The most common adverse weather phenomena impacting the Iberian Peninsula

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Introduction

In recent years the media have been focusing attention on bombogenesis events, cut-off lows, heavy coastal storms with high winds and high waves, and even some tornados. These weather phenomena take place occasionally, that is to say, infrequently. Nevertheless, they can in some cases cause high human casualties and have a high economic cost . While their probability is low, when they do occur they leave long-lasting after-effects, and that is why they are often referred to as high-impact weather events.

The atmosphere is a layer surrounding our planet, with most of the weather phenomena affecting us being located in a region extending up to 10-12 km in altitude. This region is known as the troposphere. Masses of air move through this layer in the direction of the rotation of the Earth, giving rise to a sort of engine – anticyclones – that for the most part occupy semipermanent positions at latitudes of around 30º - 33º in both hemispheres.

It comes as no surprise that the vast expanses occupied by the atmosphere should contain air masses that have different characteristics and thus that they have different temperature and humidity levels. When these masses come into contact with each other, certain weather phenomena like storms occur. When the contrasts between air masses are more pronounced, the associated weather events form and evolve more quickly. Where other factors triggering these processes are also involved, the probability that these phenomena will turn violent increases. That is how many of these adverse weather events come about, through the convergence of several factors in a synchronised manner at the same time. That is, first there needs to be a set of predisposing conditions, then there needs to be a triggering mechanism.

The remnants of extratropical cyclones have sometimes reached the Canary Islands. This is very unusual but should not be overlooked.

The storms Gloria and Filomena are two examples of events like those described. They caused heavy economic losses, and much has been written about them.

Modelling and improved systems for making observations have made it possible to make progress in detecting and predicting these events. One very interesting case, to some extent forgotten, took place on 11 March 2011. There was a break in the troposphere with intense penetration by stratospheric air to a height of 600 hPa. Modelling has provided much more detailed information about that episode. The snowfalls in the mountain ranges near Segovia and Madrid were spectacular.

They can sometimes affect large areas, i.e., they develop into large-scale events meteorologists broadly call closed low pressure systems or hurricanes. In other cases they are smaller, referred to as meso or microscale events. Mountain waves and tornados are examples of these.

Since they are uncommon, they are called extreme phenomena, defined as those with a very low probability (sometimes a threshold is set at a frequency rate of 5%). These events have been seen to be becoming more and more extreme and are being associated with global warming, something that appears to be quite reasonable, in that raising the temperature by 1ºC or a bit more in an enclosed space, e.g., a house, requires considerably higher energy inputs. Succinctly put, warming has made the atmosphere more capable of producing more severe weather phenomena. One example is the torrential downpours associated with closed low pressure systems, which seem to be becoming more frequent.

Most but not all high-impact processes are associated with cyclones (a generic term encompassing hurricanes, typhoons, low pressure areas, polar lows, medicanes, and the like). These are low pressure systems where the winds blow counter-clockwise in the Northern Hemisphere (clockwise in the Southern Hemisphere).

This article concerns itself with the systems that are more frequently encountered in the Iberian Peninsula.

Synoptic scale disturbances: genesis of polar cyclones

The general motion of air masses in the atmosphere on a planetary scale can be seen to follow a wave pattern of movement. This was first studied in some depth by the Swedish-American Rossby in 1939, and it has taken his name. There are basically two reasons for their wave nature: the disturbances undergone by air masses in their movement around the globe (e.g., those caused by large mountain ranges) and the action of the Coriolis force produced by the rotation of the Earth. Their wavelength is several hundred kilometres long, and they move around the planet from west to east.

A look at a weather map suffices to show that thanks to their wave nature they have troughs (in meteorology this is associated with the action of troughs around a low-pressure centre) and ridges (in this case caused by the presence of anticyclones). Therefore, the larger or smaller size of Rossby waves depends on the presence of rotating structures of this type, with low pressure areas tending to occur at around 60º latitude and high-pressure areas at around 30º - 33º latitude.

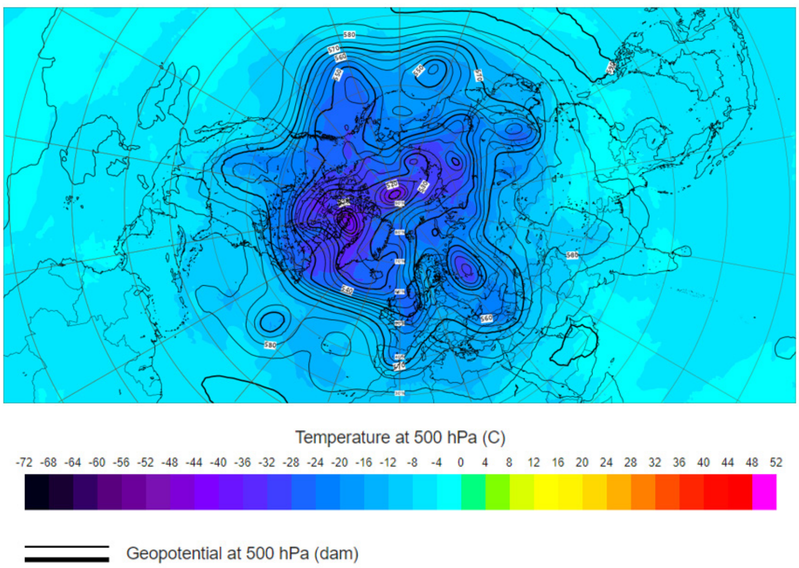


Figure 1. ECMWF map showing the 500 hPa geopotential isolines in decametres and temperature in ºC.

Figure 1 shows a weather map depicting Rossby waves and the undulations formed by the presence of cyclonic and anticyclonic flows at the level of 500 hPa (at an altitude of around 5,500 m). By way of a first approximation, we can say that the wind blows along the isolines moving from west to east because of the rotation of the Earth. In meteorological terms, we say that this form of motion is caused by geostrophic approximation, in which the wind blows parallel to the isobars. It generally realistically maps what is happening at mid to high altitudes but becomes less realistic as we come down to ground level.

Looking at Figure 1 in detail, we can see that the temperature distribution does not always adhere closely to the course of the isolines. Where it does, that area is said to be barotropic, and where it does not, baroclinic. Where the latter occurs, the wind blows across the isotherms, producing what is known as advection. The air from higher density, hence colder, masses may sometimes be carried to lower density, hence warmer, regions. This is referred to as cold air advection. However, the opposite can also happen, in which case it is referred to as warm air advection. Colder, denser air tends to drop to levels closer to the ground and warmer air tends to rise to higher altitudes. This produces conditions conducive to the formation of cyclonic flows rotating counter-clockwise in the Northern Hemisphere.

After the First World War, a group of Norwegian meteorologists led by Vilhelm Bjerknes developed a conceptual model that explained cyclone formation and development at middle latitudes based on the cyclonic waves generated by warm/cold air advection. This air thus consisting of two masses with differing characteristics ends up producing vorticity, i.e., rotation. These studies gave rise to the polar front theory, which was associated with inputs of cold air from higher latitudes, displacing the warm air at lower latitudes.

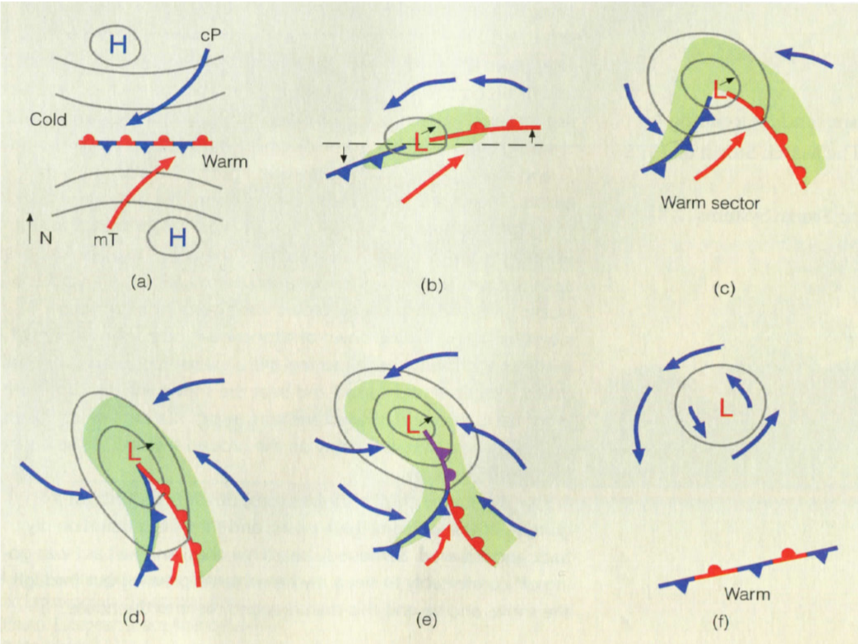


Figure 2(a) and (f). Plots showing the formation of mid-latitude cyclonic flows and the associated polar fronts.
Source: From C.D. Ahrens, Thomson Publications.

Figure 2 illustrates the formation of a warm and cold polar front caused by the presence of cold continental polar air (*cP*) displacing warmer, less dense maritime tropical air (*mT*). The Figure shows how in the initial phase of cyclogenesis there are two anticyclonic centres (*H*), with cold air masses (*cold*) at higher latitudes and warmer (*warm*) air masses further south. The separation between the two air masses is called a polar front, a cold front if the colder air mass tries to displace the warmer air mass and conversely a warm front if the opposite occurs.

The motion of cyclonic circulation causes the warm and the cold air masses to reach a situation in which they mix, giving rise to a third air mass that could be termed tepid, thus producing a new type of front called an occluded front. The formation of this front is an indication that the cyclonic flow cycle is coming to an end.

This conceptual model is relatively simple and somewhat incomplete. Numerical models that attempt to explain the three-dimensional movement of air masses have resulted in revisions to the Norwegian model, giving rise to another, more complex type of model in which air movements are treated as if they were similar to motion on a conveyor belt. These models take into account rising and falling air. An in-depth explanation is outside the scope of this article aimed at the general public.

High-impact lows

Hurricane force winds, heavy waves, and conditions producing high levels of precipitation or hail are in the main caused by several different sets of circumstances. This article focuses on three.

Bombogenesis

Mid-latitude vorticity formation can sometimes reach very fast levels of development and give rise to extremely adverse events. One example of this is a type of cyclogenesis that occurs in conditions of high thermal contrast between the warm and cold air masses that is much more pronounced than “ordinary” conditions.

These cases give rise to cyclonic flows that rotate at very high speeds, and the air is displaced upwards from lower layers very quickly. In these conditions, pressure at ground level decreases appreciably. When this happens at middle latitudes, if the pressure decreases between 9 and 10 hPa in 12 hours or even 18 or 20 hPa in 24 hours, we say that explosive cyclogenesis occurs, with the formation of low-pressure areas that can have very severe repercussions.

To understand how structures of this kind can form, we need to bear in mind that there has to be an interaction between two phenomena occurring concurrently. On the one hand, there has to be cyclonic flow at low levels, a wave when all is said and done, with a sharp contrast between cold dry air and warm moist air. Vorticity begins and the warm air starts to rise, causing different situations that serve as triggers.

1. Very strong winds at high levels (sometimes in the presence of a trough) can draw the air from lower layers upwards. This causes the low pressures at ground level to deepen and quickly increases vorticity. That is why this situation is termed explosive.

2. It can also happen that there is a warmer than usual air mass at high levels (in fact this is a warm anomaly that causes the geopotential to be situated at a lower level than “usual”). In these conditions it may interact with the warm, moist air layers as they rise, producing a form of circulation that in meteorological terms is called a deepening of the low, which develops rapidly and can become explosive.

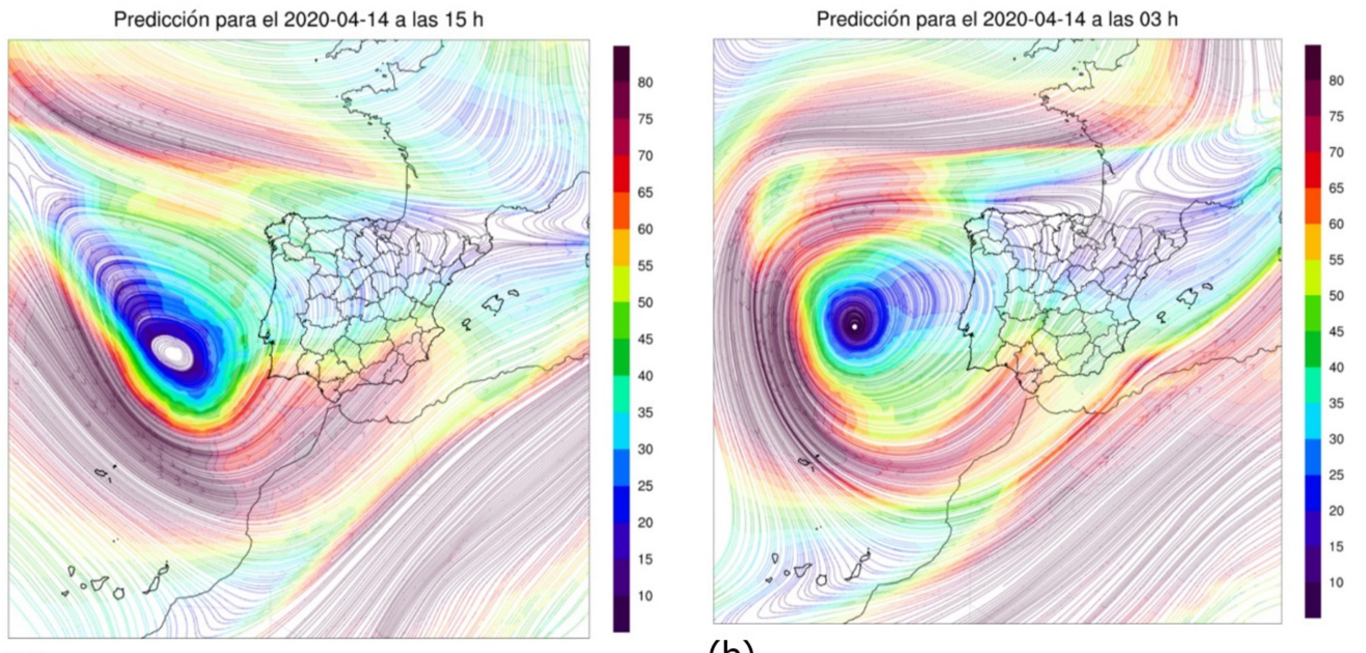
3. A variation on the preceding case is a break in the tropopause that allows warmer, very dry air to enter from the stratosphere, the layer of the atmosphere located above the troposphere. That air then “replaces” the troposphere. In these cases, interaction with strong convection from the lower layers can result in explosive cyclogenesis.

We should not overlook the fact that there must be a contrast between a cold (and therefore dry) air mass and other warmer, moister than usual air masses at ground level. One of these situations may be caused by the remnants of a tropical cyclone whose course has shifted to higher latitudes, where it can be located next to a cold air trough. This gives rise to a strong thermal contrast, which is one of the elements necessary to produce cyclogenesis that can turn explosive, with very strong winds.

Higher level cut-of lows

A closed low pressure system, or cut-off low, occurs when the jet stream shifts from its usual latitude more or less at around 60º to other, lower latitudes, giving rise to an offshoot that is ultimately cut off from the general circulation. This shift moves cold, dry air at high levels towards other regions where the air mass is warm and moist at lower levels. This strong thermal contrast causes the air to rise, creating a vortex and cyclonic flow. The result is a system that can result in heavy precipitation. It is not explosive but rather a consequence of a twist in the flow, as shown in Figures 3(a) and 3(b). That Figure depicts the wind at the level of 300 hPa at a height of about 9,000 m. Formation of a closed low pressure system west of Portugal caused by displacement of the polar jet stream is observable. The air current lines have been plotted in this case and show that once the closed low pressure system has been isolated, the "eye" of the jet stream appears, circulating around the cyclone.

The precipitation associated with closed low pressure systems depends on a series of factors: first of all, inputs from low levels. The warmer and moister the air that is displaced upwards and the greater the vertical thermal gradient, the heavier the precipitation. If, moreover, the disturbance is long-lasting, the likelihood that greater impacts will be produced becomes higher. This happens with some frequency in the Mediterranean region, but it is not exclusive to that region. There are important indicators suggesting that we are going through a period in which situations of this type are increasing in different parts of the world.



(a) (b)

Figures 3 (a) and 3 (b). Plot of wind at the level of 300 hPa according to models used by the Atmospheric Physics Group at the University of León. Regions with very high speeds, a sign that the jet stream is present, are the regions with the highest intensities. Figure 3(a) shows a closed low pressure system in formation, Figure 3(b) shows it already formed. An "eye" can be seen in both cases, an indication that high vorticities are present.

Mesocyclones

What can sometimes happen at middle latitudes is that an area of mesoscale rotation appears, produced by highly organised convection caused by rising warm, moist air. This is what happens in the case of storms.

We can, rather infrequently but by no means exceptionally, have small cyclones called mesocyclones with highly organised convection centred around a single central axis inside the storm. These structures are formed by a vortex of air that is usually not more than 10 km in diameter. When this occurs, we speak of supercells that have a structure that can be mapped using weather radar. We have measured (and experienced) ascending currents with speeds higher than 20 m/s on scientific flights through storms of this kind.

Hydrometeor measurements in these cases taken using instruments suitable for these observations have yielded interesting data. The surveys we have conducted in the framework of the EURICE project using the INTA (Spanish abbreviation for National Aerospace Technology Institute) cloud physics platform showed that as a storm grows more intense, microphysically speaking it becomes more organised. That is, regions where different processes are taking place can be distinguished inside the storms. When the storm starts to dissipate, that organisation begins to be dispelled, and hydrometeors become much more mixed.

Figure 4 depicts the cloud particles observed and measured on one of those flights inside a hailstorm. Cloud physics instruments of this kind are capable of taking and even classifying images particle by particle. The scale of the vertical bar is about 1.12 mm. Larger, irregularly shaped hydrometeors are termed “graupel” and in this case are the nuclei of hailstones. The rounder images are supercooled water droplets (less than 0ºC). The smallest, most irregularly shaped ones are ice crystals. The particles that have been classified appear in black, particles that have not been classified appear in red (the latter are usually termed “artefacts”).

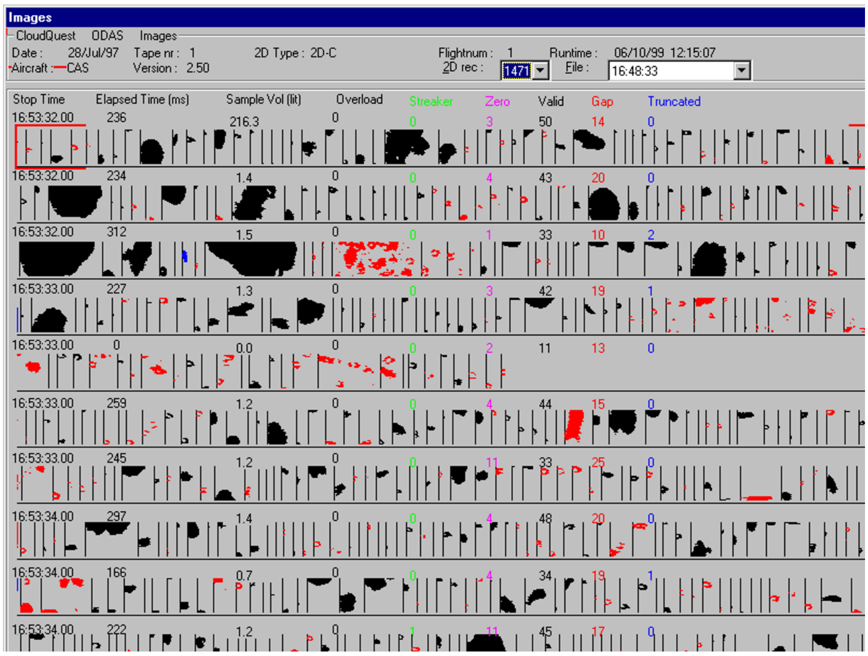


Figure 4. Images of hydrometeors taken on a flight into a hailstorm (explained in the text). Most can be seen to be hailstone nuclei.

On some flights the author has been able to make into summer hailstorms, the fastest ascending currents inside the storm tend not to be less than 10 m/s, allowing the hailstones to stay inside the storm until they grow to a size where they weigh too much, when they precipitate out. That is why it is not uncommon for hailstones as large as 10 cm to fall. Figure 5 shows two images of the aftermath of storms of this kind, like one that took place in Alcañiz on 16 August 2003.

Figure 5. The aftermath of hail that fell in Alcañiz on 16 August 2003. At left, holes left in a PVC table, and at right, one of the hailstones that fell, an aggregation of hailstones cemented together by supercooled liquid water (SLW) as if it were glue.

Storms that have one of these mesocyclones inside produce both intense precipitation and high winds. This imparts added energy to the hail, so the force they strike with is much greater and the damage caused is also greater. The left-hand image in Figure 5 is an example of this.

Supercells may very occasionally be accompanied by tornados. They are not entirely uncommon in the Iberian Peninsula. They tend to be highly localised, making it difficult to record them. There are usually more than 200 in Europe each year, and it is likely that the Iberian Peninsula has around 10 a year. They are nearly always low in intensity. We also need to take into account comparable phenomena that take place at sea, where they are called waterspouts. They tend to be more highly concentrated around the Balearic Islands, where they are feared because of the damage they do to boats.

Some cases of highly adverse cyclones

The remnants of extratropical cyclones have sometimes reached the Canary Islands. This is very unusual but should not be overlooked.

The storms Gloria and Filomena are two examples of events like those described. They caused heavy economic losses, and much has been written about them. They are extreme cases, but as mentioned at the beginning of this article, because of their consequences they are not readily forgotten.

Modelling and improved systems for making observations have made it possible to make progress in detecting and predicting these events. One very interesting case, to some extent forgotten, took place on 11 March 2011.

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Figure 6 is a representation of the vertical profiles for the PVU value (potential vorticity related to the dynamic troposphere height) in the vicinity of the Navacerrada (Segovia) mountain pass. The values in red are equivalent potential temperature[1] (EPT) and the values in green are humidity relative to 100%. These situations are opportunities to further our knowledge of disturbances caused by sudden stratospheric collapses.

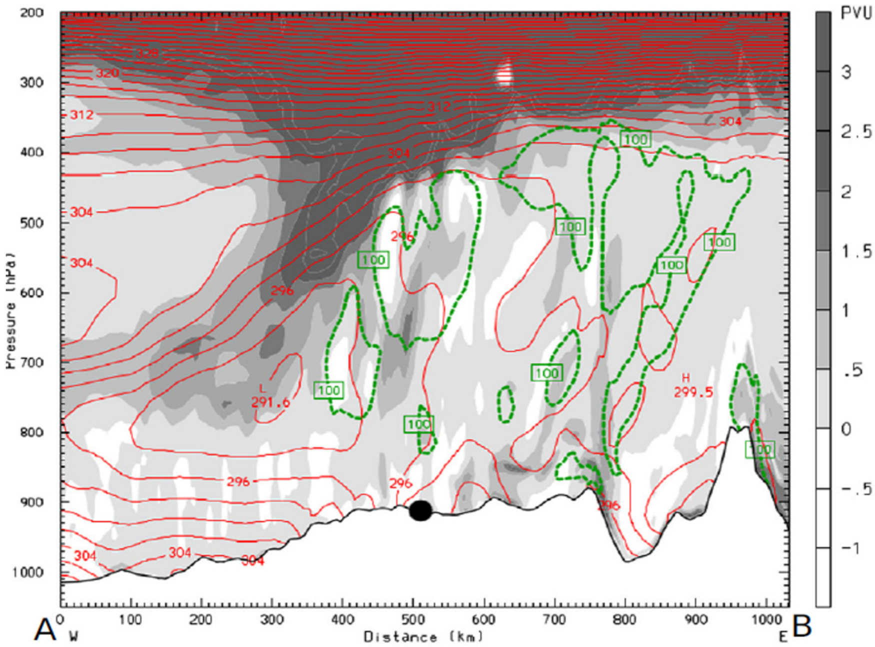

Figure 6. Figure 6. Vertical profiles for PVU and EPT along the W–E axis in the vicinity of the Navacerrada mountain pass (explained further in the text). A PVU value of 1.5 or higher is indicative of inputs of air from the stratosphere. The black dot shows the location of the Navacerrada mountain pass.

As long as the planet continues to warm up, the atmosphere will have more energy available to use in its processes. It is nearly impossible to attribute a given "anomalous" event to global warming, but it seems reasonable to expect extreme whether phenomena to become more common. This is not the same as saying that they are new. What the data do show is that they are becoming more frequent.

[1] Equivalent potential temperature is the temperature that a volume of air would have if all the moisture it contains was condensed and it was compressed adiabatically (i.e., without exchanging heat with its surroundings) to a reference level of 1,000 hPa. It is helpful in determining the source of the air, because this value is conserved rather well through all the changes experienced by air masses.

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