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Interactive comment on "Atmospheric Conditions Leading to an Exceptional Fatal Flash Flood in the Negev Desert, Israel" *by* Uri Dayan et al.

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This manuscript deals with a very interesting case of a high-impact storm. There were floods in the Negev desert in southern Israel, in which unfortunately 10 people died. The event had not been expected as it hit at the end of the cold season. A scientific investigation of this storm is important in order to understand the underlying processes and to improve the forecast for such flooding events. Additionally, a climatological classification as carried out in the work, helps to better estimate the potential of these events. However, the work is essentially limited to large-scale processes that are also not completely discussed. In addition, there are attempts to connect small-scale processes to the synoptic scale, which fail because of the separation between dynamics and thermodynamics and not least because of the selection of data and the way these

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are presented. Finally, the manuscript gives repeatedly undisputed hypotheses, as well as some inconsistencies. The main goal of this work as given in lines 50-52 ("In section 3 we describe the event and identify the unique dynamic and thermodynamic conditions that lead to the severe convection, as well as the sources of moisture for the rain formation in this storm.") needs to be elaborated more, especially with respect to across-scale processes with respect to rain production. Evidence needs to be given to the hypotheses that are presented.

Response: Following your valuable comments, we intend to rewrite the discussion section.

Specific comments:

1) The manuscript is focused on the analysis of the large-scale flow, which is compared with similar flooding events. The intensity and track of the corresponding cut-off low in 500 hPa is unusual for the season. Parts of the work, however, disagree on whether the event is a typical weather situation, with flooding occurring outside the rainy season in the desert or whether it is a unique situation (compare lines 42-45: "The rest of the annual rainfall occurs in the transitional seasons and is contributed by precipitating tropical synoptic-scale systems and by Cyprus Lows. A significant part of them occur in the desert areas and are characterized as intense rain events of small spatial extent and short duration, some of which produce flash floods (Kahana et al. 2002; Dayan and Morin 2006, Greenbaum et al. 2010)." and lines 245-247: "The location of the surface cyclone was similar to the 'Syrian low', defined by Kahana et al. (2002) as one of the major systems causing floods in the Negev Desert." with line 51: "unique dynamic and thermodynamic conditions"). The impression is that the large-scale weather conditions are well known for flooding, whereas only the temporal appearance and the intensity and coverage were unique. Readers unfamiliar with the given weather patterns, i.e. 'Syrian low' and 'Cyprus Lows', can be confused which of these two is mainly associated with flooding events. It would be good to explain these weather patterns at the beginning of the text in some detail, e.g. mid-level flow and surface pressure field.

Response: We agree that the status of this storm, in the regional and seasonal context, is not set properly, and leave the reader with an unclear impression. We will include (a) climatological background and (b) a general statement in the introduction section:

(a) "The majority of the annual precipitation in Israel is associated with Mediterranean cyclones, in the stage when they reach the Middle-East (i.e., Cyprus Lows, HMSO 1962; Saaroni et al. 2010; Zappa et al. 2015). Two-thirds of the rainfall occur during December through February (Alpert et al. 2004; Ziv et al. 2006). The focus in this study is on the Negev desert and the Judean desert (Fig. 1), hereafter the ’study region’. The climatic regimes of the study region span from semiarid in the north to an arid in the center and the south (south of 31ïĆř15’, Ziv et al 2014). The rainfall during the late spring months, Apr-May, contribute 5 - 10 mm (4 - 9%) of the annual average over the northern and central parts of the Negev desert. In spite of these negligible rain amounts, the number of flash flood events in late spring cannot be ignored. The flood regime in the study region was analyzed by Kahana (1999), based on 37 hydrometric stations operated by the Israeli Hydrological Service. He identified 59 “major floods”, i.e. floods in which the recorded peak discharge reached the magnitude of a 5-year recurrence interval, for the period 1947- 1994 at least in one watershed. Eight (14%) of these major floods occurred during the late spring. The main source of major floods in the late spring over the study region is the “Active Red Sea Trough” (ARST, Kahana et al., 2002). The ARST is most frequent during fall and spring (Sharon, 1978; Sharon and Kutiel, 1986; Dayan et al., 2001). This is a lower-level trough extending from equatorial eastern Africa into the eastern and southern Israel along the Red Sea and is accompanied by a pronounced upper-level trough over Egypt. At times, it initiates severe convective storms. The secondary source of major floods are Cyprus Lows that cross the eastern coast of the Mediterranean, but remain intense. Kahana et al, (2002) entitled them "Syrian Lows". Under the influence of Syrian lows, the Levant is subjected to surface north-westerly ïňĆow, enriched with moisture from the Mediterranean. While flowing onshore, rains are produced over the northern Negev and southern Judean desert and, due to orography, over the north and western slopes of the Negev and

Judean Mountains.

(b) The storm analyzed here was severe in several aspects. One is the number of fatalities, 13, which is a record breaking for Israel. Second, a part of the Zin basin (draining the center of the Negev desert) experienced precipitation intensities reaching 75-100-year return period, resulting in discharge magnitudes of 10-50-year return period (Rinat et al. 2020). The third aspect is the rainfall totals for the storm that reached 40-50 mm over large parts of the study region, i.e., 10 times the monthly long-term mean (IMS, 2018). The aim of this study is to assess the severity of this storm in the seasonal perspective and to analyze the atmospheric conditions that explain it."

Reference: Rinat, Y., Marra, F., Armon, M., Metzger, A., Levi, Y., Khain, P., Vadislavsky, E., Rosensaft, M. and Morin E. Hydrometeorological analysis and forecasting of a 3-day flash-flood triggering desert rainstorm, NHESS doi.org/10.5194/nhess-2020-189, 2020 Moreover, this storm is compared to the other 10 "reference storms" that occurred in the same months during the latest 33 years, now in the last subsection of Sec. 3. In the summary the status of this storm is addressed as well.

2) Apart from this analysis of mid-level and SFC flow, hypotheses are (repeatedly) raised that are not discussed further: Lines 311-312 "The combination of a cut-off low with small radius and large hypsometric depth, implies high curvature relative vorticity, with strong dynamical forcing on rain formation." At this point, the authors need to be more precise. "Strong dynamical forcing" refers to quasi-geostrophic processes, and large-scale lift is the order of cm/h. Does QG lift affect rain formation directly? Moreover, only the contribution by differential cyclonic curvature vorticity advection to QG lift is mentioned. Since the weather charts indicate north-westerly flow, the reader may wonder if a cold air advection maximum may cancel QG lift in a similar event.

Response: We accept this critical comment concerning our considering the synoptic (i.e., the large dynamic processes) and thermodynamic elements (i.e., mesoscale processes permitting deep convection) separately. Therefore, we intend to reorganize the manuscript in the various relevant parts, in particular the discussion section, considering the synoptic-scale as the background for the smaller-scales, which characterized the major rain cells, as follows:

Following the quasi-geostrophic approach, most convective outbreaks occur in broad southwesterly flow aloft ahead of an approaching trough (Doswell, 1987). In April 26, under the northwesterly flow behind the upper-level cyclonic system, its direct dynamic supporting effect on rain formation is expected to be weak, or even negative (Fig. 2c). At this sector, negative upper-level vorticity advection and lower-level cold advection are typical, and both induce subsidence in the mid-levels. Inspection of the lower-level temperature and wind fields (not shown in the paper, shown for you) indicate that at that stage, the cold core associated with the upper-level cyclone was centered over the Negev desert. The lower-level winds over the study region were parallel to the isotherms, so that no temperature advection existed. Similar configuration existed with respect to the upper-level vorticity field, implying that vorticity advection also did not take place there. (See Fig. 1 below)

Moreover, the omega field at the mid-levels in the synoptic scale over the region was near zero. The above implies that the synoptic scale dynamics did not have a direct effect on the rain formation on that day. The major synoptic factor that directly contributed to the rain formation in this storm is the wind. One implication is the onshore moisture transport, accompanied by an uplift imparted by its encounter with the coastline and later on, with the mountain ridges. The other is the upper-level cold advection, leading to thermal instability. Actually, only a small fraction of the rainfall in this storm was orographic (over Judean Mountains), whereas the majority of the rain was observed far from the coastline and beyond the water divide of the mountain ridges (Fig. 1, note the divide line). The major rain cells were convective: the one that produced the flood in Tzafit, over 60 km inland, and the one developed near Beit Shean, in the Jordan valley, >200 m BSL. The dominance of convective over orographic rain suggests that instability was the prominent factor in this storm. In the EM, rains associated with Mediterranean cyclones, as in the case studied here, are convective in nature. In the winter season, cold air originating from south Europe moves over the EM, interacts with the underneath warmer Mediterranean water and enters Israel (Shay-El and Alpert 1991, Saaroni et al. 2010). In the late spring, Europe becomes warmer, whereas the Mediterranean remains cool, due to its lagged response to the annual cycle, the passage of a Cyprus low over the EM does not necessarily lead to instability. In the case studied here, the instability can be attributed to a negative temperature anomaly in the upper-levels (in the order of -5 K in 500 hPa, not shown) that covered the southern Levant, as a part of the cutoff low. Beit Dagan radiosonde profile for April 26, 12 UTC indicates that an air-parcel had to be lifted up to 1 km to trigger convection. Indeed, the negative Omega values during the storm were in the order of 1Pa s-1, implies that an entire day would be needed to reach the level of free convection. Furthermore, we observed that the major rain cells were in the order of tens of kilometers, implying that they experienced forcing in the meso-scale rather than in the synoptic. This is consistent with Doswell (1987), who showed how the thermodynamic environment favorable for intense convection is formed through large scale processes. Concerning the small radius and large hypsometric depth of the cutoff lows, we referred to the amplitude of the upper-level cyclone as a coarse measure for the general strength of the storm.

3) And what about shear vorticity?

Response: The 'measure of the curvature vorticity' (MCV) is a proxy for average curvature vorticity over the upper-level cyclone, so it evaluates its overall intensity. Since this cyclone moved along the latitudes of Israel, while the Subtropical jet shifted >7 deg southward, the jet's associated wind shear vorticity was regarded as marginal, so that the MCV can be considered as an estimate for the full vorticity. We will add this notion in the "methodology" section before introducing the MCV. (See Fig. 2 below).

4) Lines 193-195: "It should be noted that the three rain centers are located within a region of negative Omega (ascendance, Fig. 7c), with an extremum value of -10 Pa s-1. This implies that these rain systems are dynamically supported." In this manuscript,

the "dynamic factor" (quasi-geostrophic lift) is analyzed separately from the "thermodynamic factor" (thunderstorm) (lines 123-125: "Two complementing factors contributed to the rain formation. One is dynamic, i.e., vertical ascent, associated with the cyclonic system described below (Sec. 3.2). The other is thermodynamic, which is composed of instability and moisture supply, described in Sec. 3.3.").

Response: We accept and adopt the suggested approach concerning the separation between the "dynamic" and the "thermodynamic" factors. Also, we found an error in our text. The values of OMEGA reflect even lower forcing of 1 Pa/s, implying a weaker meso-scale lifting.

5) There are two criticisms to approach. 5.1) First, the omega fields show a combination of lift on different scales, including convection parametrization. It is therefore not possible to conclude that the given omega fields indicate just dynamic lift.

Response: Following your argument, and due to the small amplitude found in Omega field even in the meso-scale resolution (Fig. 7), we will exclude the Omega maps from the paper. The figure below is planned to replace Fig. 7. (See Fig. 3 below).

5.2) Secondly, both factors influence each other, so that a separate analysis cannot be recommended (see also Doswell, C.A. III, 1987: The distinction between large-scale and mesoscale contribution to severe convection: A case study example. Wea. Forecasting, 2, 3-16).

Response: We accept this comment as addressed in our response to comment #2.

5.3) In addition, it is confusing that all three rain events are supported by the dynamic factor, while in other places in the manuscript the opposite is written, such as in lines 119-122: "The maximum rainfall was obtained in the rain shadow of the Negev Mountains, and the second most intense one was found in the Jordan valley, again, in the lee side of the Samarian Mountains. The dominance of convective over orographic elements suggests that sub-synoptic scale factors took place in this storm." These two statements can be confusing since it is not clear whether strong synoptic-scale forcing is important to these events or not.

Response: Thank you for this comment, the formation of major rain cells cannot be attributed to uplift induced by upper-level dynamics as stressed in our response to comment #2. The first major rain cell that developed over Tzafit indeed was form where the terrain has a negative (though moderate) slope with respect to the northwestern wind there. As for the major rain cell developed near Beit Shean, the winds there were northerly, so that it was not formed at the rain shadow of the Samarian Mountains (see Fig. 1). We intend to propose that horizontal confluence was exerted on the surface flow by the conical shape of the Jordan Valley there. We accept that instability is the major factor, and even support it by MKI maps (see Fig. 3 below).

6) Furthermore, the profile of one radiosonde is discussed (in 24-hour intervals). Unfortunately, the authors limit themselves to standard indices for analyzing the general thunderstorm potential. A discussion about whether the vertical profile supports the potential of heavy rain is not provided.

Response: Unfortunately, only one sounding station is operative in Israel (Beit Dagan), and even this one has only 2 observations a day (00 and 12 UTC) and is located dozens of kilometers from the major rain cells. However, analysis of the thermodynamic diagram (i.e. Tephigram) for April 26, 12 UTC indicates that in spite of a shallow stable layer that was found around 700 hPa level, a convective cloud could develop if an air parcel had been lifted to 900 hPa level, with top reaching 330 hPa level. The higher instability observed further inland (see MKI map in our response to comment #6) explain why the main convective activity was observed further offshore. Moreover, the locality of the rain cells typifying this storm demonstrates the minor importance of the direct dynamic synoptic forcing relative to that of instability. This will be stressed in the discussion section of the revised manuscript.

7) In addition, the authors give no evidence to the hypothesis that the modified K-

Index (MKI) gives better results in the east Mediterranean compared to standard indices (lines 321-324: "Despite the universality of stability indices developed to illustrate the potential for convection, few of them require adjustments and modifications to fit the area being analyzed. In this study, the modified KI version adopted for the eastern Mediterranean region, has shown to be a reliable predictor for convective rain centres and therefore a good precursor for floods." In this manuscript, the MKI just indicates the possibility of thunderstorms (as well as all other listed indices; lines 218-220 "The MKI distribution over the study region for the April 26, at 03, 09, 15 and 21 UTC, is shown in Figs. 7i-l, respectively. Values exceeding 25C, indicating potential for thunderstorms, are co-located with the major rain centres at the hours 09, 15 and 21 UTC."). To convince the reader, a comparison with the K-Index can be useful.

Response: The modification of KI, to MKI, are defined and referenced in the methodology section. The MKI was proposed and examined by Harats et al. (2010), following cases of false thunderstorm alarms in the Mediterranean region. The MKI differs from the KI in that the 1st term, the temperature difference between 850 and 500 hPa, is multiplied by the average relative humidity over the 850 and 700 levels. Hence, whenever the lower- or mid-levels are dry, the MKI is reduced compared to the KI. The MKI was further elaborated and tested on a large number of rain cells over the Mediterranean Basin by Ziv et al. (2016). This is demonstrated by comparing KI and MKI for April 26, 07 and 09 UTC. The main difference is in the high KI values compared to the MKI over arid regions. (See Fig. 4 below).

Ref: Ziv, B., Harats, N., Morin, E. et al. Can severe rain events over the Mediterranean region be detected through simple numerical indices? Nat Hazards 83, 1197–1212 (2016). https://doi.org/10.1007/s11069-016-2385-y.

8) A large part of the work is focused on the transport of moisture to the desert. The prevailing north-westerly flow and the transport of Mediterranean air are mentioned several times in the manuscript. However, based on WV satellite images it is also hypothesized that moisture from tropical regions had been advected, according to 315-

317: "Moisture originating from tropical sources during such rainstorms enriches the mid-atmospheric levels, which makes the rain formation less sensitive to availability of moisture in lower levels. Hence rain cells are not expected only over mountain upslopes, but also over low terrains such as the one that caused the deadly flood in Tzafit creek." The authors may imply greater precipitation efficiency here, but this hypothesis is not further elaborated.

Response: Following this comment, we further elaborated the possibility that tropical moisture contributed to the rain through highly detailed back-trajectories (See Fig. 5 below for April 26, 09 UTC). Back-trajectories of 120 – h were derived using a 50 km resolution ERA5 data, in 20 hPa interval from the surface up to 500 mb and are colored according to the specific humidity (g/kg). We now agree that the main moisture source was the Mediterranean. Additional moisture was transported in the mid-levels from Jordan through Syria, as represented by the yellow band of trajectories in this attached figure and the red trajectory in Fig 9. We intend to modify the text accordingly. Concerning the possibility of regions that not exposed to the direct moisture advection from the Mediterranean, this can be explained as follows: The lower-level system in the storm analyzed here, can be considered as a 'Syrian low' (Kahana et al., 2002), which belongs to the Mediterranean cyclones. The Syrian low resembles the 'deep low to the east' as one of the 7 types of Cyprus low defined by Alpert et al. (2004). Saaroni et al. (2010) showed that most of the rain associated with the 'deep low to the east' is distributed over the coastal regions and the western slopes of the Judean Mountains, facing the offshore northwesterly winds from the Mediterranean. This indicates that the Judean Mountains, extending up to 800-1000 m, block effectively this moisture, which is presumably, concentrated in the lower-levels. The heavy rains that were observed inland in this storm and the signature of non-orographic major rain cells in the rain maps indicate that the moisture sources were not limited to the lower-levels. The presence of moisture at the mid-levels can be deduced from back-trajectory arriving at Tzafit at the time where the flood occurred (Fig. 9 and the figure shown above), showing band of mid-level moist air that originated east of the Levant, revolved around the cyclone

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center and entered the region from the west.

9) Finally, in the conclusions, a hypothesis appears that is not given in the previous manuscript (lines 313-314: "Quasi-stationary upper level systems allow moisture accumulation causing the increase in precipitation amounts from one day to the next."). Without discussion, this hypothesis also remains without any evidence.

Response: This conclusion is based, in addition to the present case, on a case of an Active RST (Ziv et al. 2005), which was stationary in the lower-levels for 3 days, during which its activity increased consistently. Since 2 cases are far from being a basis for such a conclusion, we will omit it. Ref: Ziv B., U. Dayan and D. Sharon, 2005: A mid-winter, tropical extreme flood-producing storm in southern Israel: Synoptic scale analysis, Meteor. Atmos. Phys., 88(1-2): 53–63.

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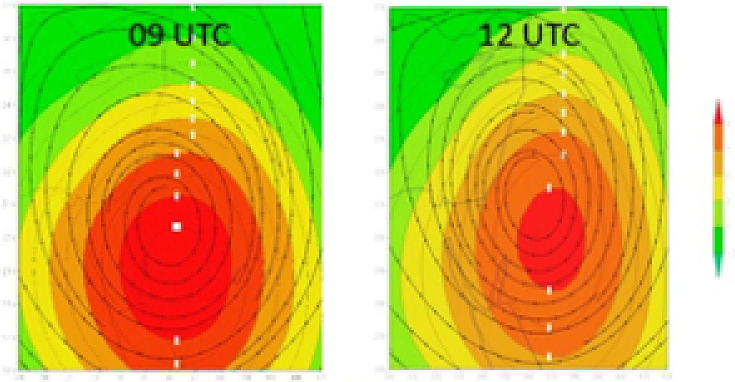
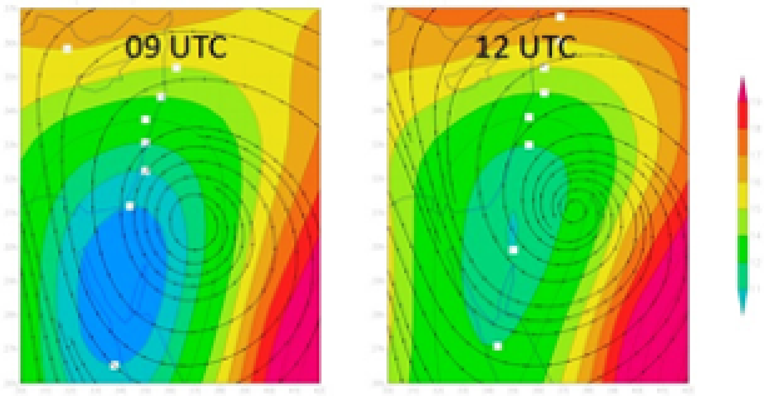


500 hPa Vorticity Advection



850 hPa Temperature Advection

Fig. 1. Upper-level vorticity advection and lower-level temperature advection, based on the NCEP reanalysis data, with 2.5×2.5 deg resolution.

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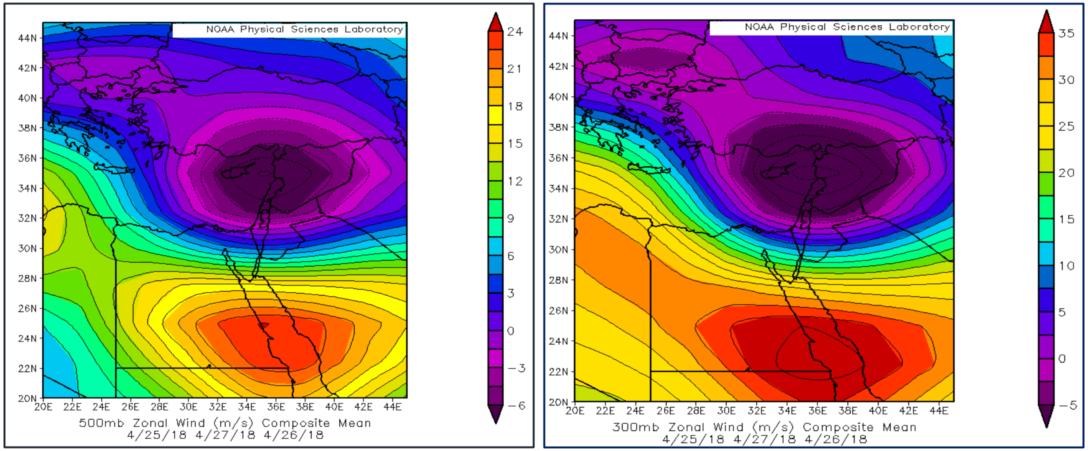

Fig. 2. The zonal component of the wind averaged over 25-27 April 2018 in 500 (left) and 300 (right) hPa

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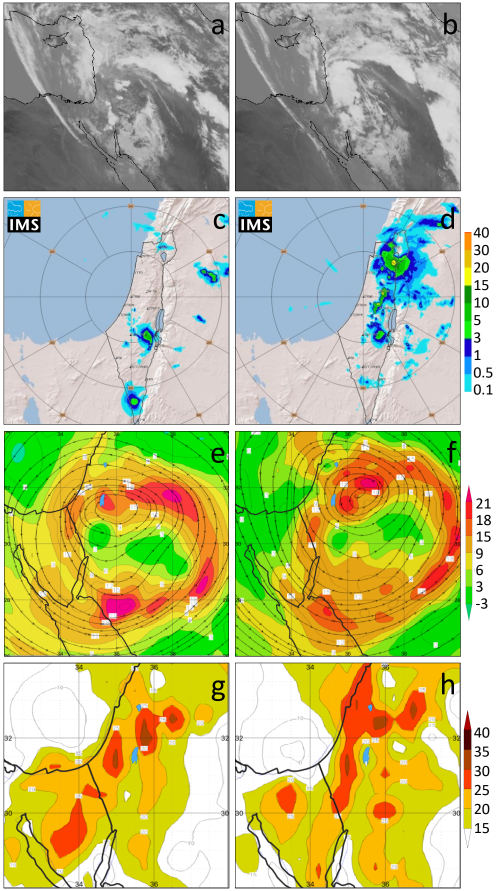

Fig. 3. Set of maps for April 26 2018, 09 and 12 UTC: Satellite image of MSG ch9 (10.8 ïĄ■m) (a,b); Radar imagery of one hour integrated rain depth (mm), (c,d); Relative vorticity and wind (e,f) and MKI (g,h).

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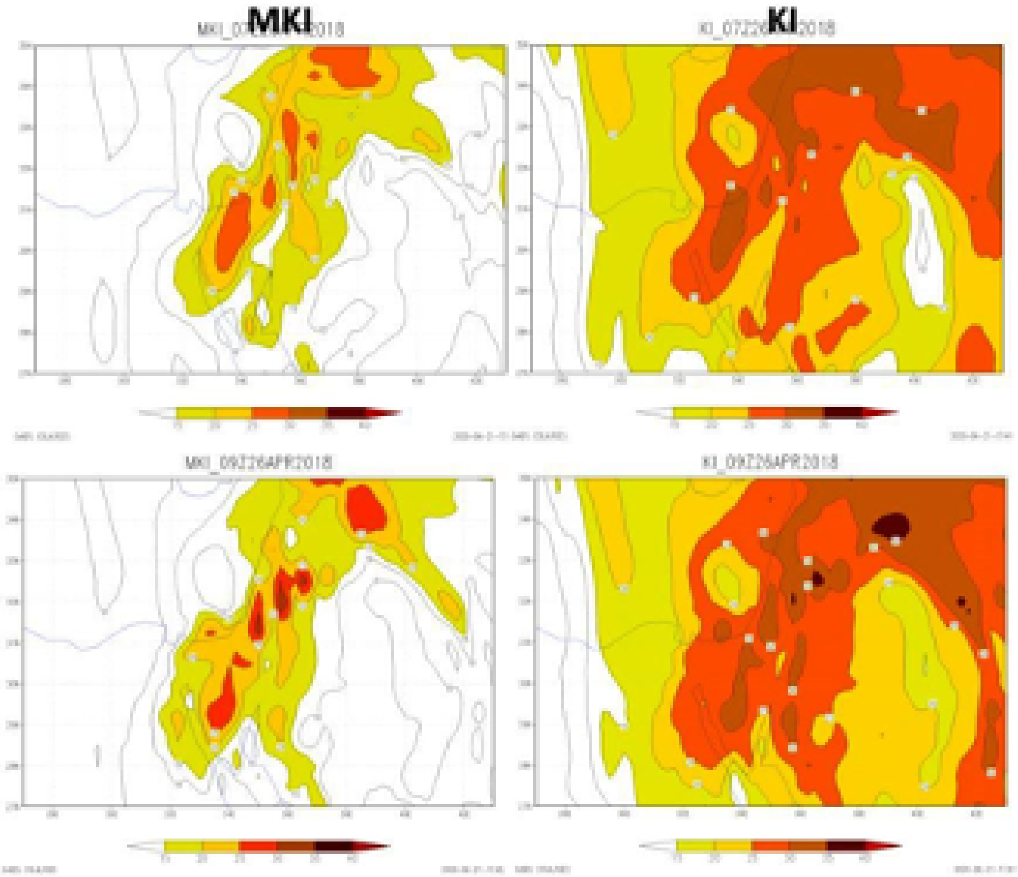

Fig. 4. MKI vs. KI

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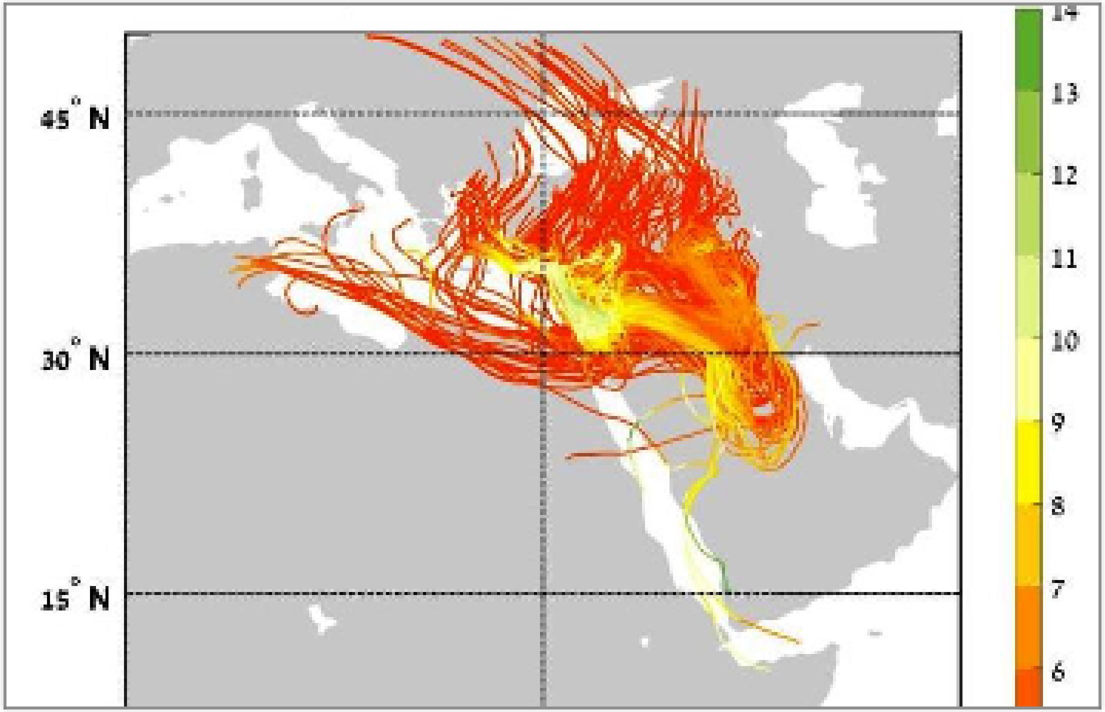

Fig. 5. Air back-trajectories arriving at Tzafit (31.1N, 35.2E) in April 26, 2018 09 UTC. The colors denote specific humidity along the trajectory (g/Kg).

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