The potential wet-bulb temperature and frontal analysis

The potential wet-bulb temperature $\theta_w$

When an air parcel, starting from a certain pressure level, is lifted dry adiabatically until saturation and subsequently is brought to a level of 1000 mbar along a saturated adiabat it reaches what is called the saturated potential wet-bulb temperature: $\theta_w$. In Figure 1 this process is graphically presented on a $\theta_s,p$-diagram.

Although in Figure 1 we have used pseudo adiabats, the difference with saturated adiabats generally is very small. In Figure 1 also the (adiabatic) wet-bulb temperature $T_w$, the potential temperature $\theta$, the saturated potential temperature $\theta_s$ and the equivalent potential temperature $\theta_e$ are indicated. The equivalent potential temperature has the same characteristics as $\theta_w$: both may be used as a "label" of the same pseudo-adiabat.

As long as an air parcel undergoes an adiabatisch process, be it either dry or saturated, and in both descending and ascending motions $\theta_w$ does not change. Even when precipitation is
evaporating adiabatically $\theta_w$ does not change. Because the mixing ratio, and hence $T_d$ will increase while $T$ decreases, but such that $T_w$ remains unaltered. For all these processes $\theta_w$ is “conservative” i.e. does not change. Of course, $\theta_w$ may change when diabatic processes such as radiative processes and mixing occur.

To get an impression of the normal range of values of $\theta_w$ Figure 2 gives the distribution of $\theta_w$ on 85 kPa, as observed in De Bilt in 1961-1970. Also average values and the standard deviation is given for $\theta_w$ on 70 and 50 kPa. Figure 3 gives the distribution of $\theta_w$ on 85 kPa for February and August. From these data it appears that a $\theta_w$ of -8°C which was recorded on 1 January 1979 on 85 kPa in De Bilt was extremely low. At the same time in Poland an even lower value -16°C was reported (see also Figure 9).

Air masses
An air mass is defined as a quantity of air with a horizontal extent of several hundred or thousand kilometres and a thickness of several kilometres, which is homogeneous in thermal characteristics. Such an air mass may form when air has been over an extensive and homogeneous part of the Earth’s surface during a considerable amount of time. This is the so-called source area. In due time, by means of radiative exchange processes and contact with the Earth’s surface, an equilibrium develops which is evident from the fact that $\theta_w$ has approximately the same value in the entire air mass both horizontally and vertically. Hence $\theta_w$ can be used to characterise an air mass, with both sensible and latent heat are accounted for.

Depending on possible source areas several main air mass types can be distinguished: polar air (P), midlatitude air (ML) and (sub)tropical air (T). Also, but these are less important arctic air (A) and equatorial air (E). These five main types can be subdivided in continental air (c)
and maritime air (m). Later on a definition of the five main air mass types is based on the average potential wet-bulb temperature on the Northern Hemisphere. In Figure 4 the source areas around Western Europe are presented. Based on the above a table can be constructed for $\theta_w$ values at 85 kPa that, depending on the season, are characteristic for a certain air mass (Table 1).

![Source areas](image)

**Figure 4.** The location of the source areas around Western Europe.

| Table 1. Characteristic values for $\theta_w$ at 85 kPa (in °C) for various air masses. |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| **Summer**                      | **Winter**                      |
| cA  < 7                         | cA  < -5                        |
| cP  7 - 12                      | cP  -6 - 2                      |
| cML 11 - 16                    | cML 1 - 8                      |
| cT  15 - 19                     | cT  8 - 14                     |
| cE  > 17                       | cE  > 14                       |
| mA  < 9                        | mA  < -7                       |
| mP  6 - 12                     | mP  -3 - 5                     |
| mML 11 - 16                    | mML 3 - 9                      |
| mT  14 - 19                    | mT  8 - 16                     |
| mE  > 18                       | mE  > 16                       |

When an air mass moves away from its source area $\theta_w$ will not directly because of its conservative character. In the long run $\theta_w$ will change by means of the diabatic processes mentioned earlier. This is called air mass transformation. If cold air flows over a warm surface this transformation may occur rapidly because of the thermal instability. For example, arctic air flowing south over a relatively warm Nordic Sea can be transformed into polar air within 24 hours. When warm air flows over a cold surface the air mass transformation may take considerably longer.
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Fronts
If the $\theta_w$ distribution is considered on a pressure surface, preferably 85 kPa, then extensive areas with a small or no gradient can be observed. These areas of homogeneous $\theta_w$ values may be associated with air masses. Often various homogeneous areas are separated from one another by relatively narrow transformation zones displaying a strong gradient. Here frontal zones intersect with the pressure surface. Generally speaking a surface front is located where at 85 kPa the “warm boundary” of the zone with the large $\theta_w$ gradient is present. Details of the exact position of the frontal zone at the various pressure levels can only be obtained by constructing a vertical cross-section. Figure 5 indicates the relation between the $\theta_w$-pattern at 85 kPa and the location of the surface front for the main frontal systems. Note the pattern of the occluded front. Figure 6 presents an example.

Figure 5. Schematic indication of the location of various surface fronts in relation to an existing $\theta_w$-pattern.

Figure 6. The location of a frontal system and the accompanying pattern of $\theta_w$ at 85 kPa.

In general two main frontal zones can be distinguished: the polar front between polar (P) air and midlatitude (ML) air, and the subtropical front between midlatitude (ML) air and (sub)tropical (T) air. The arctic front, between polar (P) air and arctic (A) air is usually confined to the lowest kilometres of the atmosphere. In the $\theta_w$ pattern at 85 kPa it can often clearly be recognised.

Practical $\theta_w$ analysis
From radiosonde data of 00 UTC and 12 UTC the $\theta_w$ at 85 kPa (and if necessary of 50 kPa) can be calculated and plotted. Usually the $\theta_w$ isoline interval is 2 °C; in summer is 1 °C should give better results. With the analysis a consistent three dimensional view of the atmosphere should be obtained. Therefore the $\theta_w$ analysis is only part of the complete analysis and should be viewed in conjunction with other observation. As an aid to the $\theta_w$ analysis use is made of:
* Previous $\theta_w$ analyses,
* Sea level pressure analysis,
* 85 kPa height analysis,
* Satellite data,
* Vertical cross-sections.

The sea level pressure analysis and the $\theta_w$ analysis are fitted into a frontal analysis which is consistent with both analyses. In practice an observed value is only disregarded every now and then. However, in an otherwise homogeneous area some deviating values may occur without having a different air mass. There are two possibilities when such a thing occurs.

In the first place sometimes “cold spots” are found in anticyclones, when there is a subsidence inversion near the 85 kPa surface. The "cold spots" are created by radiation divergence at the top of the humid layer below the inversion. Figure 7 gives an example of such a situation. A second possibility is the so-called "warm tongue" just in front of the cold front. These "warm tongues", which are connected to the conveyor belt and low level jet, are usually clearly discernible on the $\theta_w$ 85 kPa analysis. Figure 8 presents an example. Another example is Figure 9: the $\theta_w$ analysis at 85 kPa on 1 January 1979 00 UTC, just after the occurrence of a cold spell in the Netherlands.

**Figure 7.** Example of two "cold spots": one just west of France and one over Sardinia.

**Figure 8.** A "warm tongue" is located over the Atlantic Ocean, the Channel and the North Sea.

**Figure 9.** The $\theta_w$-field at 85 kPa in the case of cold air advection over the Netherlands.
Other applications of \( \theta_w \)
A table has been made containing various values of \( \theta_w \) at 85 kPa and the chance that precipitation will be in the form of snow (see Forecaster's Reference Book). Another use of \( \theta_w \) is in a number of indices for instability and for precipitation. An example is the potential stability: \( \theta_w(50) - \theta_w(85) \). Negative values indicate a potentially unstable layer. Other examples are:

* the Rackliff index: \( \theta_w(85) - T(50) \), with values over 30 indicating thunderstorms, and
* the modified Jefferson-index: \( 1.6 \times \theta_w(85) - T(50) - 0.5 \times T_d(70) - 8 \), with a value of 26 to 28 indicating showers.

Here \( T(50) \) stands for the temperature at 50 kPa; \( T_d(70) \) the dew point at 70 kPa. See eg. the Forecaster's Reference Book.

Figure 10 presents for various values of the Rackliff index, the relative occurrence of showers with or without thunder within a period of 12 hours around the time of the radiosonde observation (12 UTC) for 30 stations in Europe in July 1978. In the top figure ("local") as observed at or near the radiosonde station, and in the bottom figure ("regional") as observed within 150 km radius around the station (an area approximately equal to the Netherlands). In Figure 11 a correction for sea level pressure has been applied to the Rackliff index. Also both stratiform and convective precipitation has been accounted for. It applies for 7 stations near the North Sea.

In the winter the 50 kPa pressure surface may be too high as the top surface. It appears that better results may be obtained using \( 1.5 \times (\theta_w(85) - T(70)) \), where a value of 17 indicated precipitation (0.3 mm or more).
The above mentioned parameters are automatically calculated, plotted and analysed. The advantage of using $\theta_w$ in these precipitation parameters is that $\theta_w$ due to its conservative character can be forecast with reasonable accuracy. Furthermore, $\theta_w$ does not change very much when precipitation is falling through the layer in question. Humidity is accounted for in such a way that the occurrence of precipitation does not change the results.