immediate environment in numerical models. In some cases, this has been achieved by special observing methods. In other cases, various forms of bogussing have been used.

Evidence for the impact of such research lies in the improved forecast accuracy that has been achieved by both numerical models and official forecasts over the decade (Elsberry, 1999). The prospects are good for further major improvements in tropical cyclone track forecasting by numerical models. Particularly important to this improvement are the introduction of more sophisticated initialization methods, improved data collection in the vicinity of tropical cyclones and the use of ensemble forecasts and targeted observing strategies.

4.2 THE AEROSONDE ROBOTIC AIRCRAFT

The Aerosonde Robotic Aircraft was conceived as a means of providing an economical method for undertaking observations with considerable flexibility of operation (Holland *et al.*, 1992). A particular aim of the program has been meteorological observations in remote and otherwise inaccessible regions, such as tropical cyclones.

The international community recognition of the importance of the Aerosonde concept has been a crucial component in its development. The Aerosonde was strongly endorsed by the IDNDR/WMO Beijing Symposium on Tropical Cyclone Disasters (Lighthill *et al.*, 1993) and subsequently endorsed by the full IDNDR committee.

Following an initial prototyping period, largely sponsored by the US Office of Naval Research (ONR), a major development program was initiated in Australia in 1995. With sponsorship from an Australian Research and Development syndicate and support from ONR, Environmental Systems and Services Pty Ltd (ES&S) developed the current aircraft, between 1995 and 1998, in collaboration with the Australian Bureau of Meteorology and the US-based Insitu Group

The development program was completed in 1998 when the Aerosonde passed a comprehensive trial conducted by the Bureau of Meteorology. In August 1998, The Insitu Group and the University of Washington further demonstrated the long-range feasibility of the Aerosonde by conducting the first transatlantic flight by a robotic aircraft. This is commemorated by the Aerosonde being placed on display in the Seattle Museum of Flight.

The aircraft resulting from the development program has undergone extensive improvement to increase reliability and robustness and to expand its operational capacity The Mark 1 Aerosonde entered operations with Aerosonde Robotic Aircraft Pty Ltd in 1999 and the lessons learnt from these programs have been incorporated into the Mark 2 Aerosonde shown in Figure 3, which will be operational from October 1999.

Continued development is aimed at introducing further significant improvements over the next 3 years. The main thrust is to improve the operational

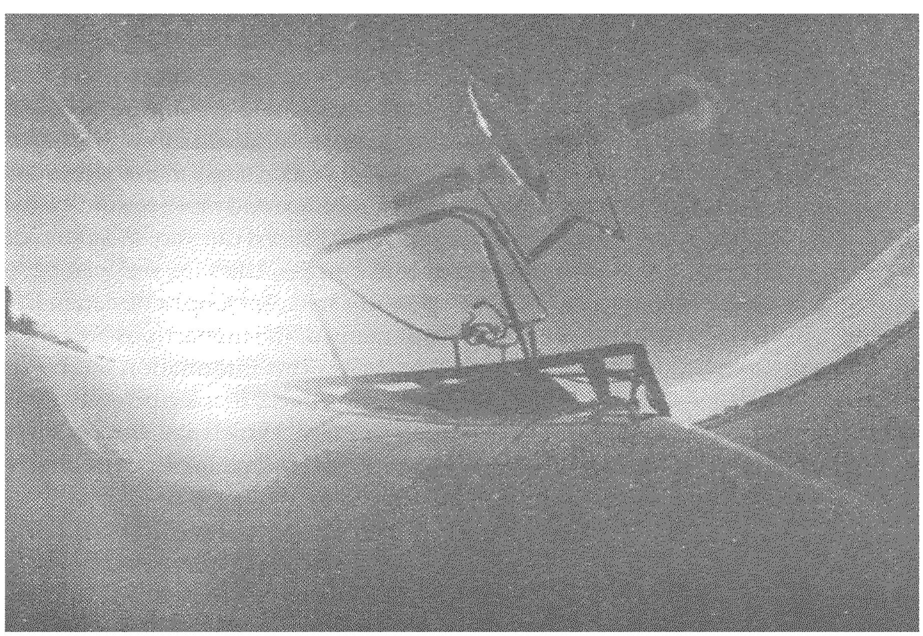


Figure 3. The Aerosonde Robotic Aircraft at launch from a car roof rack (K. McGuffie, personal communication 1998)

capacity of the aircraft, for example by development of the power plants, more flexible payload capacity, longer range and endurance, higher altitude operation, the addition of satellite communications and incorporation of a range of improved ground and airside operational systems.

A crucial component for tropical cyclone observations is the addition of a Low Earth Orbiting (LOE) satellite communications system. Delays in availability of the LOE satellite have frustrated attempts to undertake the first cyclone reconnaissance, as the range requirements are too far for the current UHF radio system. As a result, only one mission into the periphery of Severe Tropical Cyclone Tiffany (Western Australia) was accomplished in 1998. It is expected that this system will become available in late 1999, leading to the first full tropical cyclone missions soon after.

Aerosondes are particularly seen as providing an excellent support for targeted observations both within tropical cyclones and in the surrounding environment. They will be used to satisfy the requirements of numerical models and to both complement and extend other observing systems such as satellite remote sensing.

5. ANALYSIS AND FORECASTING OF TROPICAL CYCLONES DURING THE IDNDR

Please refer to Elsberry (1999) for a more detailed assessment of these trends described above.

The decade has been one of contrasts for observing tropical cyclones and related parameters. We have seen a sustained threat to essential observing systems, such as radiosondes, together with remarkable progress in others, such as satellites. The reality remains that, over much of the globe, crucial details of the core region of tropical cyclones are only obtainable by inference and assessment from external parameters. Only the USA retains direct observing capacity for cyclone core region dynamics and recent observations have shown that there is considerable variability and transient changes especially in the low-level wind fields.

The Dvorak satellite assessment technique for estimating tropical cyclone intensity is now the international standard. Indeed, much of the cyclone database has been derived largely from Dvorak analysis. Whilst this has introduced a welcome degree of consistency in tropical cyclone analysis, the lack of ground-truth validation in many regions is of major concern.

Substantial improvements in track forecasting have been achieved through the decade, largely due to a combination of improved observing systems, numerical model capacity and the understanding of relevant processes that has enabled improved forecaster assessment and proper targeting of forecast improvements. These are analyzed by Elsberry (1999). An indicative figure for the western North Pacific is provided in Figure 4.

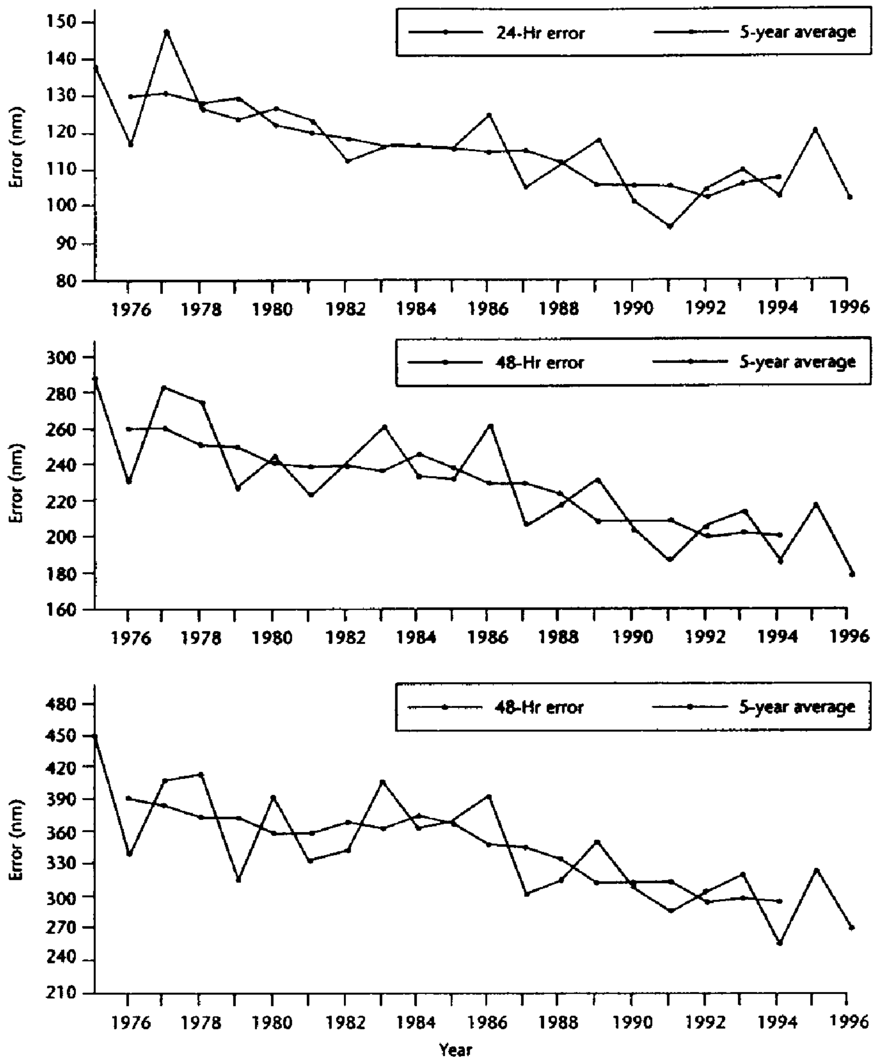
There has not been the same level of improvement in forecasting cyclone structure and intensity for which forecasts are barely better than simple climatology can provide. However, numerical models have shown considerable potential for forecasting tropical cyclone formation in recent years.

6. REDUCING SOCIETAL IMPACTS DUE TO TROPICAL CYCLONE LANDFALL

WMO members have organized five Regional Specialized Meteorological Centres (RSMC) in a number of strategic locations to promote local sharing of tropical cyclone analyses and forecasts (Figure 4). Each centre, which is hosted by a national weather service, monitors tropical disturbances and provides analyses and forecasts of tropical cyclones in their area of responsibility. The responsibility for issuing warnings resides with individual countries and the RSMCs provide analysis and forecast support for these activities, as required. Crucial to the successful analysis and prediction of tropical cyclones is the free distribution of satellite and other data to and from RSMCs and cyclone warning centres.

In addition to the forecast function, the real amelioration of cyclone impacts requires careful attention to the cultural, social and economic conditions of affected communities. Whilst there has been substantial work on such aspects in individual countries in the past, the IDNDR has seen the growth of a major international effort in this area. The IWTC-IV in 1998 contained a full session on reducing tropical cyclone impacts, and several local programs have been

Figure 4. Annual mean track forecast error (n mi) and 5-year running mean for (a) 24-Hr, (b) 48-Hr, and (c) 72-Hr made by the Joint Typhoon Warning Center, Guam for western North Pacific tropical cyclones between 1976-1996 (Elsberry, 1999).



combined into a major program aimed at reducing the impacts of landfalling cyclones under both the WMO World Weather Research Program and the WMO Tropical Meteorology Research Program.

6.1 THE AUSTRALIAN TROPICAL CYCLONE COASTAL IMPACTS PROJECT (TCCIP)

The TCCIP was initiated in 1993 as a collaboration between researchers, forecasters, emergency services personnel and local community groups. The collaboration was based on three interdependent objectives:

1. Quantification of the impact of tropical cyclones on Australian coastal communities under current climatic conditions, including:
    - Development of techniques applicable to impact studies;
    - Assessment of the level of risk and its variability, with emphasis on vulnerability of communities to high winds, flood rains, ocean waves and storm surges;
    - Assessment of changing levels of risk associated with demographic growth.
2. Scientific assessment of the potential trends in tropical cyclone impact on Australian coastal communities arising from anthropogenic climate change (the Greenhouse Effect), including:
    - Critical review of current tropical cyclone models and methods applied to climate change;
    - Critical review of available climate models and their applicability to tropical cyclones;
    - Estimation of potential climate change trends in tropical cyclones, together with the reliability of this estimate.

3. Development of improved methods to counter disasters, including social and economic adaptation through infrastructure planning and education, which are based on the findings from 1 and 2

Starting in Queensland and then joining with the AGSO cities program as part of a major assessment of threat by severe weather and geological activity to major population centres in Australia, the program has been a major success. TCCIP experience was also applied to the establishment of the USWRP Hurricanes at Landfall Program and the WWRP Landfalling Tropical Cyclones Program.

A feature of TCCIP was a series of interdisciplinary workshops that brought together participants in a medium designed to provide good exchange of views and requirements. The major progress within the program occurred in damage, impact and vulnerability assessment, particularly in the development of appropriate techniques and databases; research into the changes that occur when a tropical cyclone makes landfall, and potential changes due to enhanced greenhouse conditions, together with the relationship between long-term and short-term variability of cyclone activity.

A technique for assessing the potential for storm surge to occur during tropical cyclone landfall was developed and successfully tested at locations along the Australian East Coast. This technique, known as the Maximum Envelope of Waters (MEOW), utilized a state of the science numerical storm surge model and parametric wind field model to build up a database of potential surges occurring across the known range of cyclone activity. This database can then be accessed to provide rapid information on the potential threat to communities during impending cyclone landfall, whilst accounting for the degree of uncertainty in the landfall forecast. The technique is now established in the Bureau of Meteorology, and can be applied to any required site, by means of a menu approach.

Assessments of vulnerability have been made by comprehensive survey of all housing in the Townsville region and by community surveys in Cairns, undertaken by James Cook University. The vulnerability surveys have been extended to community education programs, including a Cyclone Game on CD-ROM for schools

The TCCIP participants identified storm characteristics at landfall and the nature of the interaction of storms with topography as a priority area. Of particular concern were the structure of the storm wind field and the nature of transient wind structure changes within the cyclone as it comes ashore. Boundary layer study programs are now fully in place, including instrumented towers at North West Cape in Western Australia and modelling studies of the cyclone boundary layer. An international workshop was organized, for the insurance and reinsurance industry, on the dynamics of landfalling wind fields with emphasis on appropriate parametric models.

Potential changes to tropical cyclones associated with enhanced greenhouse conditions have been addressed. The research focussed on the development of a technique to enable assessment of cyclone intensity and genesis changes from environmental information that is readily available from both direct atmospheric soundings and climate models (Holland, 1997). This technique provided a direct benefit to several community groups and insurance companies by defining the worst-case scenario for tropical cyclones in defined regions. It was used as the basis for the CAS statement on climate change described in Section 3.3.

6.2 THE US WEATHER RESEARCH PROGRAM - HURRICANES AT LANDFALL PROGRAM (HAL)

The USWRP has initiated a program aimed at improving hurricane landfall predictions. The goal is to improve forecasts of actual landfall (intensity and location) and the onset of strong winds and to lengthen the time available for evacuation. Coupled with this will be action on both estimating and directly measuring the degree of wind damage, storm surge and related wave activity, and the location, timing and magnitude of heavy rainfall and tornadoes.

A major goal is to determine the full cost of hurricanes to society and how to communicate warnings to produce a maximum community response and related reduction in hurricane impacts. Its specific goals are to

- Double the lead time for hurricane watches to two days and increase warning lead time for gale-force winds;
- Reduce the length of coastline warned from nearly 400 miles to as little as 200 miles;
- Provide more exact estimates of hurricane intensity, cutting errors by half, and;

- Improve forecasts of inland flooding by 50%.

Following an extensive program of discussion and development of priorities and needs, USWRP's HAL program identified the following priority research topics:

- Pre-landfall track: Crucial for the provision of maximum lead time and accuracy of landfall.
- Pre-landfall wind structure: Important for the warning requirements of onset of gale-force and higher winds, together with the intensity at landfall.
- Landfall wind structure: Provides input to storm surge and damage models.
- Landfall precipitation: Local flash flooding and especially combination with storm surge.
- Socioeconomic impact Especially defining the benefits and costs of the analysis and warning system, and providing improved warning content.

Further information is available at <http://uswrp.mmm.ucar.edu/uswrp.html>.

6.3 THE WORLD WEATHER RESEARCH PROGRAM - TROPICAL CYCLONE LANDFALL INITIATIVE

There is considerable overlap between the objectives of USWRP's HAL and TCCIPs, and also with those determined from discussions at the IWTC-IV. This common theme across many warning systems and cultural requirements means that there is a large element of transferability of techniques and research findings. The major advantage that the USWRP has is access to a remarkable array of observation systems and a highly developed research infrastructure. The goals of the WWRP Tropical Cyclone Landfall program are to take advantage of this research and coordinate national activities by developing a set of forecast demonstration projects aimed at illustrating the potential improvements in landfall warnings in other regions.

The WWRP was established by the WMO Commission for Atmospheric Sciences in 1998, following extensive deliberation and discussion on both the need for, and the roles of, such a program. The mission and objectives are:

WWRP Mission

To develop improved and cost-effective forecasting techniques, with emphasis on high-impact weather, and to promote their application among Member States.

WWRP Objectives

- To improve public safety and economic productivity by accelerating research on the prediction of high-impact weather,
- To facilitate the integration of weather prediction research advances achieved via relevant national and international programmes;
- To demonstrate improvements in the prediction of weather, with emphasis on high impact-events, through the exploitation of advances in scientific understanding, observational network design, data assimilation and modelling techniques, and information systems;
- To encourage the utilization of relevant advances in weather prediction systems for the benefit of all WMO Programmes and all Members;
- To improve understanding of atmospheric processes of importance to weather forecasting, through the organization of focussed research programmes.

WWRP Strategies

- Identify the types of weather events where multinational research collaboration is likely to lead to improved prediction and associated benefits to participants;
- Develop and apply methods for assessing the cost-benefits of improved forecasts of high-impact weather events, in conjunction with other WMO Programmes;
- Promote, organize and/or endorse research programmes including, where necessary, field experiments to develop understanding of weather processes and improve forecasting techniques;
- Organize and lead projects, in conjunction with other WMO Programmes, to demonstrate and objectively verify improvements in weather forecasting accuracy,
- Sponsor technical workshops and conferences to further understanding of the science and technology involved in improved weather prediction;
- Organize training programmes to ensure that all Members can benefit from WWRP advances

A key component of the WWRP activities will be to sponsor forecast demonstration projects, which can both illustrate the application of research findings to operations and provide an objective verification of new forecast methodologies.

Further information can be obtained from:
<http://uswrp.mmm.ucar.edu/uswrp/wwrp/reports/Bulletin_WWRP.html>.

The WMO/CAS WWRP and TMRP have proposed an international Tropical Cyclone Landfall initiative with the goal of improving specification of the rainfall and wind field occurring both at the coast and inland as a cyclone makes landfall. This will implicitly require improved track forecasts and will lead to improvements in secondary parameters, such as storm surge estimation This will require a program of research and development into cyclone intensity and structure changes that accompany landfall, including the potential for rapid intensification. Since the actual impact is crucially dependent on the landfall location, a continued program of research and development into track is required, but with an emphasis on track processes near landfall.

This program will have several components but will develop from existing programs on tropical cyclone research, including the long-standing international initiative on tropical cyclone track forecasting coordinated by the US Office of Naval Research, the USWRP Hurricanes at Landfall Program and the Australian Tropical Cyclone Coastal Impacts Project. The aim of the project is to:

- Develop an international research program aimed at improved understanding of the associated processes;
- Conduct associated field programs, especially in association with USWRP's HAL program and the ONR Tropical Cyclone Motion Initiative, both as a basis for the research and to provide indications of the likely data requirements for forecasting;
- Specify two or three Forecast Demonstration Projects, covering a range of forecast capacities, to assess the potential improvements in forecasting resulting from application of the research and development findings and the improved observing systems.

This program is expected to be one of the major initiatives to be taken from the IDNDR into the twenty-first century.

7. THE NEXT DECADE

It is always dangerous to peer into a crystal ball and even more dangerous to put in print what is seen there ! However, the IDNDR decade of the 1990s has seen steady and sustained improvements in the manner in which we forecast, prepare for and mitigate the impact of tropical cyclones. As we move into the next decade, a number of trends that will potentially lead to remarkable improvements are apparent in many aspects of cyclone mitigation.

The first trend is the major research and socioeconomic emphasis that is being placed on tropical cyclones. This has occurred through national programs, such as the Australian Tropical Cyclone Impacts Project and the US Weather Research Program. Interactions between these programs and the newly-established World Weather Research Program will strongly focus research and impacts studies on landfalling tropical cyclones and will support transition of the findings to operations through Forecast Demonstration Projects.

The second trend is the enormous increases in computer power and the associated improvements in the capacity of numerical models to forecast many components of the tropical cyclone more accurately and to undertake ensemble forecasts aimed at defining the overall uncertainty in individual forecasts. Associated with this is the potential for improved weather system observations, by use of satellite and other remote sensing and by direct reconnaissance using robotic systems, such as the Aerosonde. Provided that we can hold against the considerable economic pressures being exerted on the current observation system, we shall move into a new era — one in which we will have an unprecedented opportunity to properly combine observations and modelling in an optimal mix that can target the regions and observations crucial to the forecast process.

The last, but by no means the least, important trend lies in the combined approach to all aspects of the cyclone mitigation problem. Attention to public education and community preparedness and a full understanding of the true economic and social benefits of the cyclone warning system will produce reductions in cyclone impacts far beyond what could be achieved by forecast improvements alone.

It is likely that improvements in the combined modelling and observation system will lead to quite accurate forecasts of cyclone genesis. This is a subtle process, but one that often seems to be associated with a well-defined, large-scale signature (e.g. Holland, 1995). Current model forecasts are already showing considerable skill in this regard. Cyclone track also has substantial potential improvement before the predictability limit is reached. A combination of carefully defined observations and numerical models, supported by statistical combinations of various models or ensembles, can potentially halve current forecast errors, especially over long-time periods.

Current research trends will lead to much better understanding of the transient, and potentially dangerous, processes occurring in the boundary layer of tropical cyclones, especially those that are making landfall. Making use of this knowledge will present a major challenge to warning and communications systems and to the way in which society reacts to the warnings.

Perhaps the major continuing difficulty will lie in both fully understanding and predicting cyclone intensity change. Substantial research into the related mechanisms remains a major requirement. It may well be that, for the next decade, intensity forecasts will continue to be best undertaken by statistical techniques and prudently conservative forecast strategies.

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