Sensitivities of a cyclone detection and tracking algorithm: individual tracks and climatology

JOAQUIM G. PINTO1, THOMAS SPANGEHL1,2, UWE ULBRICH1,2 and PETER SPETH1

1Institut für Geophysik und Meteorologie, Universität zu Köln, Germany
2Institut für Meteorologie, Freie Universität Berlin, Germany

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Abstract
Northern Hemisphere cyclone activity is assessed by applying an algorithm for the detection and tracking of synoptic scale cyclones to mean sea level pressure data. The method, originally developed for the Southern Hemisphere, is adapted for application in the Northern Hemisphere winter season. NCEP-Reanalysis data from 1958/59 to 1997/98 are used as input. The sensitivities of the results to particular parameters of the algorithm are discussed for both case studies and from a climatological point of view. Results show that the choice of settings is of major relevance especially for the tracking of smaller scale and fast moving systems. With an appropriate setting the algorithm is capable of automatically tracking different types of cyclones at the same time: Both fast moving and developing systems over the large ocean basins and smaller scale cyclones over the Mediterranean basin can be assessed. The climatology of cyclone variables, e.g., cyclone track density, cyclone counts, intensification rates, propagation speeds and areas of cyclogenesis and -lysis gives detailed information on typical cyclone life cycles for different regions. The lowering of the spatial and temporal resolution of the input data from full resolution T62/06h to T42/12h decreases the cyclone track density and cyclone counts. Reducing the temporal resolution alone contributes to a decline in the number of fast moving systems, which is relevant for the cyclone track density. Lowering spatial resolution alone mainly reduces the number of weak cyclones.

1 Introduction
Extratropical cyclones are a feature of dominant importance for mid-latitude climate (PEIXOTO and OORT, 1992). An assessment of typical spatial and temporal characteristics (e.g., cyclogenesis, cyclolysis, growth rates, etc.) can serve the understanding of physical mechanisms associated with cyclones both in global and regional terms (e.g., HOSKINS and HODGES, 2002). Individually tracks and developments can be used, e.g., in studies of extreme events (e.g., ULBRICH et al., 2001).

A consideration of surface cyclones is, of course, a restrictive view. The systems and their development should be regarded as three-dimensional features of the atmosphere. This suggests a manual synoptic analysis, which is, however, rather time consuming and cannot be consistently performed for large numbers of events, e.g., as they are present in reanalysis data and in general circulation models (GCM) simulations. Thus, several numerical algorithms have been developed and

used in order to objectively identify cyclones in digital maps. Examples for such efforts are described in papers by Lambert (1988); Le Treut and Kalnay (1990); Alpert et al. (1990); Murray and Simmons, (1991, hereafter MS91); König et al. (1993); Hodges (1994); Serreze (1995); Haak and Ulbrich (1996, hereafter HU96); Blender et al. (1997); Sinclair (1997) and Lionello et al. (2002). In most cases, cyclone cores are defined in terms of pressure minima at sea level, or minima in 1000 hPa geopotential heights. Alternatively, cyclones can be defined in terms of maxima in low level vorticity (e.g., Hodges, 1994).

A combination of both criteria was also used (König et al., 1993). However, the procedures vary greatly with respect to computational details and the degree of sophistication involved.

The simplest approaches are based on the definition of a cyclone as a local mean sea level pressure (MSLP) grid point minimum (e.g., Lambert, 1988). This leads to the identification of numerous non significant “systems” which can be eliminated later on using a minimum intensity criterion. For example, Le Treut and Kalnay (1990) only regard grid points that lie 4 hPa beneath the mean pressure of 20 surrounding grid points, while Ueno (1993) demands a minimum value of pressure gradient calculated over 8 surrounding grid points. Using coarse grid input data, core positions resulting from the procedures cannot be located between these grid points, even if this seems apparent from the data. This problem has led to the idea of transforming the data to a finer grid before starting the identification procedure (e.g., Alpert et al., 1990; Hodges, 1994; HU96), in spite of the considerable computational effort. The number and depth of systems is strongly dependent on the resolution of the original data (e.g., HU96; Blender and Schubert, 2000; Zolina and Gulev, 2002). This effect is especially important for the comparison of cyclone statistics based on datasets with different resolutions and will be considered more closely in section 6 of the current paper.

Methods searching for pressure minima tend to overestimate deep and mature cyclones while they miss small scale systems that are better identified from their local maxima in relative vorticity, e.g., fast moving systems or cyclones in the early and late stages of their life cycle (MS91; Hoskins and Hodges, 2002). The search of vorticity maxima in cyclone identification was thus used by a number of authors, either explicitly or implicitly (MS91; König et al., 1993; Hodges, 1994; Sinclair, 1997). In a geostrophic sense, vorticity focuses on the small-spatial-scale end of the synoptic range. Thus, the number of systems identified from this quantity is much larger than what is obtained using sea level pressure (Hoskins and Hodges, 2002). However, vorticity maxima are not always connected with local pressure minima. For this reason, MS91 considered a (closed) cyclone only if the associated vorticity maximum could be assigned to a local pressure minimum.

The algorithms are usually tested in terms of their ability to produce patterns of cyclone climatologies which agree with synoptic experience. As an exception, HU96 discuss deviations of extreme cyclones in terms of core depth and location comparing their identified cyclones with a manual analysis of Schinke (1992, 1993). The cyclone climatologies derived from observational (re)analysis data sets (e.g., Serreze et al., 1997; Sickmöller et al., 2000; Gulev et al., 2001; Geng and Sugi, 2001; Hoskins and Hodges, 2002; Lambert et al., 2002) generally agree in producing maxima of cyclone counts over the Northern Hemisphere (hereafter NH) mid-latitude ocean basins. These areas correspond closely to the storm tracks, regions of strong height-field variance in a frequency band associated with synoptic time scales (as defined by Blackmon, 1976). These areas of high synoptic activity over the North Atlantic and the North Pacific are hereafter refereed to as ‘main storm tracks’. Most climatologies tend to identify rather few cyclones over secondary storm track regions (e.g., the Mediterranean basin), which is in contrast with methods particularly tuned for these regions (e.g., Trigo et al., 1999, 2000) and synoptic experience. Cyclones in these areas are, however, of major interest as they can have large regional impacts.

The tracking of cyclones is usually performed by assigning an individual system identified at a particular date to a successor at the subsequent date. The assignment of the most likely successor involves a search in a certain area. This area is sometimes chosen as a circle around the original position (e.g., Alpert et al., 1990; König et al, 1997; Ueno, 1993; Blender et al., 1997); it can also be defined from a local “climatological steering velocity” (e.g., MS91, HU96). Other authors (e.g., Hodges, 1994) have included a condition for “flat” trajectories in order to agree with synoptic experience.

In the present study, we use an algorithm originally developed for the identification and tracking of cyclones in the Southern Hemisphere (cf. MS91; Simmons et al., 1999, hereafter SML99) and apply it to the NH. The main goal is to obtain a cyclone climatology which successfully includes the whole range of NH cyclones: the large quasi stationary and transient oceanic cyclones, fast moving storms and smaller systems over secondary storm track areas. The original settings (optimised for Southern Hemisphere long-living large scale cyclones) are not suitable to identify all these types of systems, and thus the new choices and the sensitivities of several of the algorithm’s parameters are explained in this study. As a result, we present a new cyclone climatology and show the quality of the algorithm’s parameter settings by suitable case studies.
The structure of this paper is as follows: The second section gives a short description of the data used, while the following ones deal with the different steps of the method: cyclone identification (third) and feature tracking (fourth). These two sections include a technical description of the methods and several sensitivity tests. The resulting cyclone climatology is presented in section five. The sixth section deals with the impact of resolution of the input datasets on the cyclone climatology. A short discussion concludes this paper.

2 Data

We use the NCEP reanalysis (Kalnay et al., 1996) for the period 1958/59–1997/98. One of the main advantages of reanalysis datasets is that model parameterisations and resolution are unchanged for the complete time period. Another advantage compared to operational analyses is that assimilated observations include late observational reports. Even though the NCEP dataset is available from 1948 on, inhomogeneities have been pointed out for the first decade (cf. Kistler et al., 2001). Thus, only the period 1958 to 1998 is considered. Within this period, some systematic problems in monthly surface pressure have been detected for the time period before 1967 (Reid et al., 2001), but we found no evidence of a strong impact on our results. The spectral horizontal resolution of the numerical model (T62) and the spatial and temporal resolution of the gridded data (2.5° × 2.5°, available for 00, 06, 12, 18 UTC) does not allow a good coverage of very small and short lived systems, even if they were originally detected by the observational network.

In order to test the sensitivity of the identified cyclones with respect to data resolution, we created artificial MSLP datasets for NCEP with reduced a) spectral (T42) b) temporal (12 hours) and c) both spectral and temporal (T42/12h) resolutions. This choice of values is motivated by the resolution of many current GCM simulations. The reduction of the spatial resolution involved an interpolation to the original Gaussian grid (T62) and the removal of the high spectral wave numbers. Finally, the truncated spectral data were retransformed onto the regular 2.5° × 2.5° grid. We found that the effects of the interpolation on MSLP could hardly be noticed when subjectively comparing the respective maps. The reduction of temporal resolution was done by omitting the 06 and 18 UTC values.

The verification of cyclone positions and tracks is based on operationally produced weather maps (“Berliner Wetterkarte” issued by “Freie Universität Berlin”, “Europäischer Wetterbericht” issued by the German Weather Service) with a focus on the Atlantic and European/Mediterranean area. The maps give information of sequences of cyclone positions based on a synopsis of both surface and upper air data.

3 Cyclone identification

The initial step of the feature identification is a transformation of the gridded MSLP fields to a regular 0.75° × 0.75° grid by a polar stereographic projection via bicubic spline interpolation. This procedure does not add any information to the original data, but it permits cyclones with cores to be located between the original data grid points. We found that the use of spline interpolation (see also MS91 and Hu96) improves the localisation of the cyclones for the majority of cases. The positive effect is particularly strong for mature cyclones cores with slack gradients near their centre and for small scale cyclones.

In a second step, the high resolution grid is scanned for local maxima of quasi-geostrophic relative vorticity ($\xi$) via the laplacian of pressure ($\nabla^2 p$). $\xi$ is closely related to $\nabla^2 p$ according to

$$\xi = \frac{1}{\rho \cdot f} \nabla^2 p \quad (3.1)$$

where $\rho$ is the air density, $f$ the Coriolis parameter and $p$ stands in our case for MSLP. In a third step, the algorithm iteratively searches the interpolated field for a pressure minimum in the vicinity of the $\nabla^2 p$ maximum in order to associate the latter with a “real” low pressure core. If such a minimum is found, the cyclone is classified as a closed system, with its core located at the pressure minimum. If the search is not successful within a distance of about 1200 km (the distance equivalent to 12° in latitude), a second search is performed for the point with the minimum pressure gradient (infection point), and the system is classified as an open depression. More details on the method can be found in MS91 and SML99.

The final step of the identification procedure is the removal of systems on the basis of thresholds. Hereafter, the names of the corresponding parameters are given in italics and correspond to those in the program code and in SML99. The chosen values for these parameters (Tab. 1) have been carefully tested considering more than one hundred individual cyclones in different regions, but only a few examples can be presented here for illustration.

- No cyclones over high ground: Vorticity maxima and lows are sometimes artificially introduced into the MSLP data due to extrapolation below high ground. We found it useful to remove all systems identified at grid points with surface heights of more than 1500 m ($z_{\text{max}}$, Tab. 1) above sea level. On the other hand, cyclones close to the high orography barriers often proved to be real in areas with a dense observational network (e.g., Genoa Gulf, southern Alps) and thus we did not follow SML99 in suppressing them systematically ($flopeq$).
Minimum intensity: Spurious or artificial lows are mostly characterised by comparatively low values of the $\nabla^2 p$. The algorithm considers spatial averages of this quantity computed in an area around the low pressure core (and not around the $\nabla^2 p$ maximum as suggested by SML99). The choice of threshold values ($\text{cmnc}$ parameters for closed and for open systems) and of the averaging radius ($\text{cvarad}$) must make sure that small scale lows and cyclones in the initial stage of their life cycle are kept. Note that Mediterranean cyclones have a typical horizontal scale of 300 km (TRIGO et al, 1999). Thus, a small averaging radius equivalent to 4° in latitude (about 400 km) was chosen (Tab. 1). Smaller values were also tested, but mature cyclones with slack gradients near the centre would no longer be well represented. On the other hand, higher values imply a bias towards large steering cyclones. With respect to the thresholds for $\nabla^2 p$ (see Tab. 2), we have chosen 0.2 hPa/(deg. lat.$^2$) for open systems and 0.1 hPa/(deg. lat.$^2$) for closed systems ($\text{cmnc1}$, Tab. 1).

Minimum distance: The presence of vorticity maxima along frontal zones of major cyclones and also in the vicinity of orography frequently leads to chains of open systems. Many of them are not of any importance. We demand that only the strongest system within a radius of 3 degrees latitude is included ($\text{diflt1}$). This condition was not necessary in SML99 because of the smoothing they used in the input data.
Examples illustrating successful cyclone identification are given below. The first case (Fig. 1) refers to the synoptic situation of February 28th, 1990, 06 UTC and shows the importance of the identification of open systems. The weather situation is dominated by a mature vortex centred over Scandinavia (Fig. 1a). Out of the two secondary cyclones over the eastern North Atlantic the latter (noted W) developed into a storm cyclone called “Wiebke” by the German Weather Service. This storm is of relevance as it produced major damage in central Europe. The set of cyclone cores resulting from the identification procedure includes a large number of artificial or criterion. Position B in the finer grid) given the minimum distance is too close to the other cyclone core (corresponding to position A in the finer grid) in a first step, but it is later rejected as its position represents the type of a Genoa cyclone. Fig. 2b shows the MSLP and $\nabla^2 p$ fields for the same analysis time after spline interpolation. The identified Genoa cyclone’s core (cyclone A) is in very good agreement with the hand analysed cyclone position (cf. Fig 2a), while a band of high $\nabla^2 p$ values between the Gulf of Lions and the Balkans coincide with the frontal system. Other systems are identified within this zone, as the vorticity maxima can be attributed to pressure minima (e.g., cyclone B) and frontal wave (open) disturbances. When considering the coarse grid, the position of the Genoa cyclone is not correctly identified, even though there is a maximum of $\nabla^2 p$ close to the observed cyclone core (Figure not shown). A detailed analysis of this case reveals that the algorithm identifies an open cyclone near the correct position (corresponding to position A in the finer grid) in a first step, but it is later rejected as its position is too close to the other cyclone core (corresponding to position B in the finer grid) given the minimum distance criterion.

The set of cyclone cores resulting from the identification procedure includes a large number of artificial or irrelevant systems. Such systems can largely be eliminated by applying a smoothing procedure as suggested by SML99. Smoothing, however, also eliminates smaller
scale cyclones over secondary storm track regions. We decided not to smooth the data, accepting about 40% more identified systems than what was produced with the SML99 settings. This enhanced number is useful in respect to the subsequent cyclone tracking as discussed below.

4 Cyclone tracking

The algorithm determines cyclone tracks based on the results of the identification scheme. For each identified cyclone, the algorithm predicts a subsequent position and core pressure. The identified cyclones in the following time step which are located in the vicinity of the suggested position are examined and the most likely candidate is chosen. The estimation of the subsequent position uses a "prediction velocity" $u_{pred}$

$$ u_{pred} = (1 - \text{wsteer}) \cdot uM + \text{wsteer} \cdot (f\text{steer} \cdot uS) \quad (4.1) $$

where $u_{pred}$ is an average of velocity deduced from the "previous displacement" $uM$ and a "geostrophic steering velocity" $(f\text{steer} \cdot uS)$ term. The relative weight of both terms is given by the factor $\text{wsteer}$. The steering velocity at the surface level $uS$ is calculated from an averaged pressure gradient around the centre of the cyclone over a radius of 4° of latitude ($rdpgrd$) for the actual date. This is a simplification against SML99 who had also taken the subsequent date into account. It is not attempted to take into account steering by upper-level flow explicitly (as suggested by Hoskins and Hodges, 2002) in order to minimize data requirements. SML99 found that the additional inclusion of upper level data does not significantly change the performance of the algorithm. Instead, they multiply the value of $uS$ with a factor $(f\text{steer})$ to account for the increasing wind speed with height, for which we have chosen a value of 2.25. The weighting factor $\text{wsteer}$ is set to 0.4 (see Tab. 1). This implies a larger contribution of the displacement term than of steering velocity term to $u_{pred}$.
The probability of association between cyclones identified in the current chart, and all possible candidates as their successors in the subsequent chart, is calculated using a cost function. This function (now with shape factor $r_{pbell} = 0.4$, see MS91), involves the distance from the estimated position (looking for cyclones within a distance of $r_{cprob} = 12.5^\circ$ of latitude), and the difference in core pressures (including an estimate of core pressures from the previous pressure tendency, controlled by factors $wpten$ and $dequiv$, see Tab. 1). The associations between predicted cyclones and possible successors are sorted into groups (cf MS91, Fig. 8). The sorting into groups can be understood as a spatial clustering in order to help a correct assignment of the cyclones and to minimize computational costs. For each group, the most probable combination of associations is determined. Systems not paired up in this process have either just emerged (cyclogenesis) or ceased to exist (cyclolysis). Cyclone splitting and merging is not permitted in the scheme. Instead, the cyclone track with the closest similarity according to the cost function is continued. Further details of this part of the tracking methodology.
are found in MS91 and SML99. Regarding the filtering parameters for open and new systems ($q_{mx}$ parameters, see Tab. 1, SML99), we have chosen a 10% higher disregard of weak systems, in order to favour a continuation of weak cyclone tracks towards a strong system (instead of a weak one).

Objectively identified cyclone tracks were extensively compared with hand analysed tracks from the synoptic charts and original SLP fields. The results were also compared to calculations performed with original settings (SML99) (cf. Tab. 1). The overall result was that sensitivities with respect to the choice of the settings are generally very small for large oceanic cyclones where the assignment is not ambiguous. They can, however, be very large for secondary small scale systems, for fast moving systems, and for the early and late parts of the systems’ life cycles. In these cases, the result is also heavily dependent on the identification procedure, in particular to the question if smoothing (as in SML99) is involved or not. The tracks of three cyclones that eventually produced gales over Central Europe in early 1990 (Fig. 3) provide examples for the tracking’s sensitivities.

The track of the storm called “Vivian” (Fig. 3a) as identified with the current setting is in agreement with results obtained by a manual synoptic analysis. However, an identification of cyclone cores based on the SML99 settings (Fig. 3b) leads to a association with the track of an open system east of the Great Lakes. This is due to the less restrictive probability function ($r_{pbell} = 1.0$, see Tab. 1) and data smoothing in the SML99 settings. The latter manipulation removes some secondary systems which are needed for obtaining correct associations. Towards the end of the cyclone’s lifetime, smoothing causes the system to vanish too soon. Very similar effects are found for the storm “Wiebke” which was already introduced in section 3. Again, the track obtained with the current setting (Fig. 3c) is in good agreement with the hand analysis from synoptic weather maps. The track based on the SML99 setting begins earlier and also ends earlier because of problems with the correct identification and subsequent association of the system at weak stages of its lifetime (Fig. 3d). Wiebke’s track can only be identified over western Europe when taking into account that it is an open cyclone in the middle of its life cycle, at February 28th, 1990, 18 UTC (see also Fig. 1). This is the case both with and without application of smoothing.

Not unexpectedly, there are particular cases when our settings perform worse than the original ones. In the case of the storm called “Hertha”, the SML99 setting provides a more accurate beginning of the track (Fig. 3f). In this case, the scheme without smoothing produces many very weak systems, which turn out to be weaker than the required threshold. Thus, no systems are identified at January 31th, 1990, 18 UTC and February 1th, 1990, 00 UTC (Fig. 3e). In spite of the problems in this particular case, we found that the current settings produce fewer errors over the North Atlantic area than the SML99 settings, which is mostly caused by the effects of smoothing on the
smaller scale cyclones. The performance of the cyclone tracking algorithm is most sensitive to the shape of the probability function. Sensitivity tests show that larger values for the maximum radius \( r_{cprob} \) combined with a slow decreasing bell shaped function \( r_{pbell} \) lead to the best results for fast moving cyclones. Another focus of the analysis was on the Mediterranean Basin, which is an example of a secondary storm track region. Again, most of the problems encountered with the tracking were related with the identification of “raw” cyclones in the previous step rather than with the chosen tracking settings (results for different track settings not shown). The most sensitive tracking parameters were \( qmx \) terms (preference of open/closed systems, see Table 2) and particularly the search radius \( r_{cprob} \). A value not too large for \( r_{cprob} \) is helpful for the correct tracking of systems, especially for regions with weak SLP gradients. In order to account for both these smaller scale systems and the faster oceanic cyclones, an intermediate value of 12.5 degrees (referring to latitude) for the search radius was chosen.

The list of tracks still contains a large number of spurious systems. Cyclones with a lifetime of less than one day are in fact dominating the statistics (Fig. 4a). We have thus imposed a set of conditions as the final step of the tracking procedure that serve to eliminate them. A cyclone remains in the list of events if it (a) has a lifetime of at least 24 hours and (b) has been classified as a closed and intense system (class 00, \( \nabla^2 p > 0.6 \text{ hPa/(deg. lat.)}^2 \), see Table 2) at least once in its lifetime. The second restriction clearly reduces the number of systems with short lifetimes (1–3 days, Fig. 4b), but it has comparatively little effect on systems tracked for a larger number of days: For 6–10 days lifetime the reduction is about 10–20 %. Fig. 4c displays that the reduction hardly affects the number of closed and intense systems, as they do not usually occur on time scales below one day, which is in agreement with synoptic experience. Weak (strong) open systems are reduced by 76 % (68 %), which is reasonable assuming that most identified open systems are spurious. Weak closed systems are also reduced by 65 %. With respect to core pressure values, we found that the removed systems are generally very shallow (core pressure above 1010 hPa).

The relevance of this elimination differs between geographical regions. Fig. 5a displays the distribution of cyclone counts that fulfilled the required conditions and Fig. 5b of those which were removed. Many of the latter are located over lower latitude continental regions, which are regions of generally slack SLP gradients where orography can dramatically affect the reduction of pressure to sea level. Thus, the systems identified close to orographic borders which were not explicitly

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**Figure 5:** Cyclone counts of cyclones for (a): remaining cyclones after the removal of short-lived systems that never reached a closed status and an intensity exceeding the threshold of strong cyclones (interval: 6.0 cyclone days/winter, areas above 12.0 are shaded grey). (b): removed cyclones (interval: 10.0 cyclone days/winter), areas with differences above 99 percentile value are shaded (t-test based on monthly basis). Values are calculated for 10.0° x 5.0° lon.-lat. grid boxes. Isolines and shadings in areas with orography above 1500 m are suppressed.

**Table 2:** Classification of systems in terms of circulation (open/close) and of values of \( \nabla^2 p \) in hPa/(deg. lat.)\(^2 \). Identified closed cyclones whose strength does not reach 0.1 hPa/(deg. lat.)\(^2 \) are eliminated. For open cyclones, minimum allowed strength is 0.2 hPa/(deg. lat.)\(^2 \).

<table>
<thead>
<tr>
<th>Class</th>
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<th>( \nabla^2 p )</th>
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<tr>
<td>00</td>
<td>Closed x</td>
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<td>01</td>
<td>Open x</td>
<td>&gt; 0.6</td>
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<tr>
<td>10</td>
<td>Closed</td>
<td>0.1 &lt; x ≤ 0.6</td>
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<td>11</td>
<td>Open</td>
<td>0.2 &lt; x ≤ 0.6</td>
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removed in the previous identification step (other than in SML99) are effectively eliminated here, except when they are part of a longer cyclone track.

5 Cyclone climatology

On the basis of the remaining tracks, it is possible to construct a complete climatology. Cyclone activity is now
Figure 7: Cyclone track statistics and differences of all tracked cyclones with data at T42 / 12 h resolution for the period 1958/59 to 1997/98. (a): winter half year mean fields of cyclone track density (interval: 6.0 cyclone day/winter). Included are boxes for the North Atlantic (NA), North Pacific (NP) and Mediterranean (MM). Differences for data at T42 / 12 h versus T62 / 06 h for (b): cyclone track density (interval: 2.5 cyclone days/winter). (c): for absolute amount of cyclone propagation velocity (interval: 0.5 m/s). Arrows indicate the mean direction of changes in propagation velocity, vector length corresponds to the absolute field values. A normed vector for 2 m/s is shown in the lower left corner. (d): core pressure tendency (interval: 0.4 hPa/day). (e): cyclogenesis (interval: 1.0 events/winter) (f): cyclone counts for all tracked and manipulated systems (interval: 1.0 cyclone days/winter). For (b) to (f), areas with differences above 99 percentile value are shaded (t-test based on monthly basis). Values are calculated for areas with a radius of 7.5 lat. around each grid point in (a) to (e) and for 10.0° x 5.0° lon.-lat. grid boxes in (f). Isolines and shadings in areas with orography above 1500 m are suppressed.

Quantified in terms of track density, calculated over a certain area for each gridpoint (here 7.5° radius around each grid point of the 2.5 lon. lat. grid). This variable is primarily influenced by fast moving systems (as these systems travel a long distance and therefore produce long tracks), unlike cyclone counts, where slower sys-
erts are locally over-represented (as they are counted more often for the same grid box than faster moving ones). The cyclone track density for the NH is shown in Fig. 6a, displaying the two main storm tracks with high track density (North Atlantic, hereafter abbreviated NA, and North Pacific, the latter hereafter referred to NP). Note that track density maxima are also found over the secondary storm track areas, e.g., the Mediterranean Basin and Siberia. Cyclones in these regions are generally shallower (Fig. 6b) and have shorter lifetimes than their oceanic counterparts (lifetime data not shown; for further reference see Trigo et al., 1999). The track density is increased using our settings in comparison to SML99, especially over the secondary storm track areas. This can be partly attributed to both the smoothing of the input data and the exclusion of cyclones near orographic barriers used in SML99. Mean cyclone velocities (Fig. 6c) show maximum values close to the maximum jet regions over the western NA and NP where cyclones travel predominantly east-north-eastward over the ocean basins. Secondary maxima are found in the lee of the Ural Mountains (Siberian storm track) and over the Mediterranean.

Fig. 6d shows large negative pressure tendencies (i.e. deepening of lows) over the western parts of the ocean basins, while the rising of core pressures is found over northern Europe and near the northern part of North America’s Pacific coastline. Maxima in baroclinicity (defined as the Eady growth rate at 400 hPa, dark lines in Fig. 6d) are upstream of the maxima of deepening of cyclones, which is consistent with the notion that regionally high values of baroclinicity are generally associated with enhanced cyclone growth (Hoskins and Valdes, 1990). The main areas of cyclogenesis are located downstream of steep orography, e.g., over the lee of the Rocky Mountains and over Japan, but also over the North American east coast and the Gulf of Genoa (Fig. 6e). The main cyclolysis areas are located on the eastern coasts of the oceanic basins (Fig. 6f). The obtained cyclogenesis and -lysis areas are in very good agreement with results by other authors (e.g., Sick-Möller et al., 2000; Hoskins and Hodges, 2002).

We find that the accurate detection of individual cyclone positions and tracks and the realistic representation of the climatological cyclone characteristics provide a good assessment of cyclone activity of the NH. Moreover, the method has the ability of being adequate for both the main and the secondary storm track regions.

6 Impact of reduced spectral and time resolution

In the following section, the eventual impact of spectral (S) and temporal (T) resolution of the basic data on the cyclone climatology is assessed. We look at the two factors separately, as well as their combined effect (C). It should be noted that a complete separation of the two effects is not possible, as a negative synergy effect (ST) in terms of C=S+T+ST must be taken into account. The cyclone track density for T42/12 hour resolution (Fig.
Figure 9: Cyclone statistics considering time (left) and spectral (right) reduction separately. (a): Difference for cyclone track density with reduced time resolution (12h vs 06h; interval: 2.5 cyclone day/winter). (b): difference for cyclone track density with reduced spectral resolution (T42 vs T62; interval: 2.5 cyclone days/winter). (c) As (a) but for cyclone counts of tracked systems (interval: 1.0 cyclone days/winter). (d): as (b) but for cyclone counts of tracked systems (interval: 1.0 cyclone days/winter). Values for (c) and (d) are calculated for 10.0° x 5.0° lon.-lat. grid boxes. Areas with significant anomalies (at 99% confidence level) are shaded (t-test based on monthly basis). Isolines and shadings in areas with orography above 1500 m are suppressed.

7a) displays a similar distribution in comparison to the full resolution (Fig. 6a), with reduced absolute values over the oceanic storm track areas (relative change of minus 20 to 30 %) and Mediterranean basin, the Caspian Sea and Siberia (with relative changes reaching minus 50 %, see Fig. 7b). Deviations in the obtained spatial distributions are also found for other cyclone characteristics: Average propagation speeds are lowered (enhanced south-westerly component compared to northeasterly component in the climatological mean) over the southern parts of the main storm tracks (Fig. 7c), indicating that fast moving systems are severely affected by the change in resolution in these areas.

In terms of core pressure tendencies (Fig. 6d), the effect is mainly a reduction of deepening rates (Fig. 7d). Only small changes in these variables are observed over the regions where the large cyclones decay (Fig. 7c and 7d). Our interpretation of these results is that the main effect of reduced resolution is a loss of not only weaker (which could be expected from the resolution change) but also faster growing and propagating systems. The loss of mainly weaker systems implies deeper mean core pressures for the reduced dataset, as can be observed over the exit regions of the main storm tracks (especially for the NP) even though the changes are not significant (figure not shown).

The effect of simultaneously reduced spatial and temporal resolution of the input data is now investigated in terms of the frequencies of different core depth (from MSLP) and intensity classes (measured as $\nabla^2 p$). These are investigated as spatial sums of the respective counts using grid points over the main ocean basins (NP plus NA boxes in Fig. 7a) and for the Mediterranean Basin (MM box shown in Fig. 7a). From the $\nabla^2 p$ statistics, it becomes clear that combining the reduction in both the temporal and spatial domain generally leads to a
loss of many of the weaker systems while only minimal changes are detected for stronger systems (Fig. 8b, d). This effect is observed over all ocean basins considered. On the other hand, the relative changes for depth statistics are similar for all depth classes (Fig. 8a,c). This exhibits a clear contrast between results based on core pressure and on vorticity.

A coarser temporal resolution (12 hourly instead of 6 hourly) without a change in spatial resolution leads to a significantly reduced cyclone track density over the whole storm track domain (Fig. 9a). The reduction in track density amounts roughly half of the combined effect. An analysis of individual tracks shows that the loss of tracks is frequently related to very large displacements (fast moving systems) or to changes in the propagation speed of the cyclones. With respect to the resulting climatologies, this implies that the mean eastward propagation velocities and the deepening rates are reduced, in particular near the entrance and central regions of the storm tracks over the oceans (not shown).

Reduction of the spatial resolution alone mostly affects shallow systems. Cyclone track densities are mostly reduced between Greenland and Scandinavia, and between southern Alaska and northwest Canada (Fig. 9b), while only a moderate loss of tracks occurs over the main storm tracks. The reason for the small sensitivity to reduced spatial resolution over this latter region is simply that there are only few weak systems that could be lost. There is also little effect on cyclone velocities and cyclone deepening rates over these areas (not shown). On the other hand, sensitivity is high over continental areas, as there are many shallower systems embedded in slack SLP gradients. The loss of these weak and non-developing systems at lowered resolution results in enhanced core pressure tendencies over these regions (not shown). The growing and deeper cyclones are still identified and tracked at reduced spatial resolution of the data. This also becomes evident from the fact that the mean core pressure is lowered.

Considering the effects of reduced resolution in terms of cyclone counts, the signal is relatively small for the temporal effect (Fig. 9c), but large for the spatial effect (Fig. 9d). This result is in clear contrast to the signal in cyclone track densities. The different impacts are mainly due to the alternate nature of both variables: While slower systems are over-represented in comparison to fast moving systems for the cyclone counts, the track density is primarily influenced by fast moving systems.

The tracking of systems based on daily temporal resolution data was also tested. However, the obtained results indicate an unsatisfactory performance of the tracking scheme (using the present settings) and show a high percentage of incorrect and broken tracks in comparison to the hand analysed and 6 hourly-tracks (not shown). Of course, the large steering cyclones with linear tracks are less affected than smaller scale systems. This assessment is in agreement with results from other schemes (BLENDER and SCHUBERT, 2000; ZOLINA and GULEV, 2002). As a consequence, the resulting number of cyclones is considerably reduced, in particular over the secondary storm track regions (not shown).

As suggested by MS91, improved results at low temporal resolution of the basic input data (e.g., daily data) could be obtained by using climatological steering velocities instead of geostrophic velocities. This could provide better results for the climatology, even though individual tracks are frequently not caught correctly. Data smoothing (which we rejected in the present study) could also contribute positively to a tracking that is restricted to deep cyclones.

7 Discussion

The aim of the present study was to obtain a cyclone climatology which successfully includes the whole range of NH cyclones: the large quasi stationary and transient oceanic cyclones, fast moving storms and smaller systems over secondary storm track areas. Furthermore, insight was provided into the relevance of algorithm parameters and impact of the choice of their values for the identification and tracking of cyclones. Using a set of values suitable for the NH, the algorithm proved to be a very powerful tool not only in the generation of cyclone climatologies but also in the assessment of individual tracks. It was shown that cyclones may change between a state with or without closed isobars during their lifetime (closed and open systems, respectively) so that the inclusion of the open cyclones is a necessary ingredient in the scheme. The method is capable of identifying cyclones in a range of locations and with different characteristics, including small scale systems over secondary storm track regions and fast moving storms that produce extreme events like winter storms over Europe later in their lifetime. The characteristics of the individual cyclones were assembled at each time step, e.g., their intensity (\(V_p^2\)), core pressure, intensity tendency and propagation speed. These results provide a basis for assessing both particular life cycles of single cyclones and climatological aspects based on large cyclone ensembles, both from reanalysis and model data.

We have chosen to work with MSLP data, even though several authors have reported some problems for cyclone identification, often recommending the use of lower level relative vorticity instead (e.g., HOSKINS and HODGES, 2002; LIONELLO et al., 2002). Arguments against our technique include the difficult identification of smaller scale systems and the dependence on background extrapolation techniques with MSLP. Moreover, the pressure minimum is considered a bad indicator for
the evaluation of the strength of the circulation associated with a cyclone. On the other hand, our study gives evidence that a cyclone identification and tracking may be based on MSLP fields alone by using the $V_p^2$ field (which is proportional to relative vorticity) in the identification process. $V_p^2$ also provides a measure for the strength of the systems largely independent from the background flow. This approach proved to be extremely helpful for the correct identification of the systems, especially at the initial and final stages of a cyclone’s life cycle. The comparatively small data requirements make the algorithm suitable for an investigation of long time series as they are available in ensembles of GCM simulations.

With respect to the main storm tracks over the oceans, our results are in good agreement with other studies (e.g., Hodges, 1996; Sinclair, 1997; Serreze et al., 1997; Sickmüller et al., 2000; Gulev et al., 2001; Hoskins and Hodges, 2002; Lambert et al., 2002), even though a direct comparison of the obtained cyclone climatologies is often hampered by several differences between quantities considered and datasets used. Leonard et al. (1999) point out that the algorithm used in the present paper is able to detect a larger number of cyclones and tracks in comparison to other methodologies. This is especially important for secondary storm track regions where many other schemes identify comparatively few systems (e.g., Serreze et al., 1997; Gulev et al., 2001). Similar results in these areas were found by Hoskins and Hodges (2002) when using the 850 hPa relative vorticity fields.

Our results are also in good agreement with work performed specifically for the Mediterranean region (Trigo et al., 1999), e.g., in terms of cyclogenesis and preferred cyclone tracks. Moreover, our results for individual cyclones reveal a good agreement with hand analysed synoptic weather maps.

We related the cyclone deepening rates with baroclinicity and confirmed that enhanced regional baroclinicity is associated with an intensification of the systems. This corroborates results presented by Hoskins and Hodges (2002) and by Ulbrich et al. (2001) for individual cyclones producing extreme winds over Europe. Additional work based on the analysis of individual tracks confirmed that locally enhanced baroclinicity often leads to a higher weather relevance of systems in the Mediterranean Basin.

With respect to the spatial and temporal resolution of the input data, our results confirmed the findings of Blender and Schubert (2000) that the number of cyclones detected is reduced when spatial and temporal resolution are lowered. In terms of core pressure, it appears that both weak and intense systems are affected, but a consideration of $V_p^2$ reveals that it is in fact a loss of systems with small vorticity anomalies. Cyclone counts are predominantly affected by reduced spatial resolution, while track density changes are equally affected by both effects. On the other hand, a reduced temporal resolution (from 6 to 12 hours) has hardly any impact on cyclone counts. This is due to the different nature of these variables: Track density has an emphasis on faster moving and rapidly developing systems while slowly moving mature systems are comparatively less important due to short displacements between individual dates. The loss of fast systems at lowered temporal resolution is also confirmed by a reduction of mean cyclone velocities.

The cyclone climatology obtained with T42/12h resolution reproduces the main features of NH cyclone activity observed at full resolution. This conclusion suggests the use of this algorithm among others to validate model data at this resolution against observational data. An application to the ECHAM4/OPYC3 model is presented in the companion paper (Pinto et al., 2005).

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