Tropical Cyclone Intensity and Structure: Improved Understanding and Prediction. Evaluation of Existing and Development of New Techniques for Global and Mesoscale NWP Model Assessment

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LONG-TERM GOALS

This is the first year of a new grant and the long-term goals are as follows. First, I will continue to work on the problem of estimating the theoretical limits to tropical cyclone *track* errors. My previous ONR grant revealed that there was at least a possible halving of the present errors in mean absolute track errors over most TC basins. This is clearly a sizeable error and its reduction should continue to be addressed. My second goal is to apply similar techniques, and possible new approaches, to the predictability of tropical cyclone *intensity* out to at least 96 hours. My third goal is to identify, quantify and reduce the sources of errors in tropical cyclone track and intensity predictions. My fourth goal is to continue my work on developing improved 4D data assimilation procedures as they are vital to the third goal and also must be modified to ingest the newly emerging data sources. I note that in the third and fourth goals, special emphasis will be placed on landfalling tropical cyclones, as they are the most damaging storms. a to I have four long-term goals. My fifth, and final, goal is answering the critical question of how to carry out NWP model forecast assessment in a way that is both more rigorous than present procedures. The above goals all have implications for transitions.

OBJECTIVES

My first two scientific objectives are to finalize, over the period of the grant, work on estimating the intrinsic limits of predictability of tropical cyclone (TC) mean forecast position errors and of tropical cyclone intensity errors. These intrinsic limits exist because the equations governing the behavior of atmospheric systems, including TCs, are deterministically chaotic. The first two objectives link directly with the third objective. This third objective forms the major part of the research program of numerical analysis and prediction in this proposal, directed at identifying and understand the sources of errors in the initial conditions and in the model. I note that my focus will be largely, but not exclusively, on TCs that are approaching or making landfall, as they are the most devastating in terms of loss of life, and property. The fourth objective is the continued development of my 4D-Var data assimilation scheme. It has shown great promise when applied to the first three objectives. It is also intended to improve upon the 4D-Var scheme, especially its efficiency and its ability to ingest the many emerging data sources. Finally, my fifth objective is to evaluate and develop schemes for assessing NWP model performance. Existing assessment procedures are not acceptable as they frequently are biased towards the NWP models. The bias towards the NWP model forecasts in the present systems of analysis and prediction is seen readily, for example, by examining the S1 skill scores of global and regional model forecasts at NWP centers around the world. An S1 skill score of

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14. ABSTRACT
This is the first year of a new grant and the long-term goals are as follows. First, I will continue to work on the problem of estimating the theoretical limits to tropical cyclone track errors. My previous ONR grant revealed that there was at least a possible halving of the present errors in mean absolute track errors over most TC basins. This is clearly a sizeable error and its reduction should continue to be addressed. My second goal is to apply similar techniques, and possible new approaches, to the predictability of tropical cyclone intensity out to at least 96 hours.

15. SUBJECT TERMS

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20 or below is regarded as a perfect forecast. Presently, most NWP models are registering long term mean S1 scores below 20 out to 36 hours at SLP and out to 48 hours at 500hPa. That the models are not perfect even at 24 hours is simply untrue.

APPROACH

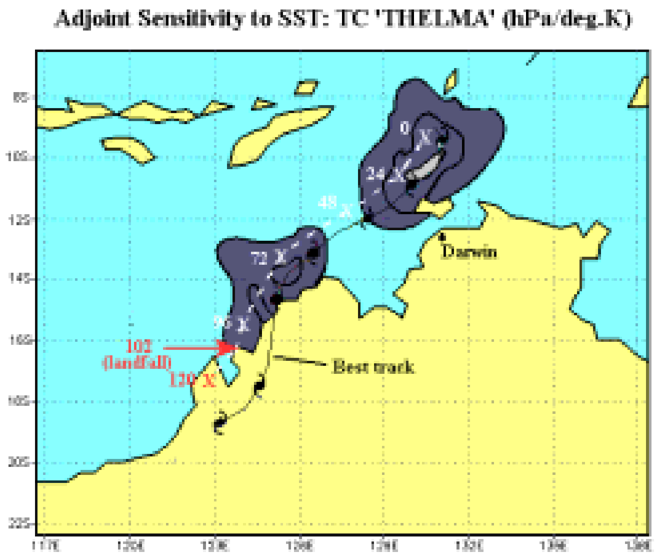
My approach for each of the five goals is as follows. The methodology employed for the first goal has been explained fully already in the ONR FY00 report and in the literature (see, eg Leslie and Abbey, 2000, Abbey and Leslie, 2001). Briefly restating matters, this work has involved the use of two very distinct techniques. That they yielded almost identical answers added confidence to the findings. The first goal, as mentioned above, is to produce estimates of the lowest possible mean forecast track errors out to 96, or even 120, hours and to determine how closely they are currently being approached in practical numerical weather prediction (NWP) models. The practical limits have been improving steadily as the sustained effort in TC track forecast continues at centers around the world. My approach has been to generate an ensemble of initial model states using the archived data sets from various operational global NWP centers around the world (Australian Bureau of Meteorology, UKMO and NCEP). The initial fields generate corresponding ensembles of forecasts at 12 hourly intervals out to 96 hours. The alternative technique, based purely on observational data, was to use a non-linear systems approach to the archived best track data sets in the manner described by Fraedrich and Leslie (1988). In this case, the spread of initially close pieces of TC trajectories is calculated over a 96-hr period for all available data sets. My second goal, which addresses one of the more difficult and significant problems facing TC research today, is to apply the procedures that proved to be successful in achieving the first goal to the new problem of estimating the predictability characteristics of TC intensity and intensity change. The task is a very large one with the goal again being to calculate predictability limits and how close we are to those in practice. These limits will then be compared for the various TC basins and will again provide information about how close current operational models are to the limits of predictability. The third goal is to obtain much more realistic TC structure, intensity, intensity change and motion as TCs approach landfall. The third goal links directly with my fourth goal, which is to employ my research program of data assimilation and NWP model prediction to obtain more realistic TC structure and intensity than has been achieved hitherto. Before this work began, I had been producing steadily improving forecasts of TC tracks but had failed to capture the intensity and intensity changes of the TCs. This failure is of extreme importance for TCs at or nearing landfall. The procedure was to use and adjoint sensitivity approach to identify the contributing factors to intensity change and the improvement in the forecasts themselves. I have built upon a breakthrough achieved in 1999, by continuing to use 4D variational assimilation procedures without TC bogussing, taking advantage of high spatial-temporal frequency satellite derived data of various types and as many other sources of data as possible (Leslie and LeMarshall, 2001). The approach to the fifth goal is to compare existing measures of assessment of NWP model skill with alternative measures.

WORK COMPLETED

So far I have carried out some work on all five objectives. However, as the grant is in its first year, the work has not been completed in any of the five objectives at this stage. Perhaps the best indicator of the completed work is obtained by perusing the publications for 2000/2001, below. The first goal was to calculate the difference between the mean absolute forecast track errors for tropical cyclones obtained in practice with estimates of what could be achieved in principle. The findings have been published extensively (eg Leslie and Abbey, 2000). I have continued this work, extending it to other TC basins and to more difficult TCs. My second goal of applying the same procedure to TC intensity predictability has also proceeded, with the emphasis again being on the more difficult storms. This work has reached the stage where it is now being prepared for submission to a peer-reviewed journal. Another part of the process, the further development of the HIRES data assimilation and prediction system has proceeded. The system can now ingest a large range of new data sources and continued success in obtaining realistic TC intensity forecasts and TC structure. This work has reached the stage where it has been published. (eg, Leslie and LeMarshall, 2000; LeMarshall and Leslie, 2000). My fourth goal of understanding and improving the forecasts of TC intensity and intensity change, especially for landfalling TCs, has yielded early promising results. The primary research tool used in this work has been the application of an adjoint sensitivity approach. The procedure enables the impact of selected variables in the initial state to be quantified. As such, it is a powerful tool. An example is given in Figure 1 of the RESULTS section, and will be discussed in more detail in that section. As mentioned at the beginning of this section, an off-shoot of the adjoint sensitivity work recently carried out by the PI and collaborators has been the revealing of the existence of precursors with skilful predictability of TC frequency, motion and intensity. This work is in its early stages but three publications are in preparation, including one to be submitted to SCIENCE. Thus far, the work has exhibited predictive and understanding capacity for the 1997/98 and 1998/99 seasons in the eastern Indian Ocean basin. Extension to the Pacific and Atlantic TC basins will commence in 2002.

RESULTS

I have now produced four main sets of results for FY00. The first set of results relates to the first goal, These results for track predictability are now nearly completed and are given in Leslie and Abbey (2000). They confirmed the major finding of FY00 was confirmed, namely, that there is still a large gap, of about 50%, between what is being achieved in current practice at NWP centers, and what is ultimately achievable. The second set of results, for inherent limits to predictability of TC intensity, is still complete enough for statistically significant statements to be made. The third set of results form the core of the NWP research program and is based on PI’s High Resolution (HIRES) data assimilation and prediction system. Largely using ONR support, this system has been developed for use in TC applications by the PI, various graduate students and part-time time research associates. It confirms the earlier findings that TC track errors are being reduced, as direct and indirect consequence of the overall research program, especially from enhancements in the data base, the 4D data assimilation procedure, the initialization scheme and the model itself. The data base enhancements have come from the PI and others working in the areas of satellite-derived wind vectors from geostationary satellite cloud and water vapor imagery; from scatterometer winds, Topex-Poseiden analyses of water surface elevation anomalies; radar data; AWS networks; special observing periods and experiments and the imminent launching of a new generation of sounders with thousands of channels. Resolutions will be at least 15km (in 1 km layers) from the polar-orbiting sounders and 4km or higher from the geostationary satellites. The PI is a collaborator with scientists from NASA Langley who are driving this program and has already worked with prototype data produced from these new instruments mounted on high flying aircraft (eg, Leslie et al., 2001). The fourth set of results is an extension of preliminary work using an adjoint sensitivity approach. The goal has to assess the capacity of NWP systems to forecast intensity and intensity change. This work will complement the predictability research to be carried out using techniques similar to those already completed for TC motion predictability. Figure 1 shows the track for TC Thelma (marked by an X), in the east Indian Ocean region near the northwest Australian coast. The track is overlaid on the corresponding regions where SST anomalies are shown by the adjoint sensitivity technique to have contributed to the intensification of TC Thelma, from a Category 1 TC to a Category 5 TC. There is a strong correspondence between the contribution of the positive SST anomalies and the intensification, as measured by the sensitivity of the adjoint to particular variables, in this case the SST anomalies. This example is just one of a large number of cases carried out by the PI.



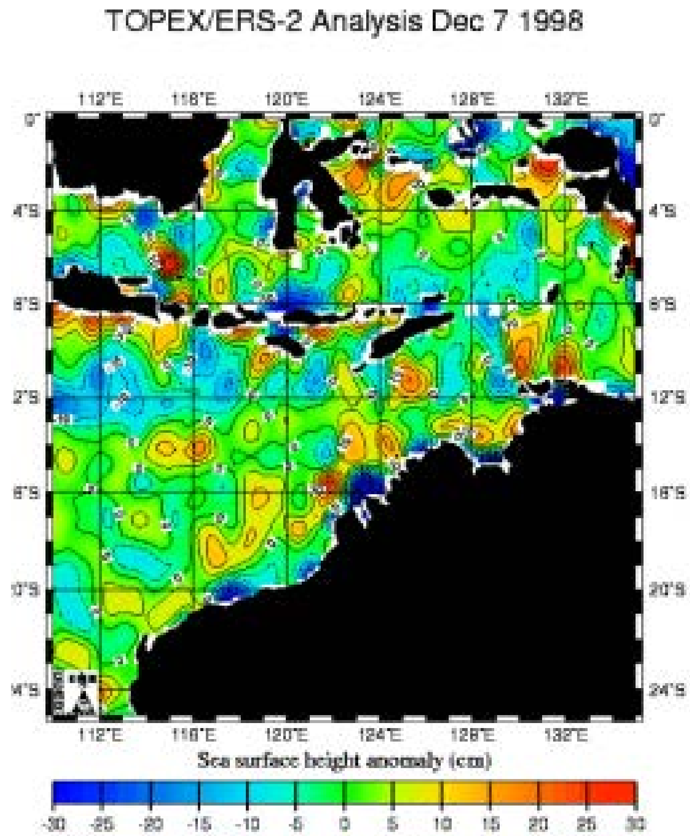


Figure 1: (Above left) The adjoint sensitivity to the initial SST anomalies. The penalty functional J is the central pressure at landfall. The contours are 0.02 hPa/deg. K. Full lines enclose regions where the state of the initial variable (in this case the SST anomaly) enhances intensification. Dashed lines indicate regions inhibiting intensification. Note that there is no inhibiting region and that the model track passes over the regions of greatest contribution to the intensification of the TC. This is consistent with observations of intensity change for TC Thelma.

Figure 2: (Above right) Initial SST anomalies inferred by TOPEX/ERS-2 Analysis for December 7, 1998. Note that the positive anomalies are consistent with the track passing over regions of positive or neutral contributions to intensification in the model.

IMPACT/APPLICATIONS

My work has yielded a number of impacts/applications. First, I have further underlined earlier work, funded by ONR, which showed that TC track forecast errors are still far larger than acceptable. I estimate that the current levels of TC track prediction is still approximately 50% larger than the errors that can ultimately expected to be achieved by continued research in this area. Such progress in reducing track forecast errors most likely would come from improving the current inadequate specification of the initial state and also from the reductions in significant model deficiencies. A second impact I have confirmed in work carried out in 2001 is that careful quality controlled, high resolution, data from existing and new sources; developments in continuous (4D) assimilation; and ongoing model improvements will continue to yield large reductions in track forecast errors, especially for “difficult” TCs and for TCs nearing or making landfall. Third, I have confirmed tentative FY99 and FY00 findings that realistic intensity forecasts are greatly enhanced by high NWP model resolutions of 10 km or less, preferably around 5km or below. This further confirms my conclusions of FY00 that the prediction of TC tracks and intensities is continuing to move within the reach of the emerging data observing systems, advanced assimilation schemes and the more sophisticated NWP models running at very high resolutions. Fourth, the adjoint sensitivity techniques developed in the previous proposal continue to produce reductions in mean TC track errors and have also improved our understanding of and capacity to predict TC structure, intensity, and intensity change. Fifth, it has been shown that existing methods for assessing NWP model performance are too crude and are biased in favor of the NWP model systems. New techniques that are far more exacting are being developed and applied to the NWP model output. These new methods are in the early stages of development. Sixth, and finally, new precursors of TC activity and intensity have been identified, initially in the east Indian Ocean, to the northwest of Australia. These precursors exist at the inter-seasonal level down through the intra-seasonal level, to time-scales of days. I regard the existence of these precursors as being of sufficient importance to submit a letter to the journal SCIENCE in the near future.

TRANSITIONS

Much of my work has potential for transition, not only in the TC forecasting area but more generally. Such transitions are not expected to occur for at least another year or so, but parallel testing with the NRL COAMPS model will take place from early 2002.

RELATED PROJECTS

I have continued close links with other ONR programs, notably the CBLAST program on which I am co-PI on one proposal with Dr Michael Banner of The University of New South Wales. This proposal is entitled “The Impact of Air-Sea Interaction Research on Larger-Scale Geophysical Flows”.

SUMMARY

The work carried out on this proposal has contributed to the knowledge base of tropical cyclones. Tropical cyclones, which are also referred to as hurricanes and typhoons, are the most devastating storms on earth. As such it is vital to understand and predict their behavior. To do so requires research on their motion, their structure, their intensity and, especially, their behavior upon nearing or making landfall. To achieve these aims, a program of data collection and computer model simulations is being carried out, with the predictions then compared with observations of selected storms. Deficiencies in the initial data, the model formulation and the model predictions are then identified and research is carried out on improving these aspects. The ultimate goal, expressed as succinctly as possible, is the provision of accurate, timely and reliable model predictions of TC tracks and intensity, especially for storms that threaten coastlines

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