NOTES AND CORRESPONDENCE

Sensitivity of Feature-Based Analysis Methods of Storm Tracks to the Form of Background Field Removal

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ABSTRACT

For the tracking of extrema associated with weather systems to be applied to a broad range of fields it is necessary to remove a background field that represents the slowly varying, large spatial scales. The sensitivity of the tracking analysis to the form of background field removed is explored for the Northern Hemisphere winter storm tracks for three contrasting fields from an integration of the U.K. Met Office's (UKMO) Hadley Centre Climate Model (HadAM3). Several methods are explored for the removal of a background field from the simple subtraction of the climatology, to the more sophisticated removal of the planetary scales. Two temporal filters are also considered in the form of a 2–6-day Lanczos filter and a 20-day high-pass Fourier filter. The analysis indicates that the simple subtraction of the climatology tends to change the nature of the systems to the extent that there is a redistribution of the systems relative to the climatological background resulting in very similar statistical distributions for both positive and negative anomalies. The optimal planetary wave filter removes total wavenumbers less than or equal to a number in the range 5–7, resulting in distributions more easily related to particular types of weather system. For the temporal filters the 2–6-day bandpass filter is found to have a detrimental impact on the individual weather systems, resulting in the storm tracks having a weak waveguide type of behavior. The 20-day high-pass temporal filter is less aggressive than the 2–6-day filter and produces results falling between those of the climatological and 2–6-day filters.

1. Introduction

A wide variety of methods have been used to provide diagnostics of the midlatitude storm tracks. The most popular approach has been to use methods that are intrinsically Eulerian in nature. These can only be used to infer the properties of weather systems since these systems are not directly identified. Examples of this type of approach are the often used spectral methods, which subjectively assume the nature of the spectral properties of the transient systems. Following Blackmon (1976) the 2–6-day band is typically considered as representative of synoptic timescales. However, the use of such a restrictive band cannot capture the complete life cycles of weather systems. Other spectral bands have been explored (Blackmon et al. 1984) and while these are interesting in highlighting the differing spatial patterns associated with various timescales, these patterns are not always easily related to actual weather system behavior.

An alternative approach is to identify the weather systems, track them, and produce diagnostics from the track ensembles. Most recent studies using this approach have been restricted to lower-tropospheric fields such as mean sea level pressure (MSLP) (Simmonds and Keay 2000; Blender et al. 1997; Serreze et al. 1997), geostrophic vorticity (Sinclair 1994), and 850-hPa relative vorticity (Hodges 1996; Ayrault and Joly 2000). Recently Hoskins and Hodges (2002, hereafter HH) showed that by exploring a wider range of lower- and upper-level tropospheric fields, new perspectives could

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be achieved on the Northern Hemisphere (NH) wintertime storm tracks.

To enable the range of fields studied by HH to be used in tracking studies it was found necessary to remove a background field before identifying the systems. This raises the classic problem of defining what is the mean flow and what is the perturbation. This has not been confronted in previous tracking studies. At each data time, HH used a filter based on removing the planetary scales represented by wavenumbers $n \leq 5$, which represent the large spatial scale, low-frequency variability (Blackmon 1976).

The aim here is to test the validity of the filter used by HH and the robustness of some of the results. The usefulness of the often used bandpass filters is also explored in the context of feature tracking. A small subset of the fields considered by HH are considered where it is either useful or necessary to remove a background field. MSLP was selected as it is relatively unaffected by zonally averaged meridional gradients but is strongly affected by planetary scales. Temperature at 850 hPa, T_{850}, is chosen because of its dominance by a strong meridional gradient. This field was shown by HH to be of interest in terms of the contrast in behavior of thermal anomalies between the Atlantic and Pacific. The potential temperature on a 330-K isentropic surface, PV_{330}, was chosen as an example of an upper-level field. It too has a strong meridional gradient and if no filtering is performed, the results are dominated by small features on the large positive PV background found at high latitudes. Hoskins and Hodges (2002) found that after removing a background field the activity can be more closely associated with that seen in upper-level relative vorticity and potential temperature. The PV_{330} features generally represent the smaller-scale end of the synoptic range.

Four contrasting filters are considered for the removal of a background field: subtraction of the climatology, planetary wave filtering as used in HH, a 2–6-day bandpass Lanczos filter, and a 20-day high-pass Fourier filter. Wallace et al. (1988) pointed out that the features highlighted by the 2–6-day pass band tend to occur in a baroclinic waveguide. It is of interest to see just what effect this filter has on individual weather systems.

The choice of methodology for comparison between the various filters is necessarily somewhat subjective. The view is taken here that a good filter is one that allows weather system structures to be identified without significantly changing their nature. For example, cyclones should in general be more intense and mobile than anticyclonic systems.

2. Dataset

The data used in this study are from a high-resolution integration of the United Kingdom Met Office (UKMO) Unified Model (UM), the Hadley Centre Climate Model (HadAM3) version. This is an atmosphere-only global circulation model integrated at a horizontal resolution of $1.25° \times 1.87°$, with 31 levels in the vertical. The integration is performed using the Atmospheric Model Intercomparison Project (AMIP) experimental specification. A more detailed description of the model and its general performance is detailed in Pope et al. (2000). The model was run for the period 1979–96. Throughout this study only the NH December–January–February (DJF) season is considered. All the analyses reported here are conducted for model data truncated to a spectral resolution of T42 (triangular truncation 42), a resolution suitable for studies of synoptic systems and providing some smoothing for noisier fields such as PV_{330}.

3. Description of filtering methods

In the case of the MSLP the simplest means of generating anomalies relative to a large-scale background field is to subtract the global mean pressure ~1013 hPa (GLB). However, this takes no account of the spatial or temporal variation of the large scales and has been applied to MSLP only.

The next level of filter entails the subtraction of the time mean (average) climatology (TAV). The MSLP climatology is dominated by the usual Aleutian low in the Pacific and the Icelandic low in the Atlantic with high pressure over the continents. For T_{850} the climatology is dominated by the equator to pole temperature gradient moderated by land–sea contrasts, with strong baroclinic regions off the west coast of America and Asia. For PV_{330} the climatology consists of a meridional gradient concentrated in the midlatitudes, at around 30°N. The relevant climatology was subtracted from each field at each time step.

For the planetary wave spectral spatial filter (SPC), each field is represented by a spherical harmonic expansion and the large spatial scales are removed by setting the spectral coefficients for total wavenumbers less than some prescribed cutoff to zero. Additionally some spectral smoothing is performed to suppress Gibbs noise by tapering the spectral coefficients using the filter of Hoskins and Sardeshmukh (1984). The filter used by HH removed wavenumbers $n \leq 5$. This approach has the benefit that the scales removed include minimal contributions from the synoptic-scale weather systems, un-

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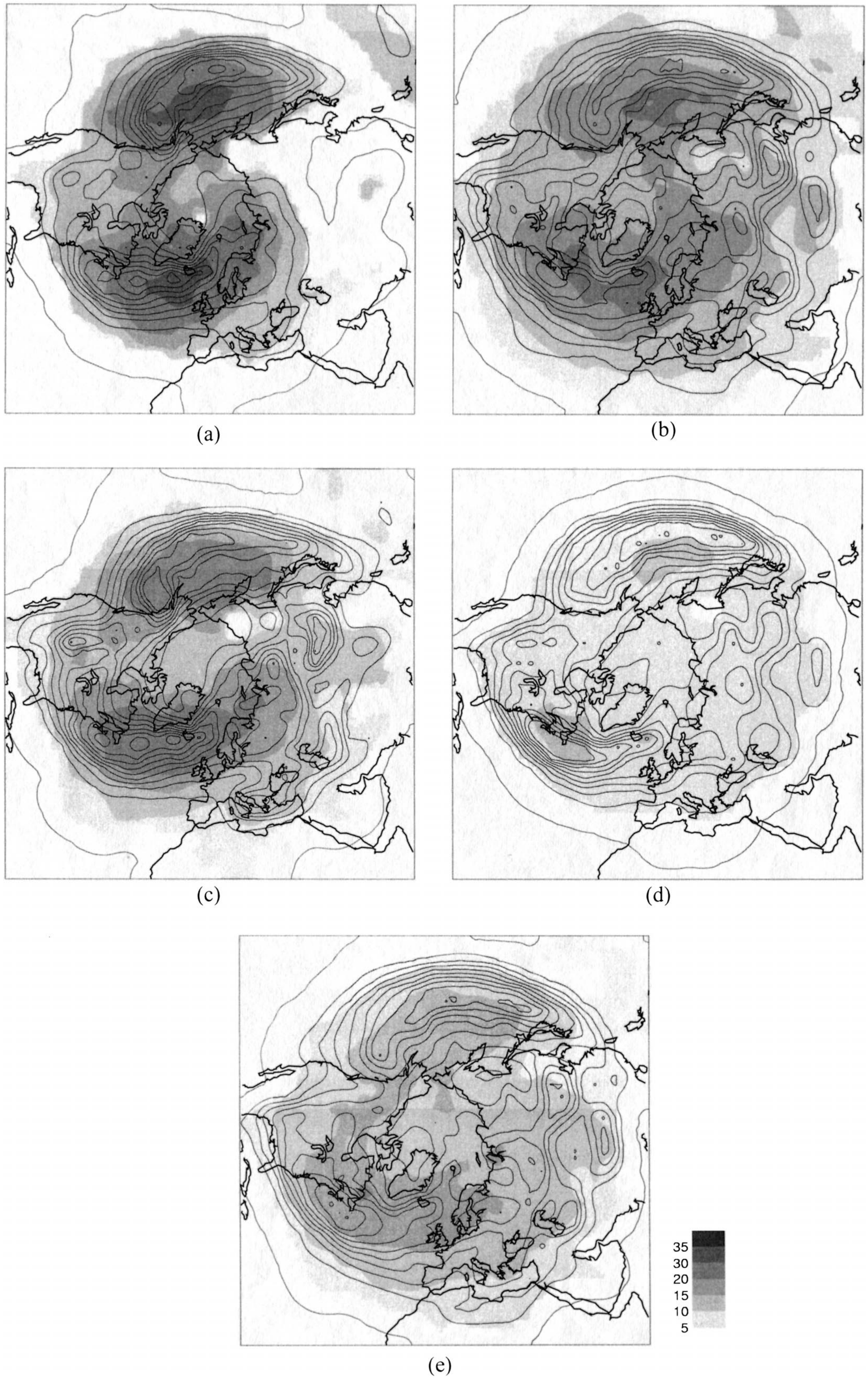
FIG. 1. Track density and mean strength statistics for negative MSLP anomalies: (a) with respect to the mean hemispheric pressure (GLB), (b) subtraction of climatology, (c) subtraction of planetary waves ($n \leq 5$), (d) 2–6-day Lanczos filter, and (e) 20-day high-pass Fourier filter. The grayscale shows mean strength of systems (contour interval, 5 hPa) and the contours show track density (contour interval, 1 per 5° spherical cap per month.)


(a)
(b)
(c)
(d)
35
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(e)

like the time-average subtraction for example, and it also takes account of the time-varying nature of the large spatial scales.

The other types of filter considered are temporal in nature. The first is the 2–6-day bandpass Lanczos time domain filter (LAN; Duchon 1979). This filter has the advantage that it is relatively simple and computationally inexpensive, although several passes of the filter through the data may be required to emulate a sharp response filter. A further attribute is that it is symmetric (acausal): the filter draws on subsequent as well as previous time steps when producing the output. The second temporal filter used was a 20-day high-pass frequency domain filter (FOR). The frequency response of the 20-day Lanczos filter was rather poor, so a Fourier filter was used instead. This entails fast Fourier transforming (FFT) the data to the frequency domain, applying the filter, and then transforming back to the time domain. Other types of filter could have been considered. For example, the subtraction of the seasonal means to account for interannual variability might be considered to be a halfway position between the TAV and SPC filters and should also be explored.

Inspection of the result of applying the various filters to the MSLP field at a particular time indicates that the GLB, TAV, and SPC filters are qualitatively very similar. The general shape and position of various maxima and minima are mostly preserved. There are however some differences in the finer details. The climatology in the two oceanic basins is dominated by areas of low pressure; thus, subtracting the climatology results in the low pressure centers tending to be weaker in these regions and high pressure systems more pronounced. In general going from the GLB data to the SPC, and then to the TAV filtering, results in the asymmetry in the strengths of the high and low pressure systems decreasing. These differences at first do not appear to be very large but they can have a significant cumulative effect on the tracking statistics.

Application of the LAN filter has a more significant effect on the systems and appears to seriously degrade their nature in terms of both position and intensity. This type of filter produces anomalies in the form of weak propagating wave trains in the midlatitude belt as noted by Wallace et al. (1988), who highlighted the distinction between ''storm tracks'' and ''baroclinic waveguides.'' The tendency for highs to move south and lows to move to the north is only recovered when the evolving background state is restored. Consequently the anomalies can be geographically dislocated from the weather events that are present in the raw data and in the TAV- and SPC-filtered data. The FOR filter gives results that lie somewhere between the LAN-filtered data and the TAV-filtered data. The general perception from MSLP and from T_{850} and PV_{330} is that for TAV, SPC, and FOR the positions are reasonably robust but there are differences in the relative intensities between the two signs of anomaly.

4. Tracking diagnostics

The tracking is performed using the automated tracking system of Hodges (1995, 1999). It is performed directly on the sphere and is based on the minimization of a cost function for the ensemble track smoothness, subject to adaptive constraints on the displacement distance and track smoothness. Only the mobile systems that last at least 2 days and travel farther than 1000 km are retained for the statistical estimation.

The tracking diagnostics are computed from the track ensembles using the spherical kernel estimators described by Hodges (1996). The diagnostics used here are the track density (scaled to number density) and the mean intensity, as used in HH.

a. Tracking statistics for MSLP

The track density and mean intensities for negative (minima) anomalies in the MSLP field for the filters GLB, TAV, SPC, LAN, and FOR are shown in Figs. 1a–e. The overall picture of the two oceanic storm tracks is clearly robust. However, the details of the two main storm tracks and the extent to which the Mediterranean and Siberian regions are also highlighted do vary with respect to the different forms of filter, related to how different spatial and temporal scales are treated.

Comparing the track density for GLB- and SPC-filtered data (Figs. 1a and 1c), a number of differences can be seen. The Atlantic and Pacific storm tracks are weaker in the GLB data than in the SPC-filtered data. Fewer lows are observed at the start of the storm tracks over the eastern United States and near Japan. Indeed fewer minima are observed over continental regions in general. This is due to using the global average pressure to partition the data, which does not take into account the tendency for pressures to be higher over land areas in winter. Lows over land are often quite weak, and only exhibit closed centers in filtered data or at very high resolution.

Comparing the TAV (Fig. 1b) and SPC tracking results, the peak values of track density are higher in the two storm track regions in the SPC-filtered data than in the TAV-filtered data. This can be understood in terms of the differences in the definition of the background field. As noted previously the removal of the climatology tends to affect the data such that lows are weakened and highs become more prominent when compared to the SPC-filtered data, giving a tendency toward equivalence between the two signs of anomaly. This is apparent in the mean intensity statistics, where there is greater parity between the two signs of anomaly for the TAV-filtered data, and also to some extent in the track density. This is partly a consequence of the synoptic systems themselves contributing to the time mean. It is notable that the peak in negative anomaly track density on the coast of Alaska in the SPC-filtered data is absent in the TAV-filtered data. This is a favored region for the occlusion and decay of slow-moving low pressure systems.

The tracking statistics for the LAN-filtered data (Fig. 1d), are very similar to those for the positive anomalies (not shown), consistent with the baroclinic wave train view of the anomalies. It is clear that the mean intensity is much reduced compared to the statistics for the other types of filters, illustrating the weakness of the anomalies. Interestingly, the results for the LAN filter indicate the nature of the activity described by the 2–6-day bandpass-filtered variance (see HH). The peak in variance in both ocean basins coincides more closely with the peak in mean intensity in the tracking results rather than with the peak in track density.

The effect of the FOR filter (Fig. 1e) lies somewhere between that for the TAV and LAN filters, with greater parity between the two signs of anomaly for both track density and mean intensity than in the TAV-filtered statistics, but not to the extent seen in the LAN-filtered data.

The tracking statistics for positive features (not shown) exhibit much less consistency with respect to the different filters than for the negative anomalies. As noted in HH, due to an artifact of the SPC-filtering process high pressure systems over the pole are enhanced by the removal of a background low in this region when using only $n \leq 5$. However, the effect is quite localized, resulting in the infrequent mobile highs in this region being enhanced and biasing the mean intensity statistic there. Of more concern is the general enhancement in the activity for the TAV and FOR filters relative to the SPC filter. This redistribution of systems relative to the removed background state makes it much harder to associate anomalies with particular cyclones or anticyclones. In general the tendency of the TAV, LAN, and FOR filters to equilibrate the numbers and intensities of positive and negative features makes them undesirable in terms of our acceptance criteria that the nature of the systems are not unduly affected. The SPC filter gives results more in line with our synoptic understanding of the relative occurrence and intensity of high and low pressure systems.

b. Tracking statistics for T_{850} and PV_{330}

Tracking statistics for the T_{850} field are given in Figs. 2a–f for the TAV-, SPC-, and FOR-filtered data. Results for both anomaly signs are presented for this field to explore the sensitivity of the contrast between the Atlantic and Pacific storm tracks shown in HH. The track density statistics in the Atlantic are qualitatively similar for the SPC- (Figs. 2c and 2d) and TAV-filtered data (Figs. 2a and 2b). The most striking difference between them is the continuation of storm track activity into the east Atlantic for positive temperature anomalies for the SPC-filtered data.

The track density statistics in the Pacific show less agreement. This is in part due to an artifact of the SPC-filtering process. The storm track feature seen in the western Pacific, for positive features in the SPC-filtered data (Fig. 2c) and the associated region of high mean intensity, is a residual of the background field. This residual occupies a spatial scale smaller than the first five planetary waves and constitutes a semipermanent region of positive temperature that vacillates as the field evolves. This appears to be a more prominent artifact of the UM compared to that seen by HH using reanalysis data. As was the case for MSLP, removal of the climatology (TAV) tends to shift the distributions of mean intensity toward a symmetry between the two signs of feature. The strip of strong positive features across the Atlantic seen in Fig. 2c for the SPC-filtered data is absent in the TAV-filtered data.

The statistics for the LAN-filtered data (not shown) exhibit little resemblance to the results for the TAV- and SPC-filtered data. As with MSLP, the two signs of anomaly show almost total parity with considerably weaker magnitudes than their SPC and TAV counterparts. The tracking statistics for the FOR-filtered data (Figs. 2e and 2f) again show results that lie between those for the TAV- and LAN-filtered data with mean intensities weaker than either the TAV or SPC results.

The warm (positive) Siberian feature track density and intensity maximum highlighted by HH appears to be a robust feature with respect to the different filters. Rather less robust is the contrasting behavior of warm and cold anomalies in the Atlantic. With SPC, cold anomalies form over North America and decay over the western North Atlantic whereas warm anomalies tend to form over the warm waters to the south of the storm track and move along it. This contrast in behavior is less apparent with the other filters. However, the much higher intensity seen upstream and in the Atlantic storm track than in the Pacific storm track is robust to the filter used.

The tracking statistics for PV_{330} (not shown), as with MSLP and T_{850}, show differences between the results for the SPC- and TAV-filtered data that reflect differences between the climatology and the mean planetary wave components. The intensity of negative features is enhanced in the TAV-filtered data in the Pacific and positive features are enhanced in the Atlantic, relative to the spatially filtered data. The net result of these changes acts to increase the parity between signs of anomaly in the TAV-filtered statistics as seen previously. The LAN results are consistent with those for MSLP and T_{850} in that the difference between signs of anomaly are almost indistinguishable and the resultant anomalies are much weaker than for the SPC- and TAV-filtered data.

c. Summary

In general the most appropriate filter appears to be the SPC filter in terms of our acceptance criteria. This has the least effect on the individual weather systems

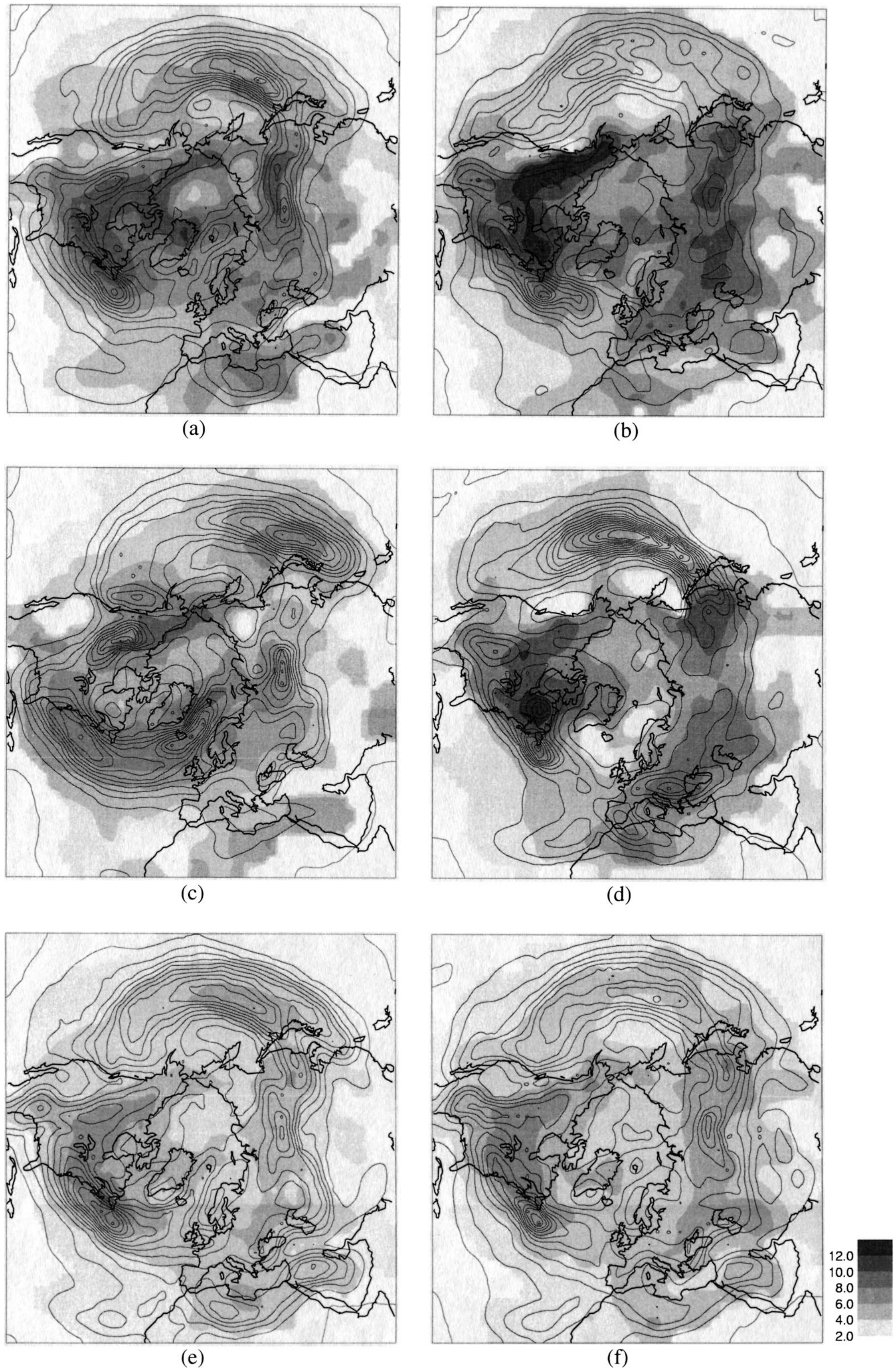

FIG. 2. Track density and mean strength statistics for positive (left column) and negative (right column) T_{850} anomalies: (a),(b) subtraction of climatology, (c),(d) planetary wave filtering ($n \leq 5$), and (e),(f) 20-day high-pass Fourier filter. The grayscale shows mean strength (contour interval, 2 K) and the contours show track density as defined in Fig. 1.

while allowing them to be easily identified in a wide range of fields. However, examples have been shown in which spurious features have been identified in certain regions associated with residual planetary scales. This raises the question of what wavenumber cutoff is optimal. Different cutoffs may be required for fields that emphasize different synoptic spatial scales. This will be explored in the next section. If a temporal filter is required then it should really encompass a broader band than the 2–6-day bandpass typically used for variance studies.

5. Sensitivity to the spectral spatial filter

In this section the sensitivity of the diagnostics obtained using the SPC filter to the number of wavenumbers removed will be discussed through a comparison of the results obtained using cutoffs at total wavenumbers 7 and 10 with those already presented where a wavenumber 5 cutoff was used.

a. MSLP

Removing seven wavenumbers from a single instance of MSLP gives a general increase in the intensity of positive anomalies in the northern North Atlantic and a weakening farther south. A similar effect occurs in the Pacific basin, with highs appearing stronger relative to lows in the north and the reverse happening at low latitudes. The positions and structures of the lows are still well preserved. However, the shapes and positions of the highs appear to be more sensitive to the change, with double centers and shifts in position appearing in some cases. Removing 10 wavenumbers gives the field a noisier appearance and alters the structure of many features.

Figures 3a and 3b show the MSLP tracking statistics for negative anomalies for the 7- and 10-wavenumber cutoffs, respectively, and should be compared with the wavenumber-5 results in Fig. 1c. The wavenumber-5 and 7 cutoff results are very similar. There is a slight weakening in both the track densities and mean intensities with the removal of the extra harmonics, but the distributions of both storm track measures are well preserved. This is consistent with the above analysis of the individual systems. The statistics for positive features (not shown) are more sensitive to the removal of seven wavenumbers, with a reduction in the artificial peak in mean intensity over the pole.

Differences are less subtle when examining the statistics for the 10-wavenumber cutoff. There is an increase in track density in both storm track regions with increased activity in the upstream part of the Pacific and the Atlantic. The Atlantic now exhibits a double-storm-track structure not seen with any of the other filters. The distribution of mean intensity appears similar to its counterparts for five- and seven-wavenumber filtering, but it is clear that the tracked features are now significantly weaker.

Accompanying the move to filtering with respect to 10 wavenumbers is a loss of track density in the cyclolysis region in the Gulf of Alaska. Cyclones in this region are clearly characterized by large length scales and are strongly affected by the removal of 10 wavenumbers. However, the region of small-scale cyclones in the Mediterranean is somewhat better defined when more of the background field is removed. This is consistent with the well-defined Mediterranean storm track highlighted by HH using the 850-hPa relative vorticity field.

b. T_{850} and PV_{330}

Removal of the extra wavenumbers from an instance of T_{850} indicates that the effect is quite localized. In particular, the residual large-scale positive temperature anomaly in the western Pacific that biases the tracking statistics for a five-wavenumber cutoff is greatly reduced.

Tracking statistics for the 7- and 10-wavenumber cutoffs are shown in Figs. 3c,d and 3e,f for positive and negative anomalies, respectively. These show that the additional filtering has a greater impact on the statistics for the positive features. The most obvious difference is the removal of the artificial peak in mean intensity and the accompanying track density in the western Pacific. In the eastern Atlantic there is evidence of a decrease in activity and intensity, due to the removal of a background with a closer structure to the climatology. However, as with MSLP the Mediterranean activity becomes more prominent. The statistics for negative features appear quite robust to the change from 5 to 7 wavenumbers. There is a general weakening in the mean intensity of features throughout most of the hemisphere and a change in the appearance of the track density in the Pacific, but the overall nature of the statistical distributions is unchanged. For 10 wavenumbers the nature of the distributions begins to change significantly, particularly in the Pacific.

For PV_{330} the effect of the 7- and 10-wavenumber cutoffs on an instance of the field indicates the features to be reduced in intensity with some erosion of the structure, but the general shape and position of features are preserved. The tracking statistics (not shown) confirm the relative insensitivity to the spectral cutoff. Apart from the general reduction of the mean intensity, the distributions are generally consistent with their counterparts for the removal of five wavenumbers. Track density statistics also display a high degree of correlation. The main differences are a reduction of activity in East Asia and an increase in activity in the mideast Atlantic. This relative insensitivity to the cutoff is a consequence of PV_{330} emphasizing smaller spatial scales as is the case for relative vorticity as indicated by HH.

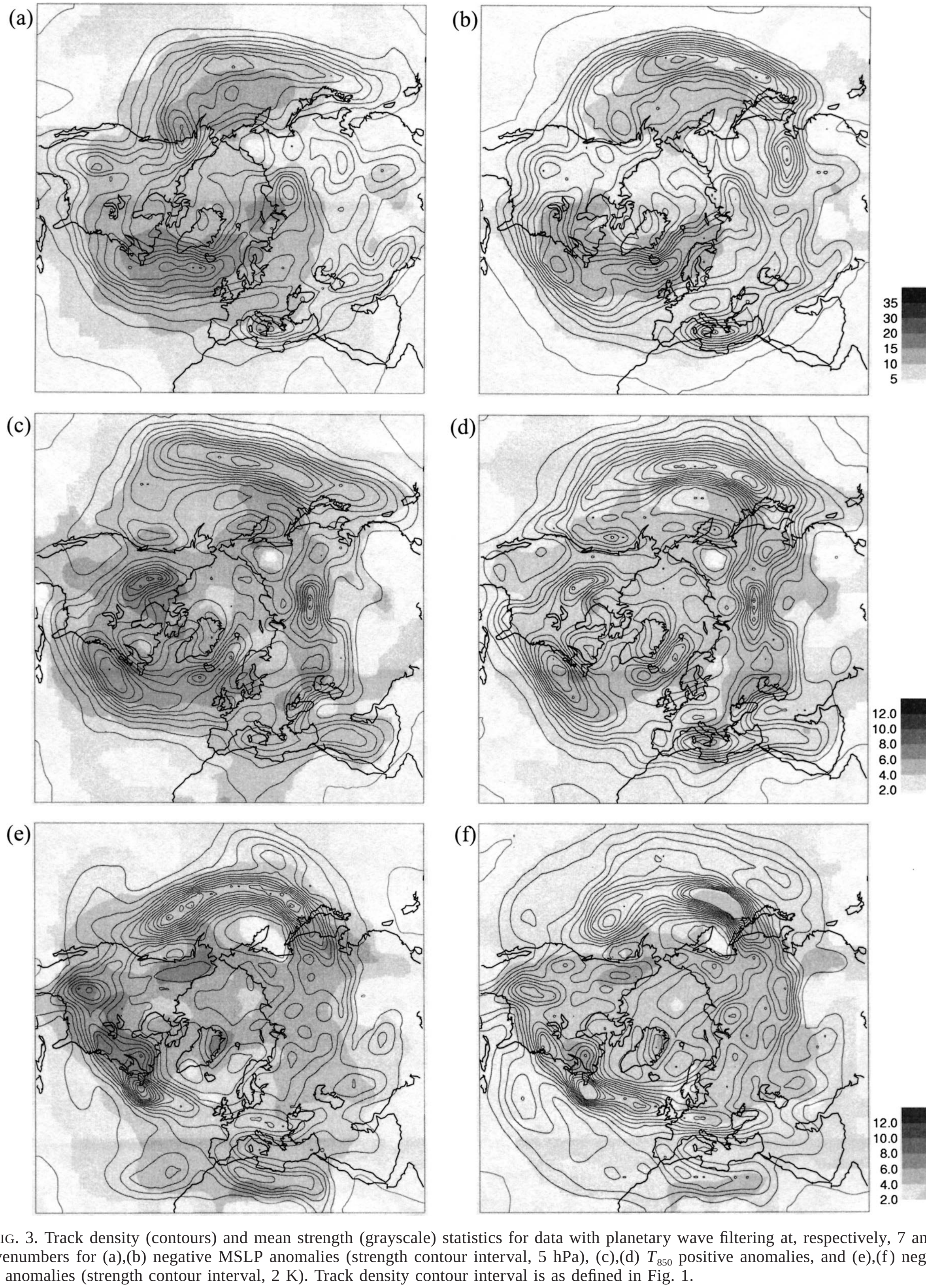

FIG. 3. Track density (contours) and mean strength (grayscale) statistics for data with planetary wave filtering at, respectively, 7 and 10 wavenumbers for (a),(b) negative MSLP anomalies (strength contour interval, 5 hPa), (c),(d) T_{850} positive anomalies, and (e),(f) negative T_{850} anomalies (strength contour interval, 2 K). Track density contour interval is as defined in Fig. 1.

6. Discussion and conclusions

Deciding on the form of background field to remove before identifying features for tracking is a difficult problem with no unique solution, but a problem that must be considered. Here the primary attribute of a successful filter is taken to be the requirement that features can be directly associated with those in the original fields where possible and should reflect the nature of synoptic-scale weather systems. This of course entails a certain degree of subjectivity.

On this basis the 2–6-day bandpass filter is rejected as a possible means of removing a background state. The anomalies behave as weak propagating wave trains confined in a narrow band in the midlatitudes (Wallace et al. 1988) and have an ephemeral relation to the original weather systems. Indeed the relationship between the traditional storm track and the bandpass-filtered variances exercised Blackmon et al. (1984) and Wallace et al. (1988). However, HH noted that there was much qualitative agreement between the 2–6-day filtered variances and the track density/mean intensity statistics. What the analysis here indicates is that the use of the 2–6-day filter for identifying anomalies for tracking is inferior to other types of filter. However, for variance studies, as shown by Blackmon et al. (1984), the choice of other bands results in a very different variance picture not obviously having a storm track character.

The remaining methods of filtering have the property of yielding anomalies with a clear correlation with features in the instantaneous raw data. The TAV and FOR filters tend to redistribute the features about the mean state. This can be a drawback if it is considered desirable to retain a bias toward one sign of anomaly. The SPC filter removes a background state from the field at each instant. The difficulty with this filter is in choosing an appropriate cutoff. A cutoff of five wavenumbers can lead to ever-present, vacillating features appearing in the residual field, giving artifacts in the tracking statistics. A more aggressive filter begins to erode the nature of the synoptic features of interest. As previously discussed a filter cutoff of seven wavenumbers usually gives a reasonable compromise between these two effects for most fields, although a more conservative cutoff of five wavenumbers may be preferred. The SPC filter appears to be at its most problematic for the MSLP field due to difficulty in distinguishing between the transient weather systems and the background state. However, these problems are mostly in the statistics for high pressure systems, with the statistics for low pressure systems being more robust to the choice of filter cutoff.

It is not possible to say categorically if a temporal or spatial filter removes the background flow most adequately. However, since synoptic features are perhaps more readily seen as sometimes becoming quasi-stationary than becoming planetary scale, then the spatial (SPC) filter may be the preferred choice, particularly if we wish to determine meaningful results that encompass the whole life cycles of weather systems.

The difference between the results for the SPC and FOR filters are in general not as large as the differences sometimes found between analyses using different tracking analysis methodologies. However, the tracking analyses all tend to give qualitatively similar results, the differences depending on the subjective choices made of what constitutes a system. Discussion of system tracking results must always be clear and consistent in the particular methodology used. Eulerian variance studies have analogous but usually unstated problems, with similar subjective choices of parameters required and uncertainties in the nature of the systems being considered.

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