



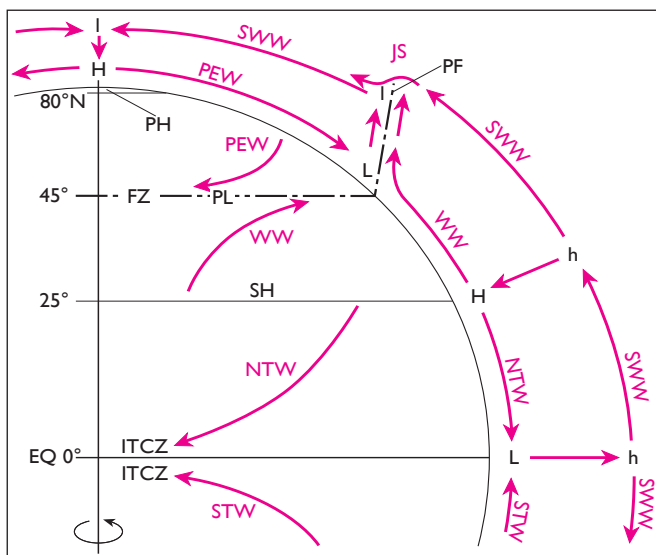
The Westerlies

The system of the westerlies¹ is the main cause of the daily weather pattern of the temperate zone on the northern as well as in the southern hemisphere – and therefore, also for Central Europe. The following two aspects can be recorded in advance:

1. The subtropopausal west winds find too little space above the subtropical anticyclones, hence they are partially pushed downwards. Parts of them descend in the horse latitudes, parts flow further to the poles. The rotation of earth diverts these winds to the right (northern hemisphere) or left (southern hemisphere), hence become west winds in both hemispheres. The steep step in the tropopause along the polar front causes very high wind velocities ($\approx 200\text{--}500\text{ km/h}$; maximum speed measured = 657 km/h over the Outer Hebrides, 11th December 1967), the so-called jet stream.
2. On its way, the jet stream causes dynamic² anticyclones and cyclones through its velocity. These pressure areas drift eastwards with the jet stream and, themselves, cause the changing course of the weather in the temperate zone.

Sources:

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Key

- PH = polar high; polar surface high pressure with an upper low-pressure zone
- PL = polar low; subpolar low-pressure zone with an upper low-pressure zone; polar depression or polar low
- SH = subtropical high; anticyclone with an upper high-pressure zone; horse-latitude high
- ITCZ = Intertropical Convergence Zone = equatorial low-pressure area with upper high-pressure zone
- PF = polar front
- FZ = frontal zone
- SWW = subtropopausal west winds from ITCZ to PH
- JS = jet stream
- PEW = polar easterlies
- WW = westerlies; west winds of the mid latitudes
- NTW = northeast trade winds
- STW = southeast trade winds

Fig. I: Schematic depiction of the development of jet stream, polar front and west winds (21/3 + 23/9).

1 OXFORD DICTIONARY OF WEATHER 2005 (p. 251): «The predominant zonal flow in the atmosphere, which occurs approximately between latitudes 35° and 65° in each hemisphere (...) The low-latitude boundary lies at ca. 30°, but the poleward boundary is extremely variable and difficult to define.»
 2 from Greek *dynamis* 'force'; 'moving'; antonym: static



Figure 1 gives you an overview of the global wind system with Hadley-, Ferrel- and Polar-cell according to the global circulation model (GCM). The following considerations will describe a simplified circulation model (fig. 1).

1. Jet Stream and Polar Front

Air masses which ascend along the ITCZ (L→h) flow as tropical, subtropopausal west winds into the subtropical high-pressure area (horse latitudes; SH). The subtropical high-pressure area (circumference of the earth along the subtropics = 33,000 km) is smaller than the ITCZ (circumference along the equator = 40,000 km). The subtropopausal west wind (SWW) as a whole cannot stay at the tropopause, neither can it descend as a whole. So it sinks partially in the horse latitudes (= dynamic descent: h→H) and partially flows further polewards as jet stream in high altitudes (h→SWW→JS→SWW→l).

The descended part of the subtropopausal west winds flows from the subtropical high area partially back to the ITCZ as trade winds (H→NTW→L), partially to the poles as west winds (H→WW→L).

The other part of the subtropopausal west winds, which stays near the tropopause, moves further towards the poles. Deviated by the Coriolis effect and unaffected by the friction of the Earth's surface, it flows very fast (up to 500 km/h) and almost as a straight west wind.

The thickness of the atmosphere does not decrease regularly from the equator to the poles, but in two steps (cf. GCM): a smaller one in the horse latitudes and a larger one – which is the only one of concern here – in the frontal zone along the polar front (fig. 1 and 5). The bigger step of a couple of kilometres causes a strong pressure gradient, hence a high wind velocity: That is where the subtropopausal west winds are accelerated enormously and therefore are called jet stream (JS). By its extremely high speed it can suck air from the boundary layer³ («perfume-bottle effect», cf. fig. 3) and, hence, dynamic cyclones⁴ will develop along the polar front, as we will discuss in the next chapter. The above-mentioned «step» is the boundary between the cold, polar air (colder → denser → smaller thickness of the atmosphere = lower level in fig. 5) and the warm, subtropical air (warmer

³ It is the thin layer near the surface of the earth where adhesion causes a different form of air flow from that in the freely moving air layers. The planetary boundary layer – or boundary layer – extends to about 500 m over the sea and 1,500 m over the land.

⁴ 'Cyclone' in the mid-latitudes means low-pressure area or depression, while 'cyclone' in the Indian Ocean is a hurricane.



→ less dense → bigger thickness of the atmosphere = upper level in fig. 5). This boundary is called the polar front.

The frontal zone is the range of the polar front, which is the limit between the cold polar (PEW; polar easterlies) and the warm subtropical air (WW; westerlies). Because there are a lot of (dynamic) low-pressure areas slightly north of the polar front, we find in the frontal zone the subpolar low pressure zone.

2. Dynamic High- and Low-Pressure Areas

Although scientists are still not capable of modelling the development of pressure in the frontal zone – too many aspects and their cross-linkings must be incorporated –, it will be shown here in an understandable way what processes basically run along the polar front and lead finally to pressure differences.

2.1 Turbulent Flow and Entrainment

What happens if a wind flows over an expanse of water [= *Wasserfläche*] (e.g. lake)? Of course, waves will develop on its surface. And how does water flow around a bridge pier [= *Brückenpfeiler*] with a rectangular base? Does it flow straight on? Or will it change its flow direction? Figure 2 illustrates this flow around such a pier: The flowing water piles up a bit in front of the pier, flows around it and turns off to the back of it. Some standing turbulences develop there and the water flows further downstream only after a while.

As it turns out, some of the turbulences stay at the back of the pier for some time, while others start flowing downstream shortly after their formation. This particular flow behaviour is restless or agitated and is called turbulent flow (in contrast to the linear flow of glaciers).

But, why on earth does water flow to the back of piers instead of bypassing them straight away? As is shown in figure 3, a depression (= low pressure) develops by the bypassing of air: The fast-flowing air out of the rubber bellows [= *Blasebalg*] of the nozzle of a perfume bottle takes with it some air molecules (which come from the bottom of the bottle) out of the tube. This effect is called entrainment [= *Mitreissen*]. It causes a small depression ('L' for low pressure) in the upper part of this tube, as

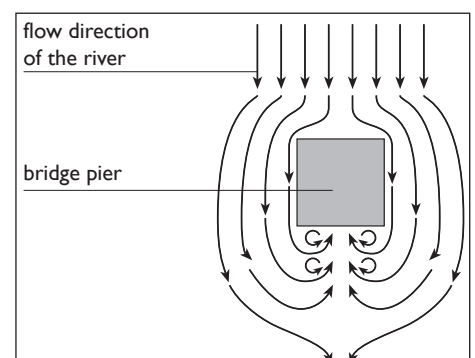


Fig. 2: Dynamic water flow around a (bridge) pier with a rectangular ground plan [= *Grundriss*].

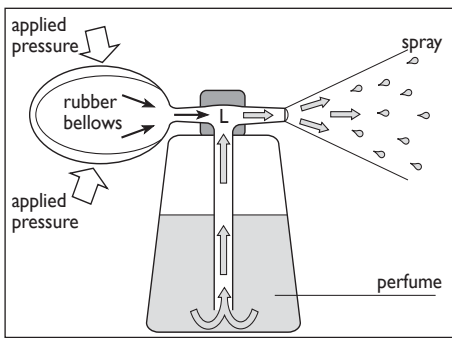


Fig. 3: The way a perfume bottle with bellows works.

there are fewer air particles now and the normal pressure in the bottle pushes up more air molecules from the bottle into the depression; as long as we press the bellows, the depression will persist and perfume will rise through the tube into the air flow from bellows. Let us look again at the water and the pier: The flowing water entrains water from the back of the pier, hence the water level at the back is a little bit lower than at the side, and hence the water flows downwards (as it always does) to the back of the pier. As soon as the water stops flowing, there will be no entrainment any more, hence no lower water level,

hence no turbulences any more. Because this effect works only with a moving medium (water or air), it is called a dynamic effect.

This effect is also demonstrated with the experiment which is described in the box in the upper right corner on page 5.

2.2 Interaction of the Two Effects

Motion alone can therefore be the cause of pressure differences, as is shown by these three experiments. The perfume bottle, the pier in the water and the simple experiment with the two paper sheets demonstrate how depressions are formed by motion. The example with the pier can even be used to illustrate that it is a low-pressure turbulence as its level is lower than at the side, and that the water flows in the direction of the lower level.

How does that relate to the polar front? First some analogies between the discussed examples and the polar front must be explained:

- The polar front defines the limit between polar and subtropical air masses. It reaches from the surface of the earth almost up to the tropopause (fig. 1). The flowing motion along the polar front deforms it in the form of waves – similar to those waves of the surface of a lake, with the only difference that the polar front stays in an almost vertical position in the atmosphere.
- As mentioned above, the polar front defines two different air masses, which amongst other things do not tend to mix very well, i.e. the front persists as such. In simplified terms: The polar front can be imagined as a wall between these two air masses – similar to the «wall» in the form of the pier in a river (fig. 2). And just as turbulences are formed behind a pier, they are also formed along



a wave peak in the polar front (fig. 4 and 5). A wave crest of the polar front can thus be schematically compared with a pier in a river.

- The jet stream flows at a high speed above the polar front (cf. GCM) and entrains air into high altitudes. Because of this there is less air above its original place, hence less air presses onto the surface of the earth, which causes a depression – similar to the effect in the perfume bottle (fig. 3).

To sum up, two effects along the polar front cause low pressure: firstly the «pier effect», which entrains air from the back of a wave peak of the polar front; secondly the «perfume-bottle effect», which explains how the jet stream entrains air by its high wind speed into tropopausal altitudes. Both effects have their cause in the difference of the velocity of the two air masses. Because of that this phenomenon is called dynamic cyclogenesis⁵ compared to the thermal cyclogenesis along the ITCZ.

Experiment

Activity: Take two light sheets of paper into your hands, hold them in front of your mouth, and blow the air through the space between the two sheets. What happens? Try to explain this phenomenon.

Solution: The exhaling breath is faster than the standing air between the two sheets and takes it out by entrainment. Because of that a dynamic depression is developing between the two sheets compared to the pressure outside, which in turn presses the sheets together.

[K1] What is the polar front?

[K2] In both types of depressions – in the thermal as well as in the dynamic version – air rises. Why does the air rise in a thermal, why does it rise in a dynamic depression? Compare and explain the two processes.

⁵ cyclone = depression or low pressure (from Greek *kyklos* 'circle'); *genesis* 'development' (from Greek *genesis* 'formation', 'development')



[K3] Describe the course, the dimension and the form of the polar front in the shortest and simplest way possible.

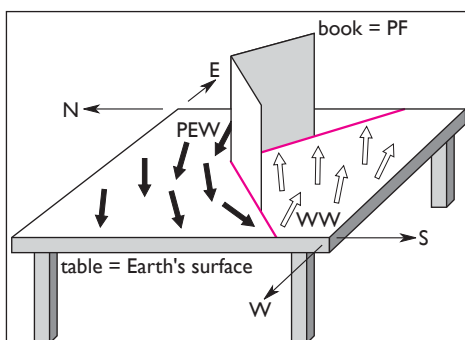
2.3 Interaction in Reality

How do we have to imagine the polar front in reality? To get a more realistic picture we have to look at it in three dimensions (fig. 4 and 5). If only one wave of the polar front is looked at (it has a vertical axis, as we already know, i.e. the wave stands vertically on the surface), it can be seen as an opened book standing upright on a table. At the right side in figure 4 is the subtropical, at the left side the polar air. The book separates both air masses from the surface almost up to the tropopause. The tropopause itself is situated at the upper edge of the book.

Of course, the polar front in figure 4 is shown in too simplified a form, but it leads to the next figure (fig. 5) in which a more sophisticated and realistic – though still quite simplified – picture of a dynamic cyclone on the polar front is drawn. In this second figure the «placed book» can still be identified – now marked as the polar front. The whole thing is topped by the tropopause, the upper limit of the troposphere.

It is also remarkable that the tropopause at the right side in the figure is thicker than at the left. To the right is the equator-facing side in which the subtropical south-westerlies or westerlies (= WW) flow.

Fig. 4: Opened book standing upright on a table as model for the polar front.



The table-edges give the direction (cf. arrows at the corners far-left and front-right).

The opened book standing upright on a table (= the surface of the earth) stands for a wave peak in the polar front. There is subtropical warm air (as southwest to west winds, WW) on the right-hand side and polar cold air (as more or less deviated polar easterlies, PEW, now become northeast, northwest, or even southwest winds) on the left-hand side. The book separates these two air masses up to the tropopause, which is situated at the height of the upper edge of the book.



Again, the subtropical warm air is less dense than the polar cold air, which is why the tropopause lies higher above the subtropical and tropical part of the troposphere than above the polar part (cf. GCM). Also well visible is the above-mentioned steep step along the polar front between these two air masses. Because of the strong pressure gradient across the front at this altitude, the subtropopausal west winds are strongly accelerated and are, therefore, now called jet stream (= JS).

Figure 5 also shows the two already-explained effects which lead to the development of a dynamic low-pressure area: Polar easterlies (PEW) flow over a wave peak of the polar front (cf. «pier effect», fig. 2) and a high-speed jet stream entrains air from lower layers (cf. «perfume-bottle effect», fig. 3).

These two dynamic effects – «pier» and «perfume bottle» – develop a three-dimensional low-pressure formation which extends continuously from the surface to the upper troposphere. The whole formation of a dynamic depression has therefore always an upper low-pressure zone [= *Höhentief*] above its surface low [= *Bodentief*]. This is a clear, distinctive and diagnostic difference to the thermal surface low, above which always lies an upper high-pressure zone. (Read the explanations about thermal pressure zones – polar high and ITCZ in step two and three – in your notes to the GCM.)

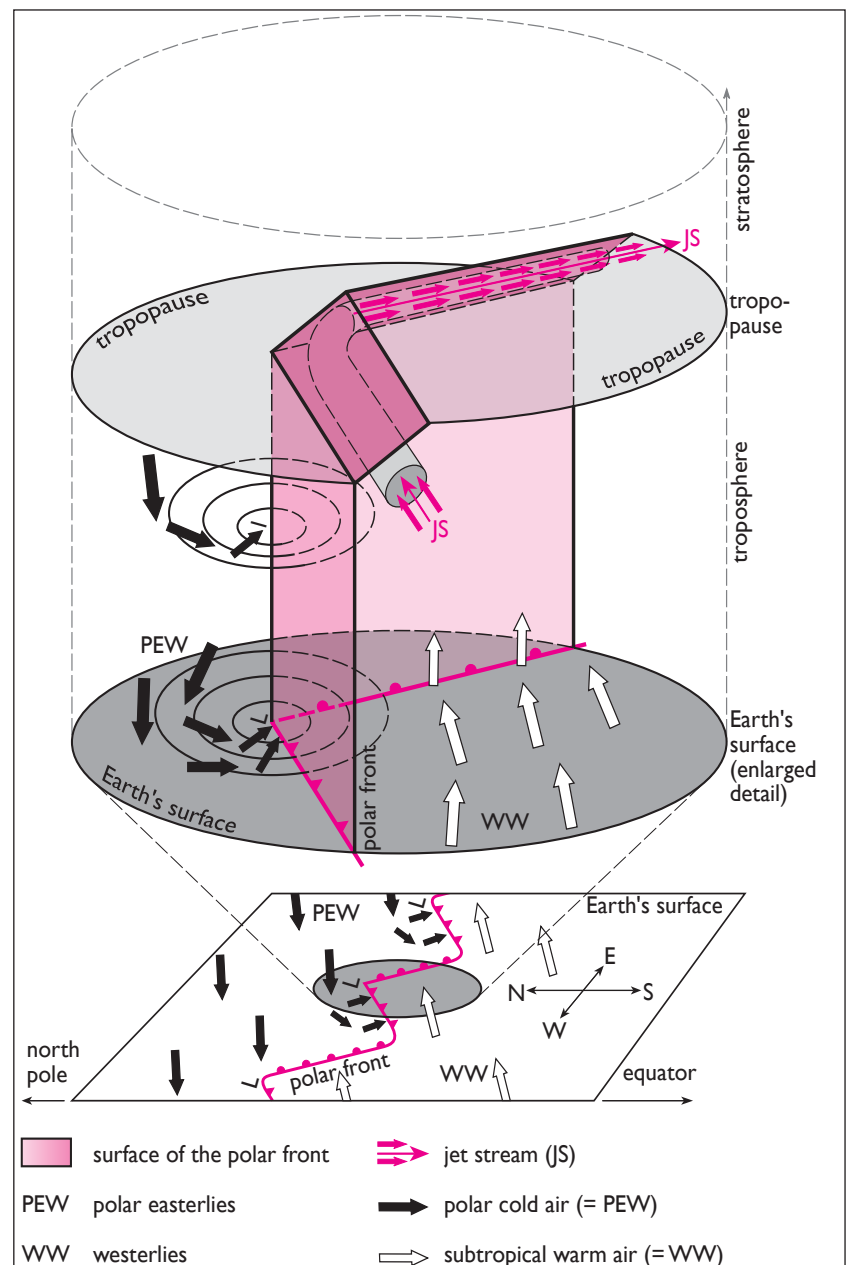


Fig. 5: Dynamic cyclogenesis on the polar front (northern hemisphere).

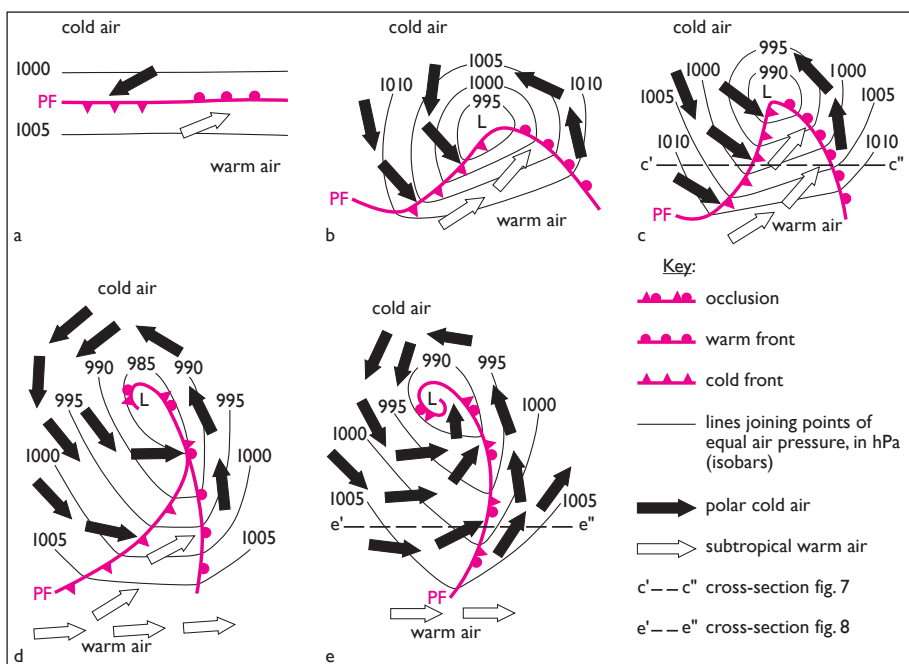


[K4] How does the steep step in the tropopause above the polar front develop?

2.4 Cycle of Wave Cyclones

To go one step further we again take a look at the waves on the surface of a lake, which change their form continuously: They are small but grow towards the shore, and they finally break in the surf, while the next waves are approaching from the open water. A similar pattern can be observed in the waves on the polar front; thus, they are also called wave cyclones (fig. 6).

Figure 6 shows the exemplary sequence of a wave cyclone from a straight line in the polar front over the typical dynamic cyclone (with a warm and cold front) till the occlusion and the dissolution of the front; then it starts all over again. It also shows how a warm and a cold front (fig. 7) develop in the polar front (i.e. they are actually part of the polar front).



[a] The polar cold air (PEW) and subtropical warm air (WW) meet along the polar front (PF).

[b-c] The polar front becomes distorted into a wave-like structure by friction between the two air masses: The advancing cold air causes the cold front, the warm air, the warm front (fig. 7).

[d-e] Especially near the centre of the depression, cold air advances faster than warm air. Therefore, sooner or later the warm front is caught up by the cold front, and an occlusion (fig. 8) has developed.

Fig. 6: Development of dynamic cyclones, also known as wave cyclones (northern hemisphere).

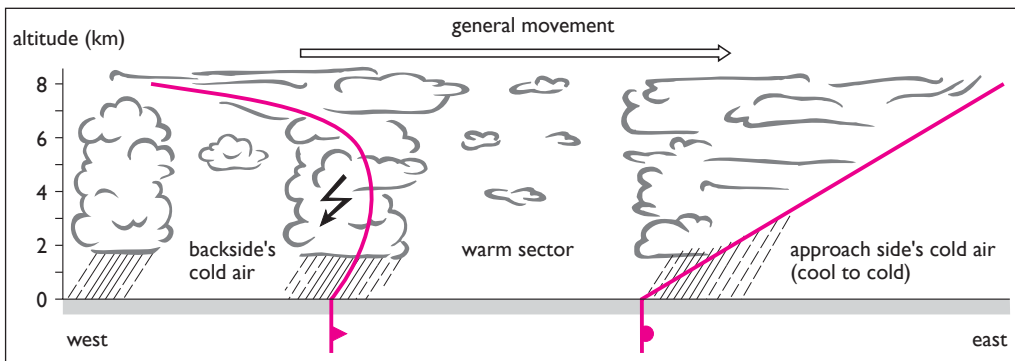


Fig. 7: Cross-section of a cold and warm front; the location of the line of the cross section can be seen in fig. 6.c.

Because of its form, the cold front advances as fast as the cold air masses push it forward. On the other hand, the warm front moves more slowly than the pushing warm air masses because they mainly rise along the warm front (and cool down, forming clouds, and it

The fronts are passing a surface-stationed observer from left to right. First, one can see gathering clouds (stratus), followed by precipitation. Shortly afterwards it gets warmer – the observer is in the warm air sector. Soon the thunderclouds (cumulonimbus) of the cold front appear as cloud towers on the horizon. They bring heavy precipitation, which will dissolve into light cloud cover in clean and cooler air – the backside weather.

Please read about the different types of clouds, their relevance and development in SCHWEIZ SUISSE SVIZZERA SVIZRA, pp. 300–306.

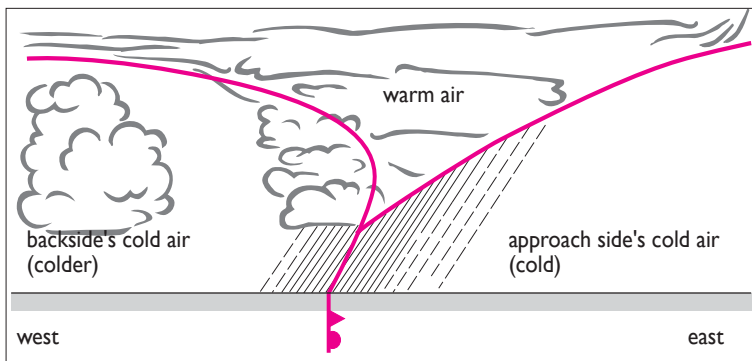


Fig. 8: Cross-section of an occlusion.

starts to rain). Therefore, within a few days the cold front catches up with the warm front, i.e. the cold air masses from the back and the front side (fig. 7) merge and push up the subtropical warm air (fig. 8): We now have a so-called occlusion⁶. On the surface two cold air masses have direct contact, a polar cold air and a mid-latitude cool air. The temperature gradient between them defines the kind of rain which will develop.

[K5] Why do dynamic cyclones and anticyclones advance eastwards in the mid-latitudes?

⁶ from Latin *occludere* 'close'.



[K6] Draw the westerlies on the southern hemisphere analogously to fig. 1.

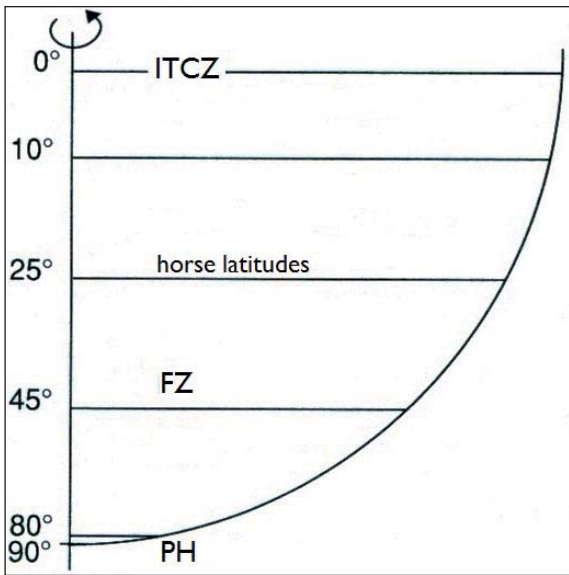
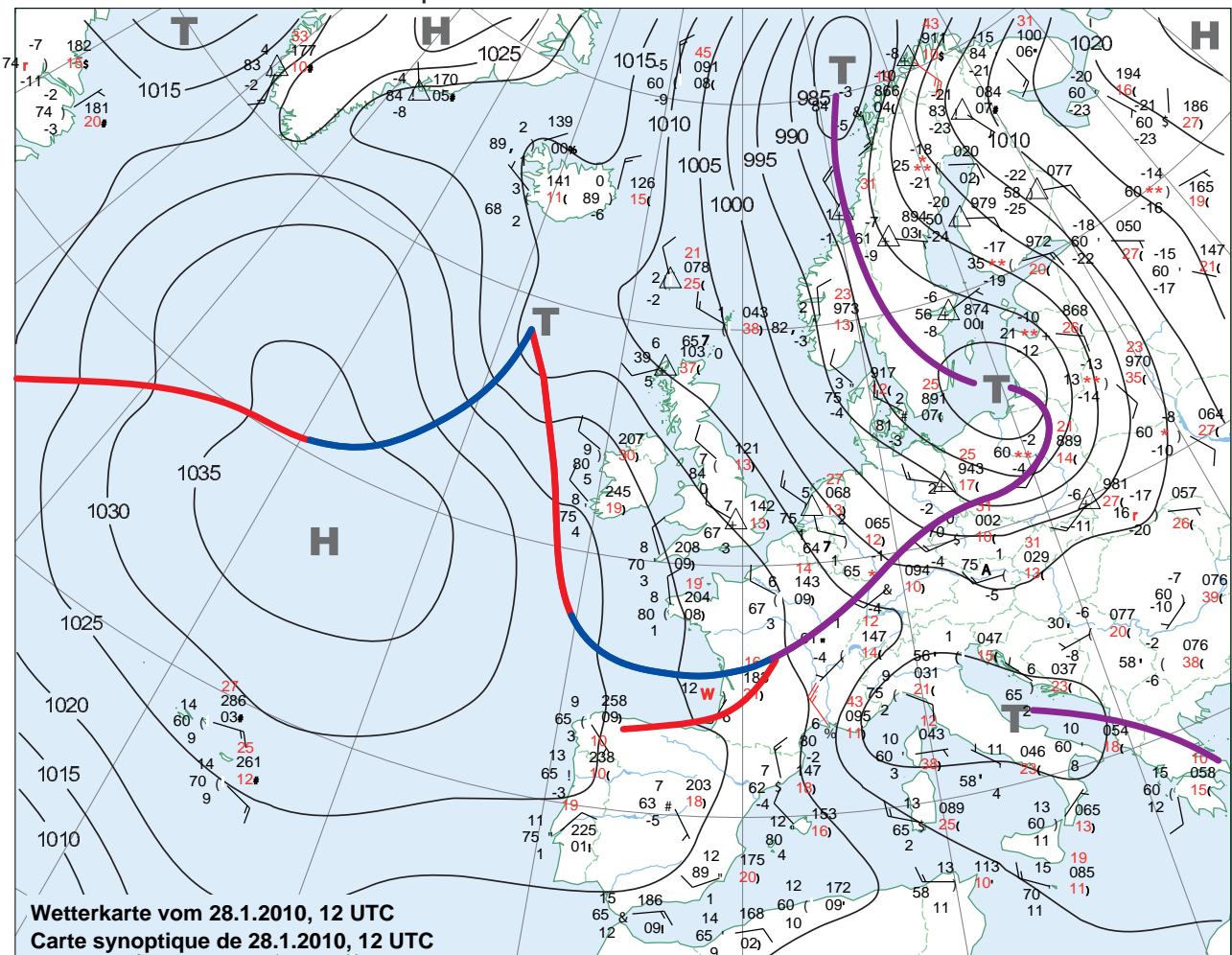


Fig. 9: Jet stream, polar front and frontal zone in the southern hemisphere (21/3 + 23/9).

[K7] Draw in the weather chart the polar front (as far and as coherently as possible), warm and cold fronts, occlusions, the polar cold air, and the subtropical warm air.





Summary

Within the westerlies lies the frontal zone, in which the polar front is a weather-active structure. The polar front itself is the boundary between the subtropical warm air and the polar cold air. Caused by friction between these two air masses, waves develop in the polar front where dynamic low-pressure zones (or depressions) are generated by air movement (and not by thermal energy or temperature differences). The advancing cold air forms the cold front, the advancing warm air, the warm front. As soon as the cold front catches up with the warm front, i.e. the two fronts are together, they build the occlusion.

3. Space for Personal Notes and Questions









Solutions to the Questions

- [K1] The polar front is the boundary between the polar cold air and the subtropical warm air.
- [K2] Thermal depression: Air ascends because it was heated up by the surface of the earth; hence it has a lower density than its surrounding air – ascent because of different temperatures.
Dynamic depression: Air ascends because it is entrained from lower layers by the jet stream (cf. perfume bottle) – ascent because of different wind velocities.
- [K3] The polar front gets around the globe at about 45° N/S. As a boundary between two air masses it reaches from the surface of the earth up to the tropopause. Thus it is stretched around the globe like a collar of ten kilometres height and 20,000 kilometres length. It is distorted by the friction of the two air masses into waves with vertical axes.
- [K4] Subtropical warm air flows as west winds on the equatorial side of the polar front. Warm air has a lower density than cold air. A lower density means that the same amount of air needs more space; i.e. the same layer with a higher temperature is thicker [= *mächtiger*] than with a lower temperature. Therefore, the subtropical warm air is thicker than the polar cold air; and along the polar front, which separates these two air masses, it must develop a steep step in the tropopause.
- [K5] The moving direction of cyclones and anticyclones in mid-latitudes is caused and given by the eastwards drift of the jet stream.



[K6] According to the General Circulation Model (GCM), the winds are symmetrically placed on both hemispheres, i.e. figure 44 can be mirrored in a axially-symmetric way.

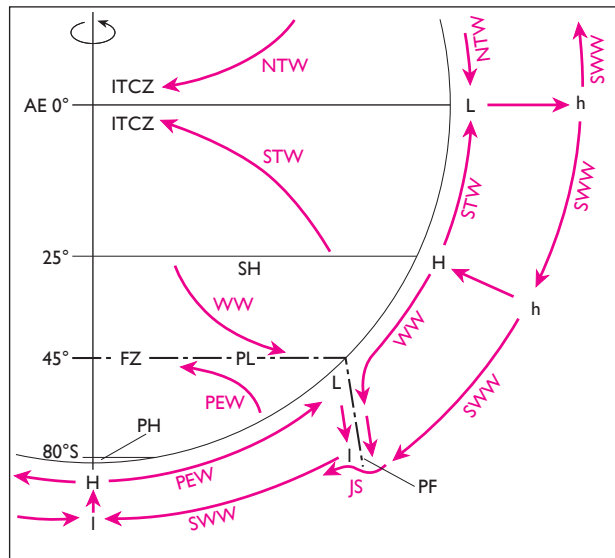


Fig. 11: GCM on the southern hemisphere; answer to K5.

[K7] Weather chart from 28/1/10: Cold and warm front and occlusion are differentiated in weather charts with symbols which can be seen in fig. 6–8. In the chart the polar front is marked with a green, broken–line [= gestrichelte Linie]. It runs along the warm and cold fronts as they separate polar cold air from the subtropical warm air.

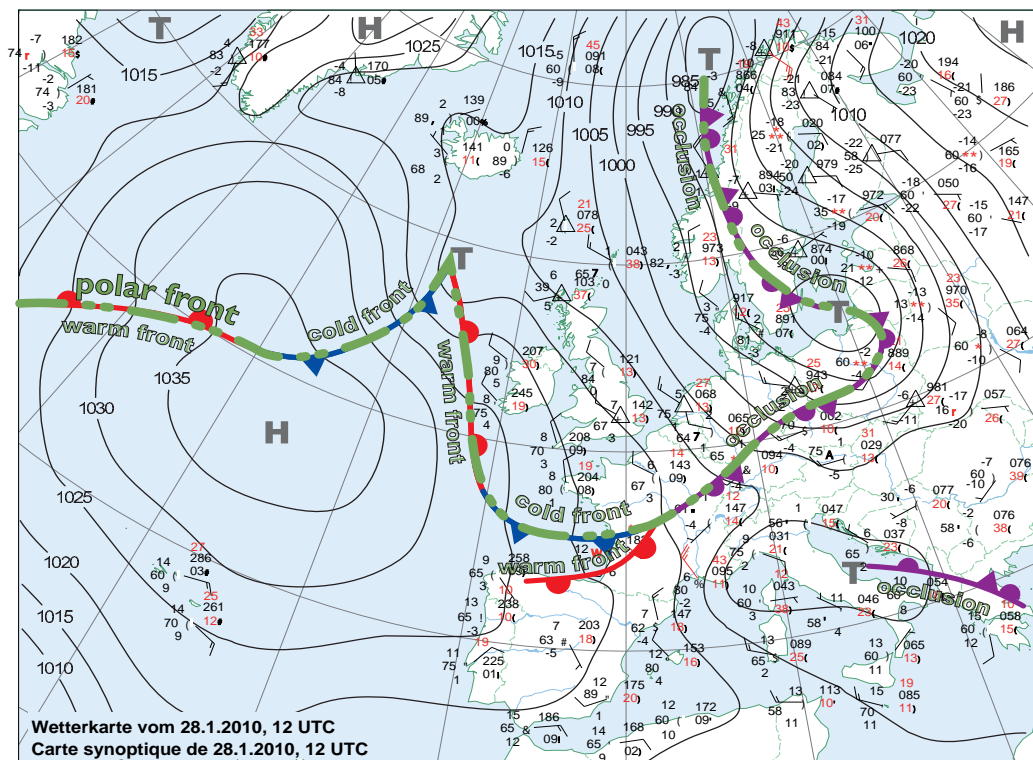


Fig. 12: Weather chart of Middle Europe with polar front, warm and cold fronts and occlusions; answer to K7.