

# Diagnostic study of a severe thunderstorm over Jeddah

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## ABSTRACT

~~In this paper s~~Several aspects of the interaction between midlatitude and subtropical systems are investigated ~~using a case study and within a~~ potential vorticity (PV) framework ~~using a case study analyses~~. Our case study occurred on 25 November 2009, where Jeddah and other regions in Western Saudi Arabia, were hit by heavy rainstorms. The analysis of absolute, relative, and potential vorticity implies the significance of the lower level dynamics in the initiation of this case of cyclogenesis. The impact of the severe convective weather process caused more than 90 millimeters of rain to fall in Jeddah in just four hours. The analysis ~~of our case indicates illustrate~~ that the heavy rainfall ~~was~~ due to the existence of an upper level cold trough in the Eastern Mediterranean, and a warm blocking high ~~is~~ situated ~~over on the~~ southeastern Saudi Arabia and ~~the~~ Arabian Sea. In addition, an evident low level shear line set up ~~in the northwest of Jeddah~~, and the southeast movement of the shear line caused dynamic lifting and unstable energy release over Jeddah. The water vapor transport ~~occurred mainly happened primarily~~ below 700 hPa, and ~~a low-level jet transporteds~~ the water vapor from the Red Sea to ~~central Saudi Arabia-central~~. Furthermore, the blocking high in southern Saudi Arabia ~~was~~ favorable for maintaining water vapor passage for a long time. The topography of Jeddah also ~~has~~ played a role in the enhancement of convection.

**Comment [MA1]:** In common usage, Americans use a mm/dd/yyyy format. Most scientists recognize that this can be awkward and use the ISO 8601 standard: YYYY-MM-DD. For ISO combined date and time see: <http://www.w3.org/TR/NOTE-datetime> (Note: this is not the complete standard doc – which is not available free of charge.)

**Comment [MA2]:** Tense should be consistent throughout (particularly in the abstract). The past tense has been used.

**Comment [MA3]:** This is ambiguous. It could mean both outside of the city to the northwest, or in the northwest section of the city of Jeddah.

## 1. Introduction

Potential vorticity (PV) diagnostics have been used extensively to gain a better understanding of the life cycles of cyclonic storms through case-studies and idealised simulations (e.g. Hoskins et al. 1985; Davis and Emanuel, 1991; Stoelinga, 1996; Huo et al., 1999; Plant et al., 2003; Agusti-Panareda et al., 2004; Ahmadi-Givi et al., 2004). The results of these studies have contributed to the introduction of new conceptual models of cyclogenesis.

However, their focus is mainly on extratropical cyclones and hurricanes. Cyclogenesis over the central Mediterranean region has become the subject of considerable research (Prezerakos, 1991, 1992; Prezerakos et al. 1999; Karacostas and Flocas, 1983; Flocas and Karacostas, 1996). ~~Such, since these significant~~ synoptic-scale ~~significant~~ events cause intense winds, precipitation, and temperature drop. Because of the intimate connection between the phenomena and local weather prediction, interest in understanding the characteristics of cyclogenesis over this region is enormous and ongoing. —

— The structure of cyclones is often conceptualised in terms of three types of anomalous PV (Davis and Emanuel, 1991; Huo et al., 1999; Plant et al., 2003; Ahmadi-Givi et al., 2004). These consist of upper-level PV (UPV) anomalies, considered to be of stratospheric origin, lower tropospheric PV (LPV) anomalies, generated by diabatic effects, and surface potential temperature anomalies, which can be viewed as a thin layer of PV at the surface. Ahmadi-Givi et al. (2004) found that strong latent heat release in a cyclone produced a negative UPV anomaly in addition to a positive LPV anomaly. Since diabatic effects can reduce PV at upper levels, some authors (Pomroy and Thorpe, 2000; Ahmadi-Givi et al., 2004) have distinguished this reduced upper-level PV (RUPV) from ~~anomalous UPV upper-level anomalous PV~~ of stratospheric origin ~~(UPV)~~. According to Hoskins et al. (1985), the potential vorticity analysis of ~~an~~ an isentropic surface summarizes the combined effect of the vorticity and temperature advection and allows the estimation of the vertical motion. ~~In addition, Besides,~~ the conservation of the isentropic potential vorticity in adiabatic processes allows the identification and examination of non-conservative processes, such as latent heat release and friction, while the inevitability principle allows the quantitative estimation of the effect of these processes. *The objective of the present work is to diagnose a case of cyclogenesis in the context of isobaric vorticity and potential vorticity analysis, in order to examine in detail the key dynamical aspects of the development.*

## 2. Data and methodology

### A) Data

The data used in this study have been taken from the archives of the European Center for Medium-Range Weather Forecasts ~~(ECMWF)~~. It consists of the horizontal wind components (u-eastward, v-northward), the temperature (T) and the geopotential height (z) on regular latitude-

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longitude grid ~~points~~-resolution of  $2.5^\circ \times 2.5^\circ$  for the isobaric levels 1000, 850, 700, 500, 400, 300, 250, 200, 150, and 100 hPa. The data used ~~was recorded is~~ at 0000, 0060, 1200, and 1800 GMT during the period 23 to 26 November 2009. The domain of study extends from  $10^\circ$  W to  $60^\circ$  E and from  $10^\circ$  N to  $70^\circ$  N.

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### B) Estimation of potential vorticity

Potential vorticity fields were calculated from the available meteorological parameters, namely temperature and the horizontal wind components on constant pressure surface. ~~For~~ isobaric coordinates the potential vorticity was approximated by the product of the vertical components of absolute vorticity and potential temperature gradients as:

$$(PV)_\theta = \left[ \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) + f + \frac{R}{\sigma P} \left( \frac{\partial v}{\partial p} \frac{\partial T}{\partial x} - \frac{\partial u}{\partial p} \frac{\partial T}{\partial y} \right) \right] \frac{\partial \theta}{\partial p} \quad (1)$$

where  $f$  is the Coriolis parameter,  $\theta$  is the potential temperature,  $u$  is the wind in x-direction of the grid (W-E in principle) and  $v$  is the wind in y-direction. Following the WMO (1986), the dynamic tropopause is defined by the potential vorticity with  $P = 1.6 \times 10^{-7} \text{ Kpa}^{-1} \text{ s}^{-1} = 1.6 \text{ PVU}$ , where, for convenience, the potential vorticity unit (PVU) is defined to be  $10^{-7} \text{ Kpa}^{-1} \text{ s}^{-1}$ .

Centered finite differences were used to compute horizontal derivatives and all vertical derivatives except those at the 1000 and 100 hPa levels, where non-centered differences were employed. The vertical motion,  $\omega$ , is computed using the Q-vector representation of the quasi-geostrophic  $\omega$  equation by using the relaxation method (Krishnamurti and Bounoua, 1996). The relative vorticity and absolute vorticity advection have been calculated from the actual data using the central finite differences method.

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### 3. Synoptic discussion

On November 25, 2009, heavy rainstorms hit Jeddah, Makkah, and other regions in western Saudi Arabia. More than 90 millimeters of rain fell in Jeddah in just four hours. This amount is nearly twice the average amount for an entire year and the heaviest rainfall in the Kingdom of Saudi Arabia (KSA) in a decade. A case of winter cyclogenesis over the Mediterranean is considered in the present study extending from 23/00 to 26/12 November 2009

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is considered in the present study. Based on 1000 hPa and 700 hPa charts, the life cycle of this cyclone can be divided into two periods. The first period (growth) is from 23/00 to 25/12 November; while the second period (decay) is from 26/06 to 27/12 November. Charts for 1000 hPa and 700 hPa charts at 0000 and 1200 GMT on each day of the period 23/00 to 26/12 are shown in Figures 1 and 2, respectively. The 1000 and 700 hPa charts depict contours of height with 20 geopotential meters (gpm/GPM) increments. The isotherms in the charts of the two levels are analyzed with 5°C increments. At 23/00 November, Figure 1a shows that a the subtropical high pressure dominates over North Africa and the Mediterranean area and it also extends easterly to cover the north of the KSA and eastern Mediterranean countries. The figure also illustrates that the Sudan low and its associated inverted v-shaped trough (Red Sea trough) oscillate northward to cover eastern the east of Egypt and the entire Red Sea region. An obvious thermal gradient associated with the northward oscillation of the Red Sea trough extends zonally to cover the southern portion of the KSA and northern the north of Sudan. During the next 12 hours (23/12), the subtropical high weakens and moves eastward, while the Red sea trough propagates slowly northward and the Sudan low deepens to 80 gpm (Fig-Figure 1b). The cyclone of special interest first appeared as an extension of the traveling depression east of the Mediterranean at 23/00 November (Fig-Figure 2). A cut-off low is formed at 23/12 November and a well-defined cyclonic depression becomes clear over Egypt (Fig-Figure 2b). At 23/00 November a thermal gradient lies along the northeast of the KSA. This baroclinic zone leads to the formation of an upper level cut-off low. At On 24/00 November a strong development occurs at the surface and at upper air, where the Sudan low at the surface and its associated Red Sea trough moves northward to cover the northern portion of the Eastern Mediterranean, Egypt, and the KSA. The center of the Sudan low centers becomes over Red Ssea at 15°N and 37.5°E; while the geopotential height at the center reaches 100 gpm. In the upper air (700 hPa) the cut-off low deepens and moves slowly eastward to a point just north of Egypt; the geopotential height at the center reaches 3100 gpm (Fig-Figure 2c). During the next 12 hours (24/12) the inverted v-shaped trough associated with the Sudan low oscillates northward and in the upper air (700 hPa) the cut-off low also moves eastward to a point just northeast of Egypt. During the period 24/18 to 25/12 November (the rainy period), a strong interaction occurs between the inverted v-shaped troughs extending from the tropical region and from the middle latitude region; the two cyclones mergejoin. The most interesting features are the strong northward warm advection from the

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**Comment [MA7]:** Here, I think you mean in the Eastern Mediterranean rather than east of the Mediterranean – which would be over Syria (approx.).

tropical region associated with the air flow around the Sudan low and the strong southward cold advection. The interaction between these two air masses causes a strong instability over the ~~Eastern of~~ Mediterranean and ~~western at the west of~~ Saudi Arabia.

After 25/12 November, the inverted v-shaped trough of the Sudan low moved ~~in a~~ southwesterly direction ~~ward and while~~ the upper air trough retreated westward ~~toward where~~ the associated cut-off low centered over ~~northwestern North West of~~ Egypt; ~~and~~ the interaction between the two troughs vanishes. During the next day (26 November) the depression starts to weaken and its central pressure increases gradually. On the other hand, the subtropical high pressure over North Africa and the ~~W~~western Mediterranean is extended with a major ridge that ~~joinst~~ the Siberian high on 27 November. In other words, no more cold advection is permitted to the cyclone. While the Siberian high pressure propagates westward, the horizontal extension of the cyclone decreases and moves slowly eastward. It becomes a stationary vortex rotating above the ~~northeastern portion of the~~ Mediterranean (Figs. 2g ~~and~~ 2h). Finally the cyclone drifts slowly northeastward and leaves the area by 28 November.

**Comment [MA8]:** This phrase is ambiguous and is not common English syntax. It could be understood to mean "to the west of" – i.e., over the Red Sea, or "over western Saudi Arabia" (i.e., in the far western portion of the KSA)

#### 4. Isobaric vorticity analysis

It has been recognized that central and eastern Mediterranean cyclogenesis is usually forced by a variety of upper-level tropospheric features; ~~While~~ the lower tropospheric physical and dynamic processes follow (Karein, 1979; Prezerakos, 1992; Prezerakos et. al., 1992). This is associated with ~~the theory of~~ Helmholtz' theory (Petterssen, 1956), ~~which that~~ supports the controlling of the relation between ~~the low-level~~ baroclinicity and ~~the upper-level forcing of~~ surface cyclogenesis ~~by the upper level forcing~~.

#### 4.1 Genesis of the initial disturbance at the upper levels

It is known that the subtropical jet ~~and polar jet reach maximum speeds has its maximum speed at approximately around~~ 200 and ~~the polar jet around~~ 300 hPa, ~~respectively~~. ~~Therefore, to show the behavior of the subtropical and polar jets during the development of the events involved in this case study, we focus on~~ So, we display the ~~2300 and 3200~~ 200 and 300 hPa isotach fields in the following discussion ~~to show the behavior of the polar and subtropical jets during the development of this case study~~. Figures 3 and 4 display the isotachs (wind speed) at 200 and 300

hPa from 24/06 to 26/00 November 2009, respectively. ~~They show the behavior of the subtropical and polar jets at 300 and 200 hPa levels during the period of study.~~

At 24/00 an omega-shaped blocking over ~~the~~ Northeast Atlantic and ~~W~~western Europe dominated the large-scale upper tropospheric circulation with a strong ~~n~~Northwest-southeast jet stream on its eastern flank (Figure 4). Because of the warm advection in the region of the jet streak, the ridge propagated slowly northeastwards, resulting in the amplification of the long wave. On 24/12 November 2009 (Figure 3b) the wind direction over North Africa ~~was~~ almost zonal and the maximum speed of the subtropical jet ~~was~~ 45 m/s and ~~was~~ located over northeastern Africa (~~over~~ Libya, Egypt, and ~~the northern portion of the~~ Red sea). The polar jet extended from northwest England to southeast Spain and north of Italy with a maximum wind greater than 60 m/s at 300 hPa; its extension at 200 hPa ~~had~~ a maximum wind greater than 50 m/s.

As the polar jet streak ~~is~~ moved southeastward, it continuously advected cold air southward. Consequently, in the following twenty-four hours, the baroclinicity ahead of the ridge increased and the jet streak ~~move~~s southward. The synoptic situation at 300 hPa ~~at 24/18 November and 25/00 November on the following two times~~ (Figures, 4c and 4d) is particularly important for the subsequent development. On 24/18 November, the subtropical jet ~~move~~s slightly ~~to~~ northeastward, ~~i.e., over Egypt~~ and its maximum center ~~became~~ ~~omes~~ greater than 40 m/s at 300 and 200 hPa ~~and was located over Egypt. At the same time, While~~ the polar jet ~~is~~ moved southeastward to amalgamate with the subtropical jet, and its maximum value ~~became~~ ~~becomes~~ greater than 60 m/s at 300 hPa. At 25/00 November, ~~the system becomes cut off at all the isobaric levels,~~ associated with relative vorticity maximum of  $10 \times 10^{-5} \text{ s}^{-1}$  at 500 hPa and  $14 \times 10^{-5} \text{ s}^{-1}$  at 300 hPa (~~not shown~~); and increased baroclinicity at these levels, ~~the system became cut off at all isobaric levels. At the surface, Ahead of and parallel to the polar jet stream,~~ a frontal surface low ~~located over Italy~~ ~~becomes~~ very pronounced ~~and located over Italy, a head of and parallel to the polar jet stream. Therefore, w~~When this type of atmospheric circulation dominates at the upper levels, intense surface cyclogenesis over the central Mediterranean is likely to be initiated, ~~assuming of course under~~ favorable low-level conditions (Prezerakos, 1992).

On 25/06 November 2009, the subtropical jet ~~was~~ shifted to the southeast. The ~~front of the~~ polar front jet ~~reached~~ ~~reaches~~ northern of Algeria, and its ~~jet~~ maximum wind value ~~was~~is