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Atmospheric fronts from a climatologist's perspective: A review

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ABSTRACT The term atmospheric front has been in use for a century. The definition of atmospheric front has evolved and changed over time. First, this concept was used to analyze and predict weather through subjective analysis of synoptic maps. The advent of computer technology has enabled the emergence of various types of objective analysis, which have made it possible to find different types of relationships between atmospheric fronts and meteorological and climatological variables. The relationship between fronts and atmospheric precipitation has been studied in detail, but a systematic analysis of the relationship between fronts and surface temperature is still missing. Climatology of fronts from different authors indicate the same main features, although they are based on different objective analyses and input data. Past and future changes in the position and activity of fronts were analyzed thanks to the objective analysis of reanalysis data and climate models.

KEY WORDS atmospheric front – climatology – objective frontal analysis – precipitation – surface temperature

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1. Introduction

Atmospheric fronts are associated with a number of weather manifestations and phenomena: clouds, precipitation, and rapid changes in pressure, wind, and temperature in midlatitudes are, among others, often related to fronts. The availability and reasonable reliability of objective methods for detecting fronts has enabled the development of climatological analyses of atmospheric fronts, which have begun to flourish in the early 2010's (see, e.g., Thomas, Schultz 2019a). These have focused on describing the climatology of fronts, i.e., identifying areas with a frequent presence of fronts (Berry, Reeder, Jakob 2011; Rudeva, Simmonds 2015; Lagerquist, Allen, McGovern 2020), and on analysing the relationship of fronts to precipitation (in particular, the contribution of fronts to total and heavy precipitation; Catto et al. 2012, 2015; Blázquez, Solman 2017; Hénin et al. 2019). In contrast to the relationship of fronts to precipitation, the relationship of fronts to surface temperature and its day-to-day changes has not been investigated so far, except for the study by Piskala and Huth (2020) for a single station. The aim of this paper is to summarize the findings regarding atmospheric fronts primarily from a climatological perspective and to identify knowledge gaps for future research.

2. What is an atmospheric front?

The atmosphere consists of different air masses, which are separated by an interface of discontinuity, named atmospheric front. This term was first used by Ansel in his dissertation in the first decade of the 20th century in the meaning of "a front of the wedge" of a warm air mass (Keilfront in German; Khrgian 1970). The first detailed conceptual model of atmospheric fronts was described by Bjerknes and Solberg (1922), and since then different types of fronts have been drawn on synoptic charts depending on the shape of pressure field, pressure tendency, localization of the appropriate type of clouds and precipitation, temperature gradient, changes in wind direction. The foundations of the Norwegian school of meteorology, also known as the Bergen school of meteorology, by Vilhelm Bjerknes in Bergen during the WW I brought new findings which significantly improved weather forecasting.

Norwegian school of meteorology described development of an extratropical cyclone based on surface observations only. A cyclone passes through three stages of its development, which are associated with typical cloud genera and weather. In the beginning, the frontal wave forms on a borderline between two different air masses. A deepening cyclone is formed by a gradual rotation of the frontal wave and its deepening. The centre of a deepening cyclone agrees with the top of the warm sector, which is bounded by a warm front on the front side in the direction of advance and by a cold front on the rear side. The occluded cyclone is the last stage of cyclone development. The faster moving cold front catches up with warm front thereby forming the occluded front. In the end, the extratropical cyclone weakens and disappears.

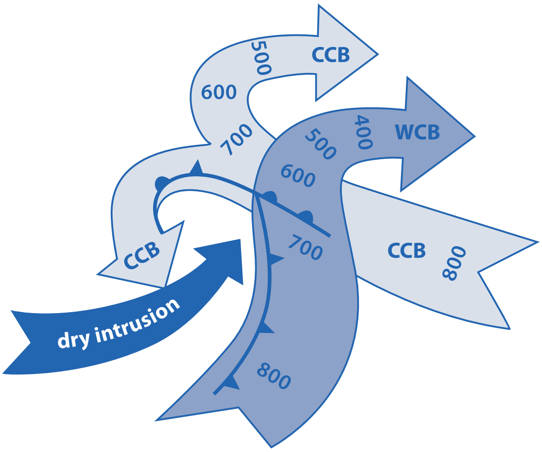
In general understanding, the atmospheric front is a narrow interface that separates air masses with different properties. During the twentieth century many attempts to provide a clear and general definition of atmospheric front have been made. Palmén (1951) in his definition of a front used the maximum horizontal change in temperature and combined it with a first-order discontinuity in the wind field. Godson (1951) used the term hyperbaroclinic zone with a first-order discontinuity in the temperature field for the frontal layer. According to Anderson, Boville, McClellan (1955), both definitions might well represent realistic conditions on the fronts but are insufficient to clearly define them. Therefore, they formulated a more accurate definition which contained (i) a 3D hyperbaroclinic zone with first-order discontinuities in the temperature and wind fields, (ii) a quasi-substantial surface which moves with the wind flow, and (iii) a reasonably continuous feature in both space and time. This article stimulated considerable discussion, for example J.S. Sawyer considered the definition too restrictive and specific to the atmosphere (Anderson, Boville, McClellan 1956). A few years later, Taljaard, Schmitt, van Loon (1961) defined the front as a narrow slant layer with a vertical range of at least 3 km, across which temperature changes abruptly in the horizontal direction by a minimum of 3 °C in subtropical latitudes, and 4–5 °C in midlatitudes and the polar regions. In general, a front can be defined as a narrow transition zone between air masses that is characterized by sharp changes in meteorological elements in the horizontal direction. The thickness of a front in the vertical direction is several hundred meters, which is usually at least an order of magnitude less in comparison with the vertical range of the air masses themselves. Its length is usually hundreds to thousands of kilometers (Kopáček, Bednář, Žák 2020).

3. More detailed mesosynoptic concepts

3.1. Conveyor belts

During the second half of the twentieth century, thanks to new technologies and the possibility of monitoring the atmosphere via radiosoundings and later satellites, it was concluded that the original concept of the Norwegian school of meteorology needed to be partially reworked. One of the new conceptual models describes the field of relative flow inside a frontal cyclone through conveyor belts. These are three-dimensional trajectories of air particles displayed in a coordinate system firmly connected to a moving cyclone (Kopáček, Bednář, Žák 2020).

Fig. 1 – Schema of conveyor belts. WCB warm conveyor belt, CCB – cold conveyor belt. The numbers indicate the approximate pressure level at which the conveyor belt typically occurs. Source: modified from Kopáček, Bednář, Žák (2020), printed with permission of the publisher.



The first parts of this theory were born by Harrold (1972), who described a basic mechanism of widespread precipitation related to conveyor belts. The overall idea was clarified by Carlson (1980), who gave details of cold and warm conveyor belts, their association with the formation of warm and cold fronts, cloud patterns, and jet stream. The final versions of the conveyor belts concept were presented by Browning (1986, 1990), who described in detail the connection of individual conveyor belts with the occurrence of clouds and precipitation. The basic components of this model are the warm conveyor belt, the cold conveyor belt, and the dry air intrusion. The basic schema of the mutual position of these belts is shown in Figure 1. During the development of a cyclone, individual belts usually partially change shape, direction, and altitude. The concept of conveyor belts explains the essence of front dynamics far better than the classical approach of the Nowegian school of meteorology (Kopáček, Bednář, Žák 2020). This concept was brought to Czech literature by Huth and Štekl (1988).

The warm conveyor belt (WCB) represents the relative flow of generally warm and humid air that is transported from lower to higher levels and is often the main mechanism of precipitation formation (Browning 1990). It forms ahead of the cold front into a continuous stream, usually several hundred kilometers long, gradually filling the entire height of the troposphere. The WCB in the deepening cyclone usually runs parallel to the ground cold front (Harrold 1973), crosses the warm front line roughly perpendicularly, then twists anticyclonally, and stops rising in a position approximately parallel to the warm front line (Carlson 1980; Browning 1986, 1990). During the ascent, it participates in the formation of frontal cloud systems of a warm front and partly also in the warm sector.

The cold conveyor belt (CCB) is the relative flow of generally cold and initially dry air, which forms on the front side of the cyclone at ground levels and is characterized by the values of the isobaric wet-bulb potential temperature being several

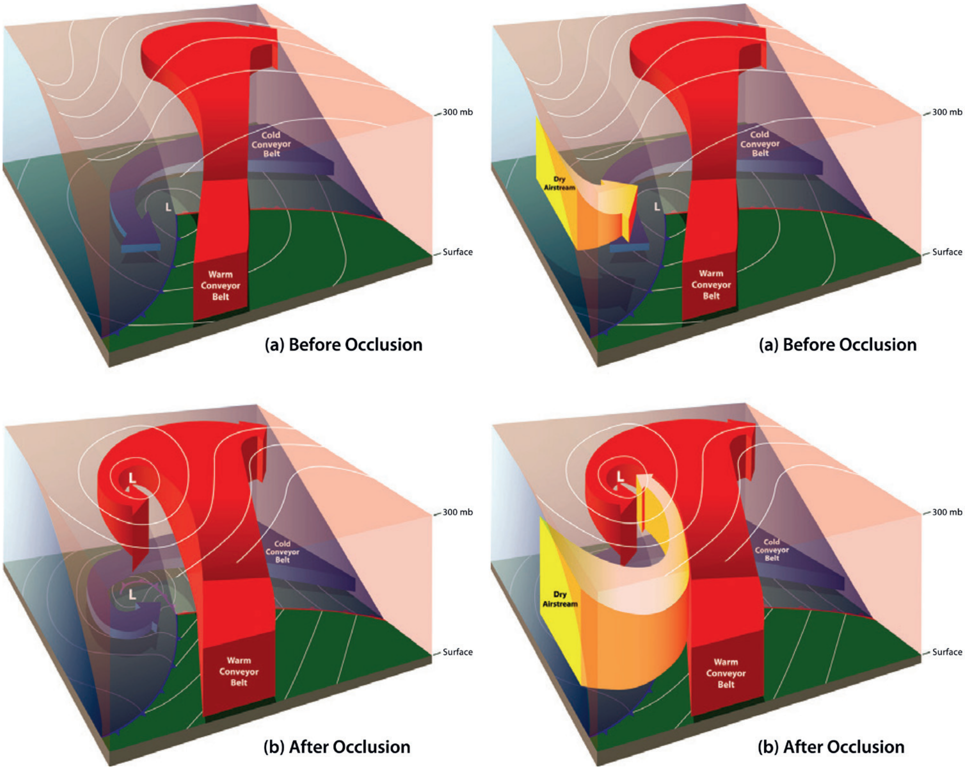


Fig. 2 – Warm conveyor belt (red), cold conveyor belt (blue) and dry intrusion (yellow): (a) before occlusion and (b) after occlusion. The characteristic horizontal scale of the domain is 1,000 km on each side. Source: Schultz, Vaughan (2011), printed with permission of the publisher.

degrees lower than inside the WCB (Browning 1990). The CCB first flows west, pass beneath the WCB, where it becomes saturated by moisture due to precipitation produced by the WCB. The CCB begins to rise near the front line of the warm front and twists cyclonically around the cyclone centre (Carlson 1980, Browning 1990). During its ascent, the moisture received from the WCB can further serve as a source for formation of the low- and middle-level clouds (Harrold 1973, Browning 1990). At the point where the CCB emerges from under the warm conveyor belt, the flow is often divided into two branches, characterized by different heights above the Earth's surface. The higher branch twists anticyclonically until it is almost parallel to the WCB. The lower branch twists cyclonically and points to the centre of the cyclone.

Dry intrusion is a descending flow of dry air, which forms in the rear of a deepening cyclone, is characterized by very low isobaric wet-bulb potential temperature, and plays an important role in cyclogenesis (Hoskins, McIntyre, Robertson 1985; Uccellini et al. 1985, Browning 1990). Dry intrusion is usually very well detected on satellite images that respond to water vapor in the troposphere (Carlson 1980, Browning 1986, 1990). It has its origin near the local reduction of tropopause height, a certain amount of air in it can originate from stratosphere (Carlson 1980), so it is characterized by high values of potential vorticity. During its descent, the air gradually rotates cyclonically around the centre of the cyclone and warms adiabatically. If dry intrusion comes close to the WCB, it can have temperature similar to the WCB. The resulting upper cold front is defined primarily by a moisture gradient (Carlson 1980, Browning 1986).

The interface between the air in the lower branch of the CCB and the air mass in the rear of the developing cyclone can be described as the atmospheric front, which is analysed as an occlusion front in the classical conceptual model of the Norwegian school of meteorology. Many authors have come up with new insights on the occlusion process (e.g. Wallace, Hobbs 1977; Browning 1990, Shapiro, Keyser 1990; Kuo, Reed, Low-Nam 1992; Schultz, Mass 1993; Market, Moore 1998; Schultz, Keyser, Bosart 1998; Martin 1999a,b; Stoelinga, Locatelli, Hobbs 2002; Posselt, Martin 2004) and have begun to question the correctness of the classical approach to the occlusion according to which warmer air is pushed upwards by cooler air at the front and rear of the cyclone (Bjerknes, Solberg 1922). Schultz and Vaughan (2011) discussed the issue of the Norwegian school's approach to the occlusion process in detail. They paid attention to four different tenets associated with occlusion and put them in perspective based on new knowledge. The first one said that the occluded front forms and lengthens as a faster-moving cold front catches up with a slower-moving warm front. Schultz and Vaughan (2011) analysed various models of the formation of occlusion fronts, including the conveyors belts theory, and they concluded that the occluded front forms as a result of the wrap-up of the baroclinic zone and lengthens due to flow deformation and rotation around the cyclone. Figure 2 shows the mechanism for wrap-upping of conveyor belts. Secondly, two types of occlusions are possible according to the Norwegian school of meteorology, depending on the relative temperature of each air mass. In fact, the type of occlusions depends on the relative static stabilities of the air on either side of the occluded front. In general, warm-type occlusions are more usual (Schultz, Vaughan 2011). The third delusion is that the cyclone will stop deepening due to occlusion. Detailed observation showed that many cyclones continue deepening after occlusion or do not occlude at all (Schultz, Vaughan 2011). The last common inaccuracy of the Norwegian school of meteorology's approach to the process of occlusion is related to the connection of occluded fronts with extensive clouds and precipitation followed by sudden clearing after surface frontal passage. Actually, "occluded fronts are associated with a variety of cloud and precipitation patterns, including dry slots and banded precipitation" (Schultz, Vaughan 2011, p. 458).

3.2. Atmospheric rivers

In the early 1990s, another possible view of the flow of air masses related to frontal systems and cyclones was published. Newell and Zhu were the first to describe a long and narrow belt of enhanced water vapor transport (Newell et al. 1992; Zhu, Newell 1994), which is temporarily formed in the lower troposphere (Ralph et al. 2019) and named it the atmospheric river (AR) because such air flows may even contain more water than the Amazon River (Newell et al. 1992). The length of ARs can reach several thousands of kilometres with a maximum width of several hundreds of kilometres and a vertical range of several kilometres (Ralph, Neiman, Wick 2004, Ralph, Neiman, Rotunno 2005). During the 1940s, a strong moisture flux was noted near the cold front of a cyclone (Starr 1942; Haurwitz, Austin 1944). Later studies have described the link between the development and movement of extratropical cyclones and the midlatitude jet (e.g. Newell, Zhu 1994; Zhu, Newell 1994; Ralph, Neiman, Wick 2004). More recent studies have described the association of ARs with the pre-cold-frontal region and the WCB (e. g. Ralph et al. 2006; Neiman et al. 2011; Catto, Pfahl 2013). ARs occur during the approach of a cold front to a warm front when the warm sector narrows, and water vapor converges along the cold front (Dacre et al. 2015). Transmitted water vapor most often comes from tropical areas. Ralph et al. (2019) categorize ARs on a five-level scale describing their strength, impact, and the amount of vertically integrated water vapor flow. The minimum value of vertically integrated water vapor must be at least 250 $kgm^{-1}s^{-1}$ for an airflow to be considered as an AR. The ARs play a very important role in the global water cycle, and they have various impacts. Ralph et al. (2019) summarised selected scientific findings and impacts of ARs, such as cycles of wet and dry years (Dettinger, Cayan 2014), floods (Ralph et al. 2006, Neiman et al. 2011, Konrad, Dettinger 2017), heaviest rains (Ralph, Dettinger 2012), and many others.

ARs and WCB are connected but these terms must not be swapped (Knippertz et al. 2018). The existence of WCB is always linked to the occurrence of a cyclone, but ARs can occur independently or even supply moisture to multiple cyclones (Sodemann, Stohl 2013). Another difference is that ARs are defined by strong horizontal motion in the lower troposphere, while WCBs have strong vertical ascent from the boundary layer to the upper troposphere (Reid 2020). ARs in the form of a low-level airflow bring moisture along a cold front to the base of WCB. Dacre, Martinez-Alvarado, Mbengue (2019) named this flux "feeder airstream". Fronts, WCB, and ARs are not the same, but they can occur together. The combination of these phenomena may bring extreme precipitation (more below).

4. Objective analysis of fronts

The development of computer technology has made it possible to process large amounts of data and reduced subjective inputs. The amount of available meteorological data gradually increased in the 1960's, and their processing began to exceed human capabilities. In addition, it was no exception that subjective analyses of the same synoptic situation differed significantly (Renard, Clarke 1965). This led to the need to make frontal analysis less dependent on the analyzing subject, that is, to objectivize it.

Nowadays, two basic methods of objective analysis exist. The first method is based on a horizontal temperature gradient and its derivatives. Renard and Clarke (1965) investigated a thermal front parameter (TFP) defined as "the directional derivative of the gradient of the thermodynamic quantity along its gradient": $TFP(\tau) = -\nabla|\nabla\tau| * \frac{\nabla\tau}{|\nabla\tau|}$ (Renard, Clarke 1965, p. 551), where τ surrogate for any thermodynamic variable (Hewson 1998). Hewson (1998) drew up a ground-breaking study aimed at inventing a simple, intelligible, accurate, tuneable, and portable method of objective frontal analysis. He used and modified the variables of Renard and Clarke (1965) and Clarke and Renard (1966) and made a more sophisticated version of a TFP. The main idea of TFP is detection of ridge lines in the TFP field which corresponds to the localization of a front on the warm side of the frontal zone. TFP = 0 corresponds to the steepest gradient, which is suitable for application only in the case of sharp boundaries of narrow frontal zones (Jenkner et al. 2010). Hewson (1998) recommended to choose masking criteria threshold values for more smooth and appropriate results. The threshold values correspond to a change in temperature per 100 km.

The TFP can recognise warm vs. cold front. The control parameter is a local geostrophic wind. The parameter values are positive (negative) under warm (cold) advection, which corresponds to the warm (cold) front (Hewson 1998). Jenkner et al. (2010), Berry et al. (Berry, Reeder, Jakob 2011, Berry, Jakob, Reeder 2011), Schemm, Rudeva, Simmonds (2014) and Parfitt, Czaja, Seo (2017) used analogy of Hewson (1998) method in their studies.

This method has become the basis for many other forthcoming objective analyses, e.g. Serreze, Lynch, Clark (2001); Kašpar (2003); de la Torre et al. (2008); Jenkner et al. (2010); Berry, Reeder, Jakob (2011); Berry, Jakob, Reeder (2011); Catto et al. (2012, 2013, 2014); Schemm, Rudeva, Simmonds (2014)…

Thomas and Schultz (2019b) attempted to answer the question of "What are the best thermodynamic quantity and function to define a front?". They summarised the advantages and disadvantages of different input thermodynamic quantities and functions. The most suitable choice of input variables depends on many factors. For example, the potential temperature is more appropriate than equivalent potential temperature associated with humidity gradients in the midlatitudes. For example, disadvantage using equivalent potential temperature in tropics is bound to the troubles with formation of borderline that objective analysis can assess as quasi-stationary fronts, but in fact it is a conjunction with the mountain ridge or sea-land contrast, so it is necessary remove these "fronts" in subsequent processing (Schemm, Rudeva, Simmonds 2014). Hewson (1998) stated that the use of the wet-bulb potential temperature is preferable to detect the front of WCB, but it has difficulties to find atmospheric fronts with a lower moisture gradient.

Thomas and Schultz (2019b) emphasized that frequently used TFPs identify boundaries between air masses, some of which are not generally considered to be fronts. Especially, atmospheric fronts do not usually occur in the subtropic and tropic regions, so this article focuses on regions of middle and high latitudes.

The other objective method of front identification relies on spatiotemporal changes in wind direction and speed. Fronts are localized by a change in direction from the southwest (northwest) quadrant to the northwest (southwest) quadrant in the northern (southern) hemisphere and a change in wind speed at least 2 m.s^{-1} (Simmonds, Keay, Bye 2012; Schemm, Rudeva, Simmonds 2014; Rudeva, Simmonds 2015). Simmonds, Keay, Bye (2012) were first to use this wind method (WND) to identify frontal climatology in the Southern Hemisphere (SH). Schemm, Rudeva, Simmonds (2014) compared analysis based on TFP and WND. The thermal method showed a very good agreement with manual analysis in the case of a strong baroclinic synoptic situation, the WND worked well in a less baroclinic situation. The WND is successful in localizing meridionally oriented, strongly elongated moving fronts, but the troubles arise with the identification of zonally oriented warm fronts.

Solman and Orlanski (2010) introduced Front Activity index (FI) for the computation of frontal activity which in general sense represents areas with a high presence of fronts. The FI is calculated as the absolute value of the 850 hPa temperature gradient multiplied by the absolute value of the relative vorticity: $FI = |\nabla T_{850hPa}| \times |\xi_{850hPa}|$ (Solman, Orlanski 2010, p. 1533). This parameter or its modification was used in many different studies in SH (Solman, Orlanski 2014, 2016; Blázquez, Solman 2016, 2017, 2018) and Blázquez, Solman (2018) evaluated this method as realistic.

The newest objective method of frontal analysis uses artificial neural networks and deep learning (Biard, Kunkel 2019). The algorithm of two-dimensional convolutional neural network (CNN) works with temperature, pressure, specific humidity, and two components of wind vector. At first, CNN must be trained with manually analysed fronts. The success rate of the algorithm was nearly 90%. Lagerquist, McGovern, Gagne (2019) compared two experiments to optimize their CNN and described these methods in detail step by step. Their CNN dramatically outperformed their best numerical frontal analysis method.

Table 1 – Overview of objective frontal analysis methods

Methods		Input variable	Principle	References
TFP	thermal frontal parameter	any thermodynamic variable at the 850 hPa level	horizontal temperature gradient and its derivatives	Renard, Clarke (1965); Hewson (1998); Serreze, Lynch, Clark (2001); Kašpar (2003), de la Torre et al. (2008); Jenkner et al. (2010); Berry, Reeder, Jakob (2011); Berry, Jakob, Reeder (2011); Catto et al. (2012, 2013, 2014); Schemm, Rudeva, Simmonds (2014)
WND	wind method	wind speed and direction	spatiotemporal changes in wind direction and speed	Simmonds et al. (2012); Schemm, Rudeva, Simmonds (2014); Rudeva, Simmonds (2015)
FI	front activity index	850 hPa temperature and relative vorticity	high values of the frontal activity index represent areas with a frequent presence of fronts	Solman, Orlanski (2010, 2014, 2016); Blázquez, Solman (2016, 2017, 2018)
CNN	neural network and deep learning	temperature, pressure, specific humidity, two components of wind vector	machine learning based on training with manually analysed fronts	Biard, Kunkel (2019); Lagerquist, McGovern, Gagne (2019)

Thomas and Schultz (2019b) pointed out that subjective elements still enter the model settings; therefore, "automated fronts are not objective – they reflect the choices and objectives of the person who created the automated algorithm and reflect the ultimate application of frontal analysis" (Thomas, Schultz 2019b, p. 889). A complete overview of objective methods of frontal analysis is shown in Table 1.

5. Global climatology of fronts

The first attempts at climatology of fronts from subjective analyses appeared in the middle of 20th century. The processing of subjective analyses is very time consuming and laborious, therefore they cover a maximum period of 10 years. Schumann and van Rooy (1951) and Reed and Kunkel (1960) found that the largest frequency of fronts is around 40°N and that fronts move poleward in summer in the Northern Hemisphere (NH). Morgan, Brunkow, Beebe (1975) provided analyses of synoptic maps for each type of front for each month in North America, they did not perform the interpretation themselves. Flocas (1984) detected the highest front activity in a cold part of the year, the frequency of front is higher, and the occurrence of cold fronts is more balanced within the year with increasing latitude in the Mediterranean area.

The results of climatologies depend on the applied methods, parameters, functions, thresholds, etc. Climatologies of fronts are made by two different approaches. The first method finds exact location of front lines counts their number over a specified area or point over a given time frame (e.g., season; e.g., in Berry, Reeder, Jakob 2011; Simmonds, Keay, Bye 2012; Schemm, Rudeva, Simmonds 2014; Rudeva, Simmonds 2014). The second approach produces climatologies based on areas with a parameter value higher than a specified threshold. The parameter values are calculated for each day and these daily values are used to create a seasonal average corresponding to the area of atmospheric fronts. A frequent occurrence of front is expected in areas where the parameter value is higher than the threshold value (eg. in Solman, Orlanski 2014; Blázquez, Solman 2017; Lagerquist, Allen, McGovern 2020). Thomas and Schultz (2019a) compared 17 climatologies for different definitions of a front and emphasized various results due to different input settings. They only used methods that work with frontal regions based on a parameter value above a specified threshold (not the exact position of the frontal line) and argued that climatological results do not depend on it. Anyone wanting to study fronts and use their objective identification should thoroughly read the research of Thomas and Schultz (2019a, b) and carefully consider the best setting for their research.

It took some time for the availability of objective analysis of fronts to become reflected in attempts to use it for studies of their climatology. The first global climatology of fronts was created by Berry, Reeder, Jakob (2011) only twelve years ago, when they applied Hewson's (1998) method to the ERA-40 reanalysis. WND method was used by Simmonds, Keay, Bye (2012) to process a detailed analysis of front climatology in the SH. Climatologies based on TFP and WND were compared by Schemm, Rudeva, Simmonds (2014) for both hemispheres. The most recent studies utilized CNN detection method to analyse climatology and variability of fronts over North America (Lagerquist, Allen, McGovern 2020).

Generally, the front frequency increases with growing latitudes, reaches a maximum in midlatitudes, then gradually decreasing (Berry, Reeder, Jakob 2011). The highest front frequency is characterized for midlatitude storm tracks of both hemispheres, and maxima orientation is similar to zonal movement of extratropical cyclones (Berry, Reeder, Jakob 2011; Berry, Jakob, Reeder 2011; Simmonds, Keay, Bye 2012; Catto et al. 2014, Schemm, Rudeva, Simmonds 2014; Solman, Orlanski 2014; Lagerquist, Allen, McGovern 2020). Generally, maxima of warm front frequencies are located more poleward than maxima of cold front frequencies (Berry, Reeder, Jakob 2011, Lagerquist, Allen, Mc Govern 2020). Lagerquist, Allen, McGovern (2020) noticed that cold fronts are twice longer than warm fronts over North America.

The frontal activity changes throughout the year. According to Berry, Reeder, Jakob (2011; Fig. 3) and Schemm, Rudeva, Simmonds (2014; Fig. 4, 5), the highest frontal activity is in winter and lowest in summer in NH hemisphere. The

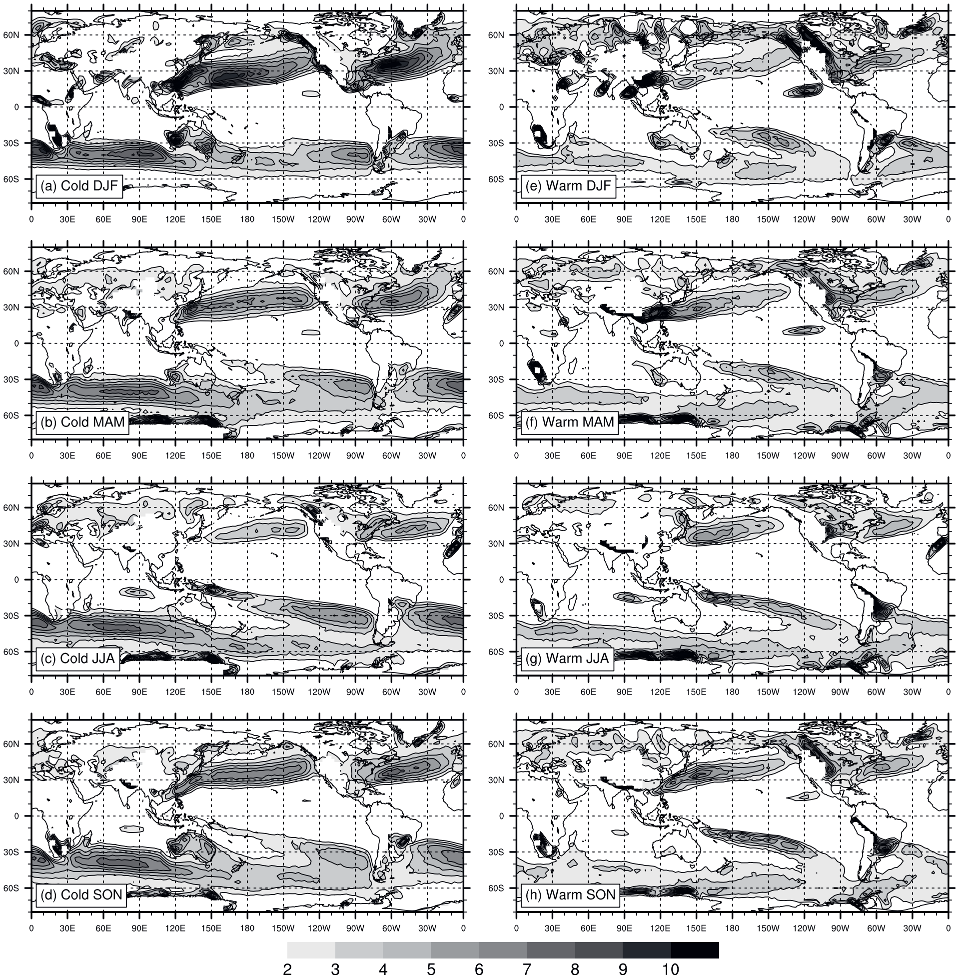


Fig. 3 – Mean seasonal evolution of (a–d) cold and (e–h) warm front frequency. Units are percentage of time at which an objectively identified front is located within each grid box during the 3-month period. Scale is displayed at the base of figure. Source: Berry, Reeder, Jakob (2011), printed with permission of the publisher.

seasonality is considerably smaller in SH; Berry, Reeder, Jakob (2011) find higher frontal activity in SH summer, while Solman and Orlanski (2014) observe exactly opposite development in the SH, i.e. higher frontal activity in winter. Berry, Reeder, Jakob (2011) emphasize that seasonal maxima of frontal activity occur at different times in the NH, for example, maximum of warm front activity in the North Atlantic occur in winter while warm front activity in the North Pacific is lowest in winter.

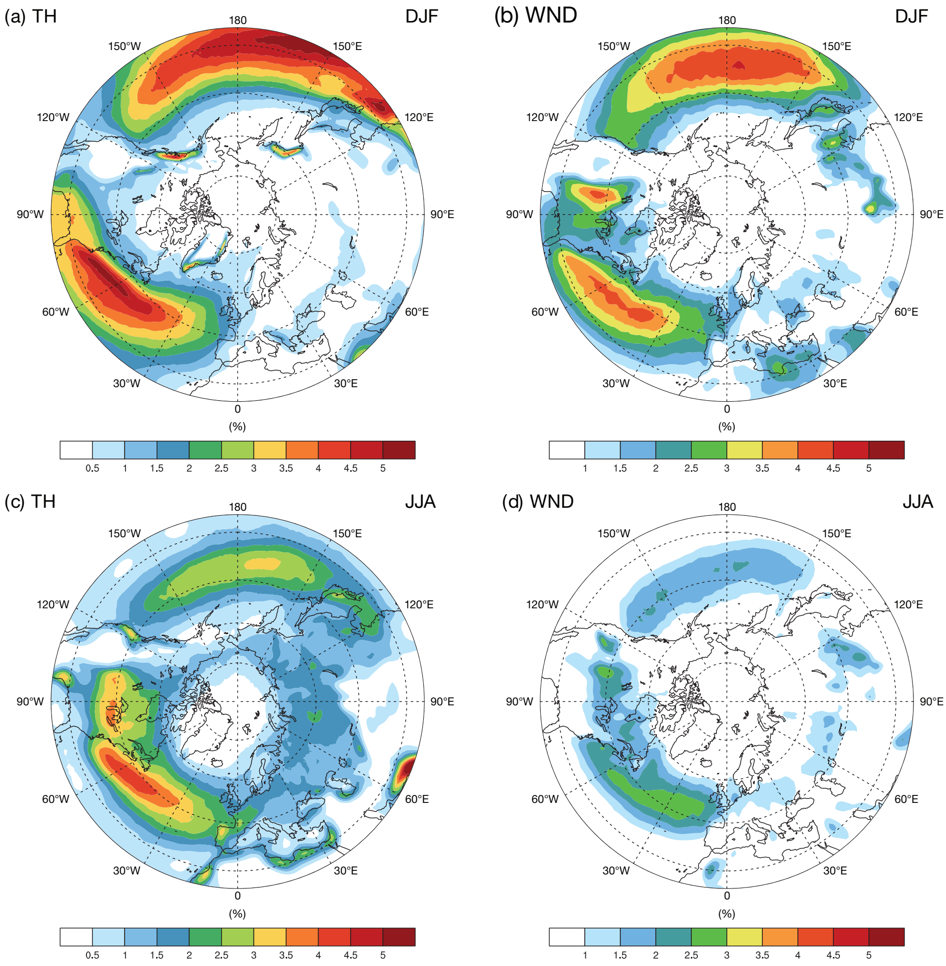


Fig. 4 – Seasonal mean frontal frequencies (%, colour shading) for the years 1979–2012 for (a,c) TFP fronts and (b,d) WND fronts for (a,b) DJF and (c,d) JJA in the NH. Source: Schemm et al. (2014), printed with permission of the publisher.

The seasonality is also clearly evident in where the position of frequency maxima, which are located farther south in winter and shift poleward in summer both in the NH (Berry, Reeder, Jakob 2011; Schemm, Rudeva, Simmonds 2014; Rudeva, Simmonds 2015; Lagerquist, Allen, McGovern 2020) and SH (Simmonds, Keay, Bye 2012; Solman, Orlanski 2014). Berry, Reeder, Jakob (2011) and Schemm, Rudeva, Simmonds (2014) determined the seasonal shift to be less distinct in the SH than in the NH, and a significant connection with the poleward migration of SPCZ exist in the warm season. Some authors were interested in climate variabilities

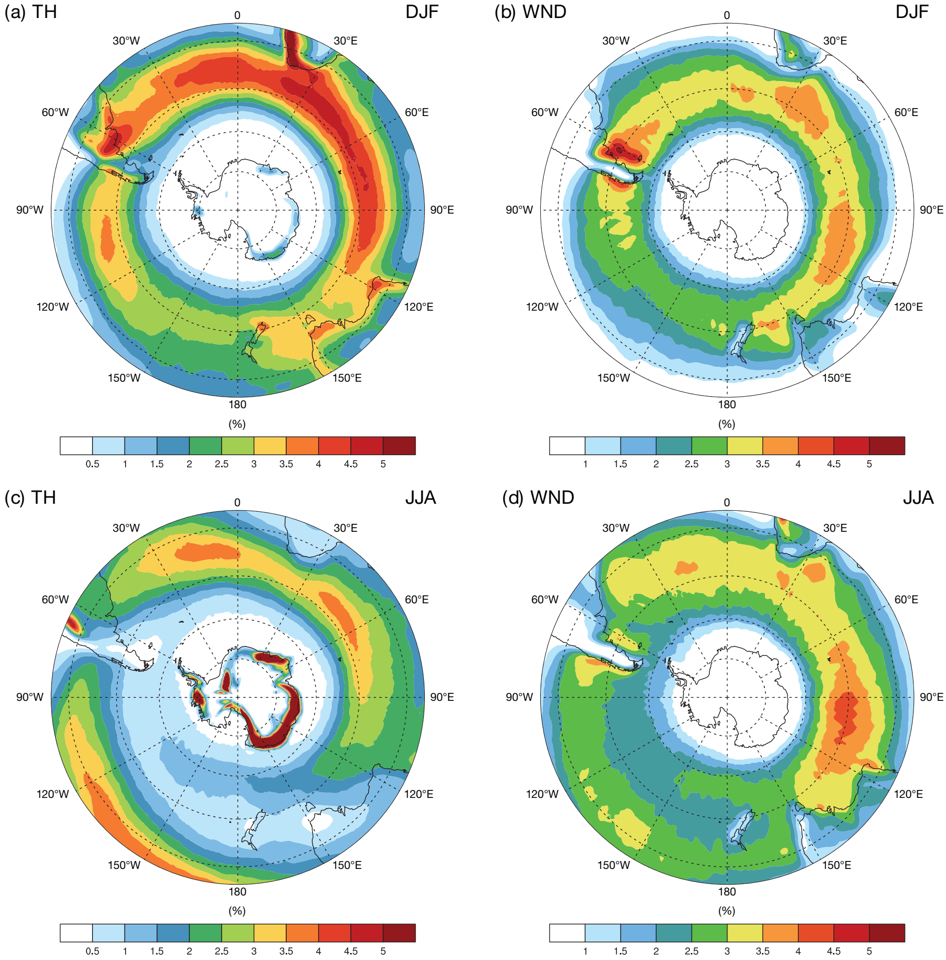


Fig. 5 – As Figure 4, but for the SH. Source: Schemm, Rudeva, Simmonds (2014), printed with permission of the publisher.

affecting frontal frequency. The El Niño caused significant increase of frontal activity equatorward and decrease in midlatitudes in North and South America in winter (Rudeva, Simmonds 2015; Blázquez, Solman 2017; Lagerquist, Allen, McGovern 2020). A strong correlation is between the North Atlantic Oscillation and frontal frequency in a wide belt from the east coast of North America over the North Atlantic to Europe (Rudeva, Simmonds 2015).

6. Past and future changes in frontal activity

There is ample evidence that the frequency of fronts has undergone considerable changes over time. Many authors noticed that the maximum of frontal activity has moved poleward in both hemispheres from the second half of the twentieth century (Berry, Jakob, Reeder 2011; Catto et al. 2014; Solman, Orlanski 2014; Rudeva, Simmonds 2015; Blázquez, Solman 2018, 2019; Lagerquist, Allen, McGovern 2020). As an example, Figure 6 clearly shows a decline of the number of fronts in lower latitudes and its increase in higher latitudes in summer of SH (Rudeva, Simmonds 2015). Specifically, Berry, Jakob, Reeder (2011) uncovered the decrease in front frequency in the area of the North Atlantic storm track, south of Japan, and in the Gulf of Alaska between 1989 and 2009. The largest increase in front frequency was noticed poleward of these regions (e.g. near Iceland and North-Eastern Canada).

The recent observed changes will continue during the 21st century. Current patterns of trends in frontal frequencies are visible over the major storm tracks in both hemispheres in the future projections (Catto et al. 2014). As it is visible in Figure 7, the model projections show continuation in decreases of frontal activity in lower latitudes, increases more poleward, and again decreases further in high latitudes (Catto et al. 2014; Blázquez, Solman 2019) and also an increasing decline in front strength with increasing latitude (Catto et al. 2014). Catto et al. (2014) explained the decrease in frontal activity and front strength in high latitudes by reduction of meridional temperature gradient and sea ice. Blázquez and Solman (2019) suggest a possible reason for a poleward shift in frontal activity to

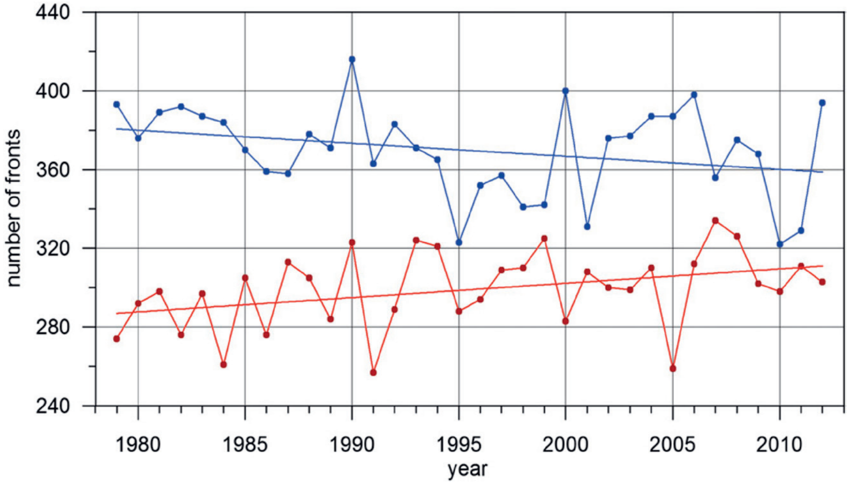


Fig. 6 – DJF time series for the number of fronts in the SH in a belt of 30°–50°S (blue line) and 50°–70°S (red line). Source: Rudeva, Simmonds (2015), printed with permission of the publisher.

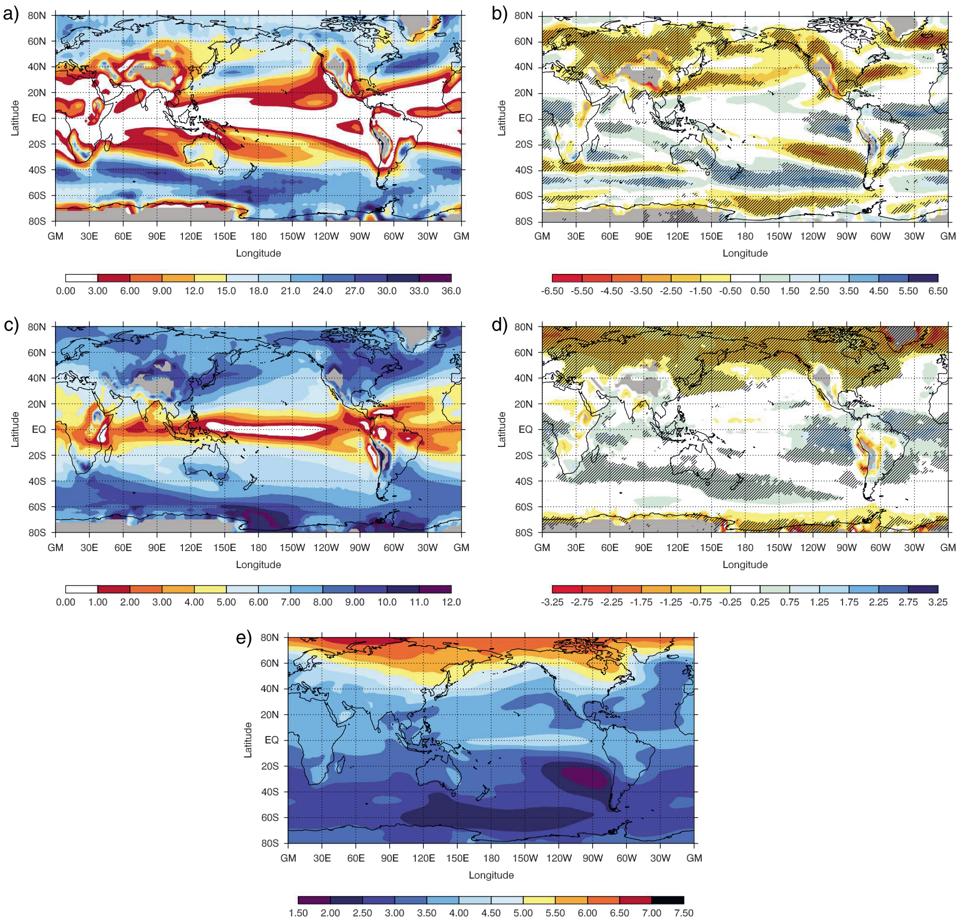


Fig. 7 – Front frequency for (a) multimodel mean from RCP8.5 simulations and multimodel mean change front frequency (%, RCP8.5 2080–2100 – Historical 1980–2005) and front strength for (c) multimodel mean and (d) multimodel mean change (K/100 km, RCP8.5 2080–2100 – Historical 1980–2005). Topography above the 850 hPa level is masked out in grey. Multimodel mean 850 hPa wet-bulb potential temperature change (e) between RCP8.5 and historical simulations (K). Hatching in Figures 6b and 6d shows where at least 15 out of 18 models agree in the sign of change. Source: Catto et al. 2014, printed with permission of the publisher.

be increase of specific humidity in these areas. Changes in frontal activity affect changes in precipitation (Blázquez, Solman 2019) because of a strong connection between fronts and precipitation (Catto et al. 2012; Blázquez, Solman 2018).

7. Climatological view of connection of atmospheric fronts with precipitation

The passage of an atmospheric front is associated with a change in air masses, the processes at the interface of these two air masses causing frontal precipitation (Bjerknes, Solberg 1922). This section describes the relationship between atmospheric fronts and precipitation from a climatological perspective. Precipitation is considered frontal if it is recorded in the vicinity of a front. What a "vicinity" means and how it is defined depends among others on the method of detection of a front and time step of the analysis. The relationship of precipitation to atmospheric fronts has been examined in the last decade. A very high proportion of precipitation is associated with the occurrence of fronts in the midlatitudes, in some places even more than 90% (Catto et al. 2012, Hénin et al. 2019). The areas with the highest share of fronts in precipitation are in the major storm track regions where the frequency of fronts is highest. In general, a higher amount of precipitation over land is associated with warm fronts, because the frequency of warm front is higher than frequency of cold fronts there (Catto et al. 2012). However, Hénin et al. (2019) found that cold fronts have a major contribution to precipitation, the opposite results justified by different input data and settings of objective analysis of front identification. Such dissimilar results emphasize sensitivity to settings of parameters of objective analysis and type of input data.

Precipitation associated with cold fronts is located more equatorwards relative to warm-front precipitation (Catto et al. 2012, Hénin et al. 2019), which is consistent with the general pattern of frontal climatology (Berry, Reeder, Jakob 2011). The cold-front precipitation is more dominant than warm-front precipitation over the North Atlantic storm track and the North American eastern seaboard in the cold half of year (Catto et al. 2012, Hénin et al. 2019). In the SH, 40–60% of precipitation is related to fronts in the band between 30°S and 60°S, this value rising to 80% more poleward (Solman, Orlanski 2014; Blázquez, Solman 2018). Berry, Reeder, Jakob (2011) and Solman, Orlanski (2014) noticed that the frequency of fronts without precipitation over southern parts of continents of the SH increases during warm season.

As we discussed above, in addition to the Norway school of meteorology approach to atmospheric fronts, the flow in a cyclone can also be described as a set of conveyor belts. Catto et al. (2015) showed that more than 70% of WCBs are connected to an atmospheric front. Pfahl et al. (2014) found that about 40% of precipitation relates to WCBs in the midlatitudes. Over 70% of heavy precipitation is connected with WCBs over large parts of southern South America, southeastern North America and Japan (Pfahl et al. 2014). More than 60% of extreme precipitation is combined with the passage of a front and over 90% of it are related to WCBs in parts of the midlatitudes (Catto et al. 2015).

8. Climatological view of connection of atmospheric fronts with surface temperature

Although fronts are defined as boundaries between air masses of different properties, especially temperature, surface temperature changes linked to fronts are complex due to boundary layer processes and local influences and have only minimally analysed. Nevertheless, in general, passages of fronts are likely to result in large changes in temperature also in the boundary layer and near surface. Although some studies (e.g., Tian, Lu, Xue 2019; Zhang, Villarini, Scoccimarro 2019) try to identify driving factors of day-to-day change in surface temperature, they ignore atmospheric fronts as a potential contributor.

Tian, Lu, Xue (2019) tried to understand a temperature difference between neighbouring days (TDN) and its driving factors in China. The TDN is lower in summer, higher in winter, and increases with latitude from south to north. The main driving factor can be a change of solar elevation angle according to Tian, Lu, Xue (2019). Unfortunately, they did not compare TDN with passing of atmospheric front, which could be another driving factor. Zhang, Villarini, Scoccimarro (2019) uncovered that some rapid changes in temperature could be attributed to an influence of midlatitude jet stream and a transport of polar cold air to midlatitudes, but the connection to atmospheric fronts was not mentioned as a potential cause.

Huth, Kyselý, Dubrovský (2001) hypothesize that frontal passages may be one of sources of the asymmetry of day-to-day temperature changes: strong warmings prevailing over strong coolings in central Europe in winter (and vice versa in summer). This hypothesis was confirmed by Piskala and Huth (2020), but for a single station only. They found that in Prague, Czechia, a large increase of day-to-day minimum temperature occurred after passage of any type of front in winter, while a large decrease of day-to-day maximum temperature is mainly associated with passing of cold fronts in summer.

Although Quan, Chai, Fu (2022) may seem to have dealt with the temperature contrast at the fronts, they investigated temperature at 850 hPa. Thus, the relationship of fronts to surface temperature changes remains to be explored.

Atmospheric fronts are associated with many other weather elements than only precipitation and temperature. In spite of it, we are not aware of any papers that would look into the climatology of associations of fronts with the other weather elements.

9. Conclusion: Motivation for future work

The concept of atmospheric front has been with us for almost exactly one century. The definition of the front has undergone considerable development over that time, from the original definition created by the Norwegian school through various very specific detailed definitions to its current wording. The connection between atmospheric fronts and the theory of conveyor belts was postulated in the second half of the 20th century (Harrold 1972, Carlson 1980, Browning 1986, 1990). In the past, there have been discussions about the difference between atmospheric fronts and air mass boundaries (Mass 1991; Thomas, Schultz 2019a, b). Many authors do not take this issue into account when interpreting results of their analyses. Examples of such misinterpretations are atmospheric fronts identified around the equator and around the transition between equatorial and tropical air masses, which are almost certainly not fronts.

The possibility of objective front analysis opened up with the advent of computer technology, which enabled the processing of a large amount of available data and limited subjective inputs. Renard and Clarke (1965) devised a method of frontal analysis using a change in temperature gradient using the thermal front parameter. This method subsequently became one of the most widely used methods of objective front analysis (e.g. in Berry, Reeder, Jakob 2011; Berry, Jakob, Reeder 2011; Catto et al. 2012, 2013, 2014; Catto, Pfahl 2013; Schemm, Rudeva, Simmonds 2014). The wind method uses a change in wind direction and speed (Simmonds, Keay, Bye 2012; Schemm, Rudeva, Simmonds 2014) and the frontal index combines air temperature and wind (Solman, Orlanski 2010, 2014, 2016; Blázquez, Solman 2016, 2017, 2018). Implementation of these methods still contains subjective elements (Thomas, Schultz 2019b), which is almost entirely removed by the latest method using artificial neutral networks and deep learning removes (Biard, Kunkel 2019; Lagerquist, McGovern, Gagne 2019; Lagerquist, Allen, McGovern 2020).

Objective analyses of atmospheric fronts have enabled global climatology to be created and provide various connections between atmospheric fronts and meteorological and climatological variables. All climatologies agree in the main features. Most fronts are located in midlatitude storm track region, maximum frontal activity shifts during the year and warm fronts occur more poleward than cold fronts. All authors concur in that most precipitation is connected with atmospheric fronts in midlatitudes (Catto et al. 2012; Solman, Orlanski 2014; Blázquez, Solman 2018; Hénin et al. 2019). Some details of analyses disagree (Catto et al. 2012, Hénin et al. 2019) as results depend on the setting of objective analysis and input data (Hénin et al. 2019). The effect of atmospheric fronts on surface temperature and its variability has not been examined yet. The maximum frontal activity has moved poleward since the mid-twentieth century (Berry, Jakob, Reeder, 2011; Catto et al. 2014; Solman, Orlanski 2014; Rudeva, Simmonds 2015; Blázquez, Solman 2018; Lagerquist, Allen, McGovern 2020), and this development is likely to continue (Catto et al. 2014; Blázquez, Solman 2019).

Many aspects of atmospheric fronts have been properly explored. However, there are still many inconsistencies, uncertainties and unexplored areas that are waiting for their clarification, e.g. (i) the existence of a front is better represented by a line or values of frontal parameters exceeding a certain threshold and how it affects the climatology of fronts; (ii) connection of fronts with surface temperature and its short-term (day-to-day in particular) changes; and thus (iii) the contribution of fronts to the distribution of day-to-day changes in surface temperature and its asymmetry. All these open questions will be investigated in our studies in near future.

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