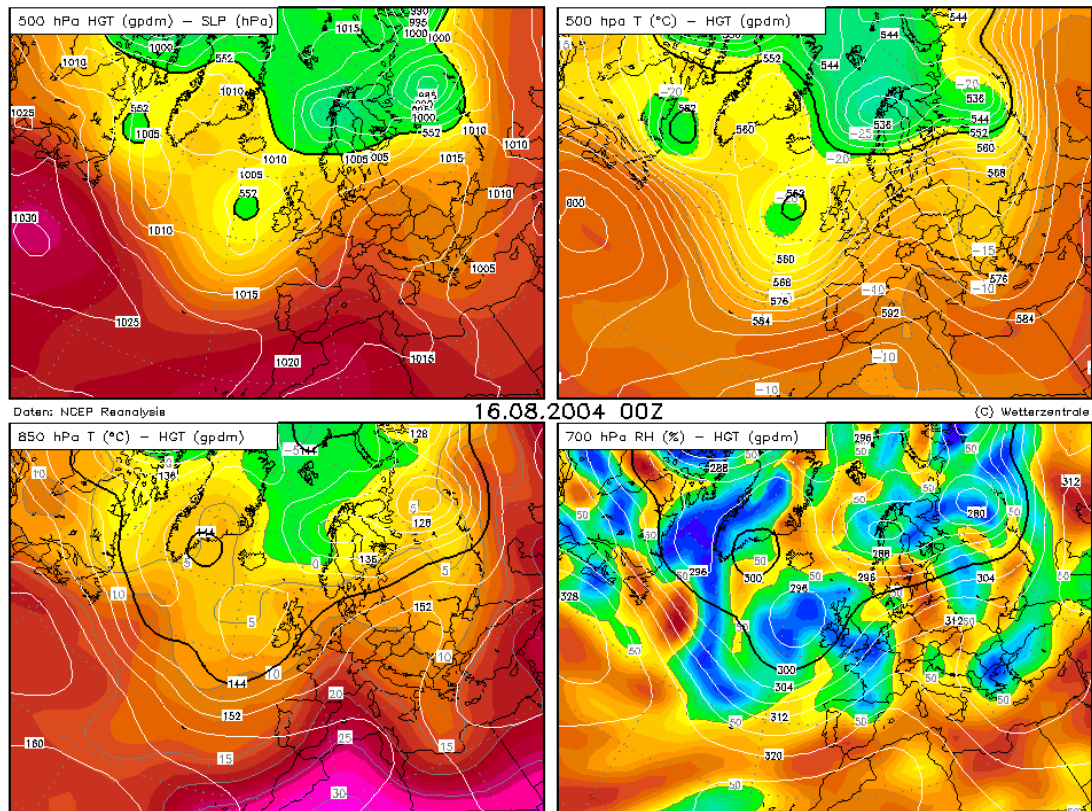


Figure A.3 : NCEP Reanalysis plots for 14.08.2004 and 15.08.2004.

APPENDIX A.4 : Total Hourly Precipitation on 06z, 15.08.2004.

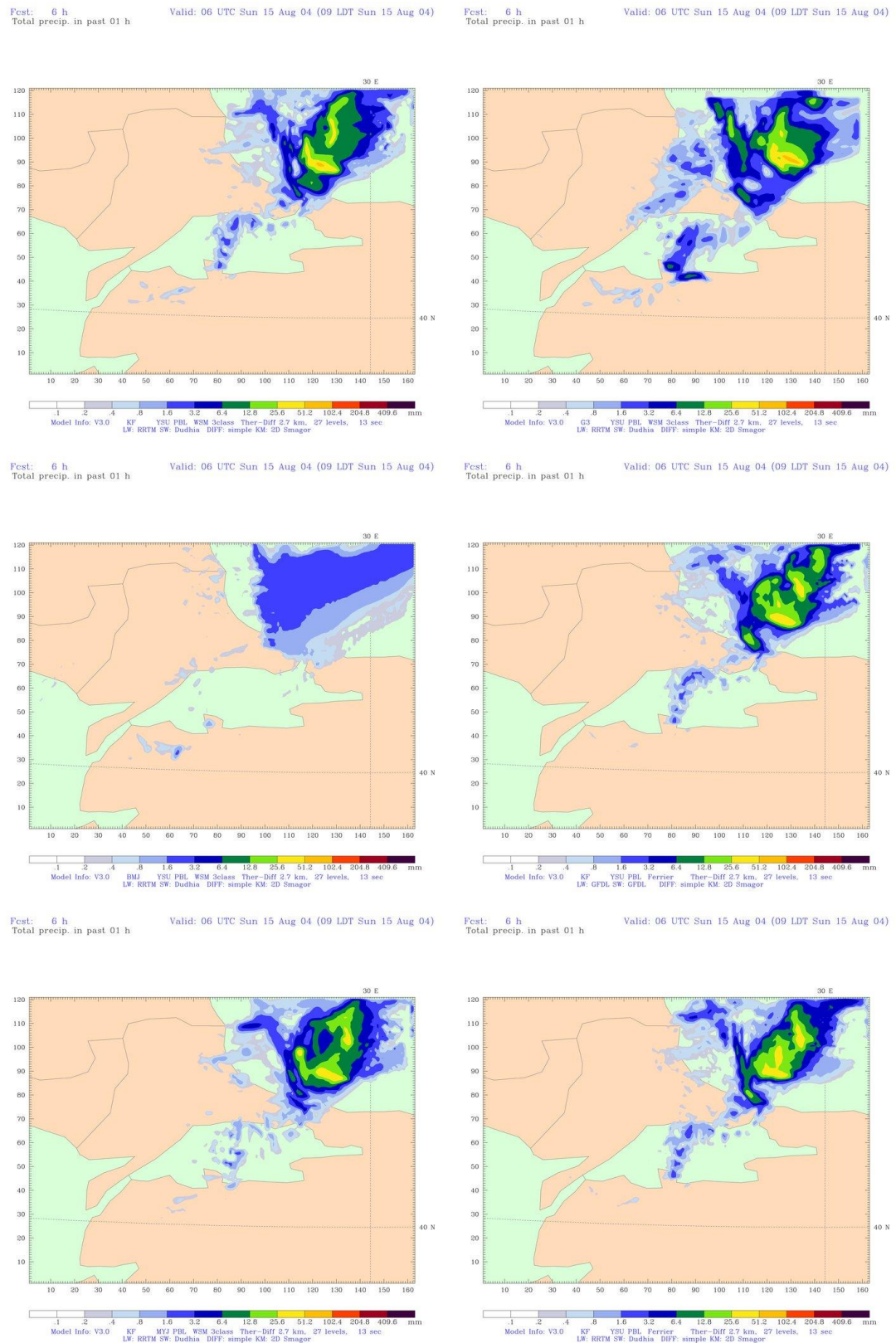
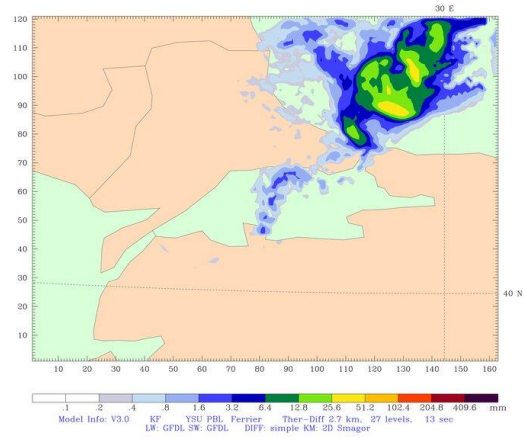
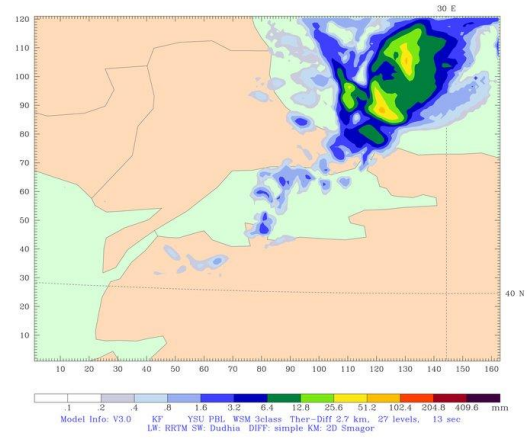


Figure A.4: Total Hourly Precipitation on 06z, 15.08.2004, according to the sensitivity test elements 15, 16, 17, 18, 19 and 20.

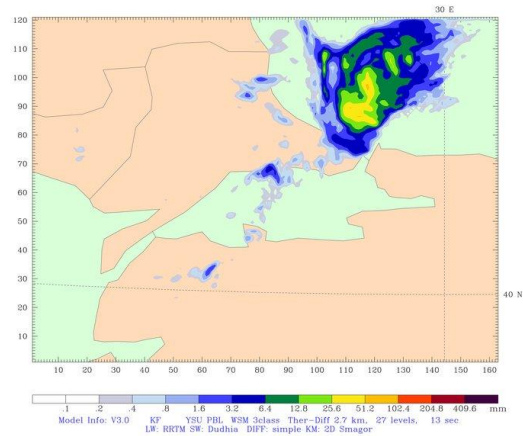
Fcst: 6 h Valid: 06 UTC Sun 15 Aug 04 (09 LDT Sun 15 Aug 04)
Total precip. in past 01 h



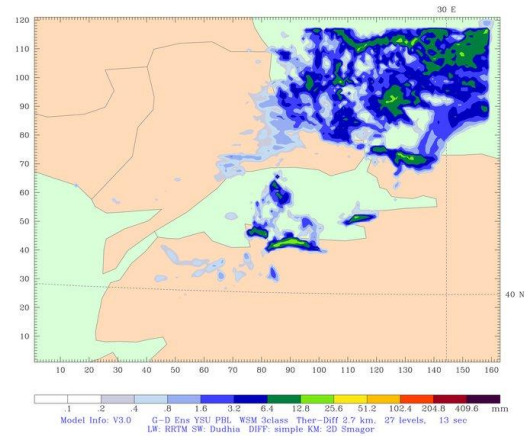
Fcst: 6 h Valid: 06 UTC Sun 15 Aug 04 (09 LDT Sun 15 Aug 04)
Total precip. in past 01 h



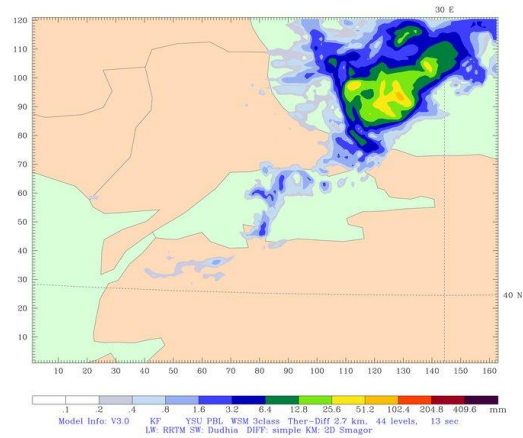
Fcst: 6 h Valid: 06 UTC Sun 15 Aug 04 (09 LDT Sun 15 Aug 04)
Total precip. in past 01 h



Fcst: 6 h Valid: 06 UTC Sun 15 Aug 04 (09 LDT Sun 15 Aug 04)
Total precip. in past 01 h



Fcst: 6 h Valid: 06 UTC Sun 15 Aug 04 (09 LDT Sun 15 Aug 04)
Total precip. in past 01 h



Fcst: 6 h Valid: 06 UTC Sun 15 Aug 04 (09 LDT Sun 15 Aug 04)
Total precip. in past 01 h

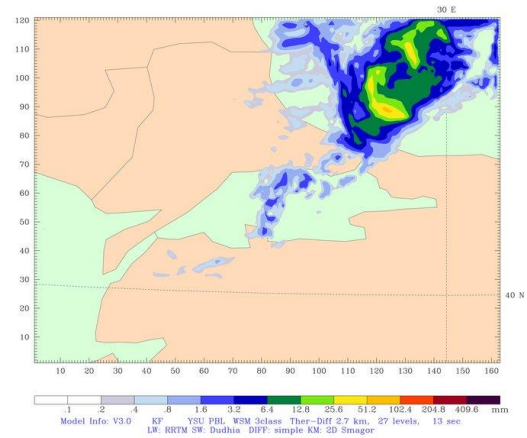
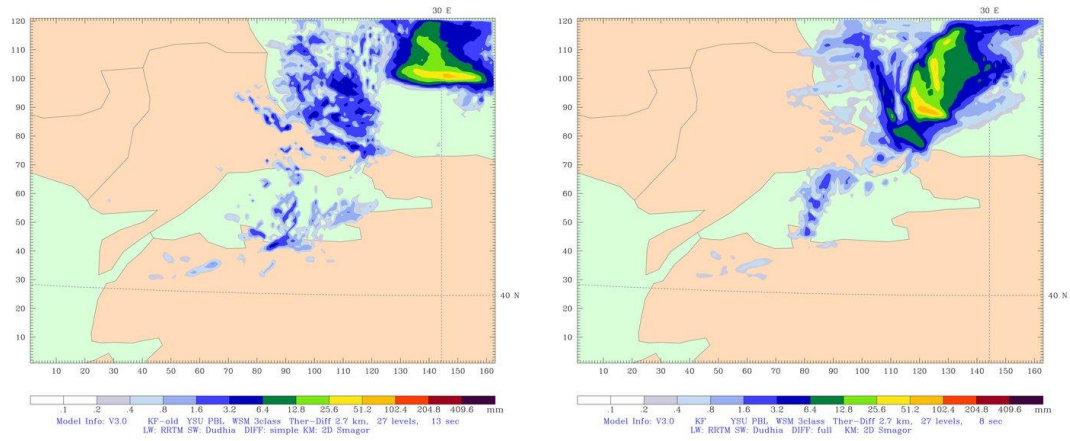


Figure A.4 (cont.): Total Hourly Precipitation at 06z on 15.08.2004, according to the sensitivity test elements 21, 22, 23, 24, 25, 26.

Fcst: 6 h Valid: 06 UTC Sun 15 Aug 04 (09 LDT Sun 15 Aug 04) Fcst: 6 h Valid: 06 UTC Sun 15 Aug 04 (09 LDT Sun 15 Aug 04)
 Total precip. in past 01 h Total precip. in past 01 h



Fcst: 6 h Valid: 06 UTC Sun 15 Aug 04 (09 LDT Sun 15 Aug 04)
 Total precip. in past 01 h

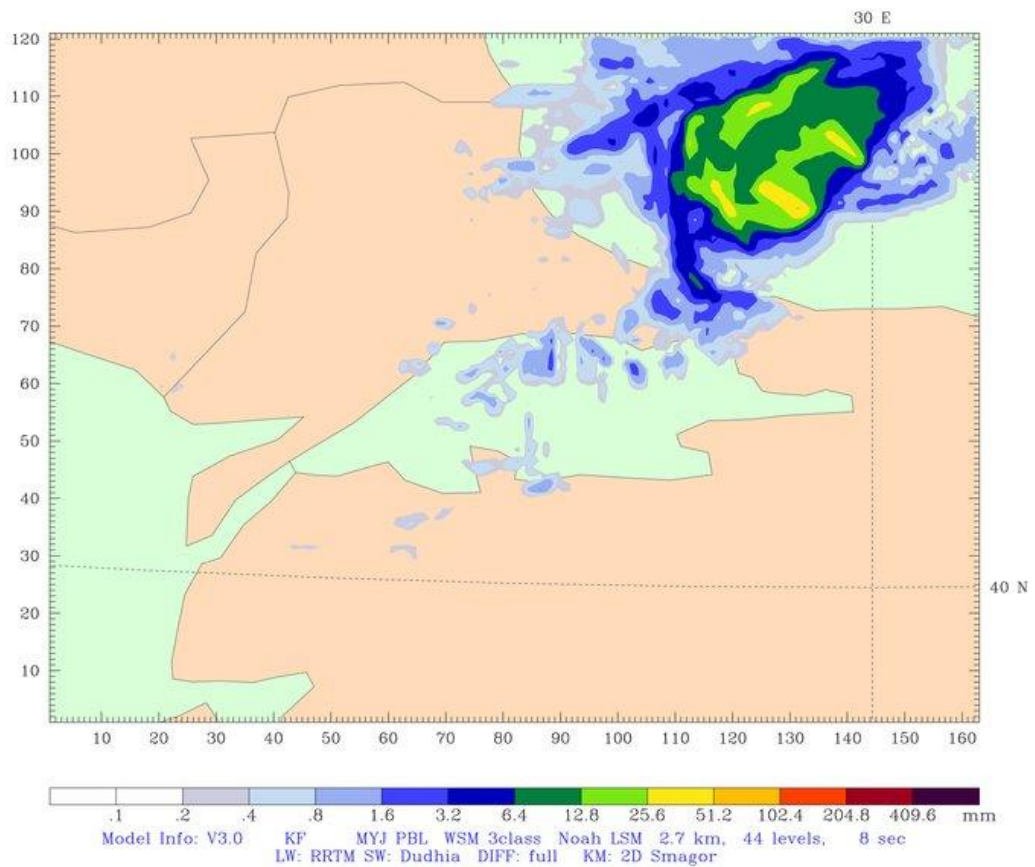


Figure A.4 (cont.): Total Hourly Precipitation at 06z on 15.08.2004, according to the sensitivity test elements 27, 28, 30.

APPENDIX A.5 : TRMM rainfall estimation for 15.08.2004

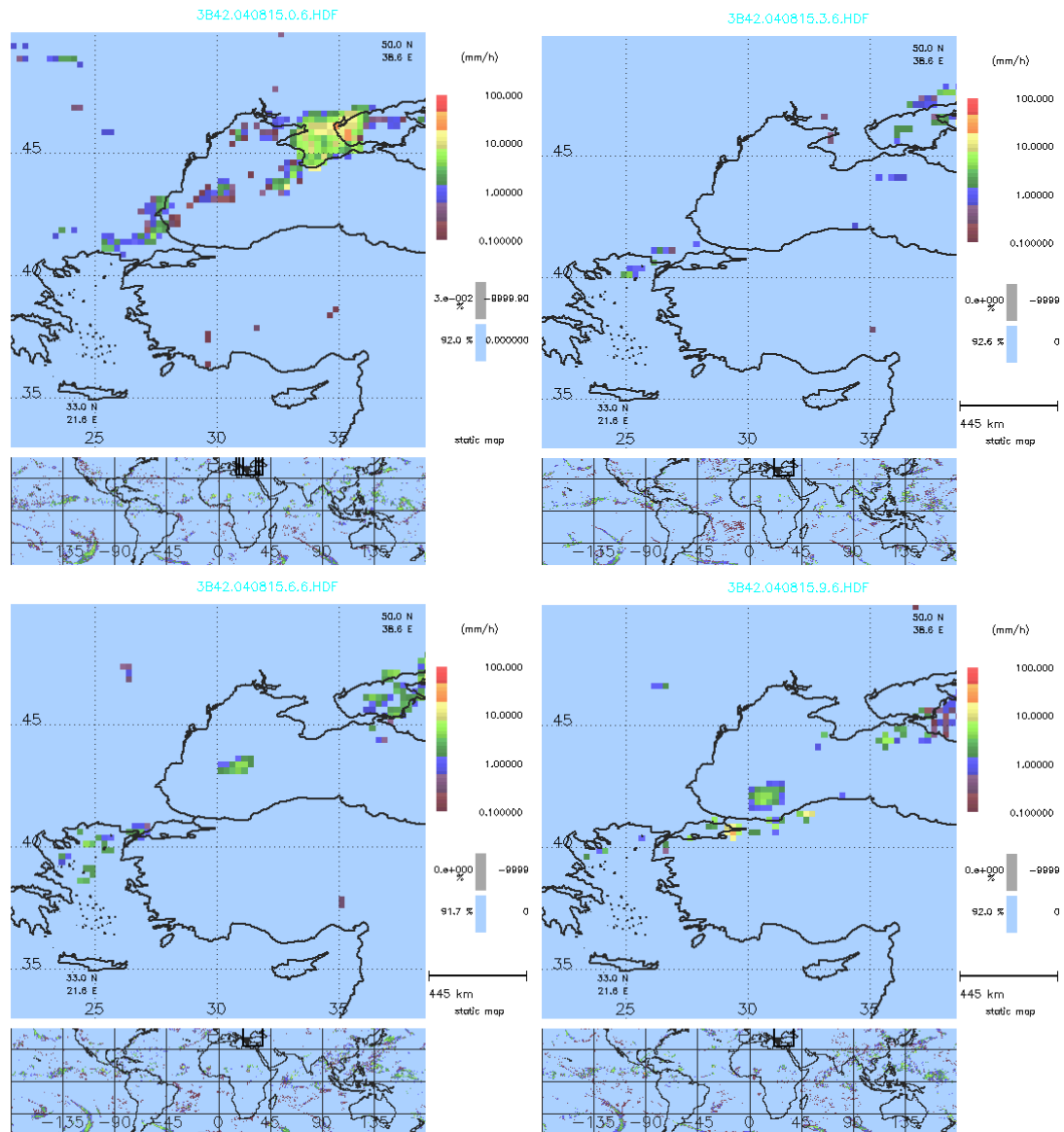


Figure A.5 : TRMM rainfall estimation for 15.08.2004.

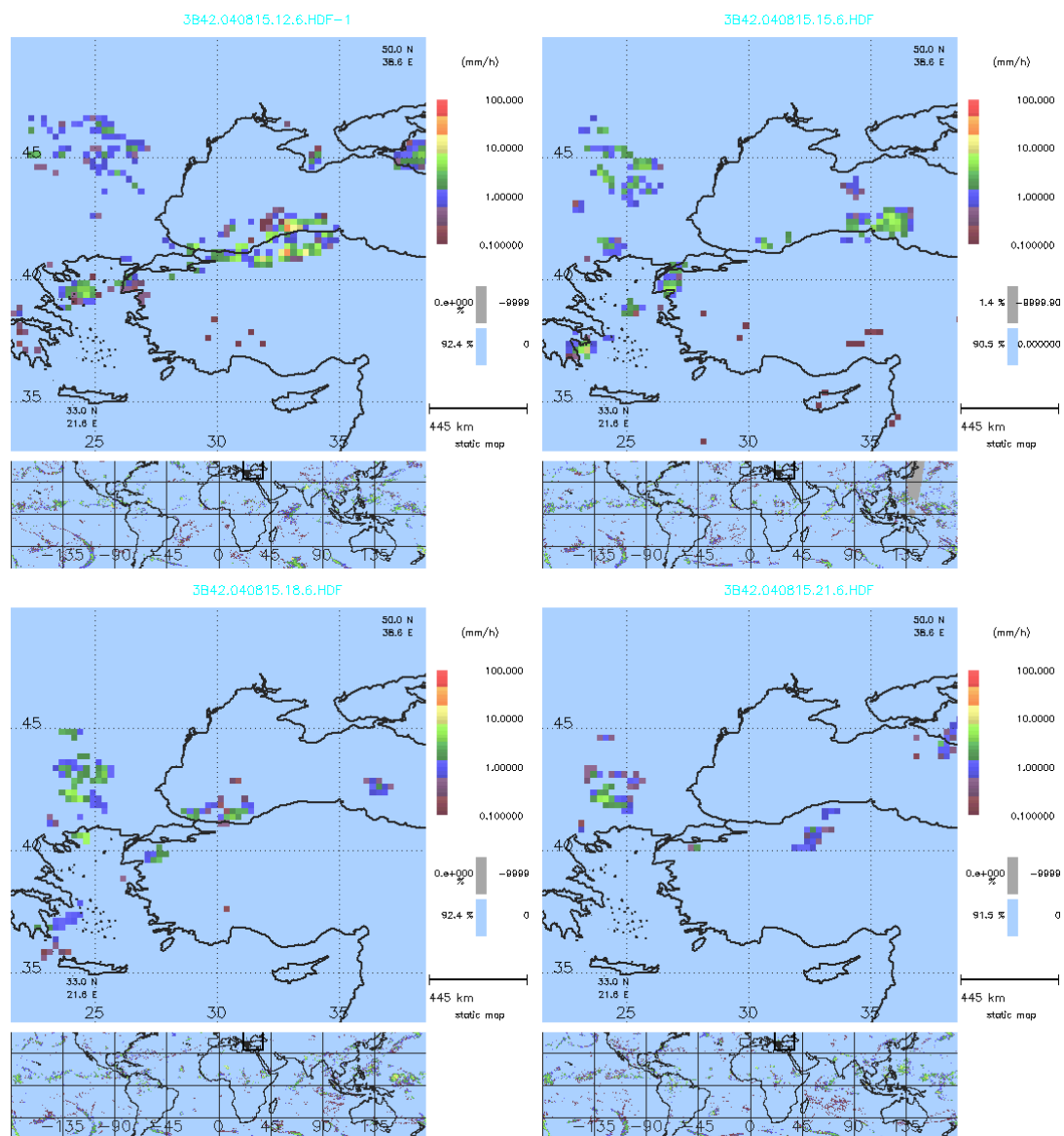


Figure A.5 (cont.): TRMM rainfall estimation for 15.08.2004.

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Publications:

- **Kahraman A.**, Kadioglu M., 2009: Numerical simulation of a mesoscale convective system and a tornadic supercell storm in Marmara Region, Turkey. *European Geosciences Union General Assembly 2009*, April 19-24, 2009 Vienna, Austria.
- **Kahraman A.**, Tanrioer S., 2009: Sensitivity and predictability analysis of Advanced Research WRF Model (WRF-ARW) in Eastern Mediterranean Region. *European Geosciences Union General Assembly 2009*, April 19-24, 2009 Vienna, Austria.
- Onol B., Unal Y. S., **Kahraman A.**, 2008: Sensitivity Analysis of Regional Climate Model (RegCM3) over Turkey. *European Geosciences Union General Assembly 2008*, April 13-18, 2008 Vienna, Austria.
- **Kahraman A.**, Kadioglu M., 2008: Determination of Threshold Values of Static Stability Indexes for Istanbul and Deriving a New Index using Correlated Variables. *4th Symposium on Atmospheric Sciences*, March 25-28, 2008, Istanbul, Turkiye.
- **Kahraman A.**, Ural D., Unal Y.S., Montes S.S., 2008: Comparison of RegCM3 Simulations of Turkey & Environment's High Level Climatological Conditions and NCEP Reanalysis Data. *4th Symposium on Atmospheric Sciences*, March 25-28, 2008, Istanbul, Turkiye.