Beyond cold and warm: an objective classification for maritime midlatitude fronts

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This study introduces a detailed and objective classification for midlatitude maritime fronts. The classification is based on a principal component analysis (PCA) to determine the dominant patterns of variability between fronts. Here, fronts are defined as three-dimensional frontal volumes, which are detected in the ERA-Interim dataset for a large number of locations in the Atlantic, Pacific and Indian oceans during both winter and summer. In addition to the well-established distinction between warm and cold fronts, the PCA exposes several new dimensions of variability: (i) front intensity, (ii) surface fluxes and (iii) along-front transports, linked to the intensity of the associated conveyor belts. These new dimensions of variability are regionally and seasonally robust and a lagged composite analysis demonstrates that each of the new front types evolves in a dynamically characteristic way. Further, the new front types can be related to established ones like katafronts and anafronts. The new front types are finally redefined based on simple parameter thresholds to simplify their application in future studies.

Key Words: fronts; front classification; feature detection

1. Introduction

Fronts are one of the essential building blocks of extratropical cyclones and hence midlatitude atmospheric dynamics (Shapiro and Keyser, 1990; Bjerknes, 1919). They go along with temperature changes, precipitation and winds that shape the public perception of weather in these regions. In some instances, the precipitation and wind speeds associated with fronts qualify as extreme weather and can lead to severe damage (Catto et al., 2012, 2015; Catto and Pfahl, 2013; Schemm et al., 2017a). For a conceptual understanding of fronts, it is essential to differentiate between front types. The conceptual models of Bjerknes (1919) and Shapiro and Keyser (1990) distinguish between warm and cold fronts, occlusions and bent-back fronts. Each of these front types is associated with a characteristic sequence of surface weather and plays a well-defined role in the conceptual life cycle of an extratropical cyclone.

Cold fronts can be subdivided further into anabatic and katabatic cold fronts (in the following anafronts and katafronts), depending on the movement of the warm air along the frontal surface (Bergeron, 1937; Sansom, 1951; Moore and Smith, 1989): the warm air is descending along the frontal surface for katafronts and ascending for anafronts. Although Sansom (1951) documented large differences in surface weather associated with anafronts and katafronts over the British Isles, this distinction has not been widely adopted, in particular in more recent decades. Nevertheless, Browning and Monk (1982) documented that, for some katafronts, the frontal surface can advance more quickly in the upper levels, leading to a forward-sloping frontal surface, in contrast to the backward-sloping one prevalent in anafronts. However, this distinction seems to have been put into use even less frequently than the distinction between ana- and katafronts.

Even though these classifications are not widely used, in many contexts it would be advantageous to have available a more detailed front-type classification. For example, for front–orography interactions, varying degrees of orographic blocking have been documented in idealized models (e.g. Davies, 1984; Egger and Hoinka, 1992; Braun et al., 1999) and case studies of cold fronts (e.g. Braun et al., 1997; Kljun et al., 2001; Neiman et al., 2004). The degree of blocking in turn impacts the following synoptic evolution and, in particular, the occurrence of lee cyclogenesis (e.g. Egger, 1995; Kljun et al., 2001). Phenomena like barrier jets or the breaking-up of the front into sections are also influenced by front–orography interactions, as is the relative importance of frontogenetical and frontolitical processes. Hence, a more detailed classification would help to order and conceptualize the various ways in which fronts are affected by orography. Although most studies on front–orography interactions focus on cold fronts, the same line of argument also holds for warm fronts, where no further sub-classification is currently available.

A more detailed front-type classification would also provide a framework to describe observed differences between cyclones better (Schemm et al., 2017b). Fronts evolve differently during the later stages in the Norwegian and Shapiro–Keyser cyclone models and this likely already manifests itself in different properties of the
incipient cold and warm fronts during the respective early stages of cyclone development. Similarly, the degree to which diabatic processes modify cyclones might manifest itself in different front types, as could the different processes leading to cyclogenesis (e.g. Petterssen and Smebye, 1971; Plant et al., 2003; Dacre and Gray, 2006; Schemm and Sprenger, 2015).

The aim of this article is therefore to propose an objective yet dynamically meaningful classification of midlatitude maritime fronts that could provide the foundation for such studies. We aim for a classification that is not limited to a specific location, storm track or season and hence adopt a climatological perspective based on reanalysis data.

2. Front detection and classification

For our front classification, we require a front-detection scheme that allows us to track and visualize the evolution of fronts globally. Further, the scheme should reliably detect fronts close to orography to allow its application in future studies on front–orography interactions. At the same time, we strive to avoid smoothing the input fields to retain the full smaller-scale detail available in the dataset.

A number of approaches have previously been suggested to detect fronts objectively, but none of them fulfills our requirements sufficiently. Sanders and Doswell (1995), Sanders (1999) and Sanders and Hoffman (2002) detect fronts based on the near-surface temperature distribution. Unfortunately, there is no climatology published for fronts defined in this manner, particularly if the individual procedure is difficult to automate, due to a noisy surface temperature field. Hewson (1998) and Berry et al. (2011) automatically detect thermodynamic front lines, but require a third derivative of a thermodynamic field η to pinpoint the exact location of the front line. The third derivative leads to a strong amplification of small-scale gradients, which causes problems in the vicinity of orography and at high latitudes. Nevertheless, Jenkner et al. (2010) use an approach closely related to Hewson (1998) and Berry et al. (2011) to detect fronts in a high-resolution reanalysis dataset covering the Alps. They mitigate the numerical sensitivity of the algorithm by a modified criterion to locate the front line that only requires a second derivative, but nevertheless resort to a heavily smoothed thermodynamic field at 700 hPa to detect front lines. Finally, Schemm et al. (2015) refine the Jenkner et al. (2010) detection scheme and apply to it the climatology, we find a very good agreement between the line- and volume-detection methods, because nearly all front volumes match a detected front line.

Climatologically, frontal volume detections over the oceans follow the storm-track location closely (Figure 2), with a slight focus towards the equatorward entrance of the respective storm track. In this respect, our front volume detection is consistent with published front-line climatologies (Berry et al., 2011; Schemm et al., 2015). In addition to these maritime fronts, our method picks up large-scale land–sea contrasts in the summer hemisphere. As these contrasts are comparatively immobile, they result in locally very high detection rates exceeding 0.3. In the winter hemisphere, however, land–sea contrasts are too spatially scattered to fulfill our minimum size requirement.

Along the storm tracks, front volumes are more frequently detected in the summer hemisphere (Figure 2). The front-line climatologies in Berry et al. (2011) and Schemm et al. (2015) exhibit the same behaviour for the Southern Hemisphere storm track, even though the increases in detection rates are less pronounced. However, for the Northern Hemisphere storm tracks, detection rates for all variants of front lines peak during winter. As our detection scheme is based on the same data as the Schemm et al. (2015) thermodynamic scheme and uses a very similar |∇θ|K threshold, the different Northern Hemisphere seasonal cycles are likely due to variations in the across-front length-scale of the front. In our frontal volume detection, widened front zones lead to an increased detection rate, whereas the detection rate of front lines is unaffected.

2.2. Regional front volumes

As apparent in the snapshot in Figure 1, frontal volumes can in some cases extend over large parts of the North Atlantic. In such cases, frontal characteristics vary considerably along the length of the frontal volume, such that the front cannot meaningfully be represented by a single set of characteristics. For example, within...
Figure 1. Detected frontal volumes, defined as coherent volumes exceeding a $|\nabla \theta|$ threshold and a minimum size, in colour, and Schemm et al. (2015) front lines for a synoptic example from 27 January 1984 at 0000 UTC. Different colours indicate different front objects and are consistent through the panels, but are independent from the colour codes used for the variability patterns below. Grey shading shows equivalent potential temperature in K with a contour interval of 2.5 K. The panels show (a) 700 hPa, (b) 850 hPa and (c) 925 hPa, respectively. [Colour figure can be viewed at wileyonlinelibrary.com].

Figure 2. Seasonal frontal volume detection rates at 850 hPa for (a) DJF, (b) MAM, (c) JJA and (d) SON. [Colour figure can be viewed at wileyonlinelibrary.com].
Table 1. List of parameters used in the principal component analysis.

| Parameter                                      | Symbol | Pattern |
|------------------------------------------------|--------|---------|
| Squared Brunt–Väisälä frequency                | $N^2$  |         |
| Convective Available Potential                 | CAPE   |         |
| Energy                                          | $\delta$ | Kinematic intensity (green) |
| Deformation, stretching in natural coordinates | $\sigma$ | Along-front transports (pink) |
| Deformation, total $\delta$                    | $\tau$ | Moist baroclinicity (yellow) |
| Divergence, isobaric $\sigma$                  | $\theta$ | Advection type (orange) |
| Equivalent potential temperature $\theta$      | $D$    | Kinematic intensity (green) |
| Frontal volume intersection with isobaric surface | $A$ |         |
| Isentropic slope $\delta$                      | $S$    | Moist baroclinicity (yellow) |
| Moisture transport, parallel to $\theta$       | $\sigma_n$ | Advection type (orange) |
| Moisture transport, perpendicular to $\theta$   | $\sigma_n$ |         |
| Precipitation, convective $P_c$                 | $P_c$  |         |
| Precipitation, large-scale $n$                  | $\omega$ | Moist baroclinicity (yellow) |
| Quasi-geostrophic omega $\omega$                | $R$    | Along-front transports (pink) |
| Relative humidity                               | $\tau$ | Advection type (orange) |
| Heat transport, parallel to $\theta$           | $\tau$ | Advection type (orange) |
| Heat transport, perpendicular to $\theta$       | $\tau$ | Surface fluxes (dark red) |
| Surface latent heat flux $\sigma_l$             | $S$    | Surface fluxes (dark red) |
| Surface sensible heat flux $\tau_z$             | $E$    |         |
| Wind speed                                      | $U$    |         |

Defining parameters for their respective variability pattern are marked bold. * Additional information in Spensberger and Spengler (2014).
† Additional information in Papritz and Spengler (2015).

one frontal volume, some parts might show warm-air advection while others show cold air advection.

For this reason, in the following analysis we consider the intersections of all frontal volumes with predefined regions. We call these intersections regional front volumes. The regions are defined by circles with a radius of 700 km around an array of reference points from 69° W to 3° E and 30° N to 60° N with a spacing of 3° in both longitude and latitude, yielding a total of 275 regions (and analogously for other ocean basins, see Appendix B).

Some regional front volumes are very small, because the full frontal volume and the target region barely overlap. For the following classification, we therefore select only the regional front volumes that reach within 200 km of the respective reference point. In summary, we use a 700 km radius for the definition (and later characterization) of the regional front volumes, but a 200 km radius for the selection of regional front volumes to be included in the analysis. With this selection criterion, we obtain a set of suitable regional front volumes for each of our regions, on which we can base the front-type classification.

2.3. Front-type classification method

For the classification, we first characterize the regional front volumes by the median of several parameters within the regional front volume (Table 1). The only exception is front size, where we instead include the size of the intersection with the 850 hPa surface. The parameters listed in Table 1 capture both kinematic and thermodynamic properties of the front volumes comprehensively, while at the same time avoiding redundancy. Redundant parameters can pose problems because they potentially skew the results of the statistical analysis.

Figure 3(a) shows the normalized distribution for selected parameters for all regional front volumes belonging to an example region (centred on 54° N, 30° W). While the parameters in Figure 3(a) by-and-large follow a Gaussian distribution, others like precipitation or relative humidity have upper or lower bounds and are hence strongly non-Gaussian (Figure 3(b)).

We then follow the methodology of Graf et al. (2017) and for each region use a principal component (PC) analysis to determine the groups of parameters that explain most variance between the different regional front volumes linked to each particular region. In contrast to Graf et al. (2017), we rotate the eight leading PCs using the Varimax criterion (Kaiser, 1958), which tries to minimize the number of parameters that contribute to each PC and thereby simplify the physical interpretation of the PCs.

About 1.7% of the consecutive PC pairs in the underlying PC analyses for all regions are degenerate, according to the rule-of-thumb of North et al. (1982). For such degenerate PC pairs, the difference in explained variance is too small to allow a clear separation of the PCs in the presence of sampling errors. Our front-type classification in the following section is based on rotated PC that recur in nearly all regions, such that degenerate PCs in a small number of regions can hardly affect the front-type classification.

The eight leading PCs typically represent more than 80% of the total variance, although the exact fraction depends on the region considered. This fraction does not change in the Varimax rotation: the explained variance is only redistributed between the eight leading PCs. Furthermore, as Varimax is an orthogonal rotation, the rotated PCs remain linearly independent.

3. Patterns of front variability from recurring PCs

So far, the rotated principal components (RPCs) are based on the analysis for one specific region (e.g. the one centred around 54° N, 30° W). They therefore represent the local variability between fronts and do not allow for any inferences on globally applicable front types. However, when repeating the analysis for all the regions (as defined in section 2.2), we note that some RPCs recur in very similar form. In particular, five RPCs stand out in that they recur for nearly all regions and typically even amongst the leading RPCs. This recurrence at different positions relative

![Figure 3](image-url)
to the storm track, in different seasons and also in different ocean basins (Appendix B), suggests that the five RPCs represent a universal variability pattern between maritime fronts. In the following, we use the term ‘RPC’ only for the local result of the rotated principal component analysis, whereas the term ‘variability pattern’ applies for a recurring kind of RPC. We also assign a colour to each variability pattern to mark its appearance in figures where applicable (Table 1, for the colour coding in the figures please refer to the online version of the article.).

Figure 4 illustrates the step from the RPCs to the variability patterns, using the analysis results for the example region around 54°N, 30°W. In the so-called biplots, each axis corresponds to one RPC. While dots in Figure 4 represent the characteristics of the individual regional front volumes that were included in the analysis, large grey and coloured circles show how the different parameters contribute to the RPCs. If a parameter circle projects strongly on to a RPC axis, it correspondingly contributes strongly to the respective RPC.

In the biplots, it is the coloured circles that establish the link from a given local RPC to a universal variability pattern. They indicate groups of parameters that project on to the same RPC in nearly all regions and seasons. For the example region, green (kinematic intensity, $\delta$, $D$), orange (advection type, $\sigma_{n}$, $\tau_{n}$), dark red (surface fluxes, $\sigma_{z}$, $\tau_{z}$), pink (along-front transports, $\sigma_{s}$, $\tau_{s}$) and yellow (moist baroclinicity, $S$, $R$) circles project both significantly and most strongly on to the RPC axes 1, 2, 3, 4 and 7, respectively. We therefore identify these five RPCs as the local representation of the respectively coloured variability patterns. To demonstrate the recurrence and illustrate the methodology by further examples, we show two additional biplots for different regions in Appendix C.

To some of the RPCs, other (grey) parameters contribute similarly strongly to the coloured parameters. Hence, based on Figure 4(a) only, one would be inclined to define a variability pattern based on $\delta$, $D$, $P_{h}$ and $\omega$, because they all project strongly on to the RPC 1 axis. However, only divergence $\delta$ and deformation $D$ co-vary consistently for all regions and seasons, such that we define the green variability pattern by $\delta$ and $D$ only. Analogous arguments apply to $\theta$ in the dark red pattern in RPC 3 and $U$ in the yellow pattern in RPC 7.

So far, we have identified five variability patterns and, for the example region, have attributed them to five corresponding RPCs. The attribution allows us to quantify the fraction of variance explained by a variability pattern. According to Figure 4,

Figure 4. Biplots for (a) RPC 1 & 2, (b) RPC 3 & 4 and (c) RPC 7 & 8 and regional frontal volumes in the central Atlantic close to 30°W and 54°N during winter. Parameters belonging to the patterns are highlighted in colour: (green) kinematic intensity, (dark red) surface fluxes, (orange) advection type, (pink) along-front transports and (yellow) moist baroclinicity. Large grey dots show additional parameters in the RPC analysis that are not part of any pattern and small grey dots show all regional front volumes in the dataset used for the analysis. Dots and circles inside the unit circle are dimmed. Parameters projecting outside the unit circle are considered significant and are annotated. [Colour figure can be viewed at wileyonlinelibrary.com].

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Figure 5. Spatial distribution of the explained variance during winter for the following patterns: (a) kinematic intensity, (b) moist baroclinicity, (c) advection type, (d) along-front transport, (e) surface fluxes and (f) the leading unclassifiable pattern for DJF. Contours show climatological frontal volume detection rates with contours from 0.06 to 0.14 in steps of 0.04. The example regions used in the text and Appendix C are highlighted by thickened white and light grey borders, respectively. [Colour figure can be viewed at wileyonlinelibrary.com].

The green pattern explains 15.3% of the variance, the orange 14.6%, the dark red 13.7%, the pink 11.4% and the yellow 7.8%. Figures 5 and 6 show how these results for the example region generalize to the North Atlantic by geographically mapping the explained variance associated with each variability pattern. The maps demonstrate that the orange, pink and dark red variability patterns occur throughout the Atlantic array of regions with very few exceptions, in both summer and winter.

The maps of explained variance for the green and yellow patterns are more patchy, in particular during summer. The reason for that patchiness is, as will be shown later, a conceptual similarity between the two variability patterns. As a consequence of this similarity, in some regions one RPC matches both the yellow and green pattern. If, in such a region, they project similarly strongly on to one RPC, we cannot disentangle the patterns and attribute the explained variance to both of them. The explained variance maps for winter exhibit some regions with such a double attribution just to the south of Iceland and east of the Canary Islands, where the two patterns jointly explain more than 15% of the variance. When, in contrast, one of the two patterns projects considerably more strongly on to the RPC than the other, the RPC will only be attributed to the stronger pattern. In that case, the weaker pattern typically will not occur again as one of the higher RPCs, leaving a gap in the explained variance maps.

The same five variability patterns also occur in other ocean basins. The meridional variations of the explained variance are largely consistent with those in the North Atlantic (Appendix

† The exact definition follows from that of a match between a RPC and a variability pattern: all of the parameters of the variability pattern must project significantly on to the RPC in question and by at least half as much as the maximum projection of any parameter. Hence, considerably more strongly means that the projection of at least one parameter of the weaker variability pattern is less than half of that of the strongest projecting parameter.
B). Hence, our five variability patterns do not reflect a regional feature of the North Atlantic, but represent globally applicable front types. In the following, we describe the different front types in greater detail.

3.1. Advection type (orange)

First off, we focus on the orange circles that make up RPC 2 in the example region, because this variability pattern can serve as a proof-of-concept for our analysis method. It is defined by two parameters:

1. heat transport perpendicular to $\theta_E$ isolines ($\tau_n$)
2. moisture transport perpendicular to $\theta_E$ isolines ($\sigma_n$).

These parameters distinguish fronts advecting warm and moist air from those advecting cold and dry air. Hence, the variability pattern captures the established distinction between warm and cold fronts.

A lagged composite analysis supports this interpretation (Figure 7). This and the following composites are based on the RPC index exceeding $\pm 1$ and contain approximately 660 cases each. The front at the reference point at lag $\Delta t = 0$ is associated with the arrival of either a cold air mass from the northwest (Figures 7(a) and (c)) or a warm air mass from the south (Figures 7(b) and (d)). In both cases, the moving air masses are associated with developing baroclinic disturbances, which, however, differ in their maturity. Indeed, the comparatively smaller vertical tilt of the system and larger magnitude of the geopotential anomalies in the cold composites (Figures 7(a) and (c)) indicate that the cyclones contributing to this composite are more mature than the ones in the warm composite (Figures 7(b) and (d)). The shape of the frontal structures for both composites is in line with the Shapiro and Keyser (1990) model, which is characterized by a long curved cold front with a trailing end and a shorter combined bent-back and warm front.
According to the maps of explained variance, the distinction between warm and cold fronts is not equally important for all regions (Figures 5(c) and 6(c)). The pattern consistently explains most variance in the poleward exit of the Atlantic storm track and exhibits little difference between summer and winter. In the more temperate latitudes, however, it is less important – most likely reflecting the predominance of cold fronts on the equatorward side of the main storm track.

The consistent interpretation of the orange variability pattern as the difference between warm and cold fronts supports the usefulness of our method. Without prior knowledge, we are able to recover this distinction as one of the dominant variability patterns. It is hence plausible that the other variability patterns introduced in the following also point to physically meaningful distinctions between fronts.

### 3.2 Kinematic intensity (green) and moist baroclinicity (yellow)

RPC 1 in the example region represents the kinematic intensity pattern. As it co-varies with the moist baroclinicity pattern in some regions, we discuss the two patterns together.

The kinematic intensity pattern is defined by the following parameters:

1. total deformation ($\delta$) and
2. convergence ($-D$),

whereas the moist baroclinicity pattern is defined by

1. the local slope of the isentropic surface ($S$) and
2. relative humidity ($R$).

Total deformation reflects the stretching and shearing of the wind field across the front and hence measures this aspect of front intensity. In addition, both strong deformation and strong convergence require a more vigorous balancing frontal circulation, which again is a kinematic measure of front intensity. In contrast, we interpret the combination of increased relative humidity with steep isentropic slopes as a measure for the thermodynamic intensity of the front. Steep isentropic slopes combined with high humidity can cause phase changes due to adiabatic upglide or, conversely, are themselves the result of diabatic heating (Papritz and Spengler, 2015).

This interpretation of both variability patterns as measures for different aspects of front intensity provides a plausible explanation as to why they align in some regions. The two patterns tend to co-vary at the fringes of the storm track during winter (Figures 5(a) and (b)). Here, the identical spatial pattern of explained variance indicates that both variability patterns are attributed to the same RPC. A somewhat different situation is found in the Gulf Stream region, along the United States East Coast. There, the local maximum in explained variance of the kinematic intensity pattern coincides with a vanishing contribution of the moist baroclinicity pattern. Hence, in this region, both patterns do also co-vary, but with kinematic intensity dominating moist baroclinicity, such that the respective RPCs are only attributed to the kinematic intensity pattern (Figures 5(a) and (b)). During summer, the two patterns generally become less
important, but together they still explain a considerable amount of variance in the Gulf Stream region (Figures 6(a) and (b)). The similarities in the lagged composite evolution of the two front types supports our common interpretation (Figures 8 and 9). In particular, kinematically weak (Figures 8(b) and (d)) and less moist baroclinic fronts (Figures 9(b) and (d)) evolve very similarly and propagate slowly from a cyclonically dominated region towards the centre of an anticyclonic anomaly. In contrast, in the composite evolution, kinematically intense fronts form in an explosively developing cyclone (Figures 8(a) and (c)). For moist baroclinic fronts, the horizontal extent of the cyclonic anomaly is, however, considerably smaller (Figures 9(a) and (c)), indicating that diabatic Rossby vortices (e.g. Boettcher and Wernli, 2013) contribute to the composite (Figures 8(c) and 9(c)). Despite the difference, the general spatial configuration of the temperature and geopotential anomalies is also quite similar for moist baroclinic and kinematically intense fronts.

3.3. Surface fluxes (dark red)

The third RPC in our example region represents the variability pattern linked to surface fluxes. Unsurprisingly, the pattern is defined by

1. surface sensible heat fluxes \( \tau_s \)
2. surface latent heat fluxes \( \sigma_s \).

Consequently, this variability pattern distinguishes between fronts that are either heated or cooled by the ocean. In the composite for weak (or even negative) heat fluxes, the front evolves in conjunction with very strong warm advection from the south (Figures 10(a) and (c)), as discernible from the narrow spacing of the geopotential and surface-pressure isolines between a trough–ridge couplet (Figures 10(c)). The associated warm temperature anomaly is, in fact, the strongest of all the composites. In contrast, high-flux fronts typically occur along the leading edge of a cold-air outbreak originating from Arctic Canada and the Labrador area (Figures 10(b) and (d)). As the outbreak boundary is rather diffuse and the temperature and geopotential anomalies are not particularly strong, we expect a considerable variability between the cases contributing to the high-flux composite.

In winter, the distinction by surface fluxes is most important around the southern tip of Greenland, but also in a belt surrounding the climatological maximum of front occurrence (Figure 5(e)). In contrast, surface fluxes explain only a little variance over the Iberian peninsula and North Africa. During summer, however, these southern land regions dominate the explained variance map. The particularly high sensible heat fluxes over the hot land masses (Figure 6(c)) are likely associated with land–sea circulations. Over the ocean during summer, the explained variance is considerably reduced, with only a secondary maximum to the southeast of Greenland.

3.4. Along-front transports (pink)

The fourth RPC in our example region and final pattern of variability is defined by

1. heat transport parallel to \( \theta_e \) isolines \( \tau_e \)
2. moisture transport parallel to \( \theta_e \) isolines \( \sigma_e \).

As these transports are largely along-front, we interpret them as measures for the strength of the conveyor belts adjacent to the front (e.g. Madonna et al., 2014, and references therein).

The composite evolution for large along-front transports (Figures 11(a) and (c)) follows closely that for cold fronts (Figures 7(a) and (c)). They differ, however, in important details. In contrast to the composite for cold fronts (Figure 7(c)), here the isolines of geopotential and surface pressure are mainly oriented along the front (Figure 11(c)). Fronts with weak along-front transports typically occur as part of a weak cyclonic anomaly embedded in a large-scale situation with reduced westerly flow (Figures 11(b) and (d)). Furthermore, they are typically located at the leading edge of a warm anomaly, in contrast to the cold anomaly in the composite for large along-front transports.

During both summer and winter, the distinction between strong and weak along-front transports is more important on the equatorward side of the main storm track (Figures 5(d) and 6(d)), with the meridional contrast being slightly more emphasized during winter. Except for this, the explained variance depends only weakly on season.

4. Simplified redefinition the variability patterns

The composite analyses of the preceding section point to several new physically meaningful front types. Unfortunately, the defining method was rather lengthy and complicated, making it hard to apply the classification outside this study. However, we can redefine the variability patterns in a much simpler way based on single parameter thresholds.

The basic idea for the redefinition is to substitute the RPC scores characterizing each regional front volume by one of the parameters that went into the analysis. Specifically, we substitute the RPC scores by the value for the first defining parameter of the respective variability pattern (also marked bold in Table 1). For instance, in section 3.4 the along-front pattern was defined based on heat and moisture transport parallel to the \( \theta_e \) isolines, with potentially regionally varying additional contributors to the respective RPCs. In the simplified definition, we rely instead on the heat transport alone as the defining parameter.

The correlations between the values of the defining parameters for the different variability patterns and the RPC scores are generally between 0.80 and 0.95. Hence, given these high correlations, the respective defining parameter can suitably be taken as a substitute for the RPC. To test the correspondence, we repeated the composite analysis, but selected the composite members based on the defining parameter values instead of the RPC scores. To this end, the parameter thresholds for the composites were generalized from \( \pm 1 \) standard deviation to the respective 15th and 85th percentiles to account for deviations from a Gaussian distribution.

With the exception of moist baroclinicity, the resulting composites in Figure 12 are almost indistinguishable from the original ones presented earlier. In Figure 12, the correspondence is shown only for lag \( \Delta t = 0 \), but the close relation between the original and simplified classification holds throughout the evolution. For moist baroclinicity, the composites still share the synoptic structure, but, for example, the cyclonic anomaly in Figure 12(f) is more pronounced and extends further meridionally than in the original composite (Figure 9(c)).

In summary, the correspondence between the original and simplified front types indicates that fronts can be classified based on the local values for total deformation \( \delta \) (kinematic intensity), isentropic slope \( S \) (moist baroclinicity), front-normal heat transport \( \tau_s \) (advection type), surface sensible heat flux \( \tau_s \) (surface fluxes) and front-parallel heat transport \( \sigma_e \) (along-front transports). The simplified redefinitions therefore provide a conceptually simple way to characterize fronts by two complimentary measures of front intensity and the heat fluxes/transport in three spatial dimensions. As an additional benefit, the simplified definition translates the classification based on the statistical abstract PC analysis back into the physical realm with meteorologically intuitive parameters.

5. Relation to alternative front-type definitions

To understand how our front-type classification relates to established classifications, it is instructive to return to the snapshot in Figure 1 and classify the fronts detected in this example...
Figure 8. As Figure 7, but for (a, c) kinematically intense and (b, d) kinematically weak fronts during winter. All contours shown exceed the 99% significance level. [Colour figure can be viewed at wileyonlinelibrary.com].

Figure 9. As Figure 7, but for (a, c) more and (b, d) less moist baroclinic fronts during winter. All contours shown exceed the 99% significance level. [Colour figure can be viewed at wileyonlinelibrary.com].
Figure 10. As Figure 7, but for fronts with (a, c) weak surface fluxes and (b, d) strong surface fluxes during winter. All contours shown exceed the 99% significance level. [Colour figure can be viewed at wileyonlinelibrary.com].

Figure 11. As Figure 7, but for fronts with (a, c) strong and (b, d) weak along-front transports during winter. All contours shown exceed the 99% significance level. [Colour figure can be viewed at wileyonlinelibrary.com].
situation. To this end, Figure 13 shows the same snapshot but with the frontal areas coloured by the local value of four of our defining parameters. As the snapshot is from winter, where we found deformation to be a better measure for front intensity than moist baroclinicity, here we only show deformation.

The front-normal transports in Figure 13(a) fit well with our previous interpretation as the distinction between warm and cold fronts. These transports are generally largest near the junction point in the T-bone structure and taper off towards the front tips. The cut-off section of the bent-back front exhibits weak front-normal transports of both signs. At the same time, strong deformation occurs in the transition section between the warm and bent-back fronts, where the front starts to interact with the southern tip of Greenland. In addition, the cut-off part of the
bent-back front and a section of the cold front that is slightly detached from the junction point are associated with strong deformation. The areas of strongest deformation are also the areas in which the along-front transports are largest for both signs (Figure 13(b) and (d)). To make sense of the sensible heat fluxes close to the junction point in Figure 13(c), it is important to bear in mind that the fluxes are averaged for the preceding 6 h. Hence, the grid cells along the warm front will largely have been in the cold air mass and thus heated by the ocean, while the area under the northern tip of the cold front was located in the warm sector and consequently lost heat to the ocean. Interestingly, in this case at least, the area with the strongest deformation and along-front transports within the cold front is associated with hardly any surface fluxes.

Both this case study and the composite analysis suggest that our front-type classification can be related to established classifications. For cold and warm fronts, the translation into our type classification is straightforward: the dimension advection type captures this distinction very well. However, a subtlety has to be considered for near-stationary fronts. Synopticians tend to assign the advection type of near-stationary fronts based on their dynamical origins, such that a cold front stays a cold front until it decays or becomes retrograde. This is in contrast to any objective classification that relies on instantaneous front characteristics. Hence, this mismatch is not limited to our front classification, but also applies to the schemes of Hewson (1998), Berry et al. (2011) and Schemm et al. (2015).

Occluded and bent-back fronts likely belong to the category of near-neutral normal transports and there is no other single dimension that encapsulates their characteristics clearly. The composites for intense fronts, however, generally display the synoptic situation one would expect around bent-back fronts. Hence, we expect them to contain a substantial fraction of such fronts, leading us to speculate that the combination of near-neutral advection with strong (kinematic) intensity provides a useful definition of a bent-back front in our classification. This definition would fit the synoptic snapshot in Figure 13. Conversely, occluded fronts might be characterized appropriately by a combination of near-neutral advection with moderate or weak intensity.

Also anafronts and katafronts are potentially well described by a combination of advection type and intensity. According to Sansom (1951), anafronts are associated with a stronger wind shift across the front compared with katafronts and thus higher kinematic intensity. In addition, the wind direction changes more strongly with height for anafronts, implying stronger cold advection. Hence, ana- and katafronts might be distinguished with either a further subdivision of the cold-advection type or a separation between kinematically intense and weak cold fronts. The re-interpretation of these front types also provides a conceptually meaningful way to translate the distinction between anafronts and katafronts to warm fronts by separating, for example, intense and weak warm fronts.

Browning and Monk (1982) showed that all katafronts considered over the British Isles exhibit a ‘split front’ structure, in which the lower part of the cold front is retarded by the warm conveyor belt. Browning et al. (1997) call the resulting frontal structure ‘forward-sloping’ because the upper-level front precedes...
the surface front, whereas in anafronts the surface front arrives first. As the warm conveyor belt plays a dynamically important role in retarding the advance of the surface front, we expect the forward-sloping fronts to belong to the category of cold fronts with strong along-front transports. Interestingly, the descriptions of Sansom (1951) and Browning and Monk (1982) suggest different representations for katafronts and forward-sloping fronts in our front-type classification, whereas Browning et al. (1997) uses these concepts interchangeably, thereby implying that they might be equivalent.

In addition to the mentioned front types, our classification provides many more types that do not correspond to a traditional front type. In fact, if we split each dimension into three parts, for example by tercile to separate above, near and below average parameter values, the analysis results in a total of $3^4 = 81$ different front types (here counting the two measures of intensity as only one dimension). Figure 14 shows the distribution of real fronts in this parameter space for both summer and winter. While the distribution of fronts in this parameter space is inhomogeneous, in particular during winter, a considerable number of fronts belong to each front type. The least frequent front type contains 3076 members during winter and 8889 during summer. In both seasons, the most frequent front type is the combination of cold advection, above-average along-front transports and surface fluxes as well as weak kinematic intensity. Besides the more even distribution of the regional front volumes in the parameter space during summer, the seasons differ particularly in the shift from more frequent negative surface fluxes during winter to positive surface fluxes during summer for the combination of warm advection, below-average along-front transports and high kinematic intensity.

Note that, while in this analysis we use terciles in each dimension to subdivide the parameter space into 81 bins, both the subdivision of the parameter space and the thresholds will depend on the application, as not every application will require the same amount of detail in each dimension.

6. Summary and conclusions

We propose a comprehensive and objective classification for maritime midlatitude fronts. The classification is based on frontal volumes (defined as coherent volumes exceeding a minimum $\theta_E$ gradient between 700 and 950 hPa and a minimum size) in the ERA-Interim dataset. To capture the changing front properties along the front, we subdivide the frontal volumes using intersections with predefined regions. We characterize each regional frontal volume by a number of kinematic and thermodynamic parameters (listed in Table 1). Using a principal component (PC) analysis, we then calculate the leading patterns of variability of these parameters between different regional front volumes in the same region.

The PC analyses reveal four (to five) patterns of variability that recur consistently in summer and winter and for nearly all regions in the North Atlantic and other ocean basins. These variability patterns provide the basis for our front-type classification. A lagged composite analysis demonstrates that the thus-defined front types are each associated with a distinct dynamical evolution.

- The first variability pattern (front type) is based on the heat and moisture transport perpendicular to $\theta_E$ isolines ($\tau_{\theta} \sigma_a$). The pattern corresponds closely to the established distinction between warm and cold fronts and serves as a proof of concept for our classification method, because it rediscover this important distinction without a pre-imposition of that knowledge.

- The second front type is based on the kinematic intensity of the front, as measured by total deformation $\delta$ and convergence $-D$ of the flow field. In many regions, it is related to the moist baroclinicity pattern (local slope $S$ of isentropic surfaces and relative humidity $R$), which we interpret as a thermodynamic measure of front intensity. The extreme ends in the spectrum of both intensity measures are populated by what are traditionally considered bent-back fronts during explosive cyclogenesis and trailing fronts slowly decaying in an anticyclonically dominated area. Furthermore, kinematic intensity provides a link to the Simmonds et al. (2012) front-detection scheme, because their wind-based detection criterion in essence requires a minimum kinematic intensity in our description.

- Surface sensible and latent heat fluxes ($\tau_s \sigma_a$) capture a considerable fraction of the variance between maritime fronts consistently, thus defining the third front type. These fluxes depend strongly on the temperature contrast between the sea surface and the atmospheric boundary layer. Accordingly, in the North Atlantic, this front type is particularly important in an area to the south of Greenland that is frequently covered by both cold-air outbreaks and cyclone warm sectors.

- The final variability pattern that recurs consistently in nearly all regions is based on along-front transports (i.e. parallel to $\theta_E$ isolines) of heat and moisture ($\tau_{\theta} \sigma_a$). The transports are generally associated with a conveyor belt. Therefore we interpret this pattern as a reflection of the intensity of the conveyor belt associated with the front.

The synoptic characteristics of bent-back fronts, occlusions, katafronts and anafronts suggest that these front types correspond to a combination of the four dimensions in our classification. Bent-back fronts and occlusions likely correspond to the combination of near-neutral advection with strong or weak intensity, respectively. The distinction between katafronts and anafronts potentially translates to cold fronts with varying kinematic intensity. However, the conceptual similarity between katafronts and the Browning and Monk (1982) split cold fronts suggests that the strength of along-front transports might also need to be taken into account in the definition of katafronts.

There is an ongoing discussion on the role of gradients and fronts in sea-surface temperature (SST) of individual cyclones as well as the overall storm tracks (e.g. Sanders and Gyakum, 1980; Hotta and Nakamura, 2011; Papritz and Spengler, 2015). In this light, it is interesting to note that our method identifies surface fluxes as one of the main dimensions of variability between maritime fronts. Hence, the interaction of SST gradients with atmospheric fronts potentially plays an integral role in the way that SSTs affect cyclones in their entirety. Therefore, this dimension of variability might provide a useful intermediate step in tracing back the climatological effects of SST gradients on the storm track to individual weather events.

The variability patterns resulted from a principal component analysis of front characteristics for a large number of regions. Both the required climatology of regional front volumes and the statistical nature of the analysis make its application and physical interpretation rather challenging. Still, the new front types exhibit a clear dynamical evolution and can, as discussed above, reasonably be linked to traditional classifications.

However, to make the classification more straightforward and practical, we redefined the PC-based front types using simple parameter thresholds. These parameters are the heat transport perpendicular to $\theta_E$ isolines (advection type, orange), total deformation (kinematic intensity, green), surface sensible heat flux (surface fluxes, dark red) and heat transport parallel to $\theta_E$ isolines (along-front transports, pink). The close relation between the redefined and original patterns corroborates the link to physical features and processes. Indeed, the link of a single parameter to a process is more easily understood than that of a complex principal component.

Finally, as an outlook, we return to the envisioned applications of our front-type classification to understand both differences between cyclones and front–orography interactions better.
Concerning the interaction between fronts and cyclones, analyses following our synoptic example in Figure 13 could provide the basis for augmented conceptual models of cyclone life cycles that not only differentiate between cold and warm fronts but also take the entire spectrum of front types into account. Furthermore, preliminary results for mountainous regions indicate that the same front types also recur for fronts in the vicinity of orography. Hence, our maritime front types are also applicable to front–orography interactions. Both applications will be pursued in follow-up studies.

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Appendix A: Comparison of our front volumes with Schemm et al. (2015) front lines

Our front volume detection is largely consistent with the Schemm et al. (2015) front-line detection scheme. Compared with Schemm et al. (2015), we use a slightly more restrictive threshold for the minimum $\theta_E$ gradient of $4.5 \text{ K} (100 \text{ km})^{-1}$ instead of $4.0 \text{ K} (100 \text{ km})^{-1}$. For this reason, the vast majority of front volumes in our synoptic example in Figure 1 correspond to one or more front lines.

This statement is also valid climatologically, where more than 90% of our detected front volumes match at least one front line (Figure A1). More than 60% of the total number of front volumes intersect exactly one front line, yielding a one-to-one match. Climatologically, the slightly more restrictive detection threshold manifests itself in the relatively large fraction of 47% front lines that do not intersect a front volume. Although the distribution drops off quickly, there are a few front volumes that intersect more than 20 front lines. This finding emphasizes the point that a single front volume can, in extreme cases, span considerable parts of a storm track and several synoptic systems.

Appendix B: Comparison of ocean basins

It is computationally too costly to repeat the analyses for arrays like the one in the North Atlantic for other ocean basins. Nevertheless, to make sure that our front-type classification is...
not merely reflecting regional properties of North Atlantic fronts, we repeat the analysis for a series of regions following specific longitudes through the North Pacific (165°W) and South Indian Ocean (90°E), respectively, and compare them to a section in the mid-Atlantic at 30°W. The results of this comparison are summarized in Figure B1, which shows for each ocean basin the meridional sections of the explained variance for our variability patterns. Figure B1 shows that the same five variability patterns recur not only in regions in the North Atlantic but also for additional regions in other ocean basins. Specifically, for the variability patterns advection type, along-front transports and surface fluxes, the explained variance in the different ocean basins corresponds well to that in the North Atlantic, in both absolute magnitude and its meridional dependence. The correspondence applies both for the respective summer and winter seasons. For kinematic intensity and moist baroclinicity, the collapse of the two patterns into one for some regions leads to jumps in the explained variance and missing values, as is also visible in the explained variance maps for the Atlantic (Figures 5 and 6). Thus, the partial alignment of these variability patterns is also no special feature of the North Atlantic, but a general property of fronts.

Appendix C: Biplot examples for other regions

To illustrate the recurrence of the RPCs in different regions, Figure C1 shows biplots for the two respective leading RPCs for the regions centred around 30°W, 45°N and 30°W, 36°N. For all four RPCs shown, we can associate the RPCs with one of our variability patterns. For the more northerly of the two regions, the orange and dark red parameters, belonging to the patterns advection type and surface fluxes, dominate the respective RPCs. For the southerly region, the pink and green parameters of the along-front transports and kinematic intensity patterns make up the leading RPCs.

Figure C1. Biplots analogous to Figure 4 for winter RPC 1 & 2 in the regions (a) 30°W, 45°N and (b) 30°W, 36°N. [Colour figure can be viewed at wileyonlinelibrary.com].
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