Australian Government
Department of Defence
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Application of Numerical Weather Prediction to Rapid Environmental Assessment

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DSTO-GD-0403

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ABSTRACT

This report summarises numerical weather prediction capability available in Australia, its likely near-term development and its application to Rapid Environmental Assessment. Research at the Commonwealth Bureau of Meteorology and the Commonwealth Scientific and Industrial Research Organisation into meteorological and to some extent, oceanic forecasting, is examined.

Published by

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AR No. AR-013-082
April, 2004

APPROVED FOR PUBLIC RELEASE

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EXECUTIVE SUMMARY

Tools for Numerical Weather Prediction (NWP) and numerical prediction of ocean circulation and ocean wave heights are routinely used as an input to weather and marine forecasting in support of military operations of all kinds. NWP already forms part of the emerging doctrine known as Rapid Environmental Assessment (REA), and will play a larger role in the future. This report discusses the application of developments in NWP and related oceanic modelling to REA.

The military requirement for meteorological forecasting differs from the civilian requirement in that the areas of interest may be remote from population centres or the Australian region in general, they may arise over relatively short timescales and they may move over time. In addition, areas of military interest for REA tend to be localised, conforming to the scales meteorologists refer to as "mesoscale" rather than "regional" or "global". Hence, in addition to the requirement for global and regional forecasting tools, there is an additional military requirement for "relocatable", mesoscale forecasting tools.

There are two internationally-competitive centres for meteorological research in Australia: the Bureau of Meteorology Research Centre (BMRC) within the Commonwealth Bureau of Meteorology (BoM), and the Division of Atmospheric Research (DAR) within the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The ADF may be able to use developments from both these centres for REA applications, but it must be noted that both organisations are primarily civilian–oriented; hence development of a capability for specifically military applications may require additional funding.

Both the BMRC and the DAR have research programs into mesoscale NWP modelling. The BLUElink ocean modelling initiative, which is a collaborative program involving the BoM, the DAR and the RAN, will provide a relocatable mesoscale NWP capability as a by-product of its ocean circulation modelling processes. In a separate program, the DAR has developed an arbitrarily-scalable forecast model called C-CAM which can be run on a personal computer[1] when initialisation data is available from a regional or global model. The BMRC has also developed mesoscale NWP models, which are potentially relocatable. However, neither organisation currently assimilates meteorological measurements directly into their mesoscale models, a factor which potentially limits the usefulness of the models for military applications, particularly in remote areas where data is inherently scarce. Mesoscale data assimilation and forecasting is an area of very active research from which the ADF could potentially gain a high return on investment. The option of funding research into this area specifically for Defence purposes should be investigated.

In addition to mesoscale forecasting, the ADF could potentially benefit from developments in regional and global NWP and ocean modelling. Seasonal forecasting, currently limited to the Australian region, could provide climatological information for the planning phases of REA. Higher-resolution NWP models and the introduction of "ensemble"

[1]Other NWP models of comparable accuracy require considerably larger computing resources.

data assimilation and forecasting should increase the fidelity of forecasting generally. The increasing resolution of satellite remote-sensing systems may reduce the need for meteorological measurements, or increase their impact. The extension of wave-modelling and circulation-modelling services into the littoral could directly benefit the planning process for amphibious operations. Finally, the adaptation of forecast delivery products (graphical and otherwise) under development by the BoM could be of benefit for REA and generally within Defence.

In summary: ongoing and deliberate investments in instrumentation, numerical weather prediction and visualisation will result in fewer surprises for ADF sailors and aviators.

Contents

1 Introduction

This report was generated in the course of work intended to understand the requirements for data collection and distribution during Rapid Environmental Assessment (REA) for naval and amphibious purposes. It has become clear during preliminary studies of REA that "the weather" (more widely, the state of the atmosphere) and the state of the ocean have significant effects on virtually every aspect of military endeavour. An ability to successfully predict changes in the state of the atmosphere and the state of the ocean therefore confers a military advantage.

In this report, "weather prediction" is taken to mean the use of technology, by meteorologists and oceanographers, to extend the domain in which the state of the atmosphere is known beyond what is directly observable. It encompasses "nowcasting" – prediction of the present conditions throughout a region, and "forecasting" – prediction of future conditions. "Oceanic prediction" is taken to mean the application of similar processes to predict the ocean environment. Neither process is automatic, as the state of the art is not sufficiently advanced that all sources of data can be assimilated by appropriate numerical models. Nor are the models themselves trusted sufficiently that their outputs can be used unsupervised and unmodified. For the foreseeable future, forecasts will be generated under the supervision of skilled human operators. Nevertheless, the majority of this report deals with aspects of numerical prediction for meteorology.

1.1 Weather prediction and REA

NATO doctrine (NATO 2001) divides REA into four categories, which will be used here in the absence of an Australian equivalent. Each of the four categories of REA has a relationship to weather prediction, firstly in the sense that weather prediction is used to enable both REA and general military operations; secondly in the sense that data may need to be collected during all phases of REA in order to enable weather predictions to support military objectives.

Considering the categories in turn:

- **Category 1**: Supply of environmental data during the planning stage of an operation. Long-term weather predictions are beginning to display useful accuracy in the Australian region; hence medium- to long-range climatic weather prediction may (in future) enhance or supplant the strictly historical climatological information that is now routinely supplied to the ADF.

- **Category 2**: Overt environmental data gathering prior to an operation or as part of the Advance Force deployment. Weather prediction is one factor that is used to maximise the efficiency of data collection. Atmospheric and oceanographic measurements are made to enhance weather prediction.

- **Category 3**: Covert environmental data gathering, possibly immediately prior to an operation. The capability for covert information gathering rests on relatively limited and fragile resources that may be highly vulnerable to the weather conditions.

Hence, accurate weather prediction in support of this phase is crucial. Atmospheric and oceanographic measurements may be made during Category 3 operations to enhance weather prediction.

- **Category 4**: Ongoing, overt environmental data gathering and distribution during the operation. Accurate weather and ocean state prediction has long been a requirement during this phase. Atmospheric and oceanographic measurements are made to enhance weather prediction.

Common factors are apparent in all categories of REA. Firstly, localised weather predictions are likely to be required for remote areas. Secondly, there is a requirement to maximise the efficiency with which resources are deployed for environmental measurements, especially those relating to weather prediction. This encompasses the impact measurements will have, the resources consumed in making the measurements, and particularly in Category 3 REA, the danger associated with making the measurements. In all circumstances, it is in the interests of the RAN to minimise the number of observations that are made, to maximise the proportion of observations that are made by remote sensing, and to maximise their impact.

The limitations to weather and oceanic prediction should also be noted. The degree to which any prediction is useful depends on the precision and accuracy that can be achieved and the context in which the data will be used. In some cases, current systems struggle to generate predictions of sufficient accuracy and resolution for important applications. An example of this is the fine-scale vertical temperature/humidity gradients that lead to "ducted" radar propagation over the ocean. Studies related to the calibration of weather radar (Bech, Bebbington, Codina, Sairounic & Lorente 1998, Bech, Codina & Lorente 2003) have shown that, while mesoscale models can predict the existence of ducting conditions, their predictions are not as accurate as assuming that radiosonde observations will persist for 12 hours into the future.

1.2 Numerical Weather Prediction (NWP)

The basis of current forecasting practice is numerical weather prediction, a science that has developed rapidly over the last few decades. The Australian centres of excellence in NWP are largely the Bureau of Meteorology Research Centre (BMRC) at the Commonwealth Bureau of Meteorology (BoM), and the CSIRO Division of Atmospheric Research (DAR). The BoM provides operational data assimilation and NWP and conducts research into data assimilation and into atmospheric and oceanic modelling on timescales from immediate to climatological. The DAR conducts research into atmospheric and oceanic modelling on timescales from immediate to climatological as well, and also provides support for some contracted NWP based on third-party assimilation systems.

In NWP, "global" models have global extent, "regional" models cover a sizeable fraction of the globe, say a continental land mass and surrounding oceans, and "mesoscale" models have extents of the order of hundreds of kilometres - for example, the BoM uses a mesoscale model to predict weather conditions in the region around Sydney. The resolution of a given model is constrained by the computational and memory limitations of the computers used to run it; hence, global models have the coarsest resolution, regional models have intermediate resolution and mesoscale models have the finest resolution. For different resolutions, different models of the physical processes taking place in the atmosphere, such as cloud generation, are required.

The areas of NWP that appear to have the greatest relationship to DSTO research on Rapid Environmental Assessment are "data assimilation" and "mesoscale" weather/oceanic prediction. In particular, "relocatable" versions of mesoscale models are of interest, since the regions of military interest tend to be remote and to change relatively rapidly.

1.2.1 Data assimilation

Most NWP systems are based on time-dependent finite-difference schemes, which model the atmosphere either as a regular spatial grid, or express it using a "spectral" representation (employing spherical harmonic functions in the case of the globe). Considered as a whole, the nodes of the NWP grids represent far more information than there are observations available to explicitly initialise them (say, 1000 times more in the atmosphere and a much larger ratio in the corresponding ocean models). Nevertheless, the observational data is extraordinarily large. The observations are typically inhomogeneous in space, in time and importantly, in quality; a major task of assimilation algorithms is to address quality control, observation density issues and the error characteristics of both the model and the observations.

"Data assimilation" is the process whereby observations of the state of the atmosphere and the ocean are used to update the state of the corresponding models. The output of the assimilation step is an "initialisation", which is an estimate (model) of the state of the physical system at an instant in time. "Forecasting" is the evolution of the model state from its initialisation into the future, where (by definition) no observations are available. The fidelity of the forecast is constrained by the fidelity of the initialisation, the quality of the physical parameterization of key meteorological processes, and the overall resolution of the assimilation/prediction system.

The most prevalent assimilation algorithms in use or under consideration by the BoM and other major operational NWP centres internationally - 3dVAR, 4dVAR, ensemble Kalman filter – all employ the central ideas of the Kalman filter, that is, they are essentially huge tracking mechanisms. The assimilation algorithm attempts to calculate the optimal match between the state of the model and the state of the physical system (atmosphere or ocean) that it represents. The state of the model is constrained to match the observations to the extent that they are statistically credible, which is estimated from the known quality of the available observational platforms, the statistical variation of the data, the extent to which they match the projected evolution of the model from its previous state, and the extent to which the model itself is credible. The "innovation" made to the model at each time step in the assimilation process is thus a weighted sum of the evolving model and the quality-controlled observations, taking into account the statistical characteristics of prediction error, observation error and the full range of covariance between these quantities. Many of the available observational systems provide non-conventional quantities[1];

[1] In this context, a "conventional" quantity is a direct measurement of an atmospheric state variable, such as temperature, humidity or barometric pressure.

for example, remotely sensed microwave and infrared radiances. These quantities are reduced to estimates of conventional quantities using the state of the atmosphere as one of the inputs to the process. Thus, the assimilation system requires a component providing "forward models", that is, a priori estimates from the current model state, in order to reduce these non-conventional observations to conventional physical quantities that can be used in the model.

In principle, it should be possible to derive the relative importance of various existing data sources from their weightings in the assimilation system and indeed the impact of a number of conventional observing systems is routinely quantified within the BoM assimilation systems. Additionally and of obvious practical import, the impact of specific observational enhancements is assessed by comparing forecast fidelity with and without such observations. It is difficult to predict the impact of new data sources; however it is feasible to conduct Observation System Simulation Studies (OSSEs) where the data anticipated from a new observing system is generated from a simulated atmosphere, perturbed with appropriate error characteristics and reassimilated in the original but perturbed/degraded atmospheric simulation. Many of the major satellite observing systems have been prototyped via this methodology.

1.2.2 Mesoscale NWP models

Mesoscale models are the highest-resolution NWP models in use and consequently they are potentially the most capable of predicting the mesoscale (local) features of weather systems, including severe storms and tropical cyclones, heavy rainfall, convection and cloud formation. They are currently in a very rapid state of development. Both the BoM and the CSIRO DAR conduct research into mesoscale weather prediction systems.

A useful introduction to the current status of mesoscale modelling is given by Kuo (2003), who notes that mesoscale models are widely used for real-time local weather forecasting, with over three dozen groups employing such models in the USA alone. They are also used across the globe by the US military and by NATO, but not yet by the ADF.

There are multiple mesoscale NWP models in use - for example, ETA, MM5, RAMS, COAMP, ARPS and perhaps most recently, WRF. In most cases the code is publicly accessible and the physical models are shared between the various research groups, promoting rapid innovation. It is important to note that mesoscale NWP systems do not function in isolation. They require "boundary conditions", that is, the inflows and outflows of mass and energy from the atmospheric region surrounding the mesoscale grid, and an analysis[2] from a regional or global NWP model must be available to provide the initialisation.

Kuo (2003) notes that the high-resolution models require tremendous computational power, with each factor of two increase in vertical and horizontal resolution requiring a factor of 16 increase in computational resources. However, increase in resolution does not necessarily equate to increase in forecast fidelity. A number of statistical studies were summarised approximately as follows:

[2]In this context, an "analysis" is an atmospheric forecast expressed as a four-dimensional grid of atmospheric state variables. Three dimensions correspond to space dimensions and the fourth represents the evolution of the model in time.

1. The models perform well in regions where the local circulations are driven by local topography (for example, mountains) and land-surface variations (for example, the cycle of land and sea breezes near a coastline).

2. Increasing grid resolution yields increased forecast skill[3] up to a point, but physical parameterisations need to be improved at the finest resolutions.

3. Mesoscale forecast skill is strongly affected by the forecast skill of the large-scale model in which the mesoscale grid is embedded.

4. An ensemble of lower-resolution mesoscale forecasts taken together tends to exhibit more skill than a single high-resolution forecast.

As will be discussed later, mesoscale models can be run without data assimilation, relying simply on the assimilation mechanisms in the larger-scale embedding model as expressed by the initialisation. However, there are potential benefits in directly assimilating local measurements into mesoscale models and mesoscale assimilation is an area of active research. It has been found that assimilation of data from even a single ground-based sensor can have a positive impact on forecast fidelity, provided the assimilation mechanism is sufficiently sophisticated.

1.3 The future

Research into data assimilation could have long-term benefits to the RAN, particularly in regard to the impact of data assimilation on mesoscale NWP systems. However, DSTO REA staff are poorly qualified to undertake research into NWP and data assimilation. They have no experience with NWP models and little experience with meteorological observations, although oceanographic observations are familiar. Additionally, the tools to do such research are not readily accessible, since access to data streams and computational facilities is required. The development and implementation of operational NWP systems for both the ocean and atmosphere involves substantial infrastructure and expertise that is currently limited to a few centres around the world.

The main purpose of this work was to become familiar with the Australian capability for weather prediction and to a lesser extent, oceanic state prediction, at all scales from global to local. It was particularly desired to identify contacts within the BMRC and the DAR who could potentially assist with the task of specifying which observations are important to weather prediction (both human and numerical) and which are not, and which instruments will be most valuable in future. In addition, the REA task has an instrument development program, with atmospheric and oceanic profiling systems being actively designed and built. The assistance of outside experts will be required to determine the value of these instruments and where and when they should be deployed.

[3] In this context, "skill" is a numerical ratio that estimates the degree to which a forecasting system performs better than some reference forecast, for example, an assumption of "no change".

2 The Commonwealth Bureau of Meteorology

The Charter of the Commonwealth Bureau of Meteorology (BoM) includes the provision of meteorological observation and prediction services "in the public interest". The definition of "meteorological prediction" has been interpreted rather broadly to include meteorological and oceanographic predictions over time-scales stretching from immediate to climatological. The BoM has a very wide range of customers, including the general public, aviators and navigators, and farmers. "Defence" is specifically mentioned as a user of BoM services in the Charter, but defence-related activities form only a small part of the total effort of the BoM. There are specific services for both the RAN and the RAAF.

2.1 Atmospheric models

The bulk of the BoM's activities centre on the Australian region[4], with extra computational and observational effort concentrated around major population centres. The BoM runs multiple NWP systems sequentially. The GASP[5] model has global coverage and 75 km nominal grid resolution in the horizontal. The regional LAPS[6] and TLAPS[7] models have coverage of the Australian region with 37 km nominal grid resolution, with focus on the Australian mainland and the equatorial regions to the north of Australia respectively; these models are nested within the global model to define appropriate dynamic boundary conditions. Various "Meso-LAPS" models with resolutions from 12 km down to 5 km provide coverage of smaller areas of higher population density within the region; these models are nested within the LAPS grid point models. There is also a variant of LAPS specifically adapted for prediction of the path of tropical cyclones.

The highest-resolution Meso-LAPS models are potentially those of most benefit to the RAN, since they provide the highest resolution forecasts, particularly with regard to severe weather events. The BoM is capable of siting such models anywhere within the region or even globally, but requests of this nature must compete for resources with the maintenance of normal weather prediction services. In its current form, the weather forecasting ability of the BoM is concentrated on Australian mainland population centres. In principle, the LAPS limited-area model can be nested in the global GASP model in any region of the world. However, work is invariably required to verify and tune the fidelity of the regional model before it can be applied with confidence.

The NWP systems form only part of the Australian forecasting system. Weather forecasts issued by the BoM are the product of meteorologists, who review analyses from the Australian system and USA and European systems along with satellite imagery and other data in order to derive their forecasts. The reason for this is that no NWP system is perfect. It is vulnerable to defects in its inputs as well as to shortcomings of its modelling systems.

[4]The Australian region is loosely defined by a geographical box stretching in latitude from the South China Sea to the edge of Antarctica, and in longitude from the western Indian Ocean to the International Date Line.

[5]GASP - Global Assimilation and Prediction system

[6]LAPS - Limited Area Prediction System

[7]TLAPS - Tropical Limited Area Prediction System, which extends from 44N to 45S

2.1.1 The future of NWP

The BoM continually refines its computing platforms and the models and assimilation systems that run on them. Computing facilities will be upgraded early in 2004 with a major supercomputer upgrade through the replacement of a two-node NEC SX-5 vector facility with an 18-node SX-6 facility. Enhanced and more timely modelling and assimilation systems will be implemented with the extra capacity. The BoM operates a High Performance Computing and Communications Centre (HPCCC) within its Head Office; the supercomputer facilities of the HPCCC have for the past 6 years been shared equally between the BoM and CSIRO. The upgraded SX-6 facilities will be predominantly a BoM facility with CSIRO having access to approximately 20% of the SX-6 nodes.

The impact of refining the resolution of the global GASP model is currently being tested. The refined model has approximately double the resolution in latitude and longitude and an extra 20 vertical layers, allowing finer vertical resolution and extension of the model further into the upper atmosphere. There are similar plans to enhance the regional LAPS models, possibly allowing resolutions currently restricted to mesoscale models to be achieved over the entire Australasian region. Both developments imply refinements in the resolutions at which data assimilation takes place.

More importantly, the BoM is considering the evolution of the assimilation system to a new generation of algorithm. The current NWP system is based on initialisation/data assimilation using the "3dVAR" optimisation algorithm. This will most probably be replaced with an "Ensemble Kalman Filter" (EnKF) algorithm - effectively, a number of models are run in parallel with initial conditions that are randomly perturbed (according to instrumental observational error characteristics), in order to gauge the most likely "present" initial state and the degree of instability inherent in the initial state and forecasts derived from it. EnKF algorithms have been under investigation for some time and are considered as having significant potential in NWP generally and for high-resolution prediction of severe weather. Note that EnKF algorithms are also used for "ensemble forecasting"

2.1.2 Atmospheric and sea-surface observations

Under the framework of the World Meteorological Organization (WMO), the BoM receives and exchanges real-time observations from a range of platforms around the world. The Bureau accepts weather observations from naval and commercial shipping via radio and from aircraft via an automated satellite-based relay system. It runs a network of manned and automatic sensors, which include automated weather stations (see Figure 2.1), manned weather stations, weather watch and wind-finding radars[8] (see Figure 2.2), drifting and moored buoys and wave-monitoring buoys; some experimental use of aerosonde observations has been supported by the BoM.

[8] Weather Watch radars estimate precipitation rates - rain, hail and snow. Wind-finding radars track weather balloons, giving profiles of upper-atmosphere winds.

Figure 2.1: Automated weather stations operated by the Bureau of Meteorology

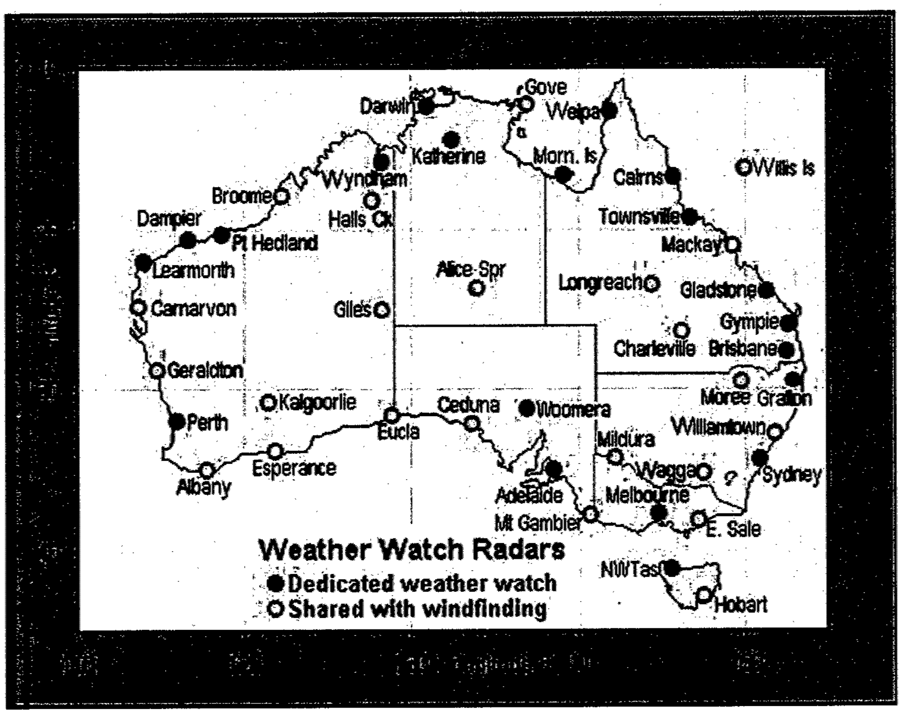

Figure 2.2: Weather watch radars operated by the Bureau of Meteorology

2.1.3 Satellites

The bulk of the data used by the BoM, both for assimilation into NWP systems and to assist meteorologists making forecasts, comes from weather satellites, which carry passive imaging and sounding[9] instruments and active radar altimeters and scatterometers. The available satellites and observing systems are extensive in number, including five operational geostationary satellites, three operational polar orbiting satellites, several experimental satellites and several USA Defense satellites (DMSP).

The imaging systems provide images in visible, infrared and microwave wavelength bands. These allow identification of weather systems, assessment of sea and land surface temperatures, cloud coverage estimation and wind speed and direction measurements via automated cloud motion analysis. Ice thickness and the dispersion of pollution, smoke and volcanic ash can also be measured.

The sounding systems are radiometers with various spectral resolutions measuring infrared and microwave reflected radiances from the Earth's surface and atmosphere. Depending on the frequency, various inversion processes are used to extract sea surface, land surface and atmospheric temperature profiles, barometric pressure, cloud and water vapour distribution, atmospheric chemistry and winds from the radiance data. Solar radiation flux is also measured.

Radar altimeters are used to derive significant wave height, and sea surface wind speeds are also derived. Other active measuring systems have only been used experimentally to date. Radar scatterometers can provide sea surface wind speed. Neither altimeters nor scatterometers give wave spectra[10], although radar sensors have been proposed that are designed to measure them[11]. The Jindalee and potentially the JORN over-the-horizon radars can provide sea surface wind speed and direction. Arrival-time fluctuations in the GPS satellite network are inverted to estimate profiles of water vapour content. The DMSP satellite series include several polarized microwave channels from which high quality marine wind speed products are generated along with an extensive range of other products.

The current operational status for satellite assimilation is:

- NOAA 15, 16, 17 polar orbiting satellites - microwave and/or infrared radiometers
- 5 geostationary satellites (various nations) - cloud drift vector winds, multispectral radiances

Additional data sources to be added in the near future are:

- DMSP F13, F14, F15 polar orbiting satellites - microwave radiometer systems profiling water content, temperature and marine wind speed

[9] In this context, an "imaging" system is an electromagnetic sensor with high spatial resolution but low spectral resolution. A "sounding" system is the opposite, having lower spatial resolution but more ability to discriminate between wavelengths.

[10] The wave spectrum is important in estimating swell characteristics, of which long-period swells are the most important for docking at sea.

[11] SWIMSAT has been proposed to measure ocean wave spectra - see http://www.cetp.ipsl.fr/1activ/21mineu/iot/resum_VAGSAT_2.html, accessed 05 Feb 2004

- DMSP F16, F17 polar orbiting satellites - will carry the new SSMIS microwave sounder when launched
- QuikScat radar scatterometer sea surface wind speed and direction[12]

Satellites have become the dominant information source; the demonstrably large impact of satellite observational data in the southern hemisphere (where other sources of observation are relatively few) is now considered such that the overall capability of NWP in both hemispheres is effectively equivalent in the medium range, that is, for predictions 4–6 days into the future.

As with any technology, satellites have limitations. The coverage of each satellite is finite, and the resolution of weather satellites is typically relatively coarse, as dictated by their altitude and the requirement to measure radiances over multiple frequencies. Geostationary satellites, orbiting at 35800 km synchronously with the Earth's rotation, each image a fixed aspect of the Earth with high temporal resolution – some imagery is updated every few minutes. Polar-orbiting satellites orbit at much lower altitudes; for example, the NOAA POES satellites have orbital altitudes of order 830 km above the Earth's surface. They use scanning sensors to image a swath perpendicular to their orbital track, as shown in Figure 2.3. As noted previously, multiple, similarly-instrumented polar-orbiting satellites are deployed, in order to maintain timely coverage of the Earth's surface. The spatial resolutions achieved by the the geostationary and polar-orbiting satellites are of similar order[13], but the polar-orbiting satellites have better coverage of high latitudes.

In addition to the physical limitations of satellites, it is common for one or more of the instruments on a given satellite to fail during the lifetime of the platform. For example, of the three NOAA polar-orbiting satellites, only NOAA 16 has both infrared and microwave sounders operational at present. To some extent, this issue is resolved by the ongoing commitment of the USA and European space agencies to maintain the integrity of the major operational satellite programs. A recent example is the deployment of a USA geostationary satellite in the Eastern Pacific upon the failure of the Japanese GMS-5 geostationary satellite.

Many sensors are complementary and all have limitations. For example, the upwelling infrared radiation measurements that are used to estimate sea surface temperature can only be used from areas free of cloud, which are intrinsically the least interesting areas for weather prediction (see Figures 2.4 and 2.5). Spectro-photometric inversions for temperature and pressure also rely partly on surface measurements made from weather stations and ships.

[12]With the failure of the ERS-2 scatterometer and the approach of the QuikScat instrument to the end of its design lifetime, this data source is not guaranteed.

[13]The horizontal spatial resolutions achieved by the 8-M imaging instrument on some NOAA GOES geostationary satellites are, at nadir, 1 km (visible), 4 km (approximately 4 μm, 7 μm, 11 μm and 12 μm infrared bands) and 8 km (13 μm band). By contrast, the GOES 8-M sounder operates over 18 thermal infrared bands with an 8 km horizontal resolution at nadir. By contrast, on the NOAA POES polar-orbiting satellite (NOAA 2000), the AVHRR instrument achieves a horizontal resolution of 1.1 km at nadir over 6 visible and infrared bands (centred at approximately 600 nm, 850 nm, 1.6 μm, 3.7 μm, 10.8 μm and 12 μm). The HIRS/3 infrared sounder achieves a horizontal resolution of approximately 20 km at nadir, over 20 visible and infrared frequency bands from 690 nm to 15 μm. The AMSU-A and AMSU-B microwave sounders achieve nominal horizontal resolutions of 50 km and 16 km, with, respectively, 15 channels in the 3.4 mm to 12.6 mm range and 5 channels in the 1.6 μm to 3.4 μm range.

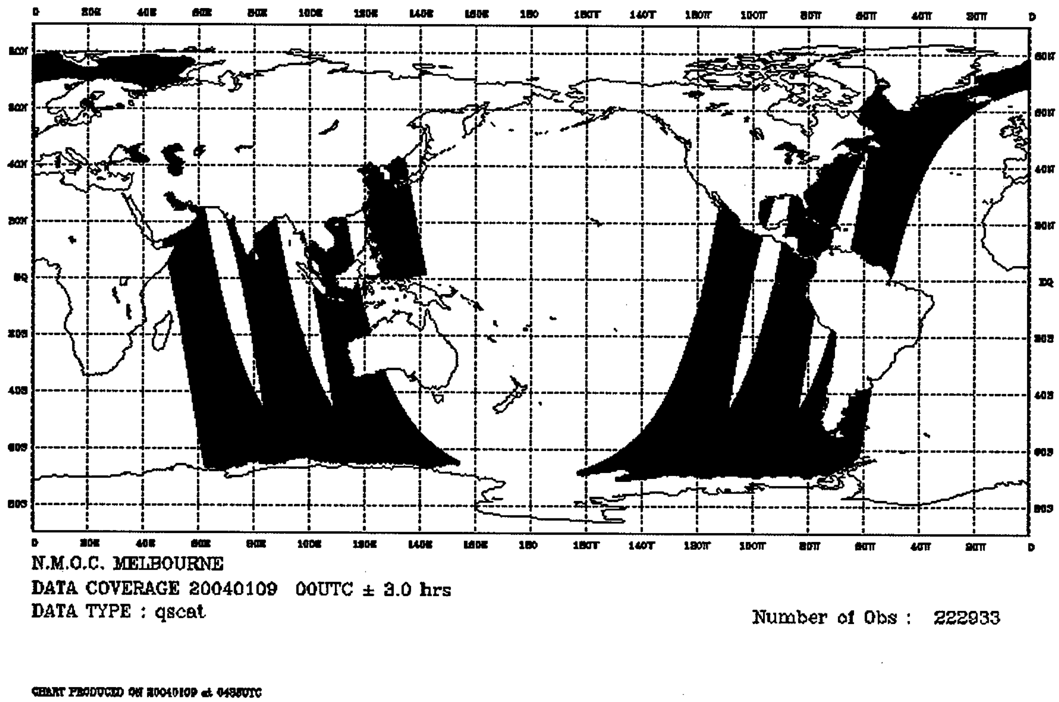

Figure 2.3: The coverage of the QuikScat scatterometer instrument during a single 6-hour assimilation period (image courtesy of the Bureau of Meteorology)

In general, in conjunction with NWP systems, the bulk of the atmospheric and sea surface parameters that have been nominated as being of interest for REA can be derived from satellite data of one form or another, or will become derivable in the medium term. However there remain issues with resolution and coverage, particularly in the littoral regions. It is therefore in the interest of Defence to be aware of the benefits that can be extracted from satellite data and the extent to which other measurements must be used to improve the quality of satellite-derived measurements.

Two experimental hyperspectral infrared sounding instruments, AIRS[14] and GIFTS[15], demonstrate the potential of satellite instruments to provide inputs to high-resolution NWP.

AIRS is an experimental satellite that has been providing real-time data to operational centres for assessment since 2002. The BoM has conducted some research, in collaboration with USA and UK researchers, into the inversion of data from AIRS for future assimilation into the NWP system. The vertical resolution of sounding instruments is limited by the spectral resolution of the instrument. Hence, the AIRS instrument, with 8461 infrared channels, is expected[16] to allow temperatures to be measured with a vertical resolution of order 1 to 2 km in the lowest 10 km of the atmosphere, whereas the HIRS/3 instrument, with 19 infrared channels, gives a vertical resolution of order 5 to 10 km.

[14] Atmospheric Infrared Sounder

[15] Geostationary Imaging Fourier Transform Spectrometer - effectively, an infrared hyperspectral sounder with the spatial resolution of an imaging system

[16] http://www.met-office.gov.uk/research/nwp/satellite/infrared/sounders/, accessed 05 Feb 2004

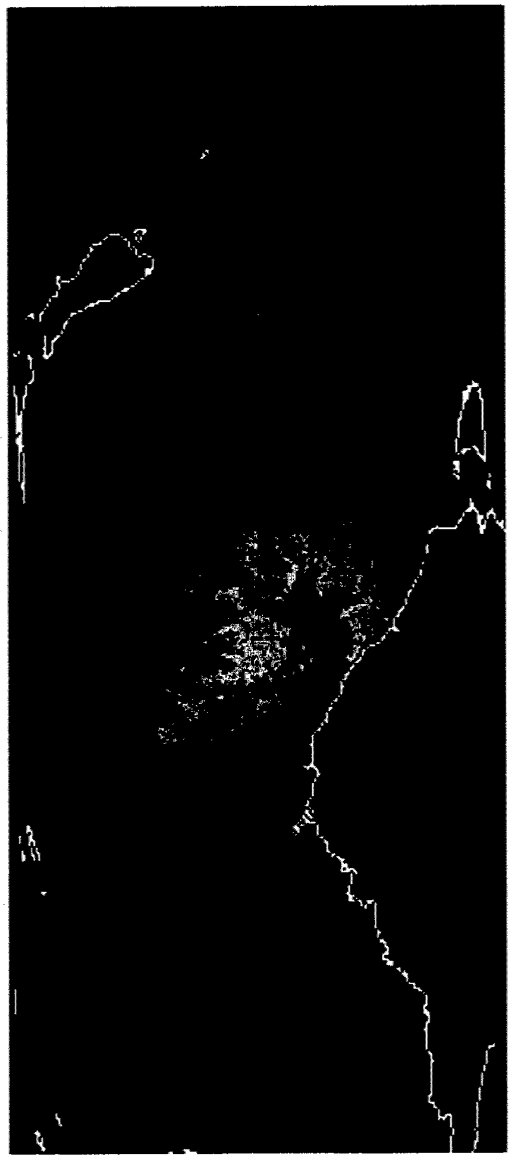

Figure 2.4: Sea surface temperature measurements derived from a single orbit

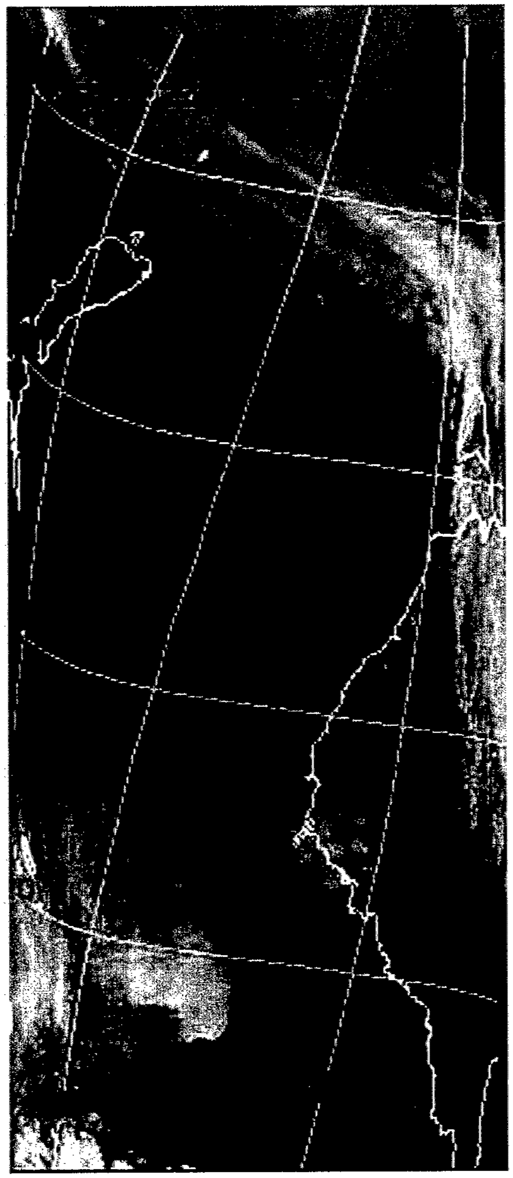

Figure 2.5: Corresponding cloud coverage

GIFTS is scheduled for launch some time in the 2006-2009 time window; it is a joint sensor development program involving NASA; the US Navy and its research arms; NOAA; and the Australian Bureau of Meteorology. Its platform, the EO-3 geostationary satellite, will initially be located over the USA, eventually being relocated over the Indian Ocean and downlinked via a ground station in Western Australia. The instrument (a variant of which has been tested from a fixed-wing aircraft) will potentially provide vertical profiles of temperature, winds, moisture content and transport, clouds, surface temperatures and atmospheric chemistry. The (horizontal) spatial and temporal resolutions are respectively down to 4 km and 10 seconds, unprecedented for this kind of sensor. Given that GIFTS instruments are likely to be integrated into the operational geostationary satellite constellation with global coverage, the impacts of this technology on NWP and mesoscale NWP in particular, should be monitored for Defence purposes.

2.2 Oceanographic models

The basic equations determining fluid motion in the ocean are similar to those governing the atmosphere; hence, numerical ocean circulation models are similar to atmospheric circulation models in terms of their solution and techniques for data assimilation, although they have different physics and resolution, and evolve over longer time-scales.

The BoM has developed the POAMA coupled ocean-atmosphere model to forecast the state of the oceans into the medium and long term, since the sea surface temperature in the Pacific and Indian oceans has been shown to have a strong effect on Australian continental temperatures and rainfall. Apart from medium-term forecasting and climate modelling, the BoM also provides marine forecasting services via deep-oceanic wave height predictions from the WAM model and storm surge predictions during tropical cyclones.

At present, the BoM provides no oceanographic prediction services in littoral waters, except as part of the BLUElink program. The ocean models for BLUElink that will be implemented operationally in the Bureau for the RAN are being developed jointly between the CSIRO Division of Marine Research and the BMRC. As a separate strategic research activity, CSIRO is developing a coupled ocean-atmosphere model under the BLUElink program.

2.2.1 Oceanographic observations

As noted previously, satellite systems give global coverage of the sea surface in terms of temperature from infrared and microwave radiometers, and significant wave heights from radar altimeters. In addition, a small fleet of drifting buoys gives conventional ground truth data.

The situation for the ocean volume is very different. Subsurface currents can be deduced by satellite altimetry[17], but electromagnetic radiation does not penetrate the ocean significantly, so other sounders cannot be used. Until recently, the ocean volume could only be sampled intermittently. This is changing with the introduction of the Argo program, in which an international collaboration including Australia is in the process of deploying

[17]The surface bulge induced by the current profile in the water column can be detected by radar

a fleet of approximately 3000 drifting buoys that profile temperature and salinity in the top two kilometres of the oceans.

The BoM collects, distributes and assimilates oceanographic observations from the Argo network and other drifting buoys, and also from CTD[18] soundings and XBT[19] casts from naval vessels, ships of opportunity and programmed research cruises.

3 The Bureau of Meteorology Research Centre

The Bureau of Meteorology Research Centre (BMRC) consists of approximately 100 staff divided into a management group and six research groups - data assimilation, model development, weather forecasting, ocean and marine forecasting, climate forecasting and climate dynamics. The following sections deal with the first four of these groups.

Dr Mike Manton is Chief of the BMRC. The BMRC has links with DSTO and would appreciate the opportunity to develop additional links with the Maritime Operations Division. Dr Manton has proposed that the BLUElink initiative could form an umbrella under which a variety of ocean and weather modelling capabilities could be developed.

3.1 The Data Assimilation and Model Development Groups

Dr Bill Bourke heads the data assimilation group, which has responsibility for research into the incorporation of weather observations into the global and regional weather forecasting systems. Dr Kamal Puri heads the model development group, which has responsibility for development of the computational engines that underlie the NWP (and climate simulation and prediction) systems. Given that the assimilation and forecasting systems are deeply interrelated, they are considered as a whole.

As noted previously, assimilation is the process by which the initial states of the forecasting models are estimated. Introduction of a new data source into a numerical weather prediction model is a labour-intensive process, so the process is resource-limited and only a subset of the total available observations is incorporated into the Australian weather prediction system. In general, one staff member is devoted to each major data source going into the system, with duties including implementing appropriate forward models (that is, estimation of model state variables such as temperature from observations such as radiances), estimation of statistical reliability models, and non-trivial data management.

Unfortunately, it is by no means easy to assess the impact of an additional data source on a numerical weather model. Impact studies are typically conducted in the BMRC in research mode, parallelling the operational suite, by comparing analyses with and without a given data source over a period of time. If incorporation of a data source consistently enhances the skill of the weather prediction system, and the process for incorporation is robust, then the data source is incorporated into the operational assimilation and prediction system. Note that some Defence needs may be additional to the basic requirements of the operational suite developed for the overall Australian community.

[18]CTD stands for Conductivity Temperature Depth sensor, a re-usable sound velocity profiler

[19]XBT stands for eXpendable BathyThermograph, a single-use sound velocity profiler

The BMRC currently has no explicitly defence-related research into weather prediction. It was noted repeatedly that determination of the impact of individual data sources on the fidelity of predictions is a difficult task. Research into meteorological data assimilation, which appears to be necessary to assess what measurements should be made in the course of REA operations, is something that the DSTO is ill equipped to investigate. The data assimilation process is inseparable from the underlying weather models. Therefore the most efficient way to undertake such work would be in cooperation with the BMRC.

Recommendation: *The option of funding researchers within the BMRC to conduct specifically military-oriented research work on data assimilation and mesoscale NWP should be investigated. This program should measure the ability of mesoscale NWP systems to deliver useful predictions in remote areas, and investigate the utility of incorporating observations made during REA into mesoscale and regional prediction systems. This research would deliver the benefit of better capabilities for weather prediction in remote areas. In the longer term, increased use of satellite remote sensing may reduce or remove the need for some surface measurements. Research should be undertaken into what atmospheric observations, if any, are essential for REA, and when and where they should be made for greatest impact.*

At the national level, two major potential sources of data are not yet assimilated into NWP models.

The first data source is precipitation data from the network of weather-watch and wind-finding radar systems located around the Australian continent (see Figure 2.2). This data is available continuously, but interfaces have not yet been developed to assimilate the information into the models. Apart from an increase in overall forecast fidelity, an additional potential benefit to the ADF lies in the fact that expertise developed in the assimilation of radar data at the regional level should make the task of assimilating radar data into relocatable mesoscale models considerably easier in the future. This is relevant to the RAN, because phased-array tactical radar systems are progressively replacing older designs. These systems are relatively readily adaptable to provide Doppler weather-sensing functions in addition to their normal duties. Suitable assimilation systems would then be required in tandem with such modifications, in order to take full advantage of the outputs.

The second potential data source is surface wind speed and direction data from the Jindalee-JORN radar network. Stuart Anderson of DSTO ISRD has developed algorithms to enable the extraction of wind speed and direction and sea state/significant wave height from Over The Horizon radar. The JORN system currently implements other, reputedly ineffective algorithms. An effectiveness study and a limited degree of funding would be required to implement the DSTO algorithms within the JORN system. Given the existence of satellite-borne scatterometers, the incremental impact of intermittent JORN data on the NWP suite is not clear a priori. However the current supply of satellite scatterometer data is not completely secure, being solely dependent at present on QUIKSCAT, with ERS ASCAT not due for launch until 2006.

Recommendation: *DSTO and the RAN should consider the benefits of updating the remote sensing capability of the JORN network and assimilating it into weather prediction systems, particularly at the mesoscale. The tropics to the north of Australia are both the region of greatest potential interest for military operations in general, and the most difficult region within the Australian region of interest in which to predict the weather.*

3.2 The Ocean and Marine Forecasting Group

The ocean and marine forecasting group is lead by Dr Neville Smith. At present, the main focus of the group is on oceanic influences on seasonal climate prediction - such as El Niño and La Niña - and marine forecasting for navigators. The group does not have the resources to make predictions for the shallower, littoral regions that are of most interest for amphibious operations, but it does have an interest in doing work in these areas, since they are a natural development of the work it already does and would employ nested versions of the same fundamental models. Given the increasing public focus on "coastal zone management", the extension of current priorities to this work is expected to occur when resources become available.

Recommendation: *Given that it is certainly in the naval interest that littoral current and wave predictions should be available in the region, it may be valuable for the RAN to formally state the value of such a capability for defence requirements, which would allow a consideration of whether BoM resources should be diverted for such purposes.*

Recommendation: *The impact of a seasonal weather forecasting capability should be examined in the context of Category 1 and 2 REA.*

3.3 The Weather Forecasting Group

Dr Tom Keenan leads the weather forecasting group, which concentrates on mesoscale meteorology and the development of observation systems, mainly for short-term forecasting (zero to 24 hours ahead). Much of the research concerns various kinds of radar instruments, with a view to increased understanding of storms and convective processes in tropical regions. Other research concerns the "downscaling" process, by which NWP analyses, manually adjusted by human meteorologists to remove biases, are statistically interpreted to provide weather forecasts at arbitrary locations.

Current weather radars allow monitoring of precipitation profiles for radii up to about 150 km. Doppler radars can additionally allow estimation of wind speeds. Depending on the design of the radar, this is accomplished by measurement of precipitation velocity - a technique requiring careful processing since precipitation and convection are not necessarily in the same direction, or aerosol velocity.

It has been noted that the high-power, phased-array tactical radars installed on large Navy platforms are ideally suited to weather-sensing applications, since they are capable of three-dimensional sensing and have high average power. In particular, the United States Navy has funded the development of a meteorological post-processor for its AN/SPY-1 tactical radar, and this hybrid system has been demonstrated to be at least as effective as conventional Doppler weather radars (Maese, Owen, Melody, Katz, Freedman, Sabin, Young, Thomson & Rogers 2000), with the result that such civilian weather radar systems are now being replaced by SPY-1 variants in the continental United States. As noted previously, similar phased-array tactical radar systems are becoming prevalent in the RAN, with the potential to serve as meteorological sensors for REA applications. Note that there are also research programs to produce cheap phased-array weather radars for autonomous aerial vehicles.

Small-scale severe weather is a most difficult aspect of the weather to predict. Weather radar systems could potentially be of great benefit to amphibious operations in reducing the impact of severe weather, subject to the resolution of deployment and safety problems. First, weather radars must be isolated from vessel or aircraft motions in order to assure the quality of the data they collect[20]. Secondly, a radar is by nature a very strong source of radiated electromagnetic energy. It is impossible to use covertly and, when used, it is an invitation to missile attack.

Recommendation: *Regardless of the problems inherent in radar usage, DSTO should investigate the possibilities of weather radars further, in conjunction with the BoM and the RAN.*

In general, RAN vessels operate in locations where other vessels and observing platforms are likely to be scarce. Therefore, virtually any observing capability is valuable for both manual forecasting and NWP, providing the information can be communicated rapidly and safely. It is useful intrinsically and as a means of removing bias from satellite-derived data. The potential observing capability includes automatic weather stations on board RAN vessels, atmospheric sounders on board RAN vessels, and atmospheric sensors on board RAN and RAAF aircraft, including autonomous aerial vehicles.

As noted previously, the problem of data assimilation into mesoscale NWP models, and particularly relocatable mesoscale models, is an active research area with many unanswered questions. However, it is this area that must be understood to properly assess the value of implementing new capability for atmospheric sensing, or connecting existing capability to a communications system.

Recommendation: *Refit or construction of RAN platforms should be treated as an opportunity for the installation of atmospheric/environmental sensors that are likely to provide data that is unavailable from any other source. The Weather Forecasting Group at the BMRC is a centre of excellence for sensor design and utilisation. It has expressed interest in interacting with the RAN in regards of the placing of sensors on board RAN platforms. This offer should be exercised.*

3.3.1 Forecast delivery

The USA National Weather Service is in the process of implementing a National Digital Forecast Database (NDFD)[21]. The purpose of the NDFD is to provide access to rapidly updated, seamless grids of "sensible weather elements", such as maximum temperature, cloud cover, and so on. The seamlessness of the data is achieved by integration of regional forecasts so that the national product is consistent across regional boundaries. The horizontal spatial resolution of products is currently 5 kilometres, and forecasts are updated 3- to 6-hourly. When the system is fully delivered, it will be possible for a user at an arbitrary location within United States territory, for example, a farmer in a remote area, to obtain forecasts of similar detail to those now available over major population centres. It will also be possible to obtain forecasts along a travel route such as a flight path.

[20]Ship-borne tactical phased-array radars are stabilised in the required manner because of their targeting and guidance functions

[21]http://www.nws.noaa.gov/ndfd/, accessed 05 Feb 2004

The BoM has implemented a digital forecasting system similar in concept to the NDFD, known as the FSEP[22] Data Base (FDB). Both systems implement "digital forecasting" via the use of statistical algorithms to automatically reduce NWP analyses and other data to numerical forecasts of sensible weather elements, which can then be used as an input to automated weather message generation. The BMRC Weather Prediction Group conducts research on such algorithms. As with the NDFD, the FDB provides the forecaster with tools to graphically manipulate forecast values. However, FDB is a system for forecasting at point locations, rather than over a grid. It is proposed that extension of the system to grid-based forecasting be implemented in future. A relocatable version of this technology would clearly be of benefit for REA applications.

The FDB is part of the AIFS 2 forecasting system[23] (Kelly, Donaldson, Ryan, Bally, Wilson & Potts 2003), which includes a set of visualisation and forecasting tools written in Java using the public domain VisAD[24] library (Hibbard 1998, Hibbard 2002, Hibbard 2004). AIFS 2 is inherently cross-platform and its components allow visualisation of BoM analyses, forecasts and raw data from a variety of instruments, such as automated weather stations, satellites and radars. It is highly probable that AIFS 2 components and sub-systems would be the optimal basis for development of software tools specifically for REA.

Recommendation: *The development of AIFS 2 is a collaborative exercise in which the RAN and DSTO may be able to participate to the mutual benefit of all parties. This possibility should be explored in the context of visualisation for REA.*

4 CSIRO Division of Atmospheric Research

The CSIRO Division of Atmospheric Research (DAR) conducts a wide range of research activities that in many cases parallel those conducted by the BoM. The primary focus of the DAR is climate modelling, but other capabilities including weather forecasting have been developed. The DAR cooperates with the BoM in a number of areas, but it also competes with it and has a commercial interest in providing services not provided by the BoM.

4.1 Atmospheric modelling and the BLUElink program

The BLUElink ocean modelling services are based around coupled atmosphere and ocean circulation models. These components are provided as part of a collaborative project between the CSIRO and the BoM. The atmospheric modelling part of BLUElink will consist of nested atmospheric models - the BoM models (GASP and LAPS) will provide the global and regional level modelling and the RAMS model (currently being tested by the DAR) will provide the mesoscale modelling. Within the DAR, the relevant staff work within the Climate Modelling and Applications Group. CSIRO Division of Marine Research staff based in Hobart will provide the ocean model components of BLUElink.

[22] FSEP – "Forecast Streamlining and Enhancement Project"
[23] "AIFS 2" is the second version of the Australian Integrated Forecasting System
[24] "Visualization for Algorithm Development" library

4.1.1 The RAMS model

Dr Debbie Abbs investigates mesoscale weather forecasting using the Regional Atmospheric Model (RAMS) model at the DAR. RAMS was developed at the Colorado State University and is now maintained and distributed by a spin-off company called Atmet as free software under the Gnu General Public Licence (GPL). Although RAMS is primarily a spatial-grid atmospheric model, it includes a data assimilation package (employing the 4dVAR algorithm) that is currently not used.

The atmospheric modelling capabilities of RAMS appear to be on par with the state of the art. The model is multi-resolution and is often used at very fine grid resolutions to model small and especially, severe weather systems. At fine resolution, it is possible to model convective processes explicitly, rather than relying on a parameterisation within a larger grid cell. The model includes sophisticated treatments of cloud microphysics and the interaction of soil and vegetation with moisture transport and precipitation[25].

The explicit connection of RAMS to the BLUElink program is that it provides the atmospheric forcing for an underlying relocatable ocean circulation model, which will be run with horizontal resolutions of between 10 km and 2 km. In this context, RAMS will be nested inside LAPS or GASP and the entire atmospheric forecasting process will be initialised with analyses from the BoM. However, this is not the only way that RAMS may be of benefit to the RAN and Defence in general. At present, Dr Abbs is testing nested RAMS models running at horizontal resolutions down to 1 km, with other models running at 2 km and 8 km over larger areas. In effect, the RAMS component of BLUElink gives the RAN a relocatable atmospheric model that is potentially capable of predicting the weather, including severe weather, with high resolution, anywhere on the globe.

At present, the assimilation capability is not being used. As the experiences of the BoM have shown, data assimilation is an extremely labour- and computer-intensive process. Under the BLUElink program, the weather models will be initialised using BoM analyses. However, at present, the CSIRO initialises the RAMS model with output from its C-CAM model (see below), which is in turn initialised using global analyses from the United States National Center for Environmental Prediction (NCEP). The fidelity of forecasts produced by this process is reputedly on par with those produced by the BoM, even for severe storm systems. Hence, one consequence of global data-sharing arrangements may be that adequate forecasting capability may be achievable anywhere. This is a potential capability, not a realised one. As mentioned previously, the current generation of mesoscale models is known to have shortcomings and the field of mesoscale NWP is developing rapidly.

4.1.2 The C-CAM model - "Weather in a Box"

The Conformal Cubic Atmospheric Model (C-CAM) was developed by Dr John McGregor. Dr Jack Katzfey investigates the use of the model for regional and mesoscale weather prediction.

C-CAM is a hydrostatic model, which means that vertical acceleration processes are not explicitly allowed for within the mathematical framework, although vertical transport

[25] One of the limitations on the fidelity of NWP models is the lack of adequate data relating to soil and vegetation types, and soil moisture levels.

is included. This is a simplification that allows integration algorithms using relatively large time-steps to be employed, thus reducing computation times. Note that the hydrostatic assumption may lead to inaccuracies in regions of strong vertical velocity. The most striking innovation in the C-CAM model is suggested by its name, which relates to the unusual horizontal grid pattern used in the model.

The basis of the grid pattern is a cube encompassing the "spherical" earth. The surface of the cube is divided fairly evenly into squares and each square is then projected down towards the centre of the Earth. The 2-dimensional projection of the squares onto the sphere - the "conformal" cube - forms the horizontal grid pattern used for the atmospheric model. Each horizontal grid element on the surface of the globe is almost square, although somewhat smaller near the points corresponding to the vertices of the projected cube. This technique has the advantage that grid cells are more evenly sized than those produced by a conventional latitude-longitude grid, whose cells are very narrow near the poles. Note that the original pattern of squares is modified somewhat, to ensure that the final grid pattern on the sphere is isotropic and forms an exactly orthogonal set of coordinates. The "primitive equation" physical models are appropriately modified to use the new curvilinear coordinate system. A standard system of vertical levels is used for the vertical direction.

An innovation that makes the C-CAM model especially powerful is a modification to the conformal-cubic grid by means of the Schmidt transformation. This corresponds to modifying the original encompassing "cube" to a more general distorted form that functions like a truncated square-based "pyramid". Thus, the grid cells corresponding to the top face of the pyramid are shrunk, while those corresponding to the base are broadened. The effect is similar to a nested grid, but with a smooth gradation in cell size from the largest to the smallest. This has the benefit that spurious "reflections", which tend to occur at the boundaries between nested grids, are avoided.

The outcome of the entire process is a model that can produce an eight-day weather forecast with 60 km horizontal resolution over the Australian region on a laptop computer in 25 minutes. The resolution is equivalent to the output of the BoM's GASP model and the quality is claimed to be comparable. The model is currently initialised using freely available global analyses downloaded from NCEP on the Internet.

In addition, the C-CAM model can run at much smaller grid spacings. This capability was used to provide weather prediction support to the Swiss team in the 2002 America's Cup. The models were run on standard Linux-based desktop computers. During the races, predictions for the surface winds in a 50 km square around the racecourse were made at 1 km resolution and updated six-hourly. Each 1-day forecast required about 76 minutes to compute. The fidelity of the models is only anecdotal, but the team won the Cup, so it is unlikely that weather prediction problems detracted from their efforts.

The fidelity of the C-CAM model at mesoscale and smaller resolutions is a matter of research within the CSIRO. The RAMS model, which is much more resource-intensive, was chosen for the BLUElink program. The main difference between the models is that RAMS can explicitly allow for convection. Hence, there should be a difference in terms of the fidelity of the models for extreme weather prediction, particularly in tropical regions. Staff at the RAN Directorate of Oceanography and Meteorology have indicated[26] that

[26] LCDR Robert Woodham, private communication

they have reservations about the C-CAM model, given that it is less likely to be useful at high and low latitudes than at mid-latitudes, and also because the communications capacity necessary to download a model initialisation (approximately 25 MB of data) in a timely fashion is significantly beyond near-term capabilities.

Recommendation: *If C-CAM does indeed represent "weather in a box", then it is certainly a tool with application to REA. It is arbitrarily relocatable and scaleable. It has minimal (computational) resource requirements and it runs extremely quickly. Investigations are underway at the CSIRO to determine the fidelity of the model. At the minimum, DSTO should maintain a watch on the evolution and validation of the model. It may be worthwhile for the ADF to consider funding its validation as part of the BLUElink initiative.*

4.1.3 The future of the BLUElink program

As it stands, BLUElink consists of two different sets of programs, along with some databases. At the global and regional scales, a variant of the MOM-4 ocean circulation model is coupled to the GASP model. For the finer-resolution relocatable model, the CSIRO Marine Research MECO model is nested within the regional ocean model, and the RAMS model is nested within the GASP/LAPS models for the atmosphere. The RAMS model provides the atmospheric forcing to MECO. Neither the oceanic nor the atmospheric parts of the relocatable model have any assimilation capability. All assimilation is done at the regional scales. The effect of adding an assimilation capability remains unknown. CSIRO has expressed an interest in exploring the addition of such a capability.

On its own initiative, the CSIRO is moving towards both wave and current modelling in littoral waters. [There is no intrinsic reason other than computational cost and lack of bathymetric data why the BLUElink program cannot provide current and mixing predictions for littoral waters, since the models will scale arbitrarily. The models are already used for estuarine modelling in other research programs.]

Addition of wave modelling in littoral waters will represent an entirely new capability. The CSIRO intend to integrate the SWAN models[27] into their system. The perceived market for the product lies in groups interested in sand and pollution transport, beach erosion and the like. The ADF amphibious forces could also potentially benefit. The main limitations would be that a relocatable model would probably be required for military use, and that bathymetry and bottom type data would be very difficult to obtain from historical sources. Hence, the best place for such a capability would probably be within the amphibious forces, to take advantage of bathymetric measurements made during operations without overloading communications channels.

4.2 Aerosol dispersion modelling

Dr Bill Physick leads the Air Quality and Dispersion Modelling team. The team's activities are somewhat peripheral to REA, but they maintain a dialogue with the DSTO

[27] Staff within the DSTO "Sensors for REA" task have employed the SWAN model in a command decision aid being written for the amphibious forces.

via the CBRNDC, since dispersion of chemical and biological weapons is one of their research interests. The focus of their research is on estimating the manner in which gases and aerosols will disperse in the atmosphere after release, and the inverse problem of determining the source of a gas or aerosol once detected. Both of these are complicated problems. As with weather prediction, an atmospheric model is used to predict the motion of the air mass, but typically data collection facilities are far too sparse in the areas of interest to allow realistic predictions and validations.

5 Conclusions

The main conclusion of this report is that the emerging technologies for mesoscale, relocatable weather and ocean state prediction offer potential for REA, in terms of potentially providing high-resolution, accurate and timely predictions in remote areas. However, in order for this potential to be realised, assimilation of observations directly into mesoscale models must be understood. In turn, an understanding of mesoscale assimilation is necessary to define the requirement for atmospheric and oceanographic measurements and to maximise their impact. It is in the interest of the RAN to promote the investigation of mesoscale models and mesoscale assimilation, primarily in the centres of excellence at the Bureau of Meteorology and the CSIRO Division of Atmospheric Research.

Acknowledgments

This report represents the first exposure of the author to numerical weather and oceanic circulation modelling. It therefore represents a step in the self-education process and may contain errors and omissions.

I wish to thank Dr Bill Bourke, who hosted me on a visit to the BMRC and generally assisted with replies to my many queries both prior to and following the visit. Similarly, Dr Deborah Abbs hosted me during a visit to the CSIRO Division of Atmospheric Research, and assisted me following the visit.

Many people put considerable effort into commenting on a version of this manuscript, a process which was both useful and necessary in view of my inexperience. Comments and clarifications were made by, among others, Dr Bill Bourke, Dr Mike Manton, Dr Tom Keenan and Dr Neville Smith at the BMRC; Dr Deborah Abbs, Dr John McGregor and Dr Jack Katzfey at the CSIRO DAR; CMDR Andrew McCrindell and LCDR Robert Woodham at the RAN Directorate of Oceanography and Meteorology; and Dr Mark Readhead and Mr Les Hamilton at the DSTO.

References

Bech, J., Bebbington, D., Codina, B., Sairounic, A. & Lorente, J. (1998) Evaluation of atmospheric anomalous propagation conditions: an application for weather radars, *in*

EUROPTO Conference on Remote Sensing for Agriculture, Ecosystems, and Hydrology Barcelona, SPAIN. SPIE Volume 3499.

Bech, J., Codina, B. & Lorente, J. (2003) Forecasting weather radar propagation conditions using NWP mesoscale model data, *in The 2003 Annual EWGLAM/SRNWP Meeting, 6-9th October, IM, Lisbon*, The Network of European Meteorological Services.
*srnwp.cscs.ch/Annual_Meetings/2003/wednesday/newsletter/Bech.doc

Hibbard, W. (1998) VisAD: Connecting people to computations and people to people, *Computer Graphics* **32**(3), 10–12.

Hibbard, W. (2002) Building 3-d user interface components using a visualisation library, *Computer Graphics* **36**(1), 4–7.

Hibbard, W. (2004) *VisAD Home Page.*
*http://www.ssec.wisc.edu/~billh/visad.html

Kelly, J., Donaldson, A., Ryan, C., Bally, J., Wilson, J. & Potts, R. (2003) The Australian Bureau of Meteorology's next generation forecasting system, *in 20th International Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology*, American Meteorological Society, Seattle, U.S.A.

Kuo, Y. H. (2003) Mesoscale numerical weather prediction. Presentation to the Orville Symposium, Institute of Atmospheric Sciences, South Dakota School of Mines and Technology.
*http://www.ias.sdsmt.edu/Orville%20Symposium/Abstracts/Kuo_New.pdf

Maese, T., Owen, H., Melody, J., Katz, S., Freedman, A., Sabin, W., Young, G., Thomson, D. & Rogers, T. L. (2000) Preliminary results of at-sea testing with the Lockheed-Martin Tactical Environmental Processor, *in Battlespace atmospheric and cloud impacts on military operations conference 2000*, Cooperative Institute for Research in the Atmosphere.
*http://www.cira.colostate.edu/GeoSci/Bacimo2000/paper/paper/maese.pdf

NATO (2001) *Rapid environmental assessment warfare support*, NATO Doctrine EXTAC 777, HQ SACLANT.

NOAA (2000) *NOAA KLM User's Guide*, Technical report, National Oceanic and Atmospheric Administration, U.S. Department of Commerce.
*http://www2.ncdc.noaa.gov/docs/klm/index.htm

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DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION DOCUMENT CONTROL DATA	1. CAVEAT/PRIVACY MARKING

2. TITLE	3. SECURITY CLASSIFICATION
Application of Numerical Weather Prediction to Rapid Environmental Assessment	Document (U) Title (U) Abstract (U)
4. AUTHORS	5. CORPORATE AUTHOR
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6a. DSTO NUMBER	6b. AR NUMBER	6c. TYPE OF REPORT	7. DOCUMENT DATE
DSTO–GD–0403	AR-013-082	General Document	April, 2004

8. FILE NUMBER	9. TASK NUMBER	10. SPONSOR	11. No OF PAGES	12. No OF REFS
490-6-221	NAV 03/169	DGMD	23	10

13. URL OF ELECTRONIC VERSION	14. RELEASE AUTHORITY
http://www.dsto.defence.gov.au/corporate/reports/DSTO–GD–0403.pdf	Chief, Maritime Operations Division

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

Approved For Public Release

OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE, PO BOX 1500, EDINBURGH, SOUTH AUSTRALIA 5111

16. DELIBERATE ANNOUNCEMENT

No Limitations

17. CITATION IN OTHER DOCUMENTS

No Limitations

18. DEFTEST DESCRIPTORS

Rapid environmental assessment; Weather forecasting; Atmospheric models; Meteorology; Ocean circulation models; Wave forecasting

19. ABSTRACT

This report summarises numerical weather prediction capability available in Australia, its likely near-term development and its application to Rapid Environmental Assessment. Research at the Commonwealth Bureau of Meteorology and the Commonwealth Scientific and Industrial Research Organisation into meteorological and to some extent, oceanic forecasting, is examined.

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