Mediterranean Storms
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IMPACTS AND INTERACTIONS OF DRY AND MOIST POTENTIAL-VORTICITY ANOMALIES DURING THE LIFE CYCLE OF AN INTENSE MEDITERRANEAN CYCLONE

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ABSTRACT

An analysis of the strong cyclogenesis event that affected the western Mediterranean on 10-12 November 2001 is presented in terms of three evolving Potential-Vorticity (PV) anomaly sets: mid-upper tropospheric anomalies associated with the undulating tropopause and low-level anomalies associated with the thermal wave (dry PV anomalies), and positive anomalies induced by latent heat release around the cyclone (moist PV anomalies). Contributions of the PV anomalies to the surface cyclone depth during its life cycle are evaluated using a PV-inversion scheme which is formulated following the Charney nonlinear mass-wind balance approximation. It is found a distinct influence of the considered PV anomalies depending on the stage of the cyclone event: during the developing phase the mid-upper trough-ridge system is the main contributor although the amplifying low-level thermal wave becomes increasingly important; during the period of the cyclone maximum intensity dry and moist PV anomalies are equally important; and in the mature and dissipating stage, only the moist anomaly contribution remains significant whereas the mid-upper tropospheric anomaly is even acting to fill the cyclone. Therefore, this mediterranean event follows a typical sequence of many extratropical cyclones developed along baroclinically unstable zones which are ultimately regulated by moist processes. On the other hand, the evolution of the PV anomalies impacts on the cyclone can be interpreted in terms of mutual interactions among the anomalies and the mean flow. It will be shown how the role of these interactions (e.g. PV anomaly advection by another anomaly-induced flow) as well as the individual effects (e.g. due to the PV anomalies self-advection) on the surface pressure tendency and vertical motion, can be quantified by switching on and off the PV anomalies in a prognostic system of balance equations consistent with the applied PV-inversion scheme.

1 LIFE CYCLE OF THE CYCLONE

The western Mediterranean area is commonly affected by cyclogenesis events. Many of these mediterranean disturbances, including the orographically induced shallow lee cyclones, are directly responsible for much of the annual rainfall registered in the coastal provinces, especially during the autumn season, when low-level water vapor availability is very high. Very deep cyclones can also be developed which induce not only heavy rainfall, but also strong winds, high amplitude sea waves and coastal storm surges. One of such extreme cyclogenesis events occurred on 10-12 November 2001 (Fig. 1). Owing to its consequences (e.g. flash floods in Argelia leaving more than 700 deaths and over 20.000 people homeless; floods in the Balearic Islands after 400 mm/24 h at some locations, and also 4 casualties, 200.000 trees uprooted and severe damages on beaches and coastal infrastructures due to 150 km/h winds and 12 m sea waves) this event can be categorized as one of the worst storms affecting the western Mediterranean countries during the last decades.

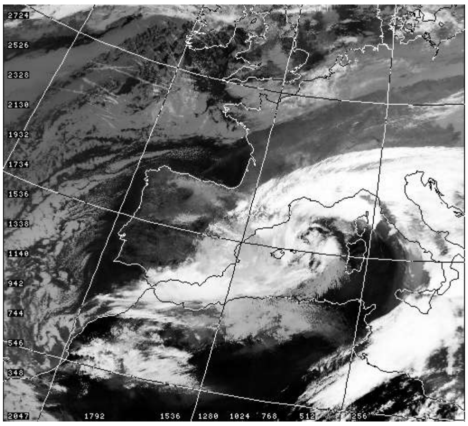

Figure 1. Infrared (channel 4) NOAA image of the storm on 11 November 2001 at 13:29 UTC.

Using NCEP meteorological analysis at 12 h intervals, the life cycle of the storm at synoptic scale has been examined. On 9 November, the presence of an anticyclone over the northern Atlantic and a low over northern Europe induced very cold air advection over much of western Europe. This situation was reflected in the amplification and extension towards the Iberian peninsula of the upper-level trough. Pressure fell very rapidly ahead of the upper-level trough over north Africa, such that on 10 November 00 UTC a well developed surface cyclone is present over the area (Fig. 2, up). The heavy rainfall in northern Algeria, well exposed to the northerly flow, was produced about this time. Later, the cyclone intensified and moved northwards over the Mediterranean waters, reaching its maximum depth about 11 November 00 UTC (Fig. 2, center). The thermal structure at low levels clearly shows the baroclinic nature of the cyclone. Meanwhile, the upper level trough adopted cut-off characteristics and exhibited two clear minima over the african coast (Fig. 2, center). Much of the storm induced damage in the Balearic Islands occurred during this stage of the episode. During the afternoon of 11 November, the cyclone started its dissipation stage (see for example the synoptic situation on 12 November 00 UTC; Fig. 2, down).

On the other hand, we argue that in addition to baroclinic instability, diabatic effects associated with the massive condensation induced by the storm over the Mediterranean (see Fig. 1), could also have played an important role on the intensification process of the system.

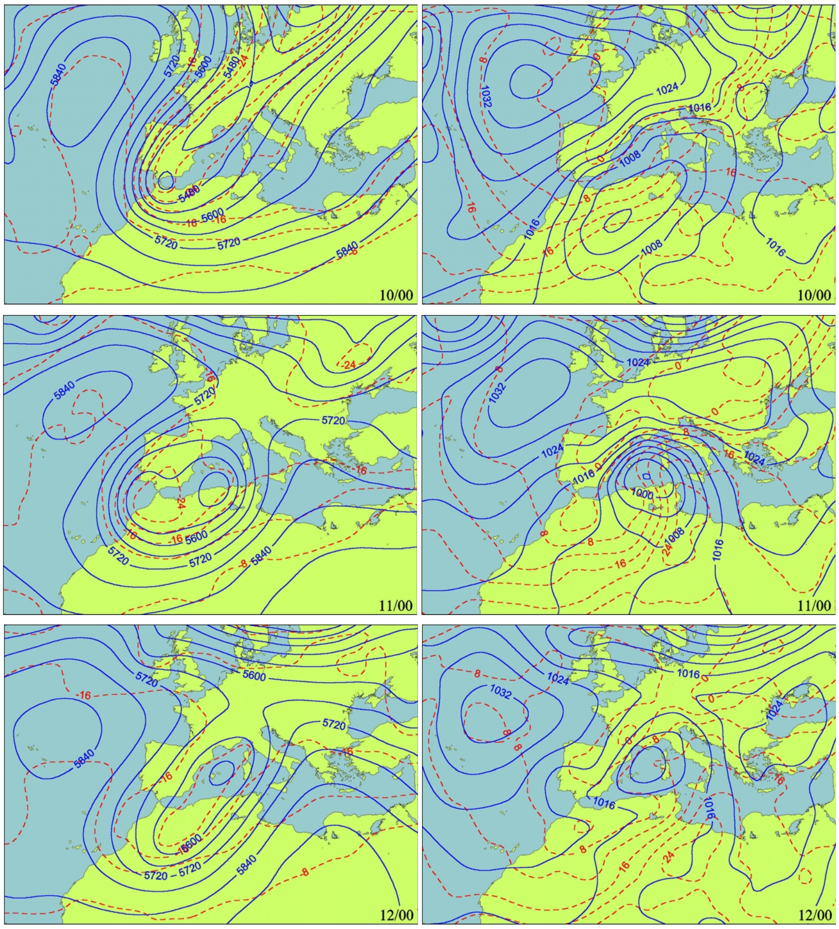

Figure 2. NCEP analysis on 10 November 2001 at 00 UTC (up), 11 November 2001 at 00 UTC (center) and 12 November 2001 at 00 UTC (down). Left panel shows geopotential height (blue, in mgp) and temperature (red, in ^{o}C) at 500 hPa. Right panel shows sea level pressure (blue, in hPa) and temperature at 925 hPa (red, in ^{o}C).

2 PV-BASED DIAGNOSIS

A diagnosis of the cyclone episode has been applied using the piecewise PV inversion scheme described in *Davis and Emanuel* (1991). The scheme uses the Charney non linear mass-wind balance equation and an approximate form of the Ertel's potencial vorticity. Both relations are solved iteratively to find a balanced flow for an instantaneous state (in this case every 12 h during the period 10 November 00 UTC – 12 November 12 UTC), a reference state (here a 7-day time average for the period 7 November 00 UTC – 14 November 00 UTC), and finally, the contribution of a given piece of the PV perturbation field (PV anomaly) to the balance flow is calculated. In this study, three relevant PV anomalies implicitly highlighted in last section were considered: **ULev** (PV perturbation above 700 hPa , composed of positive and negative values and describing the undulating tropopause); **LLev** (surfer thermal anomaly and PV perturbation below 700 hPa, both positive and negative values, in this case mainly reflecting the baroclinic low-level environment); and **DIAB** (positive PV perturbation below 500 hPa in areas with relative humidity exceeding 70%; aimed to account for the diabaticaly generated PV). A depiction of these three anomalies is shown for 11 November 00 UTC (mature stage of the cyclone) in Figure 3. It is notable the two-centres structure of the ULev field about the african coast. These two positive PV anomalies rotated about each other during the episode. Note also the baroclinic structure of the LLev anomay: cold air is present over most of Europe and western lands of Africa, contrasting with the warm thermal anomaly over the central Mediterranean. On the other hand, high values of the DIAB anomaly are observed over the western Mediterranean sea, where condensation is very intense (Fig. 1).

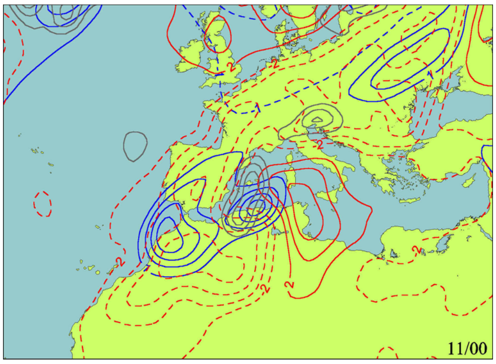

Figure 3. ULev, LLev and DIAB Potential Vorticity anomalies on 11 November 2001 at 00 UTC. ULev (blue) is shown by means of the PV anomaly at 300 hPa; LLev (red) is shown by means of the temperature anomaly at 925 hPa; and DIAB (grey) is shown at 700 hPa. Continuous line mean positive values, dashed line negative values.

The contributions of the PV anomalies to the cyclone depth are summarized in Figure 4, that shows the inverted geopotential height perturbation at surface from each anomaly during the whole life cycle of the system. The typical sequence of many extratropical cyclones is observed: ULev is the largest contributor during the growing phase of the cyclone; LLev becomes increasingly important, being the main component during the mature phase; and the moist anomaly DIAB increases its influence during the episode, being the only relevant contributor during the dissipation stage.

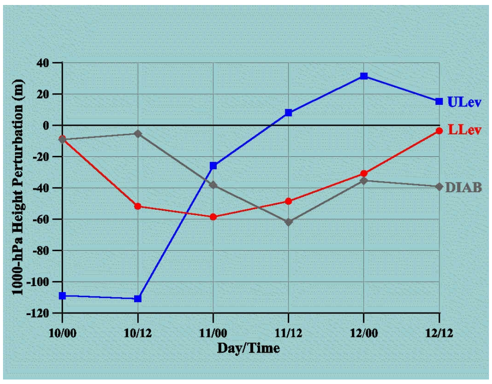

Figure 4. Contribution to the surface cyclone central height perturbation by ULev, LLev and DIAB Potential Vorticity anomalies during the life cycle of the storm.

3 IMPACTS AND INTERACTIONS OF THE PV ANOMALIES

The three considered PV anomalies (Fig. 3) behave as evolving structures with time. Much of its evolution can be interpreted in terms of the interaction among the anomalies and the mean flow. Ideally, if Potential Vorticity were an exact conserved quantity, the movement and deformation of the anomalies would be solely due its advection by the mean flow and by the anomalies induced flow (including self-advection). An example of these mutual interactions is shown in Figure 5, where upper-level PV advection by the mean flow and low-level thermal advection by ULev induced flow are shown on the left and right panels for 11 November 00 UTC, respectively.

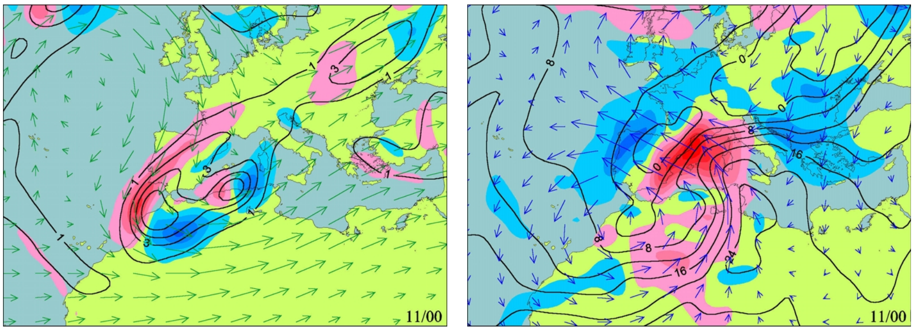

Figure 5. For 11 November 2001 at 00 UTC: (left) Mean flow in vectors, Potential Vorticity in continuous line, and mean flow induced PV advection (blue positive advection; red negative advection) on 300 hPa. (right) ULev induced flow in vectors, temperature field in continuous line, and ULev induced thermal advection (blue cold advection; red warm advection) on 925 hPa.

A method has been devised to quantify the strength of these interactions. The method is based on the PV-based system of prognostic equations described in *Davis and Emanuel* (1991). This system is composed of the equations: *(i)* tendency of the aforementioned Charney nonlinear mass-wind balance relation; *(ii)* tendency of the previous approximate form of the Ertel's PV; *(iii)* a frictionless and adiabatic tendency equation for the Ertel's PV; *(iv)* an omega equation consistent with the used scale analysis; and *(v)* the continuity equation. With proper boundary conditions (which are topographic in the lower boundary), these five equations can be solved iteratively to produce estimates of geopotential tendency, streamfunction tendency, PV tendency, vertical velocity and velocity potential function, from a given balanced flow such as those found in last section. In particular, we solve the system every 12 h during the period 10 November 00 UTC – 12 November 12 UTC, using 8 balanced flow configurations at each time: a total flow (which incorporates the contributions of MEAN, ULev, LLev and DIAB) and the configurations resulting from subtracting from the total flow the contributions induced by all possible combinations of ULev, LLev and DIAB. Then, the factor separation technique described in *Stein and Alpert* (1993) can be applied to isolate the contributions by the individual factors MEAN, ULev, LLev and DIAB, and by the synergestic factors ULev-LLev, ULev-DIAB, LLev-DIAB and ULev-LLev-DIAB. The former reflect the action of the mean flow, selfadvection of the PV anomalies and its interaction with the mean flow; the latter reflect, for example, the advection of a PV anomaly due to the flow induced by other anomalies.

The factor separation results for the present case study (considering, for example, the geopotential height tendency at 925 hPa), can be summarized as follows: MEAN induces an eastward movement of the cyclone; ULev is contributing with geopotential height fall near the center of the cyclone during its whole life cycle; LLev is contributing importantly to the cyclogenesis process during the developing stage of the cyclone, and later, to its NE movement; the interaction ULev-LLev is a leading factor, especially during the mature stage of the cyclone; all other factors are less strong and become most relevant during the mature stage of the cyclone, except ULev-LLev-DIAB which shows its greatest magnitude during the developing stage. Figure 6 shows an example of these results for the mature stage.

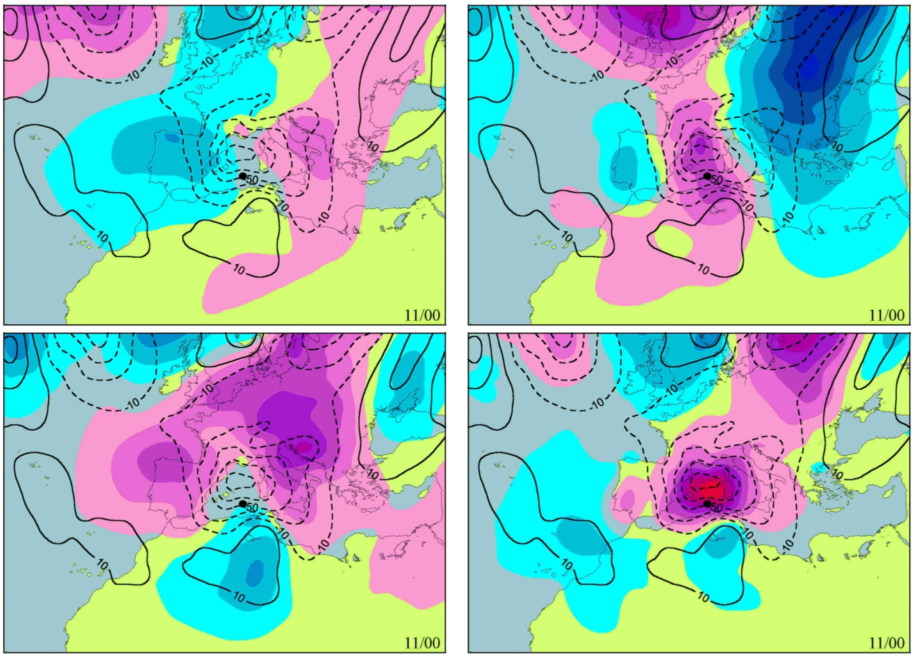

Figure 6. Total geopotential height tendency on 925 hPa (dashed and continuous line contours por negative and positive values, respectively, in mgp/12 h) on 11 November 2001 at 00 UTC; and contributions to the total geopotential height tendency by the MEAN flow (up left), ULev (up right), LLev (down left), and interaction ULev-LLev (down right). For the latter, redish color means negative tendencies and bluish colors positive tendencies.

REFERENCES

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