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Abstract

The usefulness of the European Centre for Medium-Range Weather Forecasts ensemble prediction system for tropical cyclone prediction is studied in terms of the spread in cyclone tracks and intensities. It is shown that significant spread in the tracks is obtained through the use of initial perturbations based on targeted singular vectors derived using linearised physics. Inclusion of stochastic physics in the forecast model leads to larger spread in the central pressures. The spread in the tracks shows high level of sensitivity to the background state used in deriving the singular vectors.

1. Introduction

The last few years have seen significant advances in tropical cyclone (TC) track prediction using numerical weather prediction (NWP) models. Several factors have contributed to these advances which include increases in model resolution, improvements in the parameterisation of physical processes, improvements in data assimilation and the implementation of more accurate and stable numerics. Thus global operational models are now being run at resolutions of 50 to 100 km. Although these resolutions are clearly not sufficient to resolve the inner structures of TCs and hence cannot adequately address the problem of intensity, the models are able to resolve the broad structures and the large scale environment surrounding the TCs and therefore have some skill in predicting tracks. As an example of the progress in track prediction, an ongoing WMO Working Group on Numerical Experimentation (WGNE) intercomparison of TC tracks in the western Pacific conducted by the Japan Meteorological Agency (JMA) indicates that the 72-hour track errors for the 1997 cyclone season for models from the European Centre for Medium-Range Weather Forecasts (ECMWF), JMA, United Kingdom Meteorological Office (UKMO) were below 400 km (*Tsuyuki*, private communication). Similarly for the 1998 Atlantic season *Fiorino and Goerss* (private communication) have found that the 72-hour track errors from the ECMWF, UKMO and the Fleet Numerical Meteorology and Oceanography Centre models were below 300 km.

In spite of the impressive progress, there is a considerable variability in performance of models and there can be a large variation of tracks from one day to the next. Thus a major problem facing the forecaster is a lack of information on the reliability and error bars for a particular track forecast. Ensemble prediction, which has become an established part of operational global weather prediction at a number of centres, provides one possible means of addressing the problem of track uncertainty (*Palmer et al.*, 1997, *Toth and Kalnay*, 1993, *Houtekamer et al.*, 1996, *Molteni et al.*, 1996). A key problem in ensemble prediction is the generation of initial perturbations and two types of dynamically-constrained perturbations have been proposed: one, based on 'bred' vectors (*Toth and Kalnay*, 1993), has been used for generating initial perturbations at NCEP for operational ensemble forecasts since December 1992 (*Toth and Kalnay*, 1997) while the other, based on a singular vector approach (*Mureau et al.*, 1993), has been used operationally at ECMWF also since December 1992 (*Palmer et al.*, 1993, *Molteni et al.*, 1996).

To date the practical application of the ensemble prediction systems (EPS) has been restricted to the extra-tropics. Indeed, for the ECMWF system, the initial singular vectors are only optimised for the region poleward of 30^o. The principal reason for this restriction is that although the assumption of linear error growth simplifies the computation of fast growing structures, it still requires a linearised version and the adjoint of the forecast model. For the tropics, adiabatic linear models are not optimal and there is no obvious strategy to include physical processes in the linear models because of their strong nonlinearities and the frequent dependence on logical conditionals. Recently, linear models including physical processes have been developed. For a regional mesoscale model, the accuracy of the diabatic linearisation is described in *Vukicevic and Errico* (1993) and more recently in *Errico and Reader* (1999). At ECMWF the linearised physics package of the global model developed by Mahfouf (1999) is being used to compute singular vectors (*Barkmeijer et al.*, 1999). Another feature of the ECMWF system relevant to the tropics is the inclusion of a simulation of random errors associated with parameterised physical processes in the model which is referred to as stochastic physics (*Buizza et al.*, 1999). These recent developments provide the means to extend the application of ensemble prediction to the tropics.

Zhang and Krishnamurti (1999) have recently reported on a perturbation method for hurricane ensemble prediction which consists of perturbing the initial position and the large-scale environment. The position perturbation is obtained by displacing the observed hurricane towards different directions by a small distance while empirical orthogonal function analysis is used to find fast growing modes in the initial state.

The aim of the current study is to explore the usefulness of the EPS including targeted diabatic (or tropical) singular vectors and stochastic physics in predicting the uncertainty of TC tracks. A brief overview of the ECMWF ensemble prediction system, including stochastic physics and the generation of tropical singular vectors is given in section 2. Results of basic experiments and sensitivity studies are described in section 3. Some further issues are discussed in section 4 and conclusions are presented in section 5.

2. Brief overview of the ECMWF ensemble prediction system

As noted above, the ensemble prediction system was implemented operationally at ECMWF in December 1992 and the configuration included 33 integrations with horizontal spectral truncation T63 and 19 vertical levels (T63L19, *Palmer et al.*, 1993, *Molteni et al.*, 1996). Apart from small changes (*Buizza*, 1997), the system underwent a major upgrade in December 1996 (*Buizza et al.*, 1998), when the ensemble size was increased from 33 to 51 members, and the resolution was increased from T63L19 to T_L159L31 (the subscript 'L' standing for the linear grid option). The forward and adjoint tangent models used in the derivation of singular vectors only included simplified physics comprising vertical diffusion and surface drag. Until March 1998, the initial perturbations were computed to sample instabilities growing in the forecasts, and no account was taken of perturbations that had grown during the data assimilation cycle upto the generation of the initial conditions. As a means of overcoming this problem, since March 1998 (*Barkmeijer et al.*, 1998) the EPS initial perturbations for day d have been generated using both singular vectors growing between days d and d+2 at initial time and between days d-2 and d at final time. The initial perturbations are still scaled at initial time so that, on average over the Northern and Southern hemisphere, the ensemble root-mean-square (rms) spread matches the control (unperturbed forecast) rms error around forecast day 2. Results documented in

Barkmeijer et al. (1998) indicate that the use of these so-called evolved singular vectors marginally improves the ensemble skill but significantly reduces the percentage of times the analysis lies outside the ensemble forecast range, especially during the early forecast period (up to day 3). In October 1999 the number of vertical levels were increased from 31 to 40, with most of the increased vertical resolution in the boundary layer.

The next major change, which was implemented operationally in October 1998, was a simple stochastic scheme for perturbing the parameterized physical tendencies. The scheme is based on the notion that random errors due to parameterised physical processes are coherent between the different parameterisation modules and have a certain coherence on the space and time scales represented by the model. Details of the stochastic physics implementation can be found in *Buizza et al.* (1999) and will not be repeated here. *Buizza et al.* (1999) have also shown that stochastic physics increases the spread of the ensemble and improves the ensemble performance, particularly for the prediction of weather parameters such as precipitation. Since physical processes are important in the tropics, stochastic physics is particularly relevant to the current study.

A feature of particular relevance to the current study is the derivation of diabatic singular vectors (*Barkmeijer et al.*, 1999). The development of a set of linear physical parameterisations (referred to as linearised physics in the following) for the forward and adjoint tangent model versions of the ECMWF global model as described in *Mahfouf* (1999) makes it possible to compute the SVs for situations where physical processes may play an important role in perturbation growth. The tropics are obvious areas where this is the case. The linearised physics includes vertical diffusion, gravity wave drag, surface drag, large scale condensation, deep cumulus convection and long-wave radiation. A key quantity in the generation of singular vectors is the norm, both at initial and optimisation times, which provides a measure of perturbation growth. The current operational EPS uses the so-called dry total energy norm to compute the singular vectors (*Buizza and Palmer*, 1995),

$$\begin{aligned}\langle x, Ey\rangle = {} & \frac{1}{2}\int_{1}^{0}\int_{\Sigma}\nabla\Delta^{-1}\zeta_x\cdot\nabla\Delta^{-1}\zeta_y+\nabla\Delta^{-1}D_x\cdot\nabla\Delta^{-1}D_y \\ & +\frac{C_p}{T_r}T_xT_yd\Sigma\left(\left(\frac{\partial p}{\partial\eta}\right)d\eta+\frac{1}{2}\int_{\Sigma}R_dT_rP_r\ln\pi_x\cdot\ln\pi_yd\Sigma\right)\end{aligned}$$

with $(\zeta_x, D_x, T_x, \ln\pi_x)$ being vorticity, divergence, temperature and logarithm of the surface pressure, and c_p is the specific heat of dry air at constant pressure, $p(\eta)$ the pressure at eta levels, R_d is the gas constant for dry air, $T_r = 300K$ is the reference temperature and $P_r = 800hPa$ is a reference pressure. Although not used here, an additional term $w_qL_c^2q_xq_y/(C_pT_r)$ can be added to the dry norm to allow perturbations in the moisture field. Inclusion of physical processes increases the computational cost of singular vectors considerably. In addition to more memory to store additional fields during the nonlinear integration, the required computer time increases by a factor of 6. Further details of the derivation of tropical singular vectors and their properties can be found in a companion paper (*Barkmeijer et al.*, 1999).

Considerable use has been made in this study of 'targeting' which allows the derivation of singular vectors that maximise the 2-day total energy norm (or the chosen norm) over the domain of the cyclone. This is achieved by the introduction of a local projection operator so that only perturbation growth in the target area is taken into account. Such an approach is already being attempted for short to early-medium range ensemble prediction for the European domain (see *Hersbach et al.*, 1999 for details). As noted in *Barkmeijer et al.* (1999) singular vector computation with simplified physics leads to spuriously large perturbations in the upper-troposphere unless increased vertical diffusion is used. One way of avoiding this problem without resorting to increased diffusion is to target in the vertical. In the current study a target region extending from model levels 18 to 31 (approximately 500hPa to the surface) has been used.

As mentioned above, for each initial date, an ECMWF ensemble comprises one control forecast ($T_L159L40$ forecast started from the operational analysis) and 50 perturbed forecasts. The initial conditions for the perturbed integrations are constructed by adding and subtracting to the operational analysis 25 orthogonal perturbations defined as linear combinations of SVs. The methodology used in the EPS to define these linear combinations is described in *Molteni et al.* (1996). Its aim is to create perturbations which have an amplitude comparable (in any region) with the estimates of root-mean-square (rms) analysis error. Once the 25 SVs have been selected, an orthogonal rotation in phase space and a final rescaling are performed to generate the ensemble perturbations. The purpose of the phase-space rotation is to generate perturbations which have the same globally averaged energy as the original SVs, but a smaller local maximum and more uniform spatial distribution. Once the rotation has been performed, the perturbations are re-scaled in order to have a realistic local amplitude. The rescaling factor (R_s), is a constant factor which represents an acceptable ratio between perturbation amplitude and analysis error variance. The current operational system uses a value of $R_s = 0.5$. In most of the experiments described below a larger value, namely $R_s = 2.0$ has been used. This choice was made somewhat arbitrarily to initially magnify any signals but still maintain the acceptable ratio. However further experiments with different values of R_s have also been performed and are discussed below.

3. Results

Although the operational EPS now has 40 vertical levels, the current study uses a 31 level system that was operational when the study started. The emphasis here is to examine the feasibility of using tropical SVs and stochastic physics for prediction of tropical cyclone track uncertainty and to a lesser extent intensity. The current study seeks to address the following issues:

- Is it possible to obtain 'realistic' spreads in the TC tracks in which case an attempt can be made to provide probabilistic forecasts for the tracks (the spread is considered to be 'realistic' or 'reasonable' if some members of the EPS overlap with the analysed track),
- Scaling (amplitude and scale) of singular vectors,
- The role of targeting in the derivation of singular vectors,
- The relative roles of singular vectors and stochastic physics,
- The role of diabatic processes in singular vectors.

The following cyclones in the western Pacific and in the Atlantic regions have been considered:

Pacific TC Zeb, with starting dates 11 and 13 Oct. 1998

Pacific TC Babs, with starting dates 19 and 21 Oct. 1998

Atlantic TC Bonnie with starting dates 19 and 21 Aug 1998

Atlantic TC Mitch with starting dates 23 and 25 Oct. 1998.

The only criteria used for the choice of the cyclones was that they were the most recent available and that the chosen cases included recurvature. Note that apart from TC Babs starting on 21 Oct 1998 and TC Mitch for both dates, the operational ensemble forecasts did not include stochastic physics. Figure 1shows the analysed and best tracks (obtained from Naval Research Laboratory, Monterey) for the four cyclones. Although the analyses follow the best tracks, there can differences of 1^{o} - 2^{o} for some periods.

3.1 Spread in TC track and intensity forecasts

The first set of experiments were performed to study the impact of perturbations based on tropical singular vectors and stochastic physics on the spread of the TC tracks and intensity. The following experiments were performed -

i) No perturbations in the tropics and no stochastics physics
ii) No perturbations in the tropics and with stochastic physics
iii) Perturbations based on tropical singular vectors and no stochastic physics
iv) Perturbations based on tropical singular vectors and with stochastic physics

In (iii) and (iv) the SVs were derived by targeting in a domain surrounding the cyclone. For example for TC Zeb starting date 11 Oct. 1998 (to be referred to as Zeb1) and TC Bonnie starting date 19 Aug. 1998 (to be referred to as Bonnie1), the target areas were 0 - 30°N, 110°E - 140°E and 10°N - 30°N, 80°W - 60°W respectively. The impact of the choice of target area will be discussed below.

Some preliminary experiments were performed to assess the role of physical processes in generating initial perturbations. Figure 2 shows the streamfunction for the first four singular vectors at model level 18 (which is the closest model level to 500hPa) for Zeb1 derived using full linearised physics and simplified linearised physics currently used in the operational EPS. Figure 3 shows the corresponding perturbations in 500hPa vector winds for four ensemble members. The cyclone location is denoted by a symbol in both figures. There are significant differences in the amplitude and structure of both the singular vectors and perturbations for the two types of physical parameterizations. The full linearised physics singular vectors and perturbations show well defined dipole-like structures. These features are discussed in more detail in *Barkmeijer et al.* (1999). Although the perturbations for the full linearised physics case are larger, they still are of a similar magnitude as the analysis error variances (not shown). This is important as the perturbations used to generate the ensemble members need to be within the limits of analysis uncertainty.

In order to provide an indication of differences in the TC track and intensity (as given by the central pressure) spreads obtained from the operational system which has no perturbations in the tropics and from an experimental system that uses simplified physics to generate perturbations in the region of the cyclone, the EPS was run for Zeb1 and Bonnie1. The target areas used for the derivation of SVs for the 2 TCs are as noted above. Figures 4a and b respectively show the spread in the tracks and central pressures for the two cyclones (The tracking algorithm locates a cyclone by determining the position of the minimum mean sea level pressure below a certain specified value. Tracking is stopped if the algorithm fails to locate a TC. Thus in the spread figures shown here the number of EPS members might not total 50). The tracks and central pressures from the ECMWF operational analyses, operational (T_L319) forecast and the ensemble mean forecast are also shown. The operational forecast has large position errors for TC Zeb resulting from a spuriously predicted recurvature while the forecast for TC Bonnie is much improved. The operational EPS forecasts, not surprisingly, show little spread in both measures. The use of perturbations based on simplified physics show a greater spread. However note that apart from one or two members, the spread in the tracks shows little overlap with the analysed track after 24-36 hours. Thus for the case of TC Zeb where the operational forecast has a large error, the EPS forecast would be of little value for forecasting landfall over north Phillipines. A feature of the EPS tracks is the shift towards improved agreement with the analysed track relative to the high resolution operational forecast. This shift is basically a reflection of the lower resolution control forecast which for TC Zeb, for example, exhibits a slower recurvature and hence a marginally improved track forecast. The spread in the central pressures also shows no overlap with the analysis (which tends to underestimate the observed central pressure). Part of the reason for the high central pressures in all the EPS members is insufficient resolution. Thus the control EPS forecast (rerun of the high resolution operational forecast at T_L159) has higher central pressures than the operational T_L319 forecast.

Figs. 5a to 5d show the spread in the tracks and central pressures of Zeb1 and Bonnie1 resulting from EPS runs under configurations (i) to (iv) above. For the spread in the tracks (Figs. 5a and 5b), the addition of stochastic physics results in a similar spread to that obtained by using tropical perturbations based on simplified physics. The use of tropical SVs derived using linearised full physics results in a significantly increased spread in the tracks although the spread is smaller for TC Bonnie. This difference in the spread for the two TCs is encouraging as the larger spread is associated with the case where the operational high resolution forecast has large track error. An important feature in the EPS runs with the tropical SVs is that the tracks of a significant number of members overlap with the analysed track and therefore provide a useful indication of landfall over the north Phillipines. Although tropical SVs based on the full physics lead to slightly larger spread in the central pressure than those based on simplified physics, by far the largest spread is given by the inclusion of stochastic physics (Figs. 5c and 5d). A further feature which distinguishes the spreads in the central pressures from the use of tropical SVs and stochastic physics is that the former lead to an overall weakening of the cyclone in the sense that the ensemble mean forecast has higher pressure than the control ensemble forecast whereas stochastic physics leads to an overall deepening of the cyclones. The impact on the intensity of the cyclone can be better seen in Fig. 6 which shows the 3-day forecasts for four members of the ensemble. Stochastic physics leads to large variation (positive and negative) in the central pressure compared to the members with perturbations based on tropical SVs only. Repeating the EPS run with convective forcing excluded from stochastic physics gives a similar spread as the no stochastic physics run (Fig. 5a) indicating that most of the variation in the central pressure is due to perturbations associated with the temperature and moisture fields resulting from convective forcing.

Figures 7a and 7b show the spread in tracks obtained from EPS runs with perturbations generated using tropical SVs only (ie without stochastic physics) for all the cyclones studied. A common feature for both the Pacific and Atlantic cyclones is that the spread is significantly larger for the cases of recurvature when they are not well handled by the control high resolution forecast. It is of interest that even for recurvature the spread is smaller when the control forecast is more accurate (eg TC Zeb for starting date 13 Oct 1998). The spread is smaller in the other cases considered where the control forecast has smaller track errors. Although the spreads generally encompass the analysed tracks, an undesirable feature in some of the EPS runs is that the spread is too large and could lead to incorrect conclusions regarding the track. This is particularly the case for TC Babs starting from 21 Oct 1998 where there is a clear split of the members into two tracks, one following the analysed track (containing majority of members) and the other following an incorrect northward track towards Taiwan. One reason for the spread being too large could be the choice of scaling for the perturbations. This aspect will be discussed below.

In summary the results of the above EPS runs indicate that the use of tropical SVs leads to an increased spread in tracks which could potentially be of use for TC track prediction. Although the sample size is small, the spread in tracks appears to be related to the track errors in the control high resolution forecast with larger errors leading to larger spread. The main impact of stochastic physics is on the spread in central pressures of the cyclones.

3.2 Sensitivity studies

Most of the sensitivity studies were performed for two cases namely Zeb1 and Bonnie1.

The first set of sensitivity experiments were carried out to determine the impact of the amplitude of initial perturbations on the spread of TC tracks. This was done by varying the scaling factor, R_s. The above two cases were rerun with $R_s = 0.5$ and 1.0. Note that the resulting perturbations are respectively a factor 1/2 and $1/\sqrt{2}$ of the perturbations used above with $R_s = 2.0$. Figure 8 shows the spread in the tracks resulting from varying scaling factors (The corresponding spreads for R_s =2.0 are shown in Fig. 5a and 5b, bottom left panels). Although there is a reduction in the spread with reduced scaling the sensitivity is not particularly strong, indicating the important role of nonlinearity in initial growth of the perturbations. Thus for comparison, the spread with $R_s = 0.5$ is still larger than (or similar to for TC Bonnie) the spread resulting from stochastic physics. However for TC Zeb, the spread with $R_s = 0.5$ does not overlap with the analysed track in the later stages of the forecast.. Similar results were obtained for TCs Babs and Bonnie (starting from 21 Aug 1998). It is interesting to note that for TC Bonnie starting on 21 Aug 1998, which included larger track forecast error in the high resolution forecast (see Fig. 7b), the spread for $R_s = 0.5$ (not shown) was larger than with stochastic physics (as for TC Zeb). These results suggest that a scaling with $R_s = 1.0$ would be effective for practical applications as the perturbations would lie within analysis errors. Note that the wind perturbations with $R_s = 2.0$ had similar magnitudes as analysis errors while the height perturbations were much lower.

All the experiments described so far have used 'targeted' singular vectors obtained by the introduction of a local projection operator. The target area was chosen to be a region around the particular cyclone. For example, target areas for TCs Zeb1 and Bonnie1 were 0° - 30°N, 110°E - 140°E and 10°N - 30°N, 60°W - 80°W respectively. In order to assess the sensitivity of the spread in tracks to the target domain, a number of additional EPS runs were performed with TCs Zeb1 and Bonnie1. In the additional experiments the following target areas were used

i)	Pacific Basin	0°S - 30°N,	100°E - 220°E
ii)	Tropical Strip	30°S - 30°N,	0°E - 360°E
iii	Atlantic Basin	0°N - 30°N,	100°W - 0°W

Figure 9 shows the resulting spread in the tracks of Zeb1 and Bonnie1. The spreads with the Pacific and Atlantic basins are very similar to those obtained using much smaller target areas around the cyclone (see Figs. 5a and 5b), with a number of members overlapping with analysed tracks. This feature is important for practical applications as discussed below. However the use of the whole tropical strip as the target area results in a much smaller spread which does not provide useful additional information over the high resolution forecast. This might appear surprising at first but a closer examination of the singular vectors shows that a large target area does not guarantee that the fastest growing singular vectors will be in the region of the cyclone. Indeed for the cases considered here the fastest growing singular vector is located over a totally different region. This result is considered in more detail in *Barkmeijer et al.* (1999).

The above experiments indicate that tropical singular vectors are effective in generating realistic spreads in TC tracks and have the potential to provide useful guidance regarding uncertainty in tracks predicted by the high resolution model. This leads to further questions such as the importance of using the appropriate basic state for deriving the singular vectors, and whether the singular vectors carry specific information which is important for the motion of TCs. One way of addressing these questions is to rerun the EPS with singular vectors derived from different dates. These experiments were performed for TC Zeb1 as it had the largest track spreads in the initial experiments. The EPS was run with singular vectors derived for 01 Feb 1998, 01 Jun 1998 and 19 Oct 1998. The February case represents the extreme where the SVs are derived for the winter season; the June case was performed because TCs can occur in the region although it is somewhat early for the TC season; and the choice of 19 October case was based on TC Babs being in the target domain at the same time as Zeb1. Figure 10 shows the spread in the tracks for the above experiments. All cases show a markedly reduced spread in the tracks compared to the case where the appropriate basic state is used for the SV derivation. The reduction is particularly marked for the February and June cases. The spread is considerably reduced even for the 19 October case when there was a cyclone present in the domain, emphasizing the importance of an appropriate background state. One possible reason for the reduction of the spread for the February and June cases is that the initial perturbations in the region of the cyclone are small. In order to clarify this, the February case was rerun using a perturbation scaling $R_s = 8.0$ (resulting in perturbations which are a factor 2 larger in amplitude than obtained with $R_s = 2.0$ used above). The resulting perturbations (not shown) are now of similar magnitude to the perturbations shown in Fig. 3 (top panels) which used an appropriate background state. The main feature in Fig. 10 (bottom right panel) which shows the spreads for the February case for $R_s = 8.0$ is that the spread is not significantly enhanced when the perturbation amplitude is doubled. The strong sensitivity to and the importance of an appropriate basic state suggests that the targeted tropical singular vectors contain relevant features of the circulation in the region of the TCs which impacts on the subsequent tracks. This feature of the singular vectors could therefore be used for studying TC motion. The results also suggest that the use of random perturbations would not be effective in generating adequate TC track spreads.

The use of initial perturbations based on SVs provides one way of generating ensembles such that the perturbations are within analysis errors. Another way of taking account of analysis uncertainties is to use analyses from different operational centres. In order to compare the performance of the two methods, Zeb1 and Bonnie1 were rerun with the ECMWF model (T_L159L31) initialised with analyses from United Kingdom Meteorological Office (UKMO), National Centers for Environmental Prediction (NCEP), Deutscher Wetterdienst (DWD) and Meteo-France (the Meteo-France analysis was only used for Zeb1). The differences between these analyses and the ECMWF analysis are shown in Fig 11. Comparison with the perturbations based on tropical SVs in Figure 3 indicates that the two are of similar magnitudes, the main differences being in the scale and organisations of the perturbations. The SV perturbations are of a more organised nature and larger scale. The spreads in the tracks and central pressures in the forecasts from different analyses are shown in Fig. 12. Although the central pressure spreads are similar to those using tropical SVs only, the spread in the tracks for Zeb1 is much smaller and none of the tracks overlap with the analysed track after about 36 hours. This very limited sample again shows the potential advantage of using tropical SVs.

As noted above, perturbations based on tropical SVs did not have much impact in the spread of central pressures of the TCs. The lack of sensitivity could be due to factors such as insufficient resolution in the forecast model or in the derivation of the SVs. Two EPS runs for Zeb1 and Bonnie1 were performed at T_L255 to assess the impact of model resolution (the initial perturbations were based on the tropical SVs as used above). The spread in the tracks was not significantly changed by the increase in resolution. However, as shown in Fig. 13, the higher model resolution leads to a significant increase in the spread of the central pressures. The central pressure of the mean of the ensembles is now much closer to the higher resolution T_L319 integration. Thus the combination of high resolution EPS together with tropical SVs has the potential to give reasonable spreads in both the TC tracks and central pressures.

The singular vectors used in the above studies had a spectral resolution of T42. In order to assess the sensitivity of the track spreads to the resolution of the SVs, the cases for TCs Zeb1 and Bonnie1 were rerun with the singular vectors calculated at T63 (see also *Barkmeijer et al.*, 1999). The runs showed a minor impact on the TC tracks with the basic pattern being very similar to the T42 SVs.

4. Discussion

The sensitivity experiments described above indicate the important role of targeting in order to obtain realistic spreads in the TC tracks. Larger target areas lead to reduced spread which in turn reduces the potential value of the forecasts. For practical (operational) application for TC track prediction two approaches can be followed. In the first approach, the target area can be limited to be, for example, within 15^o of the location of the cyclone as done above. The TC location is available in real time over the GTS (Global Telecommunication System) and the information is used routinely to generate TC bogus data at a number of operational centres. A second approach is to target a basin according to the cyclone season. Thus for the north-western Pacific, the TC season typically extends from June to October and so the Pacific basin target area could be used. The overlap in the north Pacific and north Atlantic TC seasons does not pose practical problems as the Atlantic basin could be targeted seperately at the same time (this latter point also holds if the smaller area target around the cyclone is used). Appropriate choice of the target area might also be relevant for application to other severe weather (tropical and extratropical) situations. As noted above such an approach is already being used for the European area (*Hersbach et al.*, 1999).

The results in this study have been presented in terms of the spread in the tracks and central pressures. The results can be readily converted into appropriate probablities. This could be appropriate when there is danger of the TC making landfall. In such cases it would be more useful to have the results presented in terms of the probability of landfall, and for the purposes of coastal warning to have the results presented in terms of probabilities of spread around the control EPS member or the high resolution forecast. Additionally, results could be presented in terms of probabilities of precipitation or wind speed exceeding certain thresholds.

Tropical singular vectors have a large impact on the spread in the TC tracks whereas stochastic physics impacts significantly on the spread in the central pressures. Although more work is needed to properly clarify this, the contrasting behaviour of the two components of the EPS can be explained in terms of the scale of the perturbations or forcing. The SVs used in the study have large scale structures which influence the tracks, while the stochastic physics (particularly convection) acts on smaller scales and therefore has an impact on the central pressures (and precipitation).

The spread in the TC tracks is sensitive to the choice of the background state used in the derivation of singular vectors, particularly for the cases with recurvature where the high resolution forecast had large track errors. A reasonable spread in the tracks is only obtained if a timely background state is used. This, together with the fact that small perturbations based on 25 singular vectors which are within the analysis errors can lead to significantly different tracks, suggests that the singular vectors carry relevant information regarding TC motion. Thus they could be used to gain a theoretical understanding of TC motion. This possibility is being considered in a follow-up study. Furthermore, given the structure of the initial perturbations, it would be of interest to determine if the analysis system at ECMWF (or other centres) is able to generate these structures. This could be done by converting the known perturbations into psuedo-observations and feeding these back into the analysis. This aspect too is being considered in a follow-up study.

5. Conclusions

The usefulness of the ECMWF Ensemble Prediction System in predicting the spread in tropical cyclone tracks and intensities has been considered in this study. It has been possible to attempt this with the development of diabatic singular vectors through the inclusion of linearised physics in the tangent-linear and adjoint models (*Mahfouf*, 1999; *Barkmeijer et al.*, 1999), and the inclusion of stochastic physics in the model (*Buizza et al.*, 1999). A number of cyclones in the Pacific and Atlantic basins have been considered.

The results indicate that a much larger spread in the tracks is obtained by the use of initial perturbations based on tropical singular vectors. Indeed the spread appears to be related to the track errors in the operational high resolution deterministic forecast. This is particularly so for the cases of recurvature where the spread obtained with the tropical SVs has a reasonable overlap with the analysed track. Stochastic physics leads to a smaller spread in the TC tracks but to a much larger spread in the central pressures.

The spread in the tracks is sensitive to the target area used in the derivation of the SVs and reasonable spreads are only obtained if a target area around the TC or in the particular region of the TCs is used. The use of the whole tropical strip as target area leads to unsatisfactory spread as the singular vectors in this case are not necessarily located in the neighbourhood of the cyclone.

The spread in the tracks also show a high level of sensitivity to the choice of appropriate choice of the background state in deriving the SVs. This suggests that the use of say random perturbations may not be effective.

The study raises a number of areas of further work such as the use of tropical singular vectors in gaining understanding on tropical cyclone motion, the ability of current analysis systems to generate structures similar to the SVs from a limited number of observations, and the use of tropical SVs to study other types of tropical phenomena such monsoon onset etc. Some of these issues will be considered in follow-up studies.

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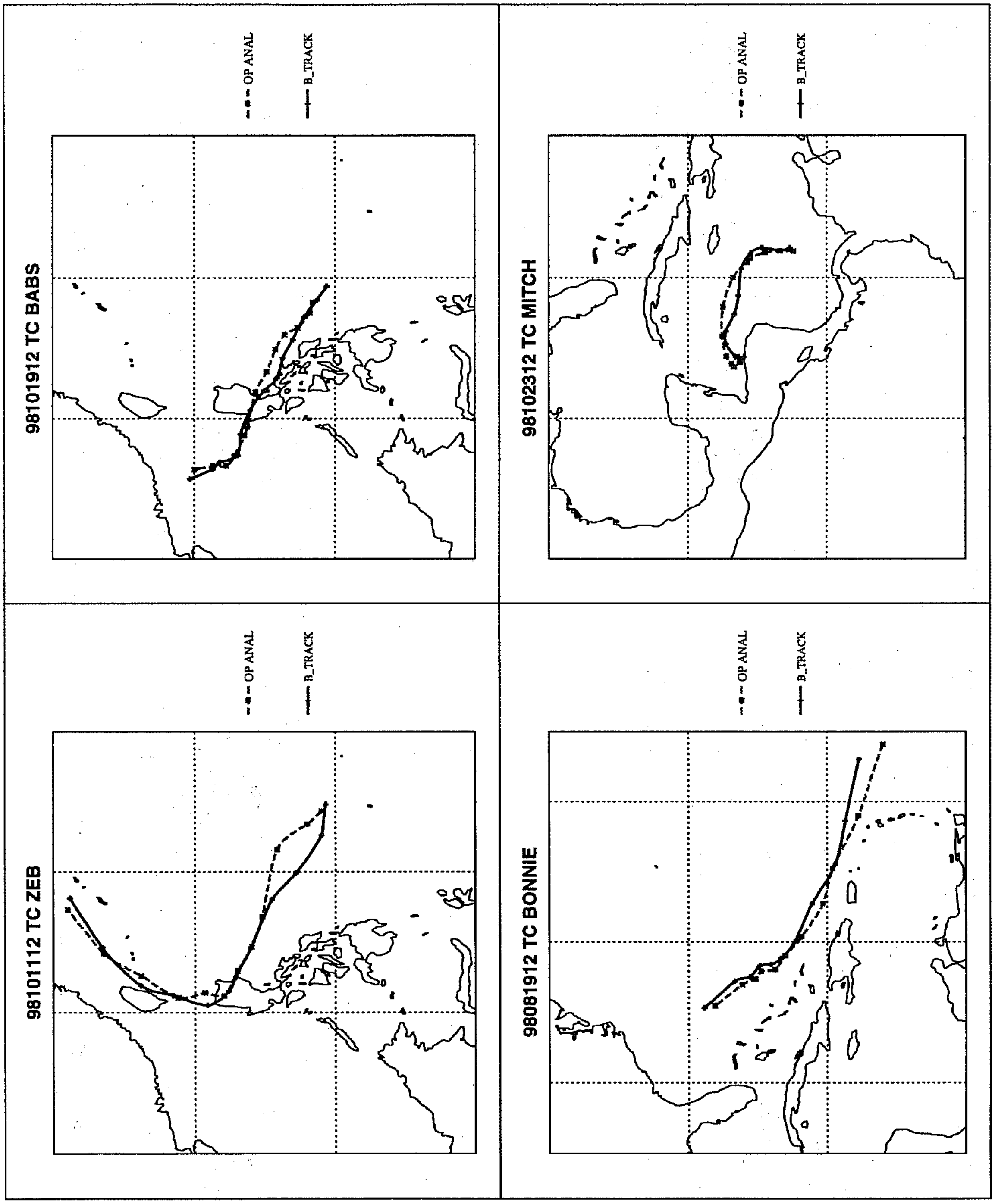

Fig 1: Analysed (solid line) and best tracks (dashed line) for TCs Zeb (starting 11 October 1998), Babs (starting 19 October 1998), Bonnie (starting 19 August 1998) and Mitch (starting 23 October 1998). The track positions are plotted every 12 hours.

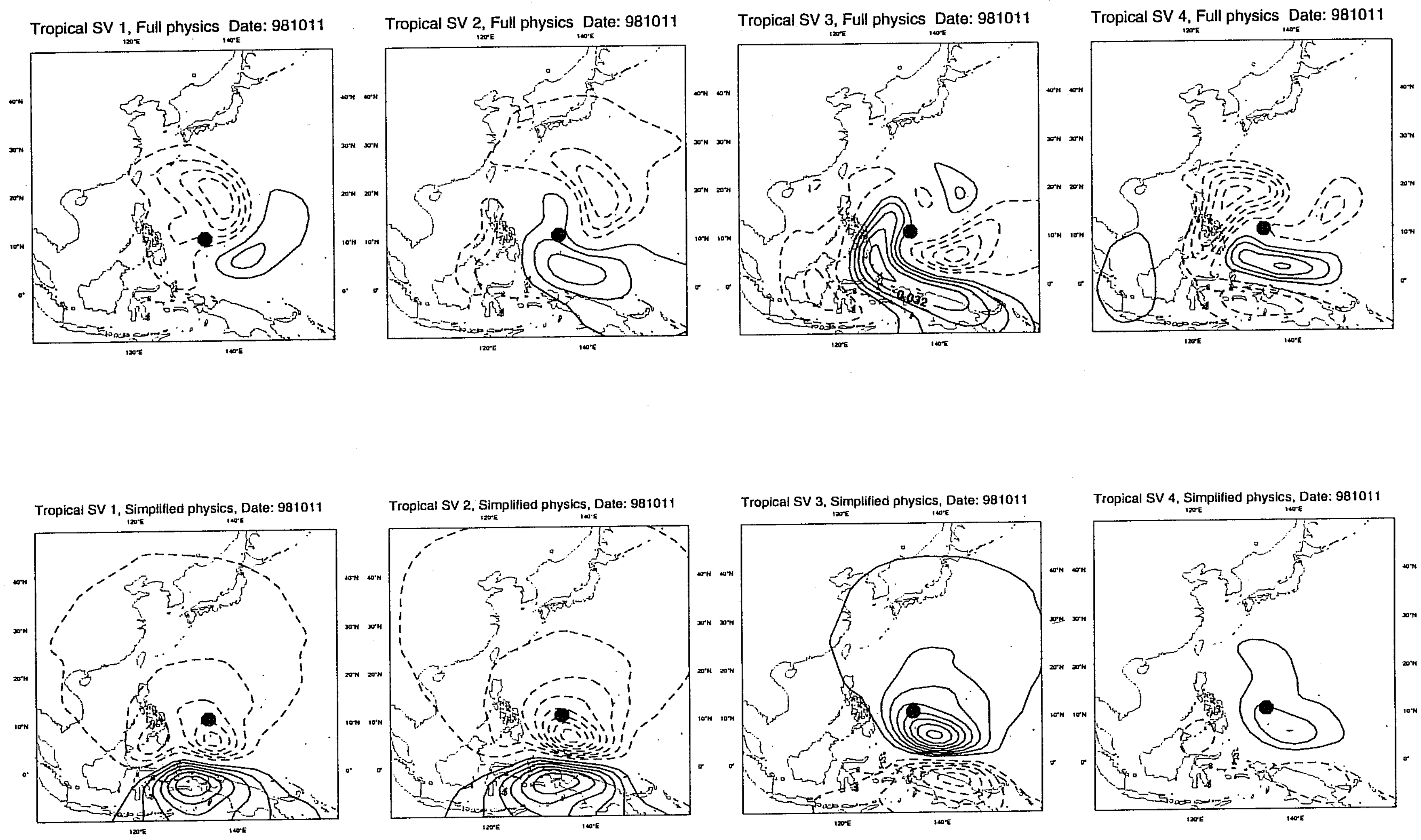

Fig 2: Stream function (in m^2s^{-1}) for the first four singular vectors at model level 18 derived using full linearised physics (top panels) and simplified physics (bottom panels). The cyclone location is indicated by a large dot.

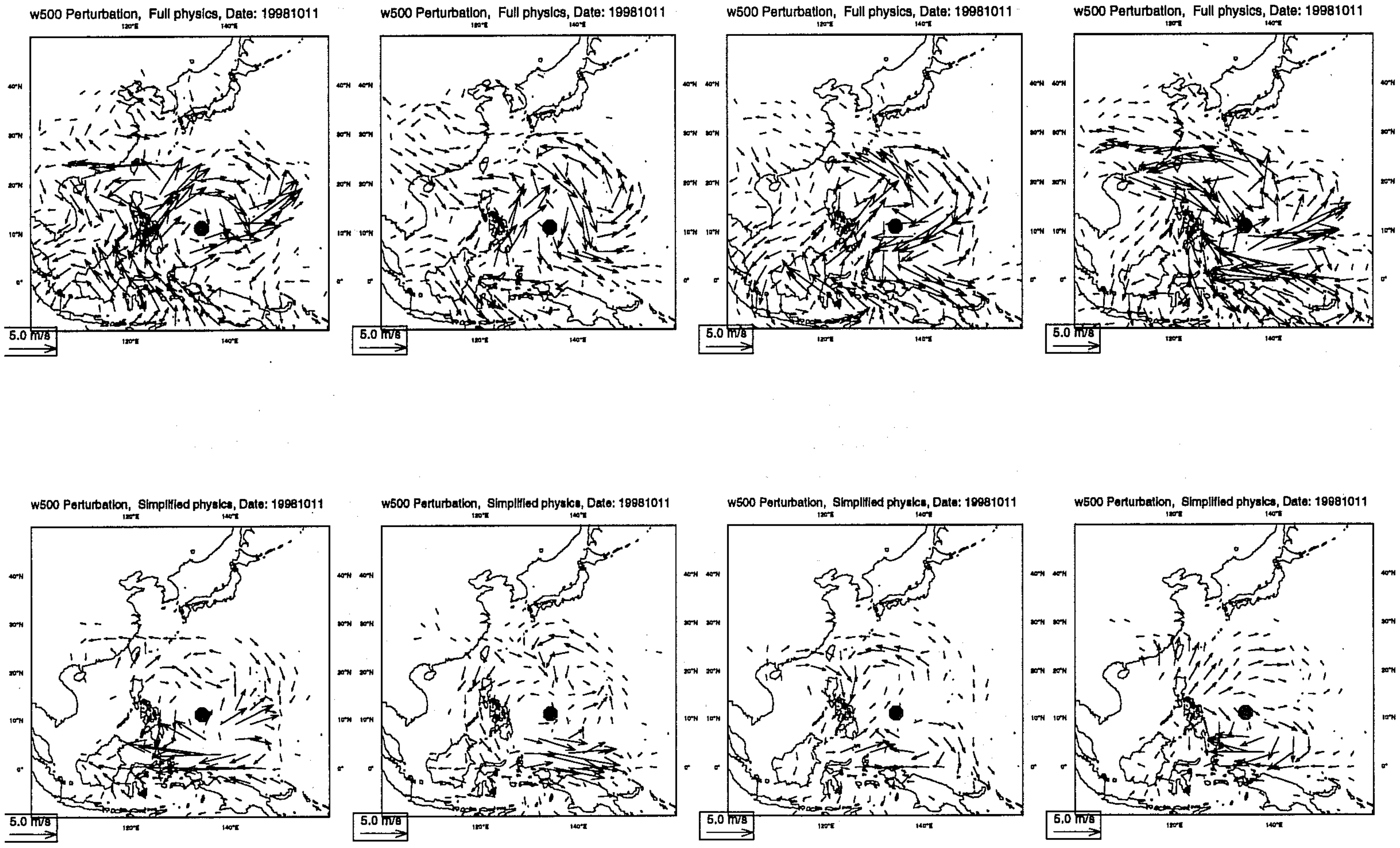

Fig 3 Vector wind perturbations (in ms^{-1}) at 500hPa based on full linearised physics (top panels) and simplified physics (bottom panels) singular vectors for four ensemble members. The cyclone location is indicated by a large dot.

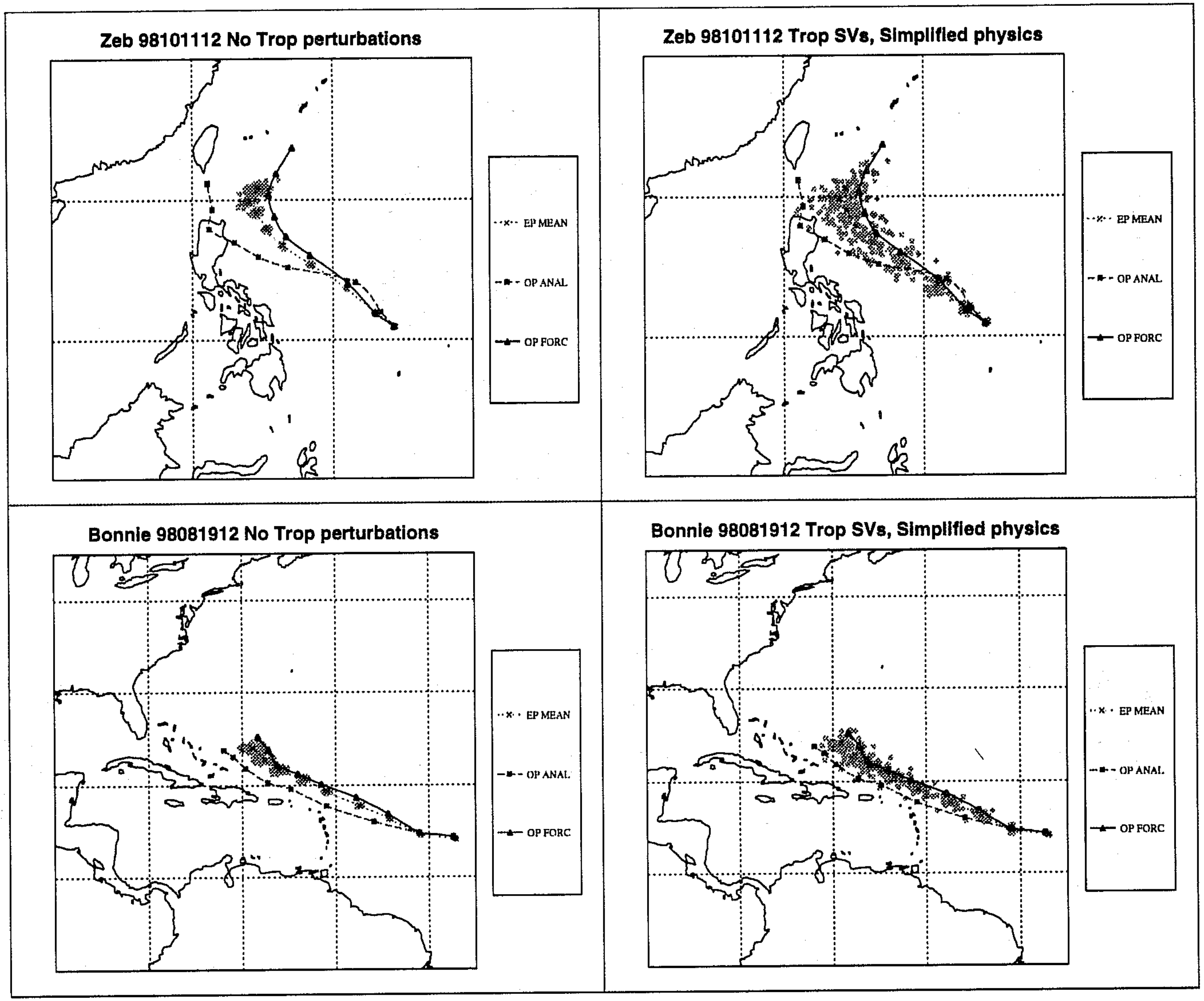

Fig 4a: Tracks for TCs Zeb (top panels) and Bonnie (bottom panels) based on operational analyses (dashed line), operational forecasts (solid line), ensemble means (dotted lines) and individual ensemble members (dots). The tracks are over four days, positions are plotted every 12 hours, and are for EPS runs with no tropical perturbations (left panels) and perturbations based on simplified physics singular vectors (right panels).

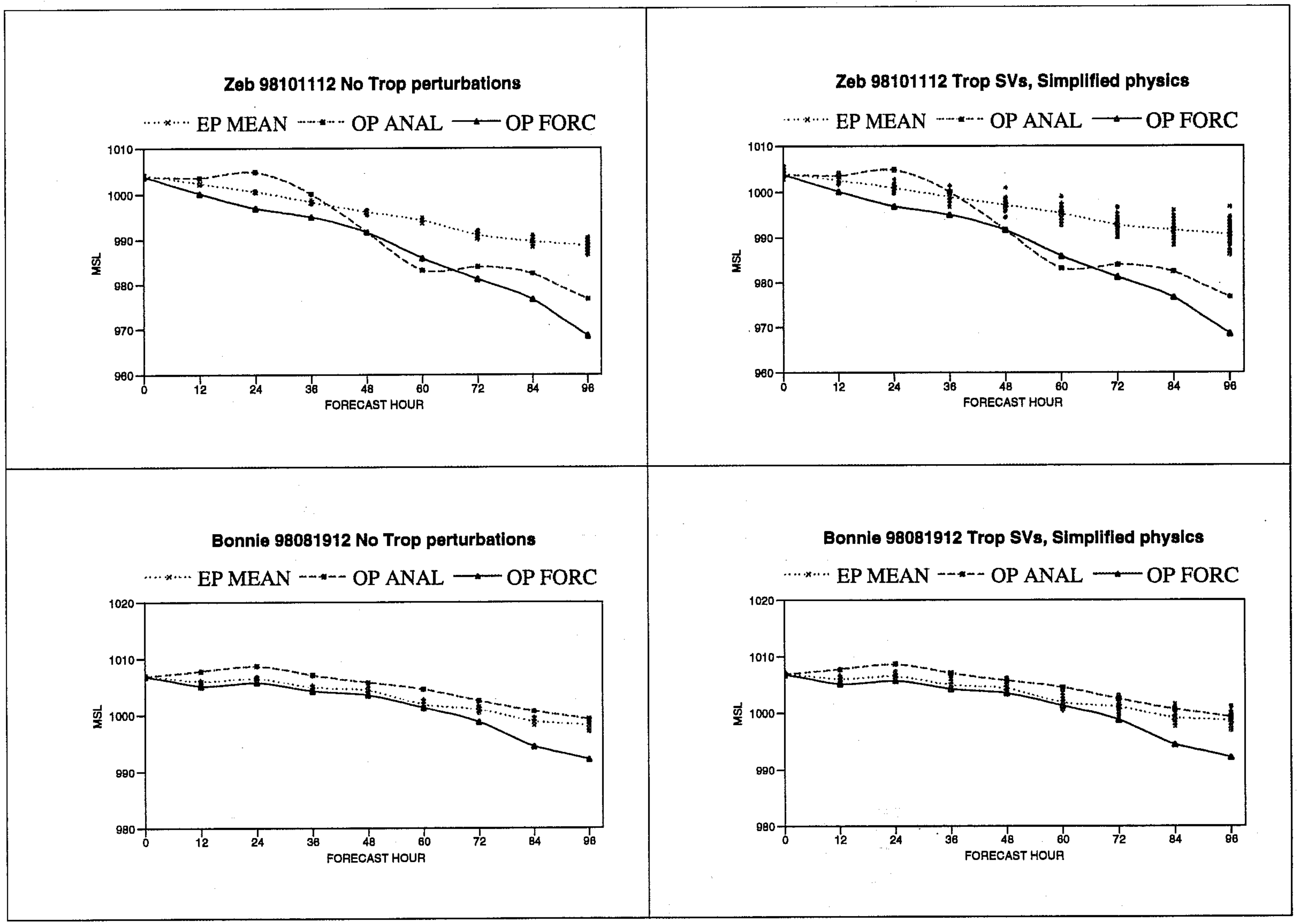

Figure 4b TC central pressures (in hPa) as a function of time (in hours) for TCs Zeb (top panels) and Bonnie (bottom panels) based on analyses (dashed line), operational forecasts (solid line), ensemble means (dotted lines) and individual ensemble members (dots). EPS runs with no tropical perturbations are shown in the left panels and perturbations based on simplified physics singular vectors are in the right panels.

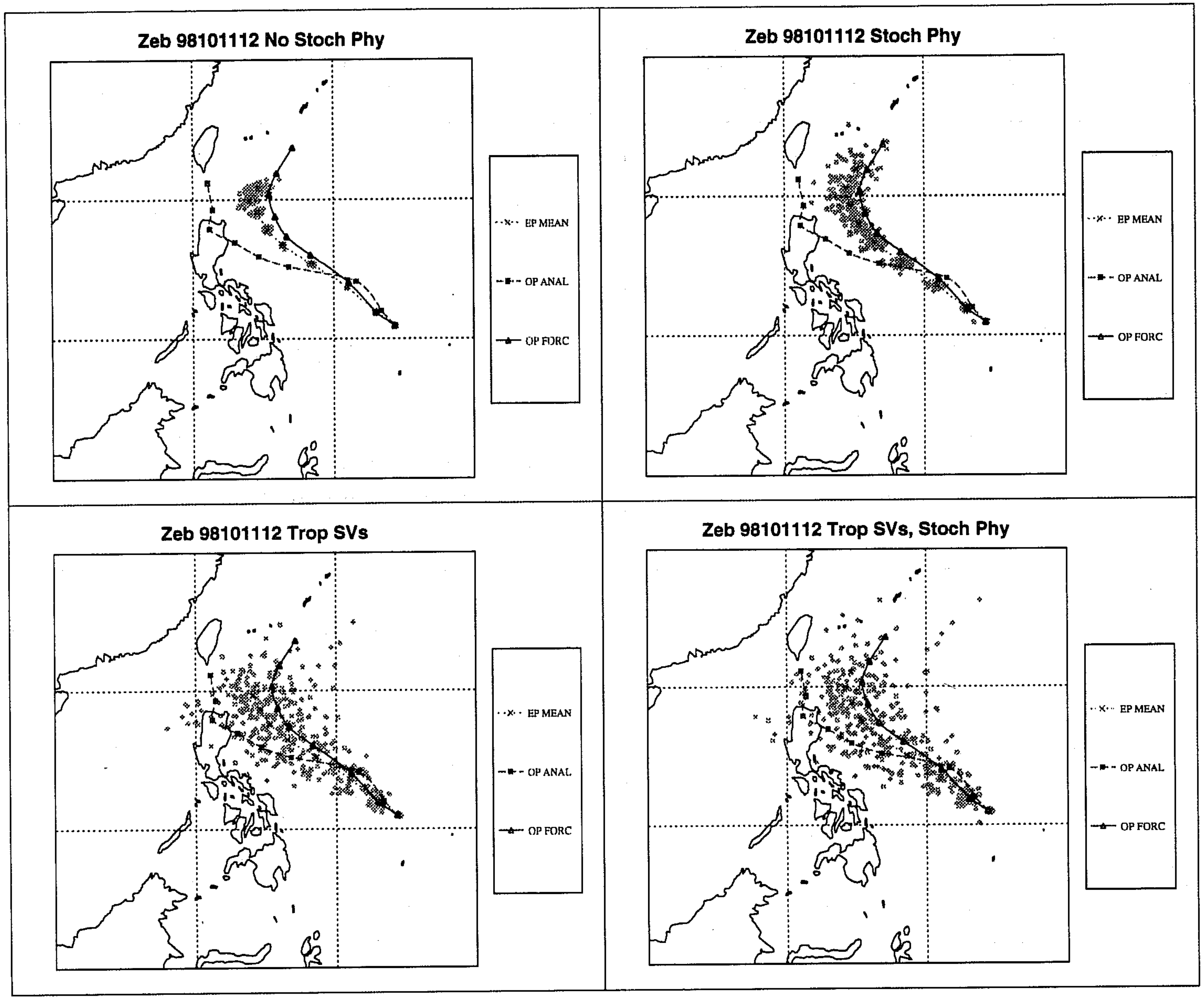

Figure 5a As in Fig. 4a but for TC Zeb and EPS runs with no stochastic physics (top left), with stochastic physics (top right), tropical SVs (bottom left) and tropical SVs + stochastic physics (bottom right).

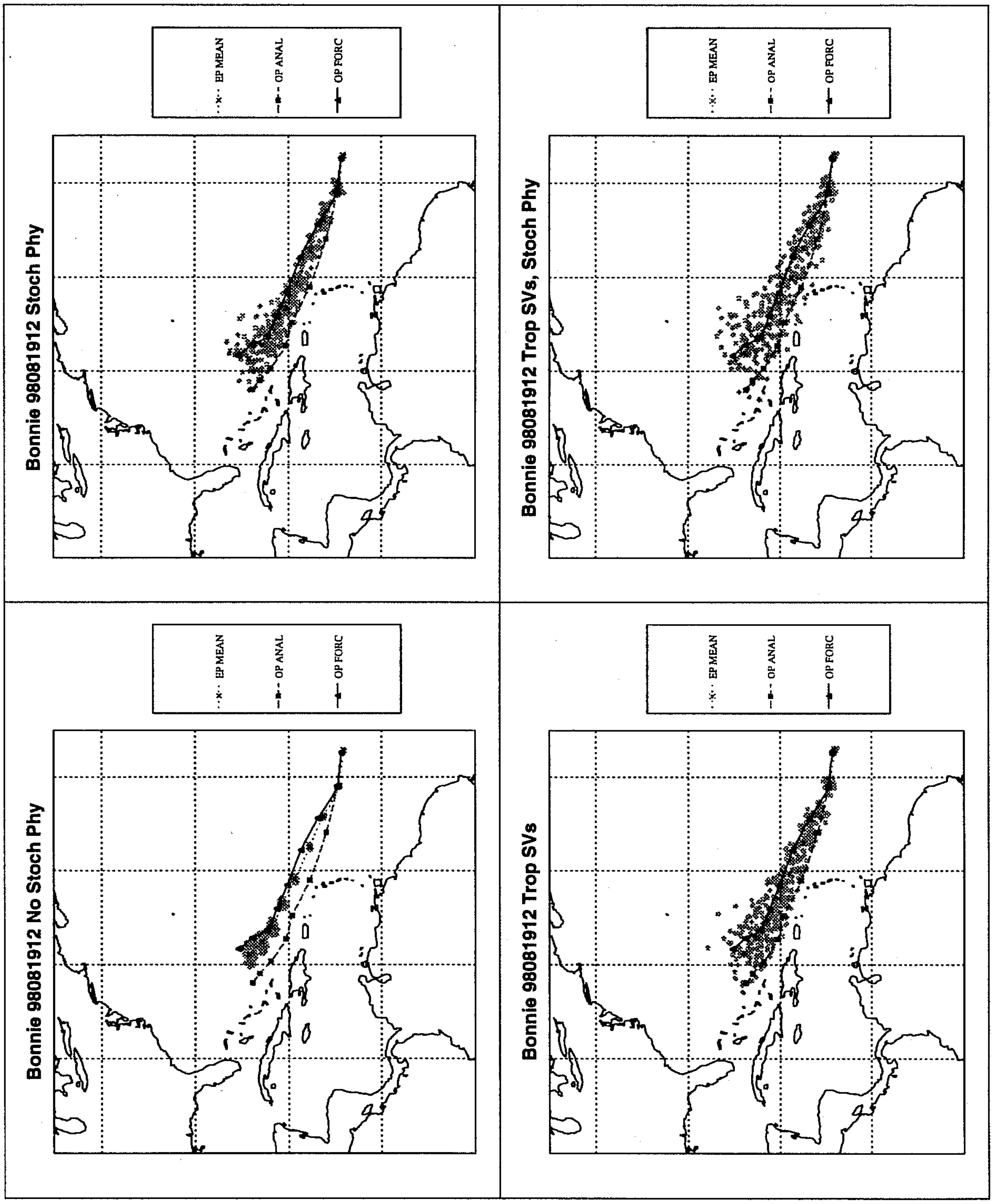

Figure 5b As in Fig. 5a but for TC Bonnie.

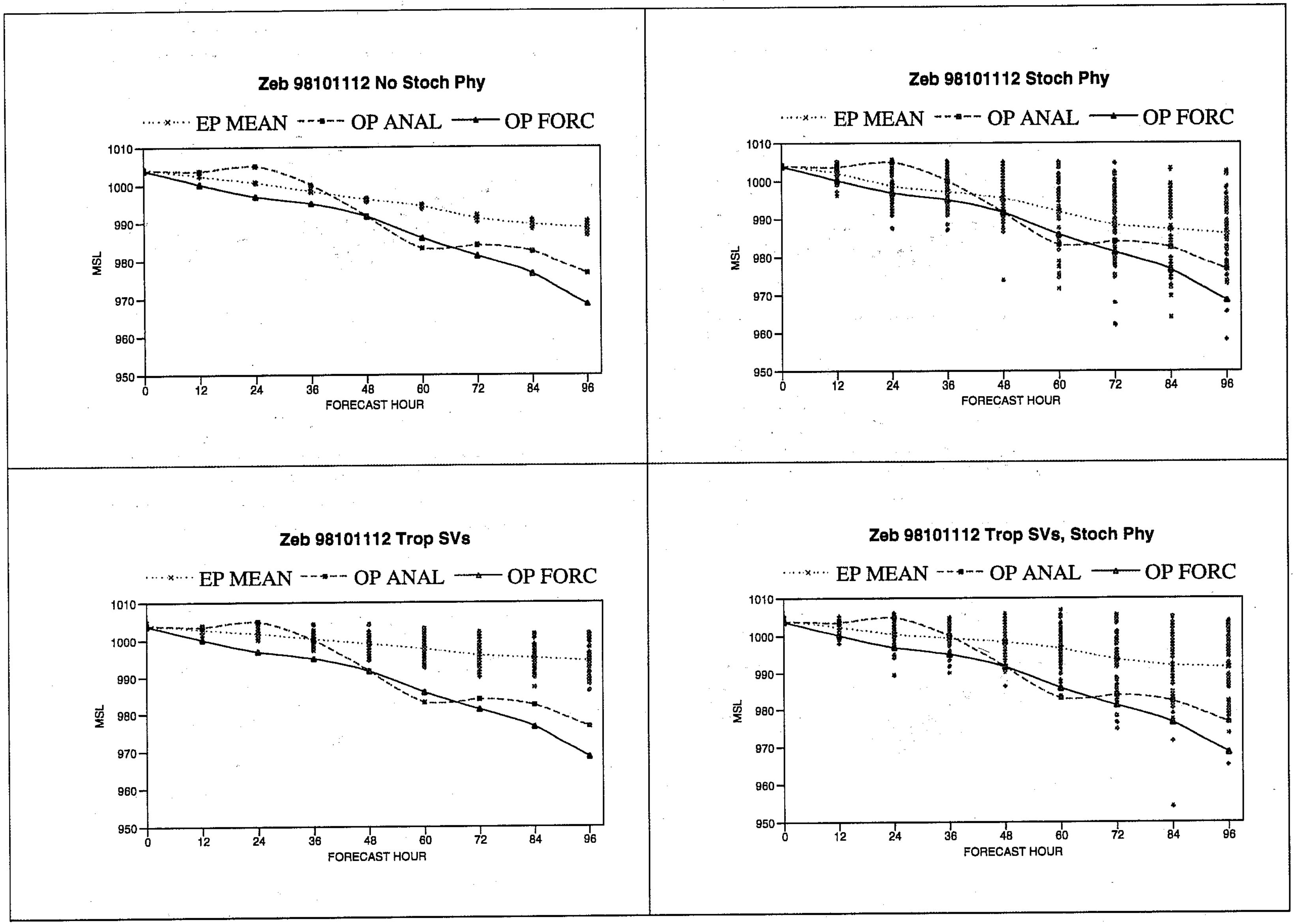

Figure 5c As in Fig.4b but for TC Zeb and EPS run with no stochastic physics (top left), with stochastic physics (top right), tropical SVs (bottom left) and tropical SVs + stochastic physics (bottom right)

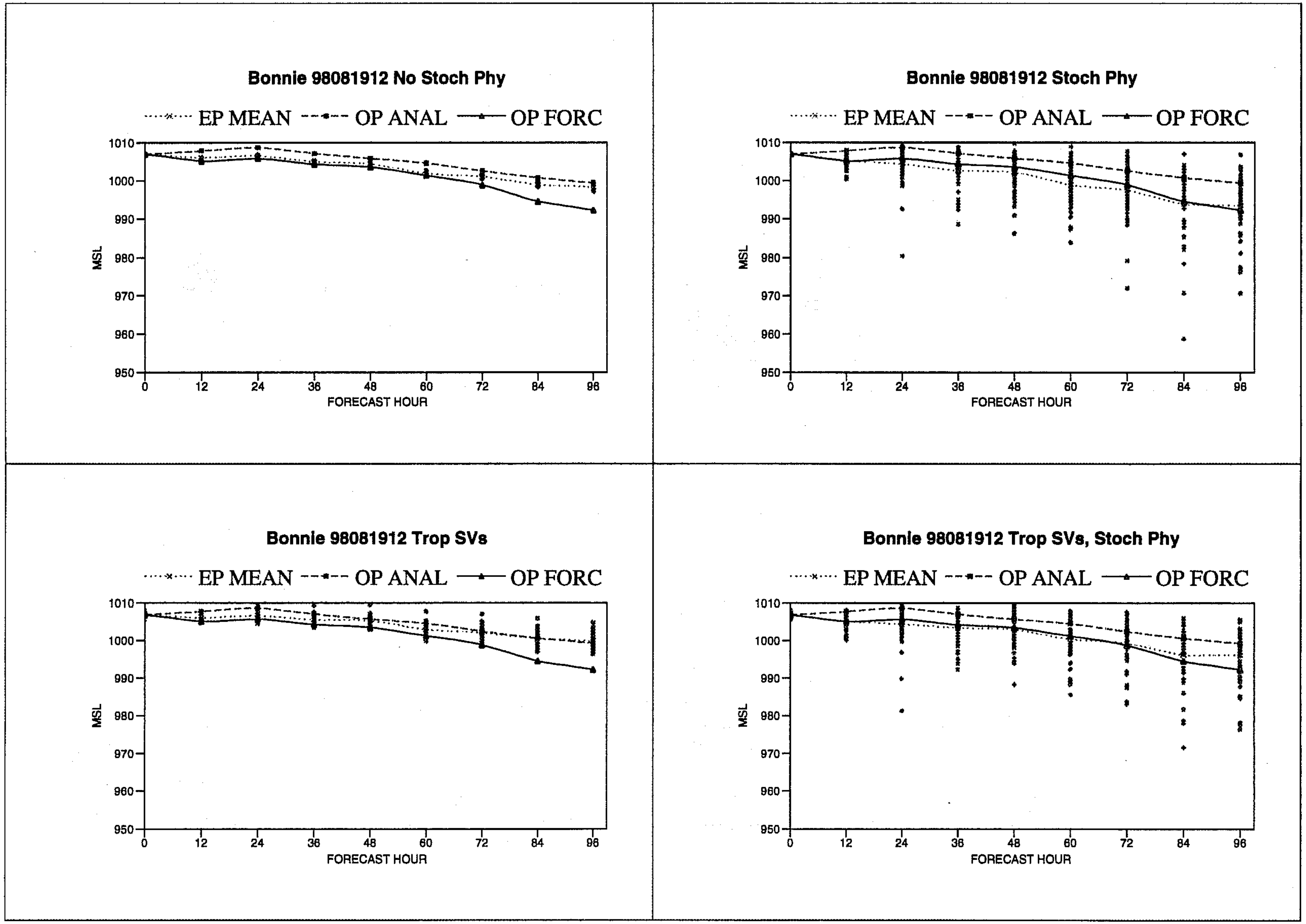

Figure 5d As in Fig. 5c but for TC Bonnie.

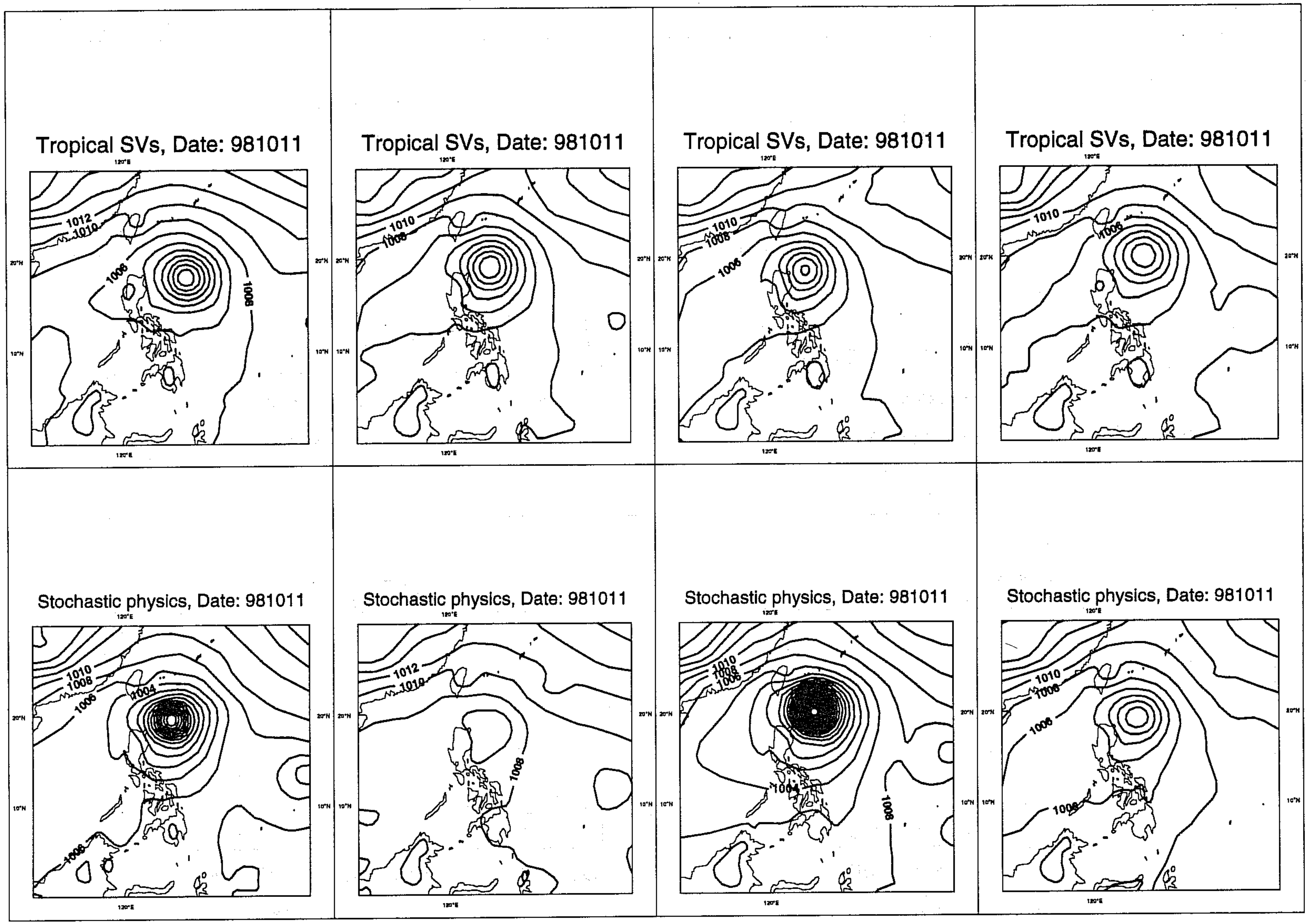

Figure 6 3-day forecasts for mean sea level pressure (in hPa) for four ensemble members from EPS runs with tropical SVs only (top panels) and with stochastic physics only (bottom panels). Contour interval is 2hPa.

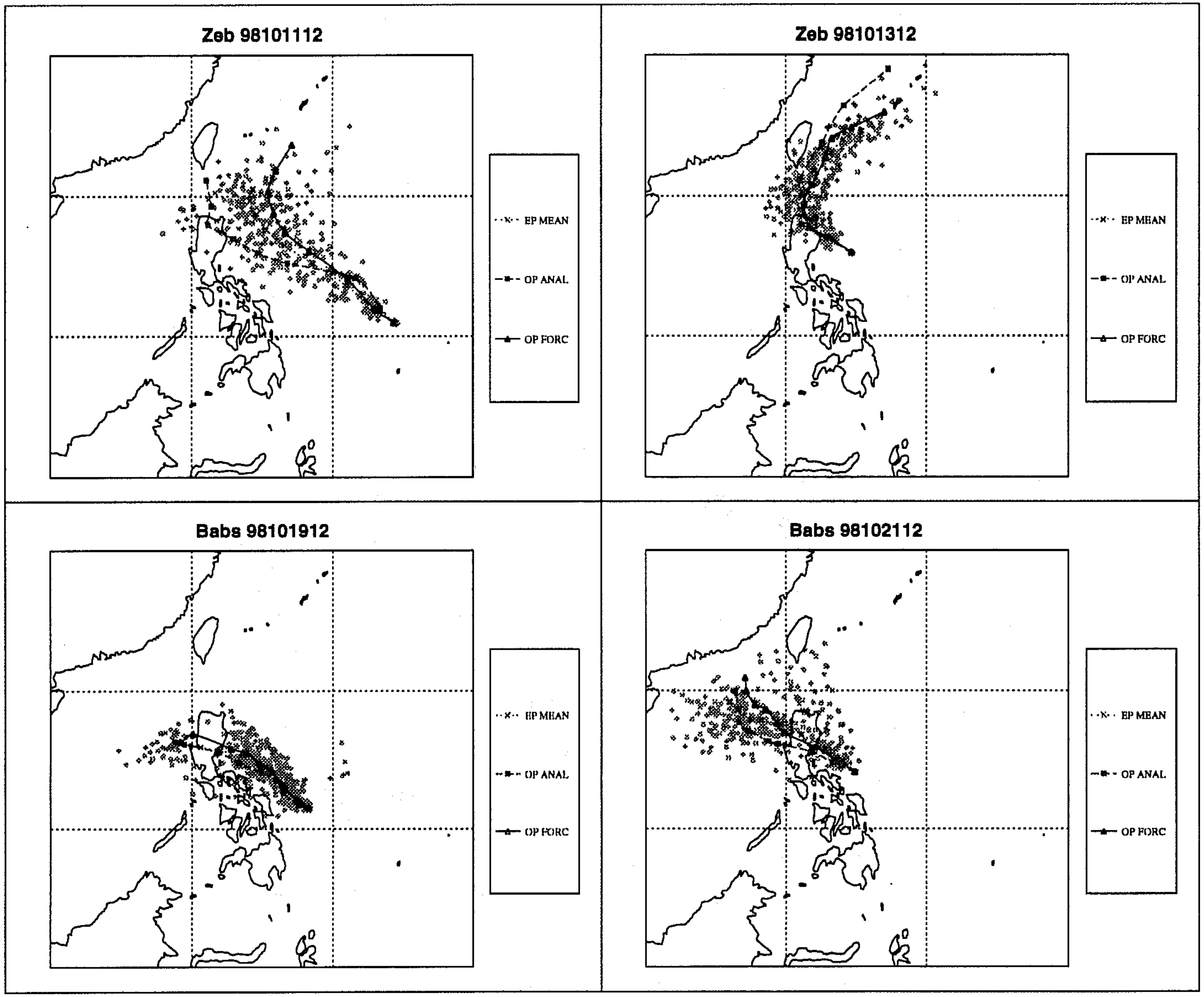

Figure 7a As in Fig. 4a but for EPS runs with tropical SVs only for Pacific TCs Zeb (starting dates 11 and 13 October 1998) and Babs (starting dates 19 and 21 October 1998).

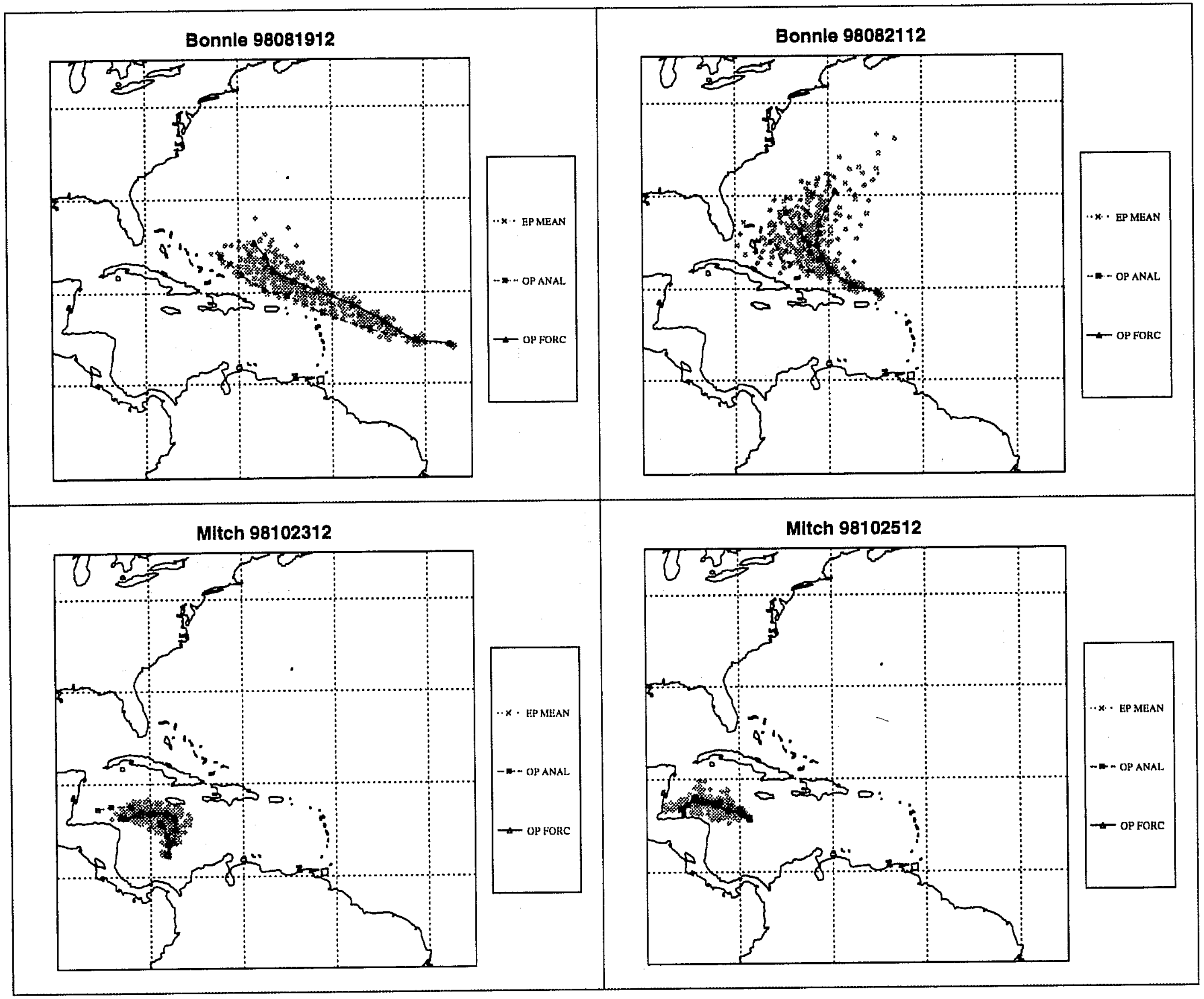

Figure 7b As in Fig. 7a but for Atlantic TCs Bonnie (starting dates 19 and 21 August 1998) and Mitch (starting dates 23 and 25 October 1998).

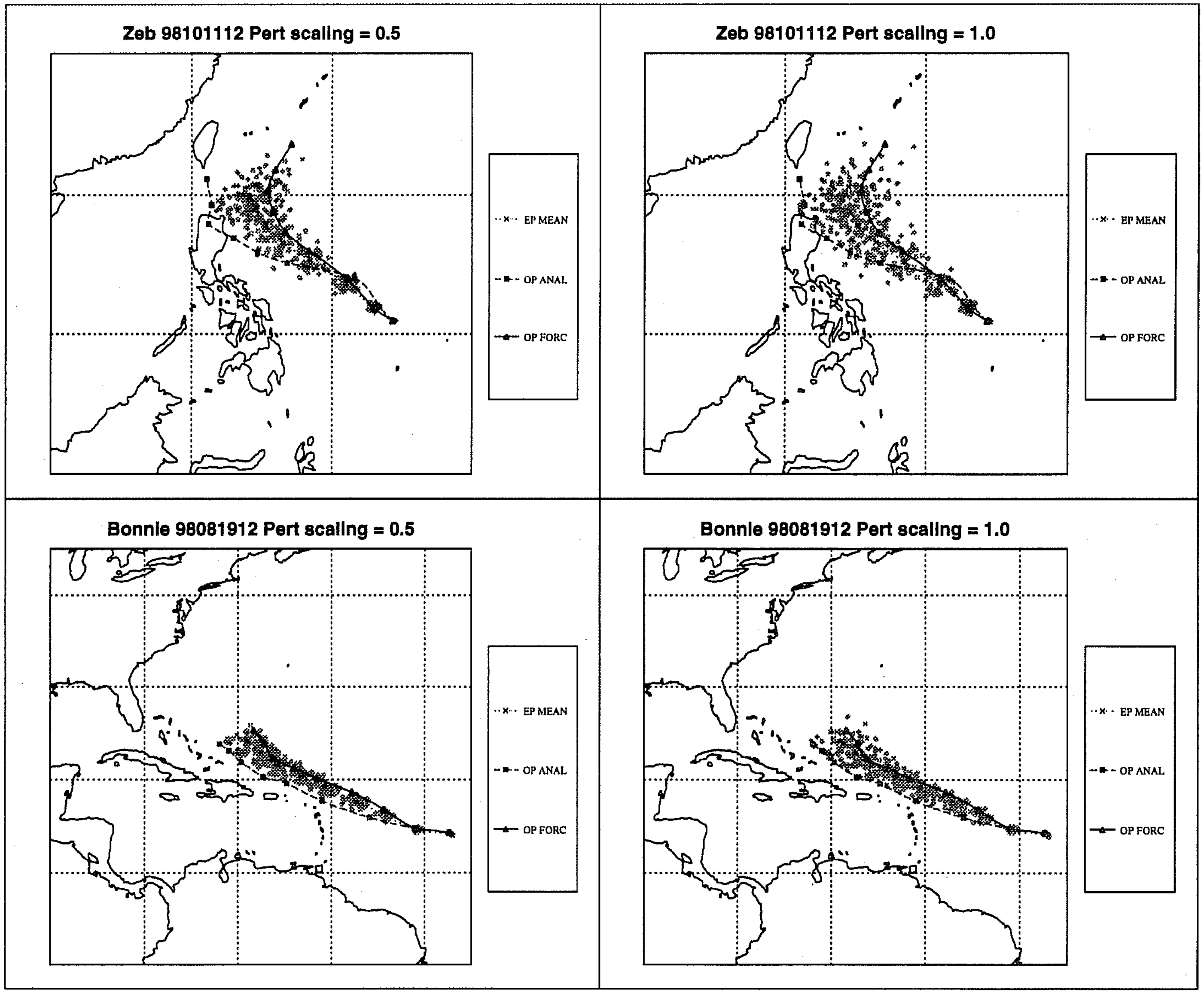

Figure 8 As in Fig. 4a but for TCs Zeb (top panels) and Bonnie (bottom panels) with rescaling factors of 0.5 (left panels) and 1.0 (right panels).

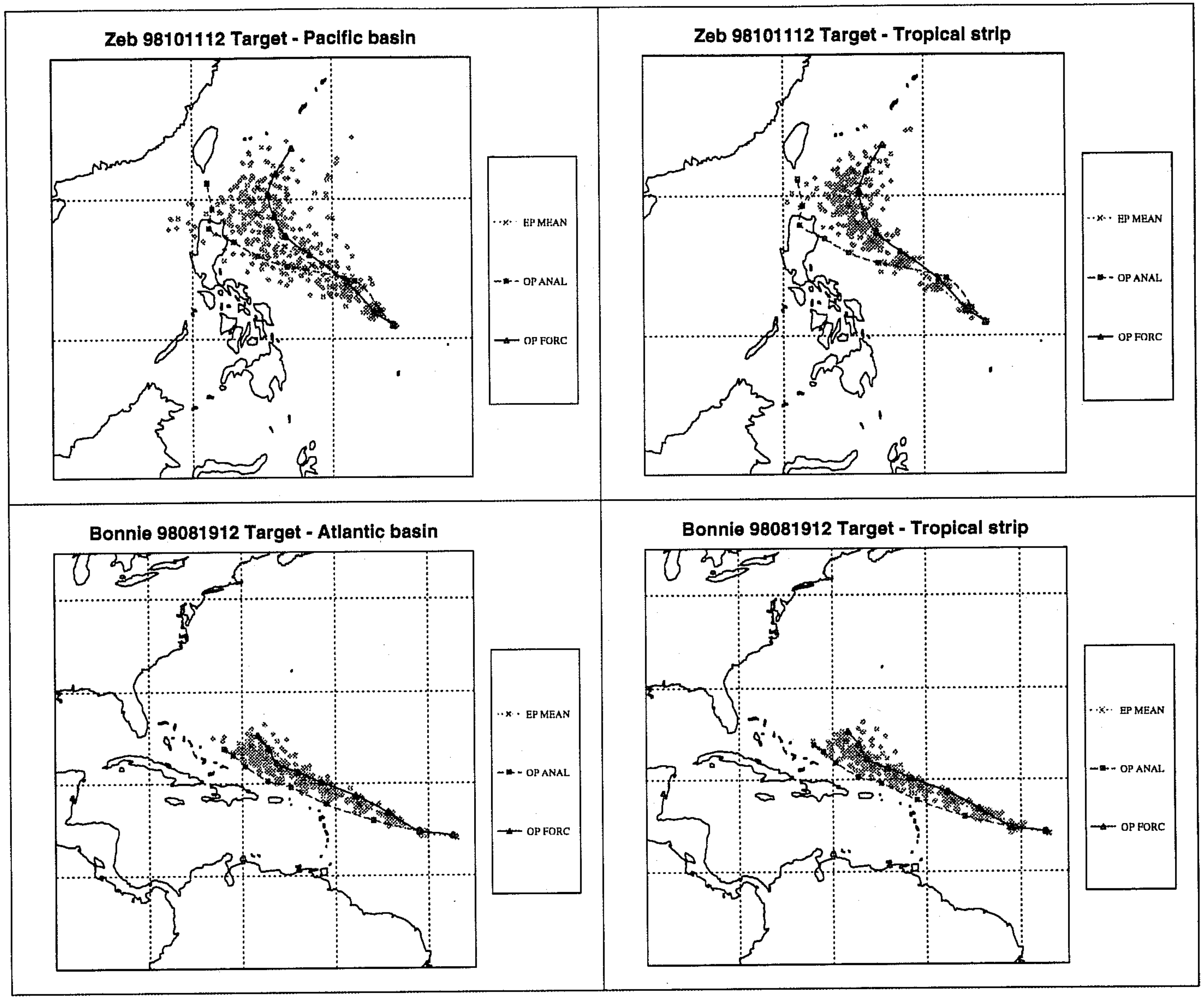

Figure 9 As in Fig. 4a but for TCs Zeb (top panels) and Bonnie (bottom panels) using Pacific/Atlantic basin targets (left panels), and tropical strip targets (right panels).

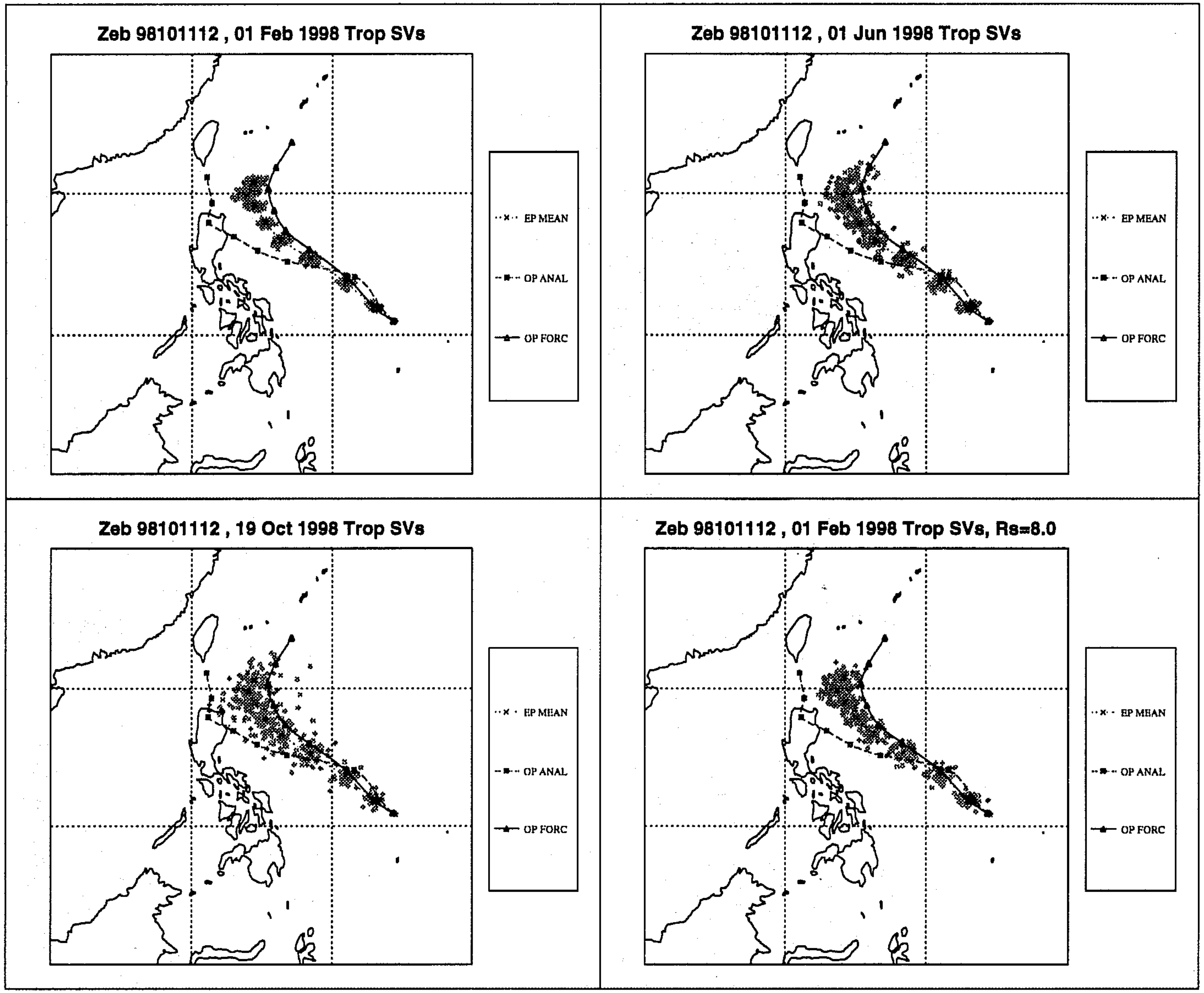

Figure 10 As in Fig.4a but for EPS runs using tropical SVs derived using background states valid for 01 February 1998 (top left), 01 June 1998 (top right), 19 October 1998 (bottom left) and 01 February 1998 with rescaling factor of 8.0 (bottom right).

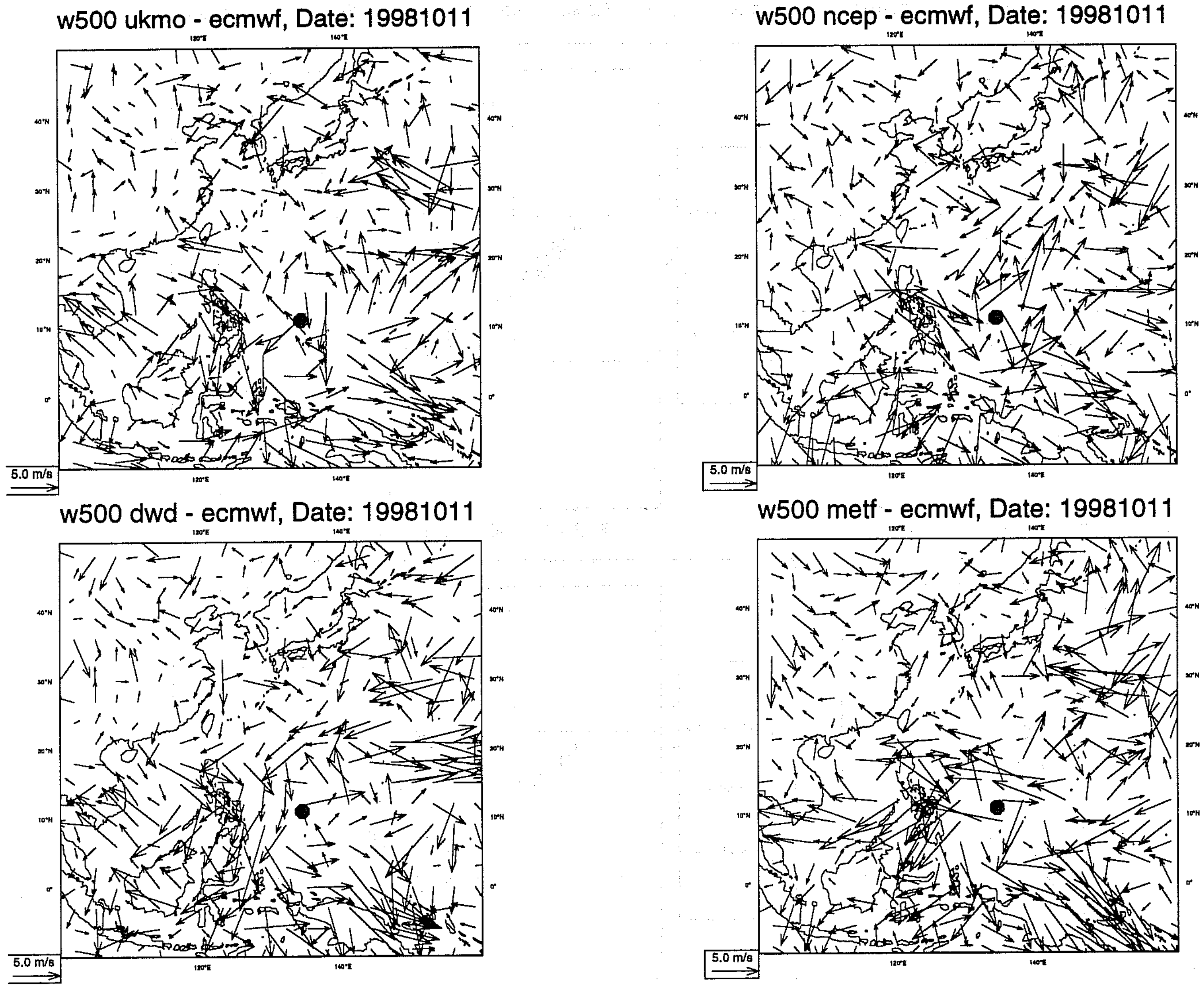

Figure 11 Vector wind analysis differences (in ms^{-1}) at 500 hPa between ECMWF and UKMO (top left), NCEP (top right), DWD (bottom left), Meteo-France (bottom right). The cyclone location is indicated by a large dot.

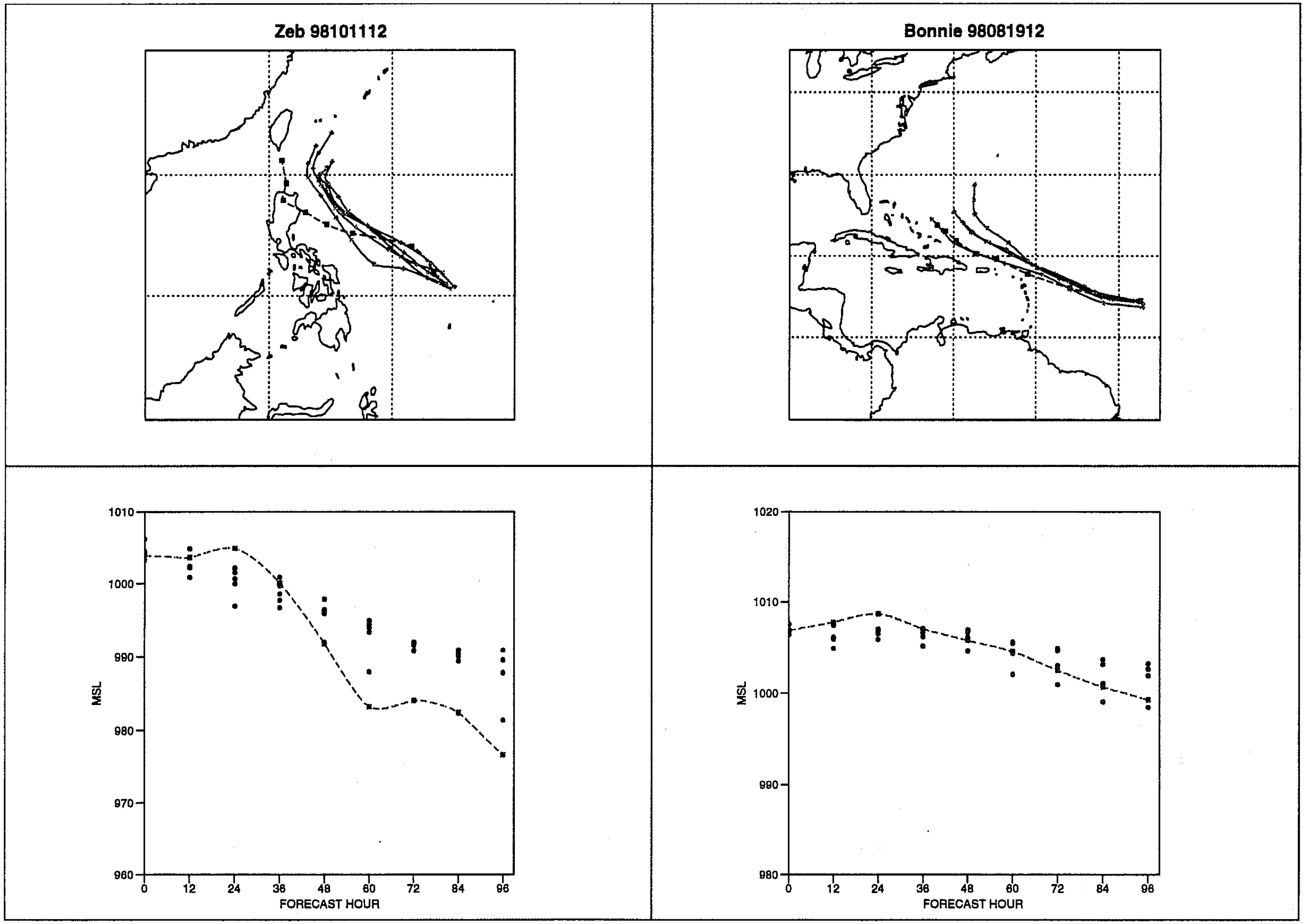

Figure 12 Tracks (top panels) and central pressures (bottom panels) for TC Zeb (left panels) and Bonnie (right panels) based on ECMWF analyses (dashed lines) and ECMWF model runs with analyses from different operational centres (solid lines).

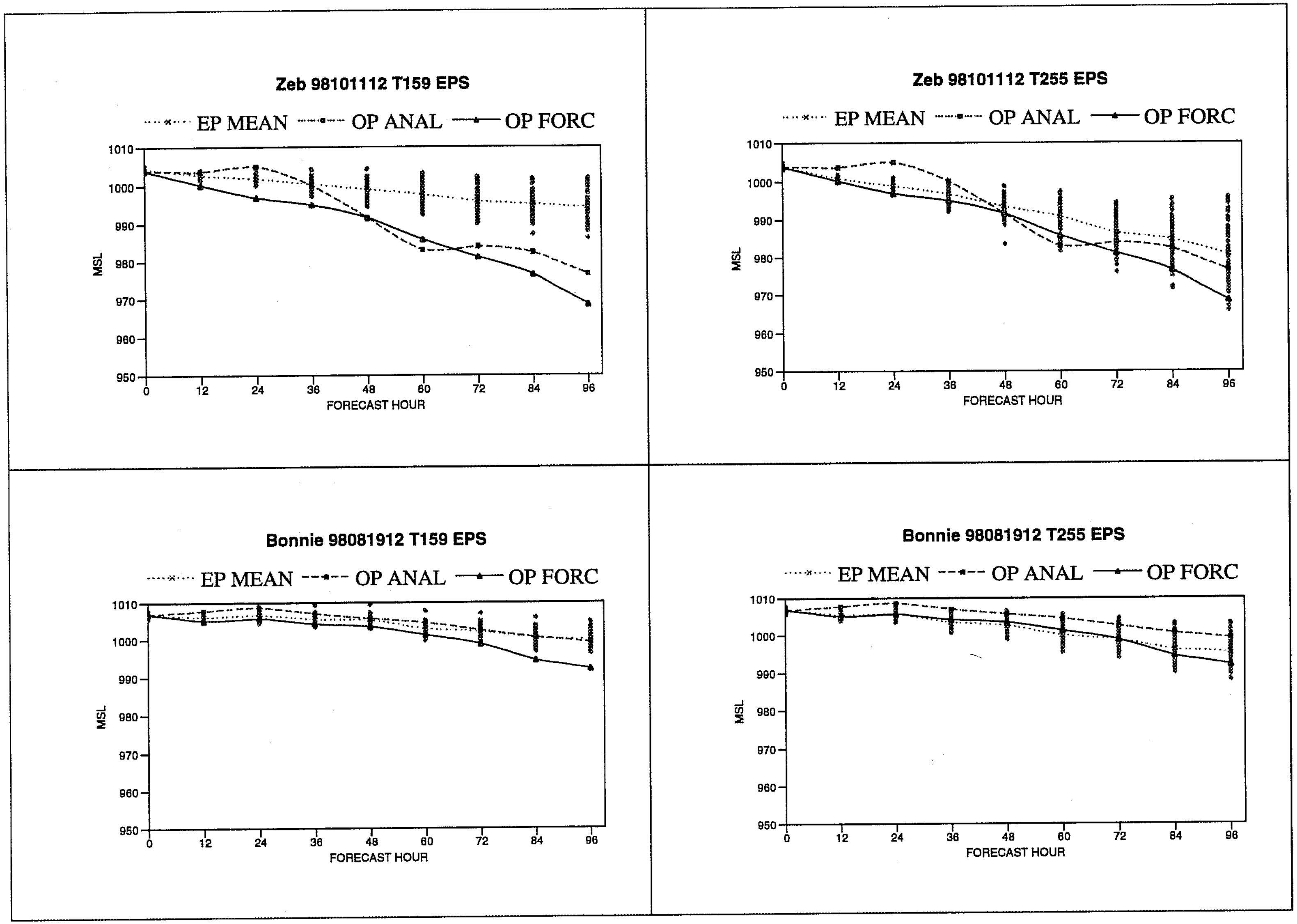

Figure 13 As in Fig. 4b but for T159 EPS runs (left panels) and T255 EPS runs (right panels).