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Reply to a comment by J. L. McBride

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Our recent paper "Simulation of hurricane-type vortices in a general circulation model", was written with the prime objective to report that global general circulation models (GCM) can generate disturbances which have phenomenological similarities to tropical cyclones. We believe this is important, since modellers of tropical cyclones, with a few exceptions (Manabe et al., 1970), have never previously succeeded in simulating intense tropical warm-core vortices with a GCM type of model. Important as it is, we have no expectation that present GCM's in general can be used for operational predictions of hurricanes/typhoons *per se*; to achieve this a much higher resolution will be required and possibly also a data assimilation procedure including cloud and moisture. This has been made very clear in B82, where we have stated "it is not the basic purpose of this paper that models with a resolution such as the ECMWF model should be used to predict tropical cyclones, but merely to point out a very interesting behaviour of high resolution GCM's".

It may be of interest in this context to remind the reader of the very first numerical general circulation experiment (Phillips, 1956), which managed to simulate some of the essential features of the general circulation, including the life cycle of a disturbance in the westerlies. However, as was pointed out by Phillips, certain aspects of this were not very realistic, since for example the space/time scale of the meteorological systems in the simulation was much too large. Nevertheless, Phillips' experiment was extremely encouraging and demonstrated the feasibility to simulate the general circulation of the atmosphere and the possibility to predict baroclinic disturbances in the westerlies for several days ahead. In the same way the purpose of this study was to encourage modellers to further their efforts to apply numerical prediction models to the study of tropical cyclones with the ultimate purpose of operational prediction. We believe that such forecasts may be possible with the next generation of super-computers, when we can hopefully use horizontal resolution down to 50 km or even less.

We therefore believe that Dr. McBride has been reading this paper in a way which is inconsistent with our intentions. He is very much taken by the fact that the model generated vortices are not identical to observed hurricanes and therefore he appears to be convinced that the simulated features have nothing to do with reality and are merely examples of deficiencies and incompleteness in the model's physical parameterization and lack of resolution. We are certainly in full agreement with Dr. McBride that the simulated vortices deviate in many ways from the observed ones. We have tried to identify and analyse these differences in the paper. In his comments Dr. McBride has raised some specific points which we will answer below.

(i) *Frequency and distribution of model generated vortices*

McBride is correct in pointing out that slightly higher temperature is required to generate the vortices. Hardly any development appears to take place when the temperature is below a value of around 29 °C. On the other hand, it is clearly demonstrated in the paper that this is *not the only condition*, since there is a very distinct time variability in the appearance of the model generated vortices—see for instance Fig. 14 in B82. It is suggested in B82 that this may possibly be related to the intensity and distribution of large scale divergence, as indicated in Fig. 10 in B82.

(ii) *Structure of the model vortices*

McBride points out that the structure of the model vortices in its early stage is quite unrealistic and that they in this stage disagree with obser-

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vations. This argument can also to some extent be made with respect to extratropical cyclones, in particular in cases of rapid development. Nevertheless, in its more developed stage the agreement with observation is reasonably good. We do not at the moment have a satisfactory explanation for the difference in the evolution of the model vortices. It appears that the first phase of the development could be the generation of the so-called onset vortex. Intense tropical vortices, see for instance Ooyama (1982), require an onset vortex, in order to organize the large scale convergence of moisture and provide the vorticity source necessary for the extreme intensification of the inner vortex. However, the onset vortex must first be generated and for that clearly a divergence source is required. Due to the coarseness of the grid, what is seen in the model in the early phase is presumably the onset vortex, which due to the limitation in the resolution finally appears to develop into a hybrid between an onset vortex and a hurricane/typhoon.

The vertical velocity is large in the early development phase but the relative humidity is not yet high enough (below 90%) to generate intense precipitation in the model. However, it follows from the case studied in the paper, that between 00 GMT 5 August 1980, Fig. 6, and 00 GMT 6 August, Fig. 7, the vertical motion increases by almost an order of magnitude from around 0.4 Pascal s^{-1} to 2.8 Pascal s^{-1} in the centre of the vortex. The ratio between the radial velocity and tangential velocity in the zonal symmetric presentation (the real vortex, Fig. 5, is slightly asymmetric) is around 1 at 00 GMT 6 August and changes to around 0.5 at 00 GMT 7 August. It is of course not possible to strictly define in this case what is a pre-development stage and what is a development stage.

(iii) *Other unrealistic features*

As mentioned under (i) and also in B82, the sea surface temperature is not the only condition for model cyclone development. However, if in one particular situation, the necessary large-scale convergence condition exists, then it appears that the cyclone develops in the areas where the sea surface temperature is at a maximum.

Concerning the remark that the low stratospheric temperatures are not observed in nature, reference is made to Koteswaram (1967). He demonstrated that this indeed is a typical feature of the hurricane structure. Whether it is playing a role or not in the early stage of the development is only offered as a suggestion by the authors.

The fact that the intensity of the vertical motion is decreasing after 00 GMT 6 August indicates that the intense development is maintained for about two days. We have not studied any other cases in this detailed way, but it appears to be a typical feature of the model developed vortices. A possible explanation is again that the scale is too large and that the vortex too rapidly consumes the available energy provided by the large scale convergence.

Dr. McBride stresses the importance of tropical cyclone development from a pre-existing large scale vorticity field (Gray, 1979; McBride and Zehr, 1981). The model on the other hand must develop its large scale vortex first, and that is probably why we observed this difference in the evolution. Clearly, as follows from the vorticity equation, a divergence field is required for the generation of the vorticity field.

We appreciate very much the critical remarks made by Dr. McBride, but we are of the opinion that at this stage of research one can certainly not expect to obtain a complete agreement between simulation/forecast and observations. Furthermore, even the observed results can be questioned, in particular when we consider parameters such as the divergence field, which is notoriously difficult to obtain satisfactorily from the present routine observing network. I am afraid that we will have to accept that model simulated vortices will differ from observations in many ways, in particular in their early and perhaps also in their decaying phase. Nevertheless, the forecasts may still be very useful in the same way as early numerical models provided good guidance for weather prediction in spite of many limitations.

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