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RESEARCH ARTICLE

Characteristics of Atmospheric Systems Accompany with Summer Dust over Northern Arabian Peninsula

Adel M. Awad*

Center of Excellence for Climate Change Research/Department of Meteorology, King Abdul Aziz University Jeddah, Saudi Arabia

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****Corresponding Author***

Adel M. Awad

Abstract

Summer dust cases over the northern Arabian Peninsula have been detected and classified using TOMS aerosol index data and synoptically analyzed using NCEP/NCAR reanalysis data. The dust cases have been detected using a threshold value of Aerosol Index, while the spread of grid points that achieved this threshold value has been used in the classification of classes. The selected cases indicated that most of the summer (82% of the period) are dusty, and Dust Raise type is the pronounced dust type observed through summer on surface stations inside the region. .

The synoptic study of the summer dust and the non-dust cases demonstrated the presence of common features between these cases, and the produced summer dust not due to the atmospheric systems only, but to the relative positions of the these systems to each other.

Although the synoptic surface and upper atmosphere features are generally similar on the dust and the non-dust cases, but it is found that the orientation of the upper trough, weakness of the upper maximum wind, deepening of the surface cyclone, and shifting eastward of the surface anticyclone are related to increases dust properties over the northern Arabian Peninsula. Further, the increase of static instability and rising motion are accompany with the dusty cases.

Generally, these very small differences between the atmospheric features for the dusty and non-dusty cases approved that the summer season is potentially dusty and not need more than very small trigger from atmospheric mechanisms to be dusty.

Introduction

Global desert belt (including Arabian Peninsula desert) demonstrated as a major global dust source region (Middleton, 1986; Prospero et al., 2002), which are more active on spring and summer seasons when dust affects atmospheric properties and aerosol loadings (Smirnov et al., 2002; Kim et al., 2011; Maghrabi et al., 2011).

The dust load in the atmosphere affected weather and climatic phenomena, via direct and semi-direct effects on the radiation budget, precipitation (Ramanathan et al., 2001; Kaufman et al., 2002), Asian monsoons (Lau and Kim, 2006; Lau et al., 2006), West African monsoon (Lau et al., 2009; Sun et al., 2009), and atmospheric stability, Awad et al. 2014.

Specifically, the northern Saudi Arabia has classified as a temporary dust source area over Arabian Peninsula, Mashat and Awad 2010, and considered as a cyclolyses area of spring Saharan cyclones, Hannachi et al. 2011. In addition, Notaro et al. 2013 identified the Saharan Desert as a primary remote source for western and northern Saudi Arabia, and the Iraqi deserts as a primary local dust source for northern and eastern Saudi Arabia.

In addition, suitable atmospheric conditions needed to left and transfer the dust from its the sources, Wang 2005, Goudie and Middleton 2006. These conditions were examined through many studies, but these studies have focused on atmospheric conditions for special cases, Mohalfi et al. 1998 and Awad and Mashat (2014-a) explained the effects of the pressure gradient produced between the Azores high pressure and the thermal low-pressure systems located over the Arabian Peninsula on dust transport from Northeast Africa to Asia. Moreover, Gkikas et al. (2012) examined the effect of Azores high and thermal low in south west Asia on Mediterranean dust episodes. Additionally, Awad et al. (2014) examined the synoptic features of spring dust cases in southwestern Saudi Arabia, where the dust region accompany with the steep pressure gradient formed between the deepen low-pressure system over the southern Arabian Peninsula, and the high-pressure system over the Arabian Sea. In other hand , the Shamal (means Northern wind in Arabic language) and frontal dust storms are identified as two primary dust storm categories influenced the Middle East, Hamidi, et al. 2013, where a high-pressure system over the Mediterranean region and a low-pressure system situated over southern Iran are characterize synoptic systems of the Shamal dust storms; while a high-pressure system located over southern Iran and a low-pressure system over the eastern Mediterranean region are the synoptic characteristics of the frontal dust storms.

Considering the local characteristics of dust events and their synoptic features, the purpose of this study is to specify the main characteristics of the summer dust events in northern Saudi Arabia and describe the synoptic factors that are responsible for the strengths of these events. In this study, dust cases are detected and classified based on a threshold value of aerosol index (AI) data (dust) collected by the TOMS satellites and the number of grid points over the northern Arabian Peninsula achieved this threshold value.

The paper is organized as follows. In section 2, the data are described. Section 3 illustrates the methodology used. Section 4 is devoted to the results, discussing the dust and synoptic patterns of the summer dusty days and their classes comparing with the summer non-dust cases. The final section contains discussions and conclusions about this study.

2. Data

The TOMS AI is one of interesting measurements of aerosol in the atmosphere, which defined as the difference between the backscattered radiation measured on two ultra-violet channels (Herman et al., 1997; Torres et al., 1998). Both of absorbing aerosols over land and water are detected using AI; however, the AI is proportional to optical depth and the dust altitude (i.e. weak TOMS AI could represent the dust close to the surface) (Mahowald et al. 2003). Avoiding the deficiency in AI measurements (surface aerosol), a threshold value for the AI has been used in this study. This threshold is also used as a condition for selecting and classifying dusty cases (details of this threshold value is described in the methodology section).

Data used in this study collected from four different TOMS instruments through 25 years of daily global measurements of UV radiances at three discrete wavelengths: 340, 360, and 380 nm. The data collection began in November 1978 and finished at September 2006, with a data gap from May 1993 to July 1996.

In addition, the meteorological data used in this study consist of the sea-level pressure (SLP), the wind components at 850 hPa and at 250 hPa, vertical motion at 500hPa and the temperatures between 1000 to 500 hPa in the summer (June, July, and August) months from 1979 to 2006. The meteorological data are derived from NCEP/NCAR reanalysis (Kalnay et al., 1996, Kistler et al., 2001) , and have a horizontal spatial resolution of $2.5^o \times 2.5^o$. The study domain is defined by the longitudes 0^oE-70^oE and the latitudes 10^oN-50^oN.

3. Methodology

In this study, the TOMS AI values and their distributions through the grid points are used to detect and classify the dusty cases, Awad and Mashat (2014-b). At the beginning, both of the average and standard deviation values of AI data, that used for calculating the threshold value, was calculated from all cases that had at least one grid point with an AI greater than zero inside the checking zone, a region delineated by 26°N to 32°N and 35°E to 48°E (rectangle in Figure 1-a). In this study, dust cases were defined to have an AI of at least 2.0 (represented the threshold value), which represents the average AI plus half its standard deviation inside the so-called checking zone. This threshold value is greater than the values used in other studies, such as Prospero et al. (2002), Barkan et al. (2004), Awad and Mashat (2014-a, -b) and Awad et al. 2014

It is worth to note that, the checking zone represents the area classified as a temporary dusty region in the Middle East by Mashat and Awad (2010) and is considered as the cyclolysis area for spring Saharan cyclones (Hannachi et al. 2011). In addition, the checking zone contains a sufficient number of surface stations (figure 1-b) that were used to identify relationships between AI and surface observations.

The selected cases must contain at least one grid-point inside the checking zone has AI value greater than or equal to the threshold value. By applying the threshold value on AI inside the checking zone for all summer seasons, the results reveals that this area is mostly affected by dust, as shown in figure 2, averaging approximately 82% days are dusty.

The dust cases are classified depend on the number of grid points achieve the threshold value within the checking zone. The following criteria are used to identify the categories:

(1) Narrow Spread "NS" class (the number of grid points inside the checking zone that achieve the threshold value is less than or equal to 25 grid points),

(2) Moderate Spread "MS" class (the number of grid points inside the checking zone that achieve the threshold value is greater than 25 but less than or equal to 50 grid points), and

(3) Wide Spread "WS" class (the number of grid points inside the checking zone that achieve the threshold value is greater than 50 grid points).

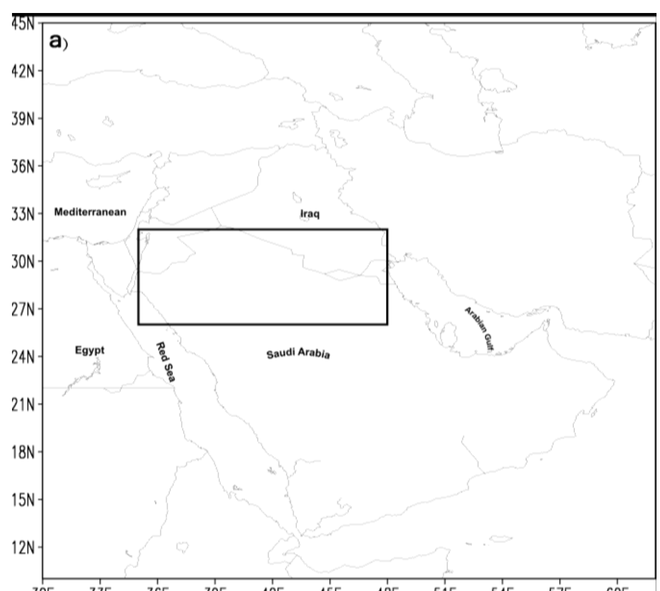
Moreover, the mean sea level pressure (SLP), the Geopotential height and wind stream at 850 hPa, the Geopotential height and vertical wind at 500 hPa, the maximum wind at 250 hPa, and the calculated static stability through the layers between 1000-850hPa and 850-500hPa are used in to examine and describe the synoptic patterns associated with summer dusty days and the distinguishable synoptic characteristics of each class.

4. Results

4.1 Statistical Study

Applying the previous procedure for 25 summer seasons, from 1979 to 2006, except summer seasons from 1993 to 1995, about 1955 dust cases are selected, table 1, which represented 82.0% of those summer seasons period. The classification of these cases, table 1, show that about 73.2% of selected cases are narrow spread cases, and 17.5% of these selected cases are moderate spread cases, while 9.3% are wide spread cases.

Further, the yearly distribution of selected cases and their classes, figure 2, confirmed the previous result and show that, in general, most of the cases are narrow spread cases, while few cases are wide spread. In details the yearly distribution, figure 2, show that summer seasons 1987, 1989, 2000, and 2003 are full seasons affected by dust, while the summer seasons 1984, 1985, 1991, 1992, and 22004 are the summer seasons have more than 90 dusty days. In other hand, the summer seasons 1980, 1996, and 2001 have the minimum number of dust cases throughout the study period. Also, the figure show that in summer seasons 2002 and 2003 the number of wide spread dust cases are larger than moderate spread cases, that in turn larger than narrow spread cases, while at summer season 2000 the number of moderate spread cases are the larger.



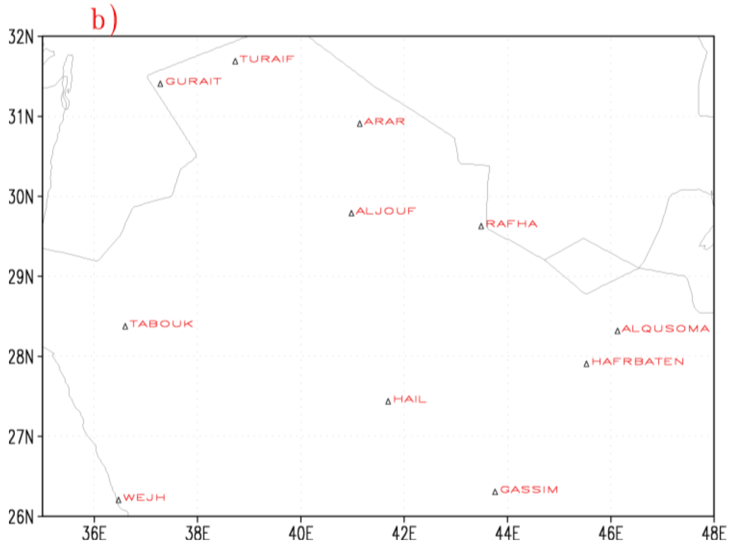


Figure 1. A map representing **(a)** the study domain (the inside rectangle represents the location of the checking zone and its location relative to the study domain), **(b)** the checking zone and names and locations of the surface stations.

CLASSES	ALL CASES	NARROW SPREAD CASES	MODERATE SPREAD CASES	WIDE SPREAD CASES
NUMUBER OF CASES (RATIO)	**1955 (82.0%)$_1$**	**1431 (73.2%)$_2$**	**342 (17.5%)$_2$**	**182 (9.3%)$_2$**

Table 1, number of the cases selected under the summer threshold value of TOMS Aerosol Index (AI). In bracket with subscript 1, is the ratio with respect to Summer periods for 25 years (2300 days) of the study, while with subscript 2, is the ratio with respect to total selected dust cases (1955 days).

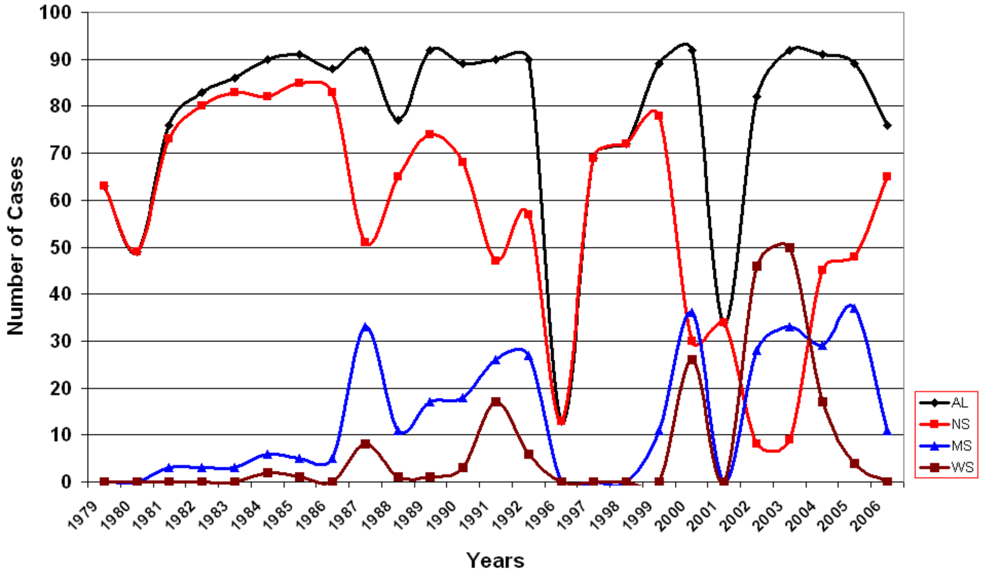


Figure 2, Yearly statistics for all selected dust cases and for the classes (Narrow (NS), Moderate (MS), and Wide (WS) spread) in the summer seasons from 1979 to 2006.

The total numbers of dust types observed at Meteorological surface stations inside the checking zone, figure 1-b, are shown in table 2. The numbers in the table explained as follow, for example, all stations observed 1460 of

Dust Raised type through the 1955 selected days, which means about 74.7% of these selected days there is, at most, one station observed this type of dust. Also, table 2, demonstrate that Dust Raised type is the pronounced dust type observed in the region, followed by Wide Dust and Haze types; respectively, while dust storms are rarely observed. Also, the numbers in the table show that at wide spread class, there are about four stations observed a type of dust, while become three stations for Moderate spread class and reached to, only, one station for Narrow spread class. In other hand, the observed dust storms show that a ratio of 8.24% ((15 observations /182 days) * 100) of Wide Spread days there is one station, at most, observed dust storms, while the ratios reached 9.49% and 5.31% for Moderate and Narrow Spread classes; respectively.

Class/Phenomena	Haze	Wide Dust	Dust Raised	Dust Whirl	W-M Storm	S. Storm
AL	719	890	1460	16	71	61
NS	262	423	720	6	33	43
MS	249	306	445	6	28	13
WS	208	161	295	4	10	5

Table 2. Number of observations of the individual dust/sand storm types (Haze, has a code, ww=5; Wide Dust, ww=6; BD: Dust Raised, ww=7; W-M storm: Weak to moderate dust storm ww=30-32; and S. Storm: severe dust storm, ww=33-35) at the stations inside the checking zone for 25 summer seasons.

4.2 Synoptic Description

The synoptic description of this study depends on the comparison of synoptic features of the dusty and non-dusty cases and between the dusty classes their self.

4.2.1 Horizontal Distribution of Dust

The horizontal distribution of the dust on the non selected cases, figure 3-a, show that the dust is concentrated in the east and south of the Arabian Peninsula, and over eastern Africa and southern Red Sea. These areas will considered as a main dust areas, which are agree with Prospero et al. 2002; Mashat and Awad 2010.

At Narrow spread class, figure 3-b, the main dust area over eastern and southern Arabian peninsula are extended around, especially over north and west wards. Simultaneously, the dust over eastern Africa and south Red Sea extended north and east wards to meet with the dust over Arabian Peninsula.

Although, the dust continue to extend around the main dust areas at Moderate and Wide spread classes, figure 3-c and 3-d; respectively, but this extension appeared strongly in these classes, in agree with Awad et al 2014. Also, it is noted that the amount of dust and its northward extension increase as the strength of class intensified.

4.2.2 Mean sea Level Pressure

The general synoptic features of the dusty and non-dusty cases, figure 4, are the Azores high pressure systems at western region, a high pressure system on northeast region, and the Indian low pressure system on Middle east and Arabian Peninsula. Although, synoptic features of the dust classes, figure 4, are similar, but it is noted that the distribution of isobars are regular on strong classes than weak classes. This distribution of Isobars on WS class, figure 4-d, are as follows isobaric line 998hPa pass through Emirates, 1000hPa through south Iraq and 1002hPa at north Iraq, but this distribution not so in NS class, figure 4-b, where isobaric line 998hPa pass through Emirates, but 1000hPa through center Iraq and 1002hPa at north Iraq. In addition, it is appeared that the synoptic features of MS class, figure 4-c, are closed to those of the WS class, figure 4-d, while the synoptic features of non-dust cases, figure 4-a, are closed to those of the NS class, figure 4-b.

Further, while at WS class the trough line above the Arabian Gulf directed to north-south, it is relatively tends to the west in non-dust cases, then back to north-south as the strength of the class characteristics increase. In addition, the extension of the western high pressure ridge into Arabian peninsula is pronounced as the strength of the class increase.

On other hand, the maximum wind at 250 hPa, figure 4, shown that their values and influenced area are decreased from NS class, figure 4-b, to WS class, figure 4-d. Although, the values weaken and the area decreased at non-dust cases, figure 4-a, in similar to those at WS and MS classes, figures 4-c and 4-d; respectively, but its location is to the north of these are associated with the previous classes.

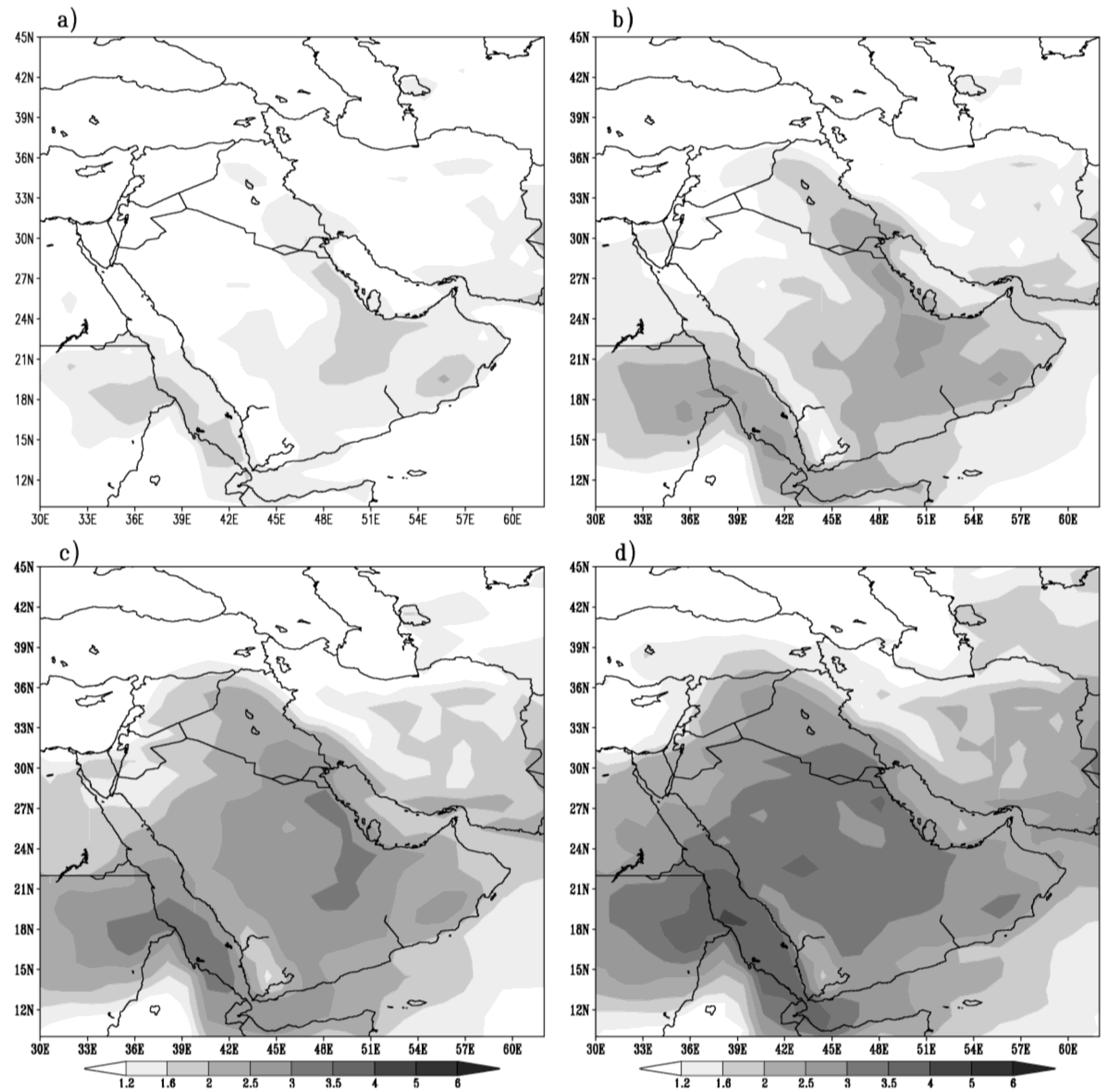


Figure 3. Horizontal distribution of the aerosol index (dust) corresponding to **a)** Non , **b)** Narrow, **c)** Moderate, and **d)** Wide spread cases for Summer seasons from 1979 to 2006.

4.2.3 Geopotential height and Wind Stream at 850hPa pressure Level

Generally, the distribution of atmospheric systems at the pressure level 850hPa, figure 5, show two main systems had separated the study region into two parts, the western which affected by anticyclonic system, and the eastern which affected by cyclonic system, in addition to an anticyclonic cell over northeast region.

Also, the figure show that the relationship between these systems distinguish the class, where at non-dust cases, figure 5-a, although the anticyclonic system built up to 1570gpm, more than the correspondence in other classes, but its affect on eastern part not pronounced as those at dust classes, compare for example contour line 1500gpm on dusty and non-dusty cases. Moreover, the shape of the ridge of the anticyclone over Arabian peninsula, formed a pronounced concave shape on dust classes, which buckle the contour line on south Arabian peninsula. In addition, the anticyclonic cell at northeast area make a sharp concave shape on dust classes more than this on non-dust cases.

Further, although the deepening of cyclonic system are the same on dusty and non-dusty cases, figure 5, but contours of cyclone shifted westward on non-dust cases, compare for example contour line 1450gpm, or 1460gpm between the dusty and non-dusty cases. Also, the orientation of the cyclone trough is directed more to westward on non-dust cases, figure 5-a, comparing with those of dusty cases, which is directed more to north as shown at WS class, figure 5-d. Also, the trough shrinking southward on dusty cases, where reached its maximum south position at WS class, figure 5-d.

In other hand, the anticyclonic wind pattern at western region for non-dust cases, figure 5-a, are located to the east and weak than those of dust classes, figures from 5-b to 5-d. Also, it is noted that the strength of anticyclonic wind intensified as the characteristic of the dust class increases.

In addition, two cyclonic wind pattern are exist on northeastern region, figure 5. The strongest one is to the east on non-dust cases, figure 5-a, comparing than those on dust classes, figures 5-b to 5-d. Also, it is noted that, this strong cyclonic wind pattern is going southward on dust classes as the characteristics of the class intensified. Whilst, the weak cyclonic wind pattern appeared at non-dusty cases and located to the west than those at dust classes. Further, an anticyclonic wind pattern found at non-dust cases over Arabian peninsula not pronounced on dust classes distribution.

Generally, it is appeared that the distribution of wind patterns producing south westerly wind over northern Arabian Peninsula at non-dust cases, figure 5-a, and westerly wind on dust classes, figures 5-b to 5-d, which strength as the class characteristic increase.

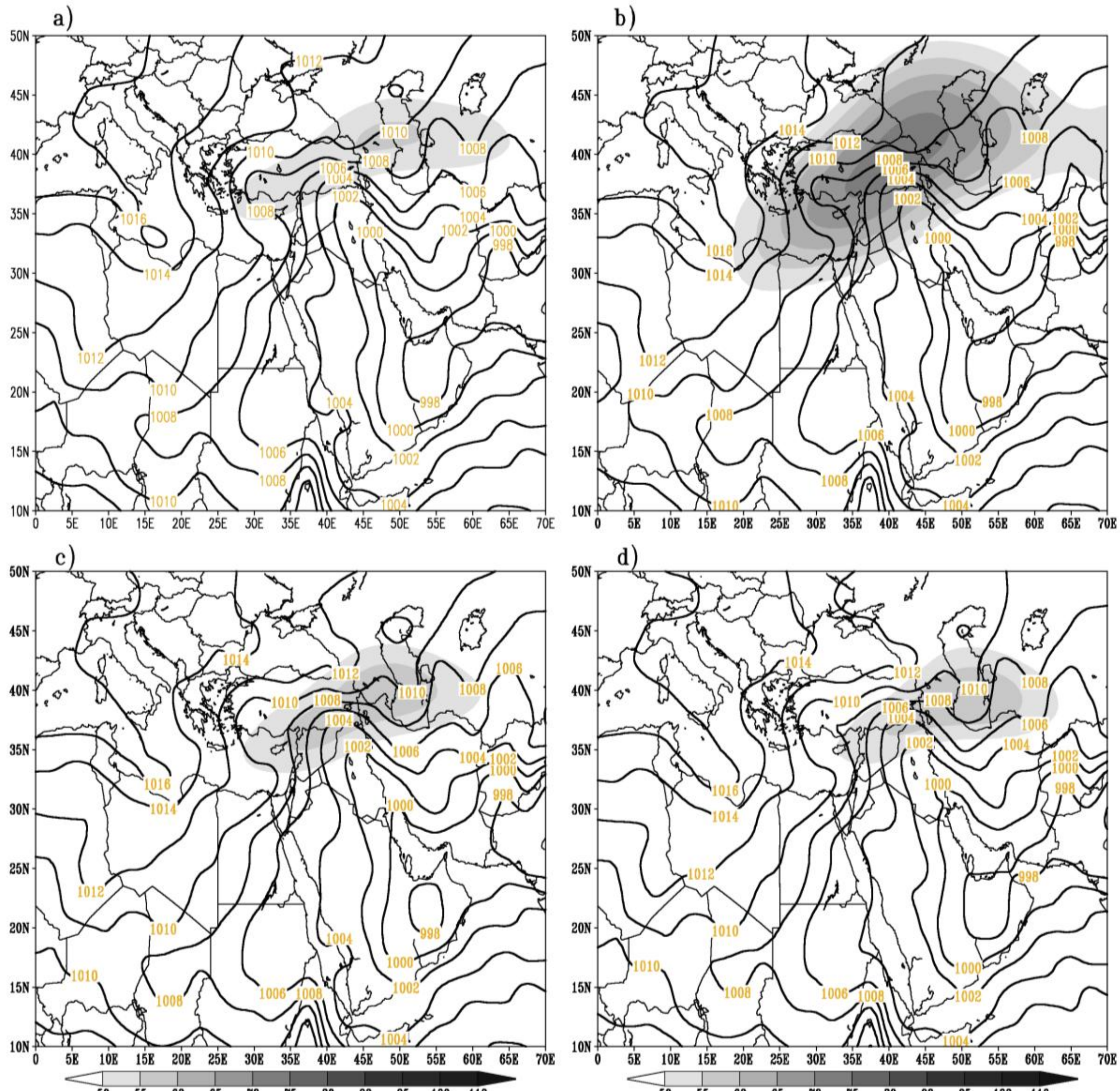


Figure 4. The average horizontal SLP (hPa) (contour)and 250-hPa maximum wind distribution (knots) (shaded) corresponding to **a)** Non , **b)** Narrow, **c)** Moderate, and **d)** Wide spread cases for Summer seasons from 1979 to 2006.

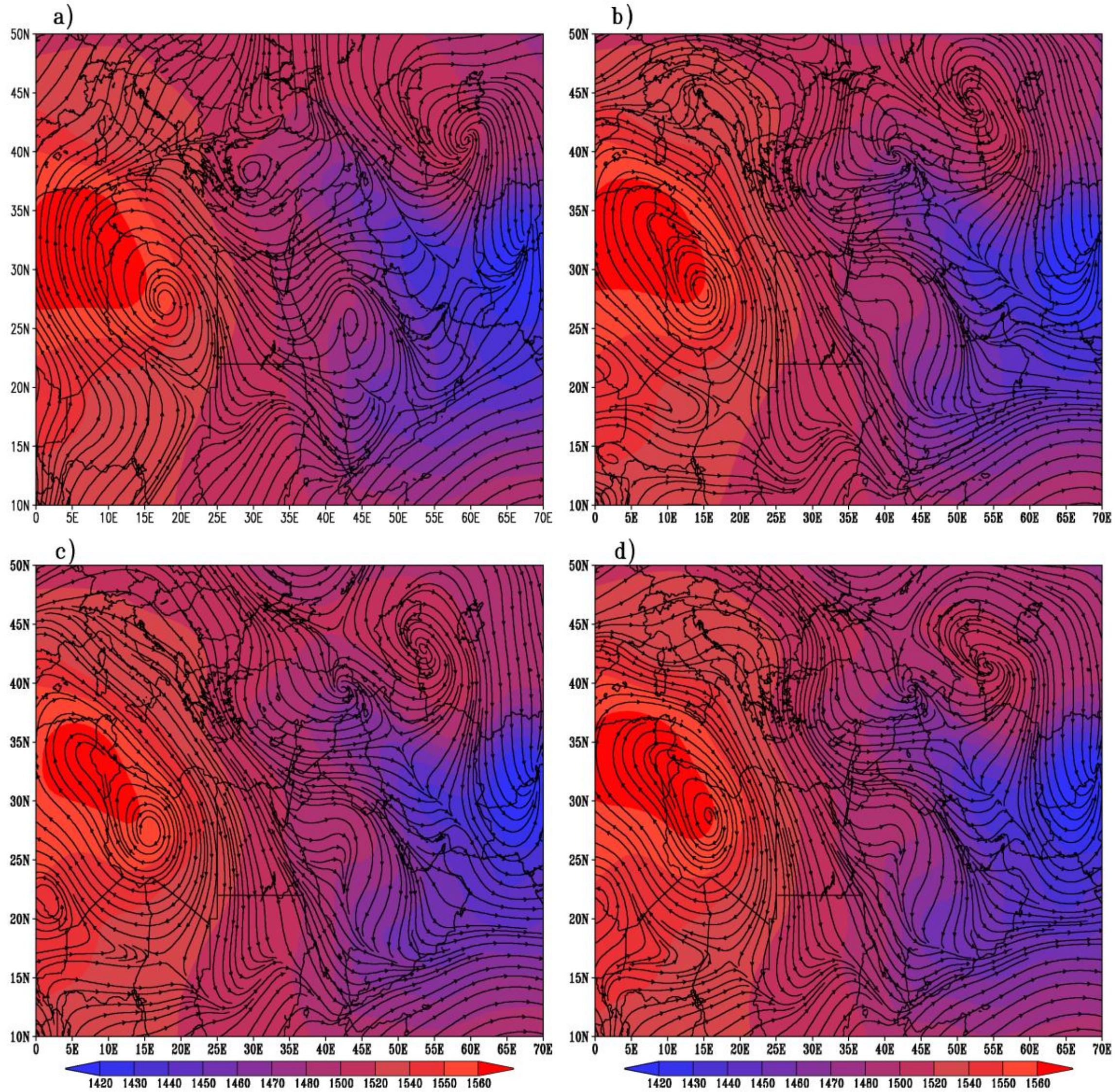


Figure 5. The average horizontal Geopotential Height (shaded) and wind Stream (stream lines) at 850hPa pressure level corresponding to **a)** Non , **b)** Narrow, **c)** Moderate, and **d)** Wide spread cases for Summer seasons from 1979 to 2006.

4.2.4 Geopotential height and Vertical Motion at 500hPa pressure Level

The synoptic features at pressure level 500hPa, figure 6, show that there are anticyclonic system on south of the study region and cyclonic system on northern region. Also, show that the cyclone deepen on Wide and Moderate classes, figures 6-c and 6-d; respectively, where the lowest contour line is 5720gpm, while it is less deepen on non-dust cases and Narrow spread class, figures 6-a and 6-d; respectively, where the lowest contour line is 5730gpm. Whilst, the anticyclone is stronger on non-dust cases, figure 6-a, the highest contour line 5940gpm, comparing 5930gpm on dust classes, figure 6-b to 6-d.

Although, the general synoptic features at pressure level 500hPa are generally similar on the dust and non-dust cases, but the trough line of the northern cyclone is oriented from northwest-southeast at non-dust cases, figure 6-a, into northeast-southwest at Wide spread cases, figure 6-d. Additionally, the gradient of geoptential height increases from non-dust cases into Wide spread cases, passing through Narrow and Moderate spread classes.

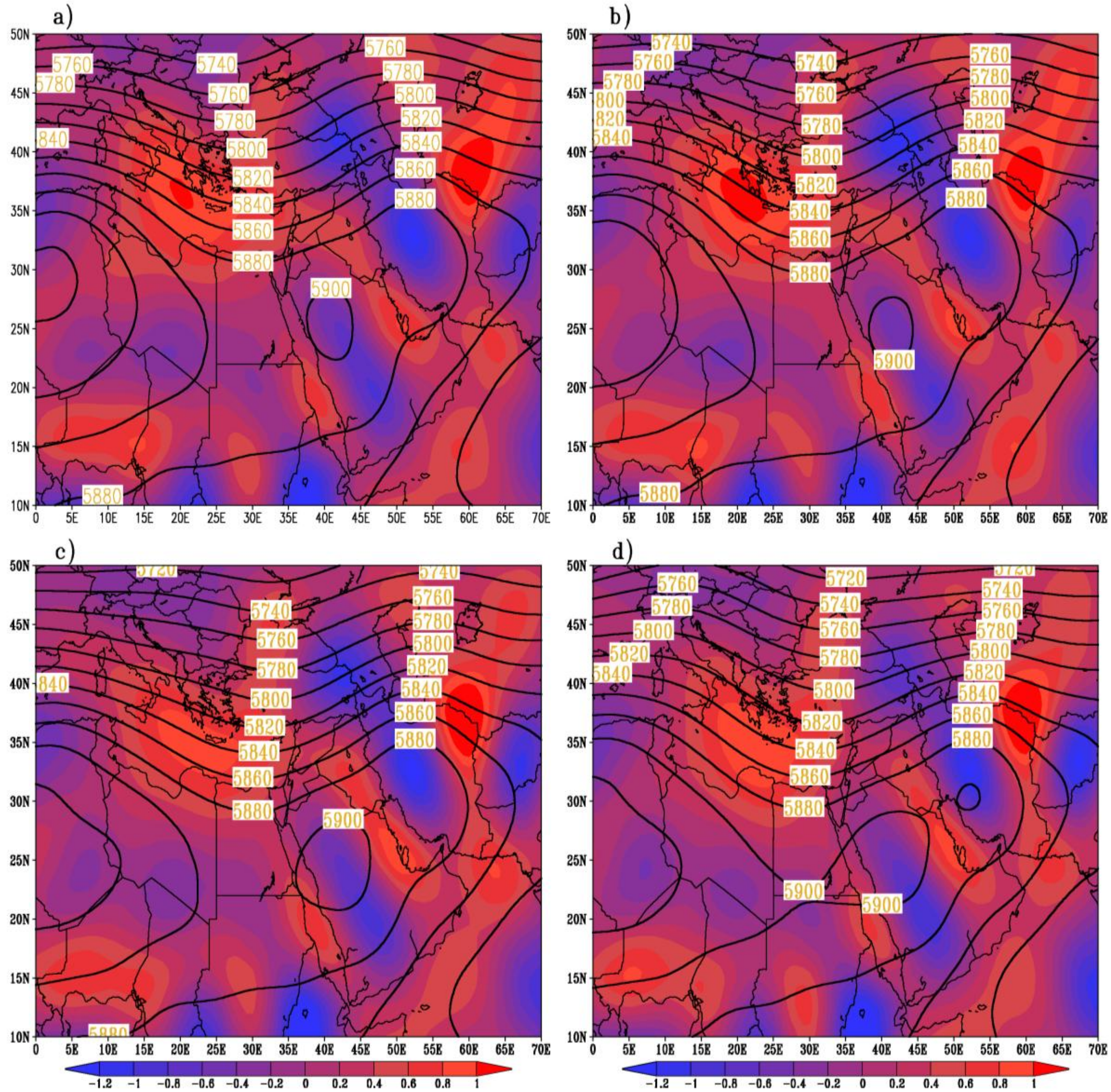


Figure 6. The average horizontal Geopotential Height (contour) and Vertical motion (ω*10) (shaded) at 500hPa pressure level corresponding to **a)** Non , **b)** Narrow, **c)** Moderate, and **d)** Wide spread cases for Summer seasons from 1979 to 2006.

In other hand, the highest anticyclonic contour over the Arabian Peninsula, line 5900gpm, shifted eastward from the non-dust cases into the Wide spread cases, which reached Iran on the Wide spread class and eastern side of Arabian Peninsula on moderate spread class.

The vertical motion at pressure level 500hPa for the dusty and non-dusty cases, figure 6, show that there are a sequence of subsidence and rising motion cells over Arabian Peninsula from Red Sea to eastward, where started with a subsidence cell over Red Sea then a rising motion cell over Arabian Peninsula, followed by a subsidence cell over eastern Arabian Peninsula and Arabian Gulf, and so on. In addition, the vertical motion of the dusty and non-dusty cases show a big cell of subsidence over southern Europe and Mediterranean sea.

Although, the features of vertical motion are approximately similar on the dusty, figure 6-b to 6-d, and the non-dusty cases, figure 6-a, but it is noted that the subsidence motion over southern Europe and Mediterranean sea decreases and shifted eastward as the dust cases strength. Also, the rising motion cell over Arabian Peninsula intensified and northward shifted on dusty cases, figures 6-b to 6-d, where reached its maximum on the Wide spread class, figure 6-d. Further, the subsidence cell over eastern Arabian Peninsula and Arabian Gulf increase on the Wide spread class and decreases downward to the non-dust cases. These vertical motion features appear as if they forms a vertical circulations between theses sequences of rising and subsidence motions.

4.2.5 Horizontal Distribution of the Static Stability layers between 1000-500hPa

In this study the static stability layer between 1000hPa to 500hPa are divided into two layers, the lower layer between 1000-850hPa and the upper layer between 850-500hPa.

The distribution of static stability between 1000-850hPa for both the dusty and non-dusty cases, figure 7, display that there are common features between the cases, where the unstable layer over Arabian Peninsula surrounded by stable layers over Mediterranean , Middle east, western Arabian Peninsula and Arabian Sea, similar to that found for dusty cases over southeastern Arabian Peninsula, Awad et al. 2014. Moreover, it is appeared that the center of stability layer over Mediterranean is shifted eastward while the stability over western Arabian peninsula increase as the characteristics of the class intensified. Also, it shown that the orientation of the unstable area over Arabian Peninsula directed eastward in the Wide spread cases, figure7-d, although unstable reached its maximum value on MS class, figure 7-c, not on WS class, as was expected. This higher values of unstable on MS class could be explained by existence of high ratio of sand/dust storms on this class than other classes, as shown in table 2.

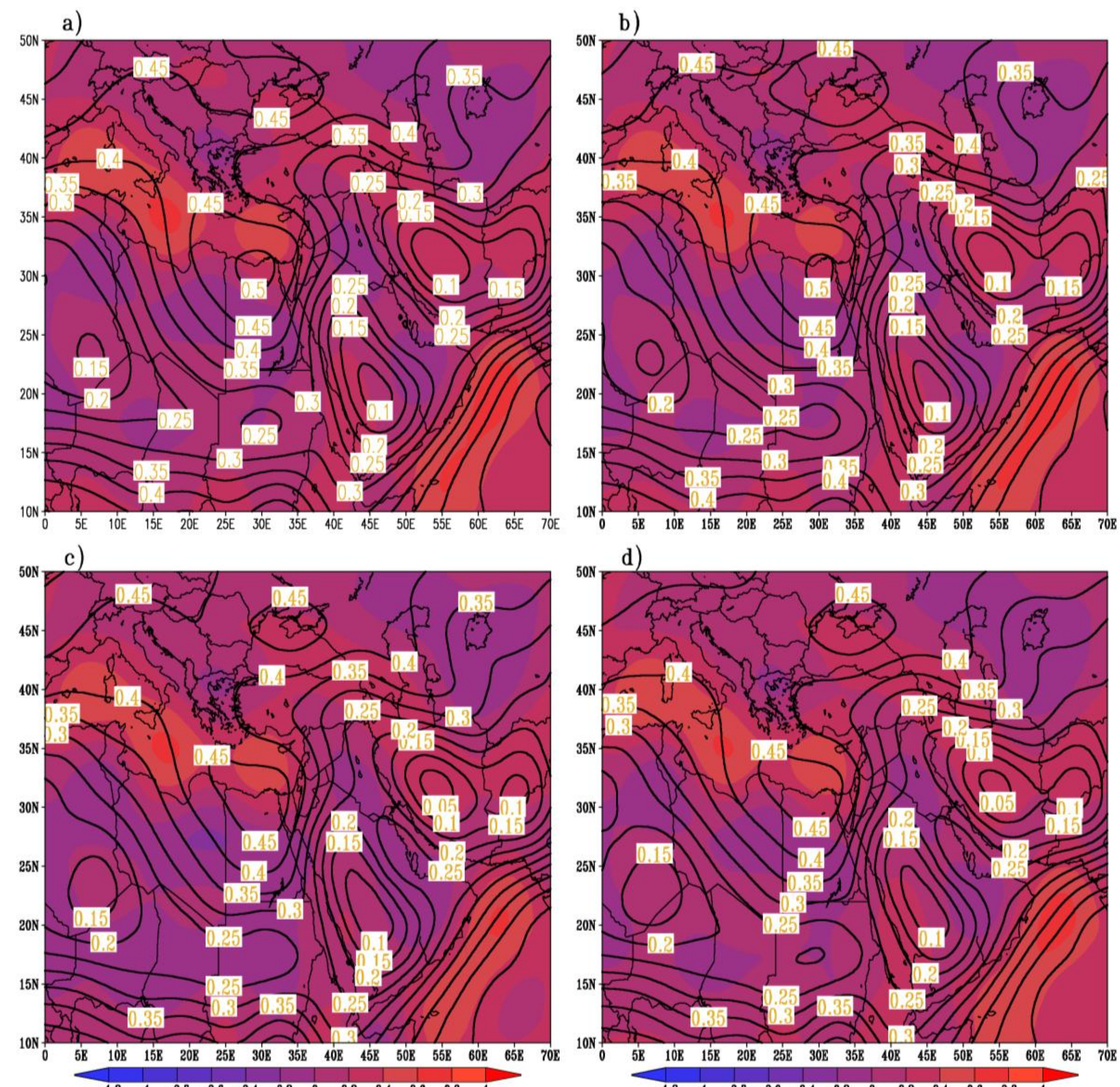


Figure 7. The average variation of Static stability (*1000) between the pressure levels 1000-850hPa (shaded) and between the pressure levels 850-500hPa (contour) corresponding to **a)** Non , **b)** Narrow, **c)** Moderate, and **d)** Wide spread cases for Summer seasons from 1979 to 2006.

Generally, the distribution of static stability over Arabian Peninsula and its surrounding are similar to the distribution of vertical motion at 500hPa pressure level (but the vertical motion lags to west), where stability corresponding subsidence and instability corresponding rising motion.

In other hand, the distribution of static stability in the layer between 850-500hPa, figure 7, also, show a common features between the dusty and non-dusty cases. These features are two layers of relative low stability over Arabian Peninsula and Middle East surrounded by two layers of stability over Mediterranean Sea and North Africa and over Arabian Sea.

The variations on these features demonstrated the characteristics that distinguish the cases, where the low stable layer above the Arabian Peninsula expands and northward extended, and the low stable layer above Middle East intensified and extended northward, as the characteristics of the class intensified. Also, the stable layer above Mediterranean and North Africa decreased and shifted to east and south wards, while the stable layer above Arabian Sea decreased as the characteristics of the class intensified. Further these variations on stable and low stable layers led to a reducing in the stability above northern Arabian peninsula as the characteristics of the class intensified.

5. Discussion and Conclusions

This study examined the synoptic features accompany with the summer dust cases over northern Saudi Arabia. The dust cases were selected and classified based on the TOMS AI distribution and values. The TOMS AI data within the checking zone (delineated by 26°N to 32°N and 35°E to 48°E) were used to determine a threshold value of 2.0.

Applying this threshold value to the summer seasons, referred that northern Saudi Arabia is dusty for most of summer (82% of summer period). In addition, the surface observations, accompany these cases, demonstrate that Dust Raised type is the pronounced dust type observed in the region, followed by Wide Dust and Haze types; respectively, while dust storm types are rarely observed. Further, the horizontal distribution of the summer dust appeared two main areas of dust over eastern and south of Arabian peninsula and eastern Africa and southern Red Sea. These areas extended around in dust classes, and their amount and extension increase as the strength of the class increases.

The synoptic study of the dust and non-dust cases, show that there is a very small differences between the surface synoptic features of the cases, but the regularity of the isobars (i.e. the shape of the isobars distribution) pronounced as the class characteristic strengthen, in which the isobars distributions are regular at WS more than MS and NS classes. Also, it is found that the maximum wind at 250hPa decreases as the class strength increases.

Further, the distribution of the atmospheric systems at pressure level 850hPa demonstrated that anticyclonic systems on dusty cases press on eastern cyclone on two directions, first change the orientation of the trough at eastern Arabian Peninsula and second make a buckle on contour lines over southern Arabian Peninsula. In addition, the wind patterns over this pressure level forced the distribution of the wind on dusty classes over northern Arabian Peninsula to become westerly and strength as the characteristics of the class increases.

In other hand, the synoptic features on the pressure level 500hpa show that the northern cyclone trough line rotated clockwise from non-dust cases into the Wide spread cases, and the gradient of the geopotential height increases as the characteristics of the case increases. Whilst, the southern anticyclone shifted eastward from the non-dusty cases into the dust cases, which reached its far east at the Wide spread class. Also, the vertical motion associated with the atmospheric systems in this pressure level show that the vertical circulation over Arabian Peninsula strength on the dusty cases more than the non-dust cases and reach its maximum strength at the Wide spread class.

Moreover, the distribution of static stability over the layer between 1000-850hPa confirm the sequence of subsidence and rising motions at 500hPa pressure level, and the distribution of the dust types observed at surface stations. Whilst, the relationship between stable and low stable layers, between 850-500hPa, around northern Arabian Peninsula appeared as an important role in changing the degree of stability in this region, which the stability highly decrease in the Wide spread cases.

Generally, the very small differences of the atmospheric features for the summer dusty and non-dusty cases show that the summer season is potentially dusty, and it needs only a very small trigger mechanisms to be dusty, and these mechanisms are very tight to be easily recognized on synoptic features, but appeared directly on dynamical terms (stability, vertical motion, pressure or geopotential gradients).

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