National Land & Water Resources Audit
An Initiative of the Natural Heritage Trust

MODELLING WIND EROSION AT NATIONAL & REGIONAL SCALE USING THE CEMSYS MODEL

National Monitoring and Evaluation Framework

H. J. Butler, Y. Shao, J.F. Leys, and G. H. McTainsh

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Postal address:	GPO Box 2182 Canberra ACT 2601
Office Location:	86 Northbourne Ave Braddon ACT 2612
Telephone:	02 6263 6035
Facsimile:	02 6257 9518
Email:	info@nlwra.gov.au
Internet:	http://www.nlwra.gov.au

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[1]Australian Centre for Sustainable Catchments, University of Southern Queensland, Toowoomba

[2]Institute for Geophysics and Meteorology, University of Cologne, Germany

[3]Department of Environment and Climate Change, Gunnedah, New South Wales

[4]Australian Rivers Institute, Griffith School of Environment, Griffith University, Brisbane, Queensland

butler@usq.edu.au

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1. Introduction

In 2005 the National Land & Water Resources Audit (NLWRA), through the National Committee for Soil and Terrain (NCST), convened four expert panels to advice on the monitoring of soil acidification, soil carbon changes, water erosion and wind erosion (McKenzie & Dixon 2006). Later, NLWRA commissioned a series of trials of the recommended approaches for monitoring wind erosion at a local, regional, and national scale.

Five trials of these complementary approaches for estimating Wind Erosion Soil Condition (WESC) were commissioned in mid-2006: i) The Wind Erosion Assessment Model (WEAM) for field-based wind erosion risk assessment; ii) Roadside surveys of vegetation cover and soil condition for wind erosion risk assessment; (iii) DustWatch Node for field-based dust concentration assessment (Sub-project 6); iv) Dust Storm Index (DSI) for monitoring wind erosion at a national scale, and v) Computational Environmental Management System (CEMSYS) for monitoring wind erosion at national scale.

Each of the approaches described above complement each other by addressing different spatial scales and using independent data to cross-check results. Two of the approaches are modelling based: WEAM which is a point based assessment model which will be used by a range of Natural Resource Management (NRM) staff and CEMSYS which is a spatial/temporal model that can be used to model wind erosion over large areas (catchments to continents) and long times periods (years) depending on data availability.

The strength of the modelling approach is that WEAM and CEMSYS use a similar wind erosion model, thus making the results comparable. The other approaches (DSI provides national and long time scale information, Road surveys for point/regional erosion risk and land management information) together with Dustwatch (i.e. community observations) and dust concentration measurements at known sites, provide measurements which can be used to i) validate the modelling and ii) interpret the results in terms of field conditions and management practices at the time.

This document examines the application of the CEMSYS wind erosion and dust transport model as a means of monitoring the impact of wind erosion at national and regional scale. In its current form CEMSYS takes into consideration the atmospheric conditions (wind speed, rainfall etc.) and land surface (soil type, vegetation cover etc.) and estimates wind erosion quantities such as sand flux and dust flux. Other wind erosion related quantities, such as deposition rates, net erosion (sand + dust flux – deposition) threshold friction velocity, and friction velocity are calculated. These quantities can be averaged on an hourly, daily, monthly, or yearly basis.

This trial of the CEMSYS model looks at its application to the Australian mainland and area of NSW bounded by 139 to 146 ^{o} E and 31 to 37 ^{o} S. The following topics are covered:

- description of CEMSYS
- application of CEMSYS on an event, monthly and yearly basis
- description of the modelling products that can be used by end user products for reporting proposes
- limitations of the CEMSYS model
- linkages of the CEMSYS output to other approaches outlined above.

1.1 Definition

Soil loss by wind erosion for a site (e.g. polygon or pixel) is expressed as a sand flux rate (g/m/s) and dust flux ($g/m^2/s$). As the dust is transported from the emission site, it changes the dust concentration of the air column, for example a dust storm. Fluxes are generally time averaged and are presented in this way in this report.

Sand flux represents the mass of material that blows off a site as saltation, e.g. sediment that is not suspended in the air and only leaves the site when it passes through a fence or paddock boundary. Dust flux occurs vertically for a unit area and as such is lost over the entire area that is eroding, e.g. every square metre that is eroding is losing dust even if it is not losing sand. Dust concentration is the mass of sediment in a volume of air, e.g. $\mu g/m^3$ and can be correlated against visibility.

1.2 Rationale

Wind erosion is a key environmental indicator for land/soil condition. Land degradation is closely lined to soil loss and associated biodiversity decline. Changes in erosion can be linked to changes in land management; both negative and positive. Therefore, by monitoring erosion levels the impact of land management and the associated benefits of better land management (lower soil loss, reduced biodiversity loss, better air quality, and reduced repair costs to infrastructure) can be quantified.

At national and regional scales, erosion levels vary both spatially and temporally. Due to the sporadic nature of erosion, it is necessary to evaluate it on several different spatial and temporal scales. For example, it is necessary to understand the direct (or event scale) impacts of large scale dust events, such as October 2002, but it is also important to understand the wind erosion landscape before and after this event.

Soil that is eroding is subject to degradation as a result of the erosion processes. Currently, Regional Catchment Management Authorities are investing in improving land management activities with the aim of reducing soil erosion. Evaluating the effectiveness of management changes is a high priority. By using a modelling framework, it is possible to show the magnitude of erosion reduction due to improved management systems.

The methodology has the capacity to contribute to:

- Australia's National Research Priority goal of overcoming soil degradation
- Fill knowledge gaps identified in 2006 State of the Environment (SoE) report about the condition of soil
- Provide improved methods for assessing soil condition that can be used to obtain trend data
- Provide more accurate data on the effects of climate and land management on wind erosion which is compatible with national and state-based SoE reporting protocols
- Create better feedback to regional bodies through improved reporting on progress towards regional targets thus enabling them to provide incentives for better land management.

The NCST expert panel on wind erosion concluded that the assessment of soil condition would require a wind erosion indictor. The panel recommended five methods of assessment dependent on the scale and the audience.

1. WEAM is for regional NRM bodies and those interested at the local/farm scale.

2. The roadside surveys for regional scales observations that provide valuable ground-truthing and trend data to show causal links between management and erosion level.

3. DustWatch to involve the community and provide educational and scientific outcomes, e.g. dust concentration records for comparison with modelling and remote sensing products.

4. Dust Storm Index (DSI) is a state to federal scale index and is the current national indicator.

5. The Computational Environmental Management System (CEMSYS) which can be used to model wind erosion at scales from paddock to the nation, depending on data availability. It is currently used at regional and state scale and has potential for national scale. It can produce outputs that measure soil loss and dust concentration, thus linking it to the other indicators.

Field measurement and monitoring of wind erosion is a major challenge for experimentalists and land managers. Such field measurement is costly and often problematic in providing the spatial and temporal details required to make decisions informed decisions at a national and state scale. In particular, few field data on wind erosion are available for remote regions of central and Western Australia. Physical models of the wind erosion and dust transport process provides one means of filling in this missing data, while increasing our understanding of the role wind erosion and dust plays in the Australian climate. In addition, such models allows end users to analyse aspects of the erosion process which are not readily accessible by field measurements, such as the amount of material being transported off shore as a result of large scale wind erosion events.

However, the model performance depends on the quality of the input data used in e calculations. Thus, there is a need to link modelled inputs and outputs, with other field approaches to validate the modelling results. Consequently, models such CEMSYS form only part of an integrated approach to monitoring wind erosion at a national or regional scale.

2. Monitoring methodology

This section outlines the CEMSYS model, the equipment needed and the resources required to run the model. It is in effect the methodology used to establish a monitoring program that utilizes a sophisticated relational numerical model.

2.1 Sampling location and scale

Models such as CEMSYS can be used at any location and scale depending on the scale of the input data as indicated by Shao *et al* (1996) and Lu & Shao (1999). CEMSYS as applied in Australia uses data collected and generated at various scales. Climate files are generated at 50 km grid then recomputed at 25 km grid. Soil and vegetation data has a resolution of 5 km grid. The model could be applied at finer scales but requires more detailed input data (both atmospheric and land surface data) which is currently not available at a national or regional scale.

2.2 Sampling frequency

Wind erosion is a highly sporadic process; as such process modelling is generally run using short time steps (minutes) and the results averaged over different time periods (i.e. hourly, 6 hourly, daily, monthly averages). The modelling is also constrained by the accuracy (numerical drift) of the meteorological sub-model which is used to generate rainfall and the wind field. Other land surface data like vegetation type and soil type are considered static but vegetation cover as inferred from NDVI data is updated monthly.

2.3 Data measurement

The modelling framework used to generate the soil loss data is CEMSYS. CEMSYS has been under development since the early 1990s (Shao, Raupach & Leys 1996; Shao & Leslie 1997; Shao 2003). As Figure 1 shows, CEMSYS comprises an atmospheric model, a land surface model, a wind erosion model, a transport and deposition model, and a land surface database. The atmospheric model has treatments for atmospheric dynamic and physic processes, including radiation, clouds, convection, turbulent diffusion, and the atmospheric boundary layer (Leslie & Wightwick 1995).

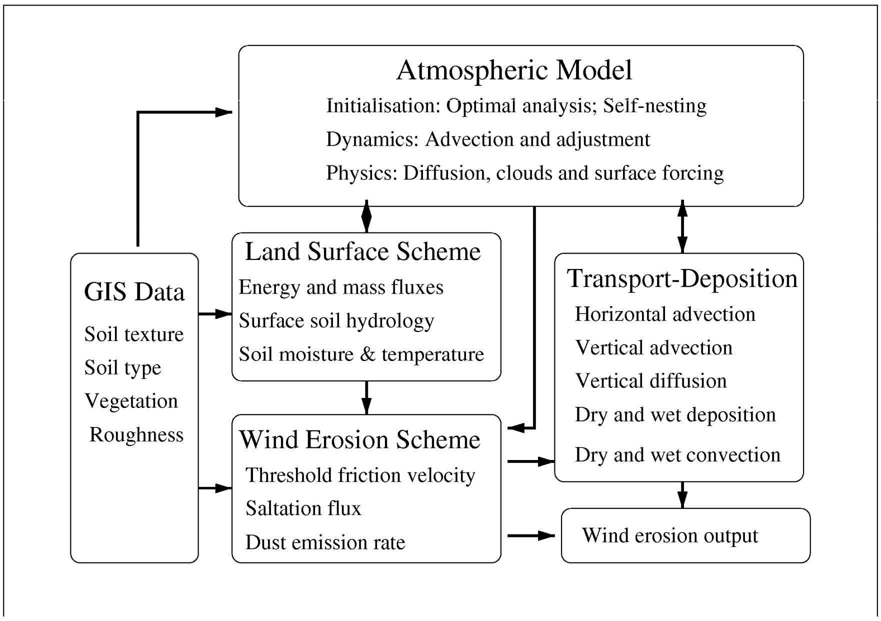


Figure 1. The framework for the CEMSYS model

The land-surface model simulates energy, momentum, and mass exchanges between the atmosphere, soil, and vegetation. The land surface model used in this study is based on the Atmosphere and Land Surface Interaction Scheme (Irannejad & Shao 1998). For wind erosion modelling, CEMSYS produces friction velocity and soil moisture as outputs.

The wind erosion model obtains friction velocity and soil moisture from land-surface model and other spatial parameters from the GIS database, and predicts sand and dust fluxes. To predict dust motion, the transport and deposition model obtains wind fields, turbulent diffusivities and precipitation from the atmospheric model, and dust flux and particle size information from the wind erosion model. The atmospheric model is run first, followed by the land surface model and the wind erosion model. Finally, calculations of dust transport and deposition are done. These sub-models are described below.

2.4 Data collation

CEMSYS has separate models that utilise different data sources to calculate the atmospheric, land surface and wind erosion values. These are described below.

2.4.1. The atmospheric model

The simulation is completed in two stages. In the first stage, CEMSYS is run over the Australian region at 50 km horizontal resolution and 25 levels in vertical. To resolve the atmospheric boundary layer, there are 10 levels from 850 hPa to the surface, with the lowest level at a few metres. The atmospheric model derived its initial and boundary conditions for this period from the NCEP analysis (National Centre for Environmental Prediction, USA).

At the second stage, the integrated system (including the atmospheric model) is run at a finer 10 km horizontal resolution. At this stage, the atmospheric model is self-nested: the atmospheric model derived its initial and boundary conditions from the first stage model predictions. Figure 2 illustrates this procedure. In Figure 2a, the flow field based on the NCEP analysis is shown for the Australian region while in Figure 2b, the flow field based on the first stage simulation is shown.

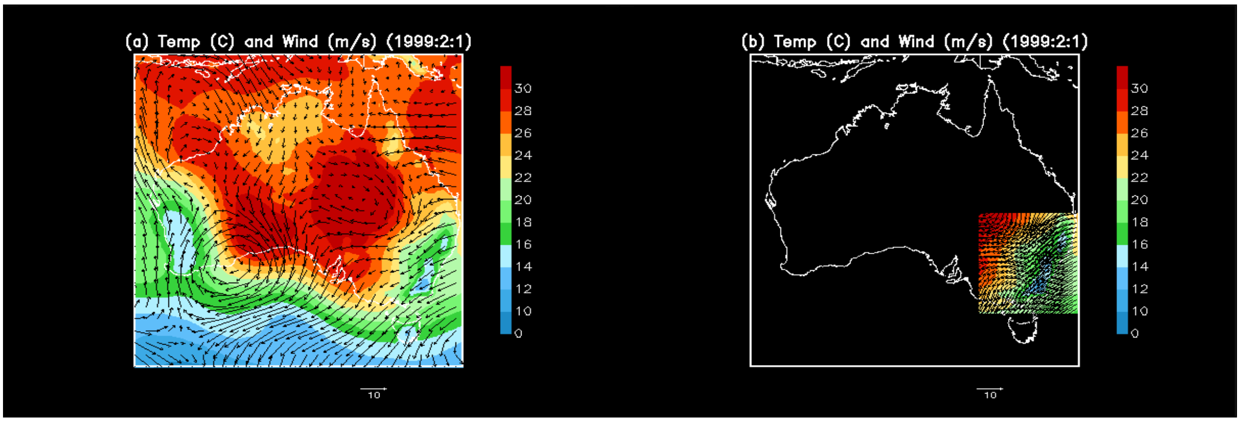


Figure 2. The nesting procedure of the atmospheric model. a) the simulation was first done over the Australian region with a resolution of 50 km, using the NCEP analysis for providing the initial and boundary conditions for the atmospheric field; b) the simulation was then done for the SE Australian region with a resolution of 10 km, using the first stage output for providing initial and boundary conditions

2.4.2 Land surface model

The wind erosion threshold friction velocity (u_{*t}) is related to soil moisture. The evolution of soil moisture depends on surface hydrological processes and the interactions between the atmosphere and the land surface, as such interactions determine the evaporation and to certain degree precipitation. In this study, soil moisture is simulated within the model.

The land surface model can incorporate as many soil layers as required to provide a better vertical resolution of soil moisture and better treatment of heterogeneity (in the vertical) of soil hydraulic properties. This flexibility in choosing the number of soil layers also facilitates a better simulation of soil moisture close to the surface, which is important to the estimation of threshold friction velocity. In the model, the land surface is divided into areas of bare soil and vegetation. The energy transfer processes over bare soil surfaces and canopies are described using aerodynamic resistance laws (Irannejad & Shao 1998).

2.4.3 Wind erosion model

Wind erosion is a function of the wind forces and the surface resistance. The wind force is represented by the friction velocity u_* and is calculated form the land surface data and the atmospheric data. The surface resistance is represented by the threshold friction velocity (u_{*t}) and is dependent on the particle-size of the soil surface, atmospheric conditions, and surface conditions such as vegetation cover and soil type, as described by Shao & Lu (2000). Information on the particle-size distribution used in these tests has been supplied by Dr G. McTainsh (Griffith University) and Dr J. Leys (NSW Department of Environment and Climate Change). While these data are sufficient for trial purposes they are still insufficient to adequately cover the Australian continent. Consequently, if this strategy is adopted addition work needs to be undertaken to improve this soil particle-size dataset.

The soil and vegetation types are derived from the geographic data based on the *Atlas of Australian Resources, Volumes 3 and 6* (1980, 1990). The spatial resolution of the data is 5 x 5 km. Australian soils are classified into 28 soil-map classes, with 21% being shallow permeable sandy soil, 17% deep massive earths, 11.2% cracking clay soils with low permeability when wet, and 11% shallow loam soil. Other relatively important soils are sandy soil 8.4%, duplex soils 13.1%, and calcareous earth, 5.4%; the rest of the soil types occupy 13.8%. For each soil class, there is a qualitative description of the soil properties and associated land-forms. Based on this information, the 28 soil-map classes are regrouped into the 12 United States Department of Agriculture (USDA) soil-texture classes ranging from sand to clay. Appendix 1 summarises the soil-map classes and corresponding soil-texture classes. For soil moisture simulation, each soil is assigned a set of hydrological parameters. These parameters are also listed in Appendix 1.

For the study region, the soil-map classes are as shown in Figure 3a. Some soils are known to be non-erodible (e.g. areas covered largely by bare rocks) and are excluded from the calculations of wind erosion. The erodibilities of the other soils are determined by the threshold friction velocity, which is calculated in CEMSYS.

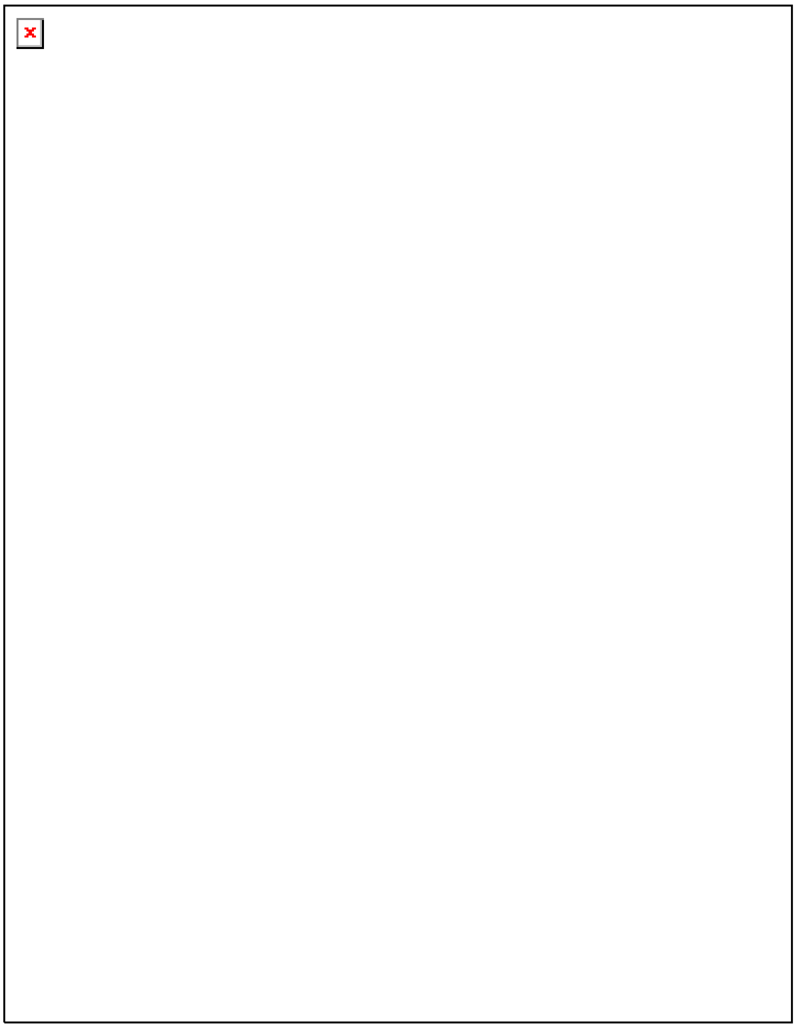


Figure 3. The soil (a) and vegetation (b) map classes for the SE Australian region

The vegetation type data provide a range of parameters such as vegetation height, minimum vegetation stomatal resistance, vegetation albedo, etc. The source of vegetation data is the *Atlas of Australian Resources*, Vol. 6 (1990). In this dataset, vegetation was divided into 35 classes according to height, density and number of canopy layers. Among the 35 vegetation types, the most extensive vegetation cover is tall shrub lands in its sparse open form (31.5%).

Low woodlands and low open woodlands occupy nearly 27%, while other medium and short vegetation covers collectively about 22% of the continent. From the vegetation database, estimates can be made for quantities such as height, fraction vegetation cover, albedo and minimum stomatal resistance. The vegetation types for the SE Australian region are shown in Figure 3b. Some areas covered by certain vegetation types are known to be non-erodible and are excluded from calculation.

The calculation of u_{*_t} requires the frontal area index of roughness elements and the soil moisture as inputs. The former is slowly varying with time and hence can be assumed to be constant for individual dust events. If modelling for periods greater than one month, then the frontal area index is updated each month. Soil moisture experiences both diurnal and seasonal variations, responding to radiation, precipitation and other atmospheric and surface hydrological factors. In this study, u_{*t} is derived from a combination of satellite NDVI (Normalised Differential Vegetation Index) data and GIS (Geographic Information System) data for vegetation types. For each vegetation type an empirical relationship between frontal index and NDVI should be established. Newer relationships are used as they become available.

Jenny Lovell and Peter Briggs of CSIRO Earth Observation Centre and Vanessa Chewings of CSE Alice Springs supplied the NDVI data used in this study. The data are in ArcView float file format and geographic lat/lon at 0.05 degree. The NDVI data are then converted to LAI data by using an empirical relationship. The LAI maps for Australia for July 2003 to July 2004 are shown in Appendix 2. In the winter months, July–October 2003, the vegetation cover in Australia was generally good. From November 2003, vegetation cover was deteriorating and was worst in May 2004. In June 2004, vegetation cover was significantly better. This seasonal variation of vegetation cover greatly influences the evolution of the wind erosion pattern, as discussed later.

2.5 Data storage and management

CEMSYS is a complex physical model that requires substantial equipment and data resources. These are outlined below. The raw and analysed CEMSYS data is being archived at the University of Southern Queensland. These archives are updated after each complete run of the model. Currently this data is only used for research purposes, and is available to provide CEMSYS products. The CEMSYS products are currently only used internally, and by DECC and GU researchers. These CEMSYS outputs can be made available on request for use by external clients provided the model has been run for the period requested and the collaborating funding groups agree to the release of the data.

2.5.1 Computing resources

CEMSYS has been successfully run on 32 bit Sun, Linux and Digital Alpha high performance computer systems. At present the model is being run on a four processor Linux high performance computers located at the University of Southern Queensland, Toowoomba.

Depending on the architecture used the GIS and meteorological data have to be converted to compatible binary formats. These databases, along with the model outputs are archived for future use and to enable comparison with future versions of the model. Each month of output takes approximately 10 Gb of storage[1]. Consequently, yearly data requires approximately 120 Gb of storage - considerable data storage and management. Currently, model outputs are calculated on a monthly basis and after analysis the raw and analysed data are archived on magnetic tapes. A secondary copy of some of the modelling data and outputs are stored on an external hard drive. All data are currently managed and archived by Dr H. Butler at the University of Southern Queensland.

2.5.2 Human Resources

Each run requires that the GIS databases and NDVI be converted to formats that are compatible with the model. This process takes approximately a day and requires expert knowledge of the model. It takes approximately 30 hours of computer time to run the model. The final analysis of the output takes approximately 10-15 days depending on the complexity and the validation required. Currently resources and funding only allow one full time day per week to be dedicated to this analysis.

2.6 Data analysis and interpretation

CEMSYS is a complex wind erosion modelling system which has been developed over the last two decades. GRADS and ARCinfo have been used to undertake the spatial and temporal analysis of the raw data produced depending on research requirements. The data analysis undertaken in these packages is often rather specialised and vary according to the products required. For this reason the analysis should only be undertaken by a group with expert knowledge of CEMSYS and the analysis tools.

The inputs and outputs of the CEMSYS need to be integrated with the other indicators and independent measures to ensure both the accuracy of the input data and outputs. Once these links are in place to validate aspects of the modelling, it will be possible to use CEMSYS to add valuable process and temporal information to these other indicators.

The major significance of CEMSYS outputs are that they provide estimates of both net soil loss, dust concentration, soil loss, through space and time. By comparing the spatial evolution of these variables through time, it is possible to track how these variables vary spatial and temporally during a given period. For example, Figure 17 shows the variation in emission for November 2002. These maps show that there are significant spatial variations in both the strength of the emissions during November, and that most state and territories are affected by wind erosion.

Once the input data have been calculated with CEMSYS, it is necessary to process it to: 1) create the spatial products; 2) analyse the output in terms of frequency distributions; and 3) interpret the outputs.

CEMSYS outputs the calculations as binary grid data in the GRADS format. To spatially represent this data, it is normally loaded into a GRADS application. GRADS scripts are then run on the data to produce spatial and time series data products outlined below (the default output file format for these plots is PNG). Using GRADS software to fully analyse the spatial and

[1] This assumes that only 6 hourly averages are stored for further analysis. The actual storage space depends on the averaging period; the shorter the time, the larger the files.

temporal data is a highly specialised procedure.

Alternatively for DECC and Griffith University, an output filter is run over the binary output file from CEMSYS to produce monthly averages in an ASCII raster file with the following format:

ncols - number of columns in the dataset
nrows - number of rows in the dataset
xllcenter or xllcorner - x-coordinate of the centre or lower-left corner of the lower-left cell
yllcenter or yllcorner - y-coordinate of the centre or lower-left corner of the lower-left cell
cellsize - cell size for the dataset
nodata_value - value in the file assigned to cells whose value is unknown. This keyword and value is optional. The nodata_value defaults to -9999.

To spatially represent these data,they are imported into a GIS (e.g. ArcGIS 9) using the raster import tool. Then the following steps are undertaken:

- Classify the data into classes for display (generally spaced to emphasise the lower classes (e.g. for sand flux 0-100, 101-200, 201-300, 301-500, 500-1000, 1001-2000, 2001-3000, 3001-5000, 5001-10000)
- Change colour ramp of classification
- Add other relevant spatial layers (boundaries, towns, landscape features) to aid interpretation
- If reporting on smaller areas than the modelled area, then further manipulation is required
- Clip the raster data to the analysis extent layer (e.g. clip a state from the national data set.)

This completes the data display. Next the analysis of the frequency distribution of the data classes is required. This is generally a two step process of clipping the raster data to the reporting area of interest.

- In Arc, turn on the spatial analysis tool and select layer to analyse
- Use the raster calculator to generate the new grid and histogram of classes.

Interpretation of the data will depend on the target audience needs. Some critical values are:

- >1000 mg/m/s sand flux per month is indicative of erosion above desirable levels
- >300 µg/m^3 dust concentration is above the background level and an equivalent visibility of about 10 km (depending on particle size and colour)
- >2 µg/m^2/s for a daily period of dust emission (or 1.7 kg/ha/day)
- >2 µg/m^2/s for a daily period of dust deposition.

These values are suggested critical values only and depend on the average period used. Consequently, these values will need further refinement as addition data becomes available.

2.7 Quality assurance

CEMSYS reliability depends on the computer architecture, data storage and operator. For this reason, generally only a group with sufficient resources and knowledge can utilise CEMSYS. Knowledge includes both wind erosion process and numerical modelling expertise.

The spatial resolution for wind erosion modelling is limited by the resolution of the GIS data and that of the atmospheric model. If the former has a coarser resolution than the latter, little can be done unless more land surface data can be created using downscaling procedures. Otherwise, additional manipulations of the GIS data are required. The important quantities for wind erosion modelling, are u_* and u_{*t}, and they usually show subgrid variations. It may happen that u_* exceeds u_{*t} in some parts of the grid while the average of u_* over the grid remains smaller than u_{*t} and vice versa.

The subgrid variations of u_* and u_{*t} are therefore of importance and deserve careful consideration. If the horizontal grid spacing of the atmospheric model is too coarse to resolve the features of the land surface, the problem can be reduced through self-nesting. The nesting procedure is often too expensive computationally and there are limitations on the size of the grid spacing allowed for a specific atmospheric model. To avoid this complication, the mosaic approach for subgrid closure is taken in this study. In this approach, each atmospheric grid cell is divided into subcells according to the soil type and the frontal area index. Areas with the same soil type and similar frontal area index are lumped together regardless of their location within the atmospheric grid cell. In so doing, each cell is divided into a number of subcells, each occupying a fraction of the grid. For each subgrid, a different u*t is calculated.

The validity of CEMSYS for predicting wind erosion at the continental scale has been demonstrated in Shao *et al.* (2003) and Shao *et al.* (2007). The underlying wind erosion scheme has also been tested at paddock (Shao, Raupach & Leys 1996) and continental scale (Shao & Leslie 1997). Therefore the validity and accuracy of the model have been demonstrated.

Ongoing quality assurance can be achieved by cross-checking model outputs against other monitoring products and indicators e.g. dust concentration from DustWatch, dust activity from DSI and DustWatch, erosion intensity and ground cover from the roadside surveys. Thus CEMSYS forms part of an integrated monitoring system for wind erosion.

2.8 Metadata

See data product description, and Appendix 1.

3. Reporting

The output of the CEMSYS can be manipulated in a number of ways to meet various client/end user needs. The most common of these maps will be 1) spatial and temporal maps of various wind erosion properties; and 2) temporal plots (*Time series*) of specific wind erosion properties.

3.1 Audiences

CEMSYS products have a wide range of uses by national and state policy makers, regional NRM managers, and the general public. This is because wind erosion, when expressed as soil loss, is easily understood by most users. This modelling approach offers the greatest opportunity to report wind erosion across a range of spatial and temporal scales.

Currently the primary audience has been regional and state NRM managers because of their needs to report wind erosion activity for SoE reports and Catchment Action Plans. A potential audience would be the federal agencies responsible for SoE if modelling was done nationally. Secondary audiences would include landholders and the wider community.

3.2 Products

The following products are presented in digital and hard copy forms to the relevant funding group for use in their reporting.

3.2.1. Wind erosion maps and statistics

Several wind erosion properties can be spatially and temporally mapped from the CEMSYS output. Similarly the input parameters of soil cover, soil moisture etc. can also be mapped. Wind erosion properties that will be of interest to most client groups, such as regional NRM agencies and land managers will be: sand flux, dust flux (emission), deposition, net soil loss, dust load and dust concentration maps. Examples of sand flux maps at two scales are given below (Figure 4 & Figure ***6***).

These maps can report average values of these variables over different spatial and temporal scales. For example, it is possible to produce maps of dust emissions that average emissions on an hourly, 6 hourly, daily, monthly, seasonal, and yearly basis. The smallest time scale of these maps depends on the temporal resolution of the original model runs. Consequently, if a finer temporal resolution were required the model would need to be rerun at that resolution. This would also impact on the storage space required, as the finer the temporal resolution the greater the storage space required to model the same period. This balance between temporal resolution and storage requirements means that the model should be run at a temporal resolution suitable to most client needs on a regular basis. If finer resolution is required, it should only be undertaken as a special project.

CEMSYS produces maps at both national and regional scale output. However, given that the minimum resolution of CEMSYS is determined by the relationship between the atmospheric and the GIS data as mentioned previously, it is not possible without improvements in this spatial data to map areas in terms of areas less than 50,000 km^2) specific catchments, as the detail in data inputs is not sufficient to distinguish differences in these regions.

Once the maps have been created, then histograms of the raster data can also be calculated (Figure 5 & 7). Examples of these are presented for the two maps in Figure 4 & 6.

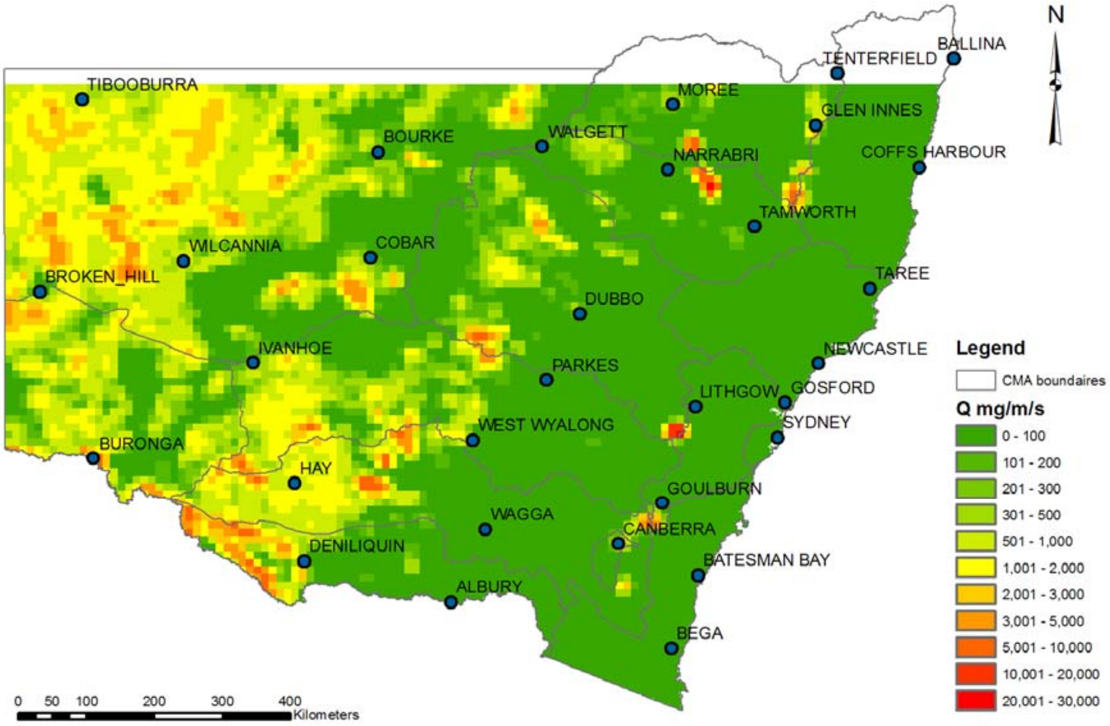


Figure 4. CEMSYS calculations of sand flux for June 2004

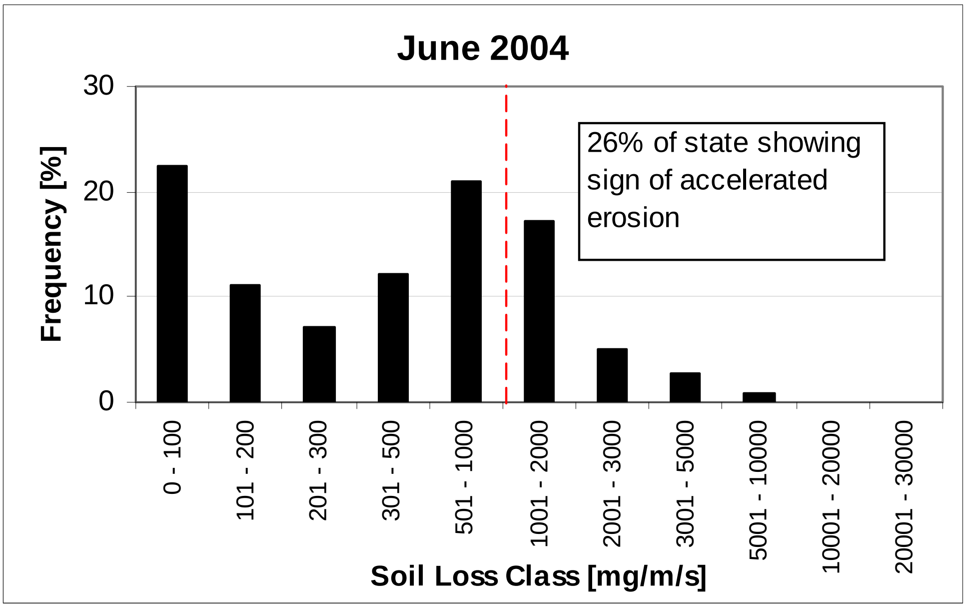


Figure 5. Histogram of erosion classes for June 2004 for Figure 4

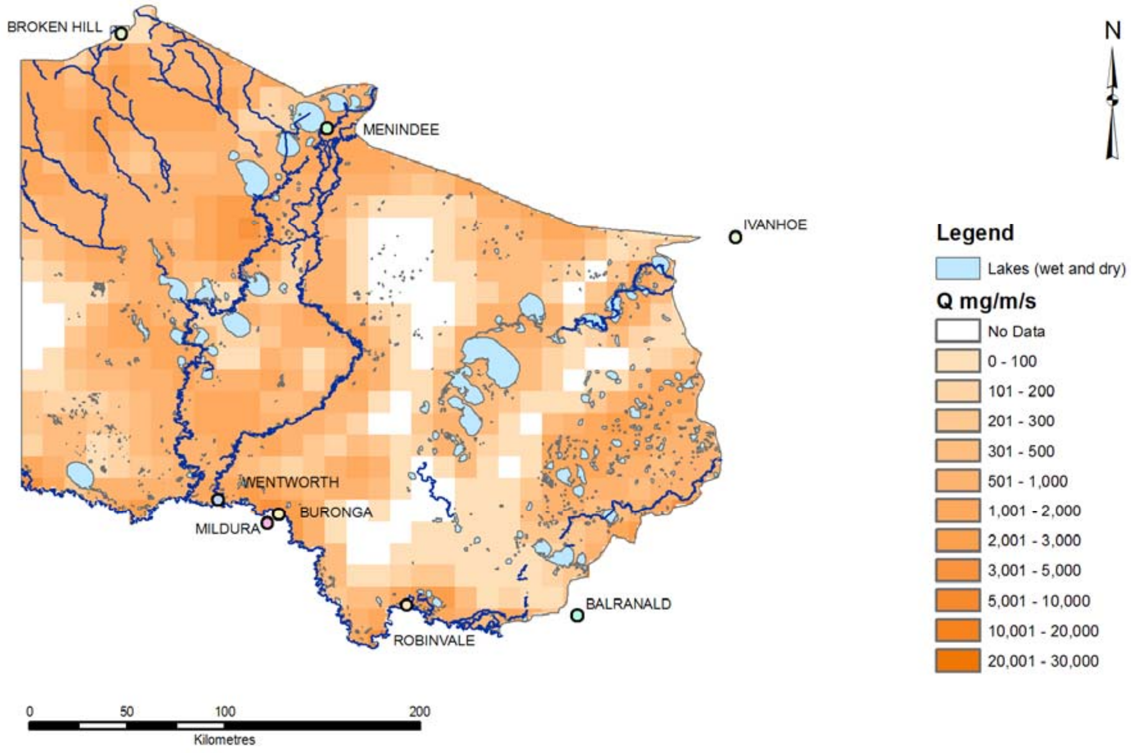


Figure 6. Lower Murray Darling CMA average monthly sand flux (Q)

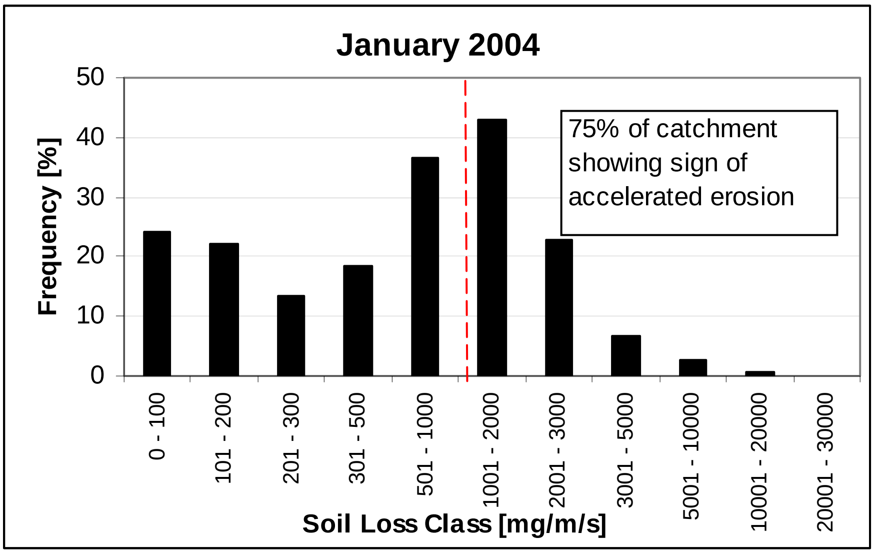


Figure 7. Lower Murray Darling CMA statistics for each soil loss class

3.2.2. Time series data

In addition to spatial and temporal maps of wind erosion properties the CEMSYS can be used to produce estimated time series for certain key wind erosion parameters Time series can be produced for each wind erosion variable at single location or averaged bulk values through time at the continental/state scale. An example of the sand flux time series data for three locations is shown in Figure 8. No significant sand flux (>1000 mg m^{-3}) is predicted for Ivanhoe, although the trend is similar to Euston. Significant sand flux is predicted by the model at Buronga and Euston, increased wind erosion in summer is predicted. At Buronga, a secondary peak appears in September associated with high velocity spring winds.

At present these time series are produced only as required for various research projects, as these plots are normally used to validate the modelling. However, it is possible to produce these temporal plots for a given location upon client requests and subject to funding.

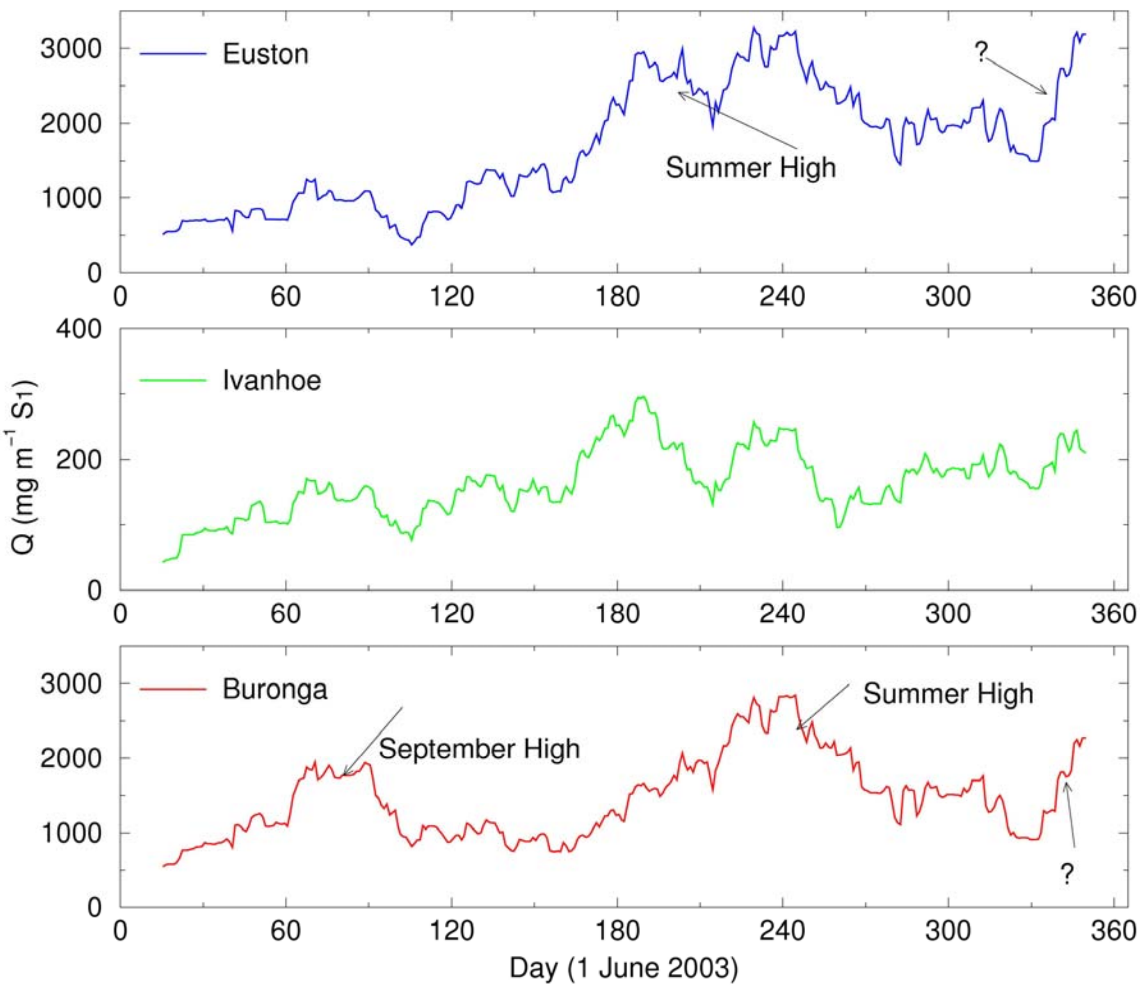


Figure 8. Smoothed sand flux intensity for Buronga, Ivanhoe and Euston

3.2.3. Trial application of the model

In this section, examples are given of using the model to examine wind erosion on an event, monthly and yearly basis. The periods chosen (22–23 October 2002 event, November 2002 and July 2003–June 2004) are based on the availability of external data, which enable the performance of the model to be easily illustrated in these scenarios. Note that the October 2002 event is covered in much more detail than other periods, as this event provided a exceptionally good base to show case the performance and the usefulness of CEMSYS.

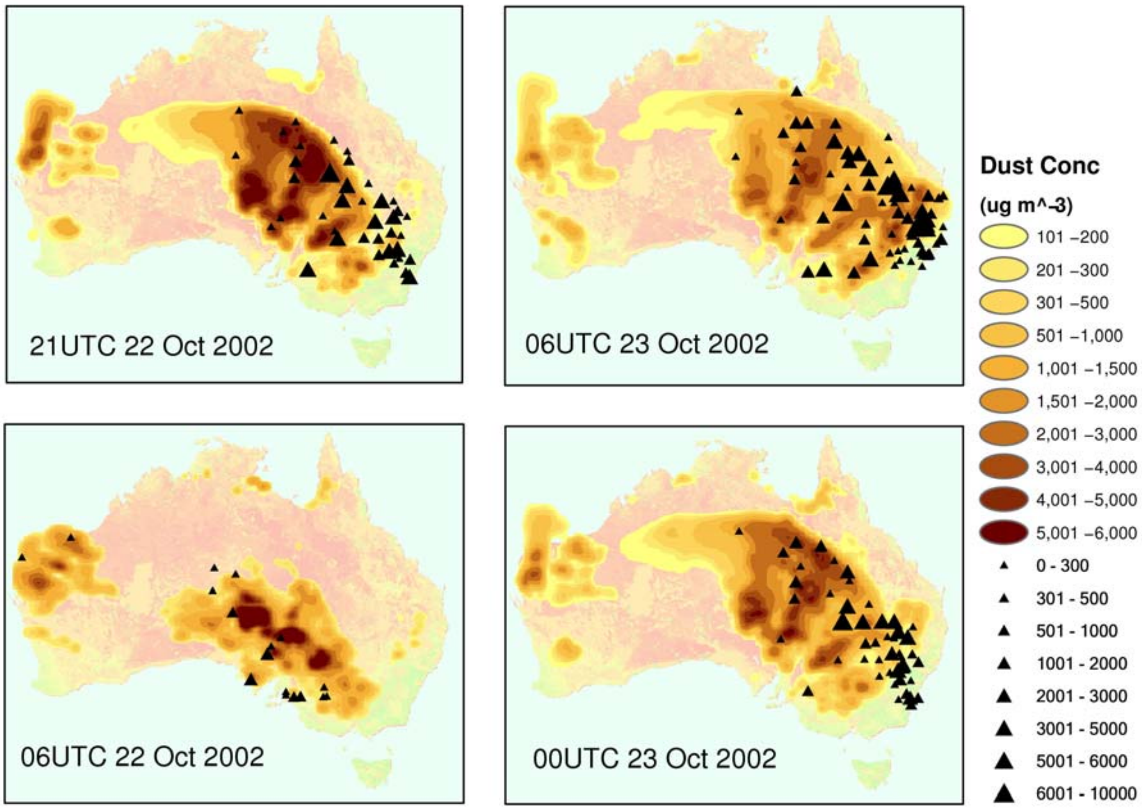


Figure 9. Comparison of simulated and visibility-derived near-surface dust concentration (triangles represent the visibility-derived dust concentration at the locations where dust weather was observed)

Some discrepancies exist between the modelled and observed dust patterns for this event (Figure 9). For example, according to the model, dust concentration was highest at 21UTC 22 Oct 2002, and dust was widespread. However, dust weather was reported only for a small number of stations. A possible explanation for this discrepancy is that at that time, the dust-affected areas were mostly desert where few weather stations exist. Further, at 21UTC (06EST) observations were not made at some weather stations. Judging from the development of the dust event, the predicted dust pattern is very reasonable.

The model failed to predict the observed high dust concentration near Sydney on 23 Oct 2002. It is almost certain that dust observed there was transported from the agricultural areas in inland NSW and Victoria. This problem is most likely caused by the inaccuracies of the vegetation and land management data used to model agricultural areas in the southern part of Australia.

The October dust storm was observed by both the GMS and the SeaWIFS satellite. From the SeaWIFS image for 00UTC 23 Oct (McTainsh *et al.* 2005), a dust front can be seen with its maximum extent of about 2 400 km long and up to 400 km across. The dust ceiling was about 1.5 to 2.5 km high. A comparison of the GMS image with the predicted dust concentration patterns on 900, 850 and 700 hPa (approximately 1000, 1500 and 3000 m above ground) is shown in Figure 10. The predicted dust pattern has good agreement with the satellite image. High dust concentration occurred over Qld and north-east NSW.

The vertical structure of the dust clouds was rather complex. Near the surface, dust was wide spread. Dust concentration decreased rapidly with height. At 700 hPa level, only a narrow dust band along the east coast of Australia can be seen. Unfortunately, the near-surface dust distribution cannot be unambiguously identified from the satellite image, as both the temperature and the colour of the near-surface dust were probably close to those of the ground surface. The predicted dust field suggests that the dust front stretched from the east coast of Australia, over NT and well into WA. This is consistent with the near-surface observations. The western part of the dust front (Section C) could not be clearly seen, but a faint dark band was identifiable. Also, the predicted dust front Section B stretching towards the Gulf of Carpentaria could not be clearly seen from the GMS image (Figure 10d) apart from a faint light-coloured band. However, Section B can be clearly seen from the NOAA16 satellite image for 03:50UTC 23 October 2002. The model suggests that along Section B, the dust clouds are relatively lower than along Sections A and F.

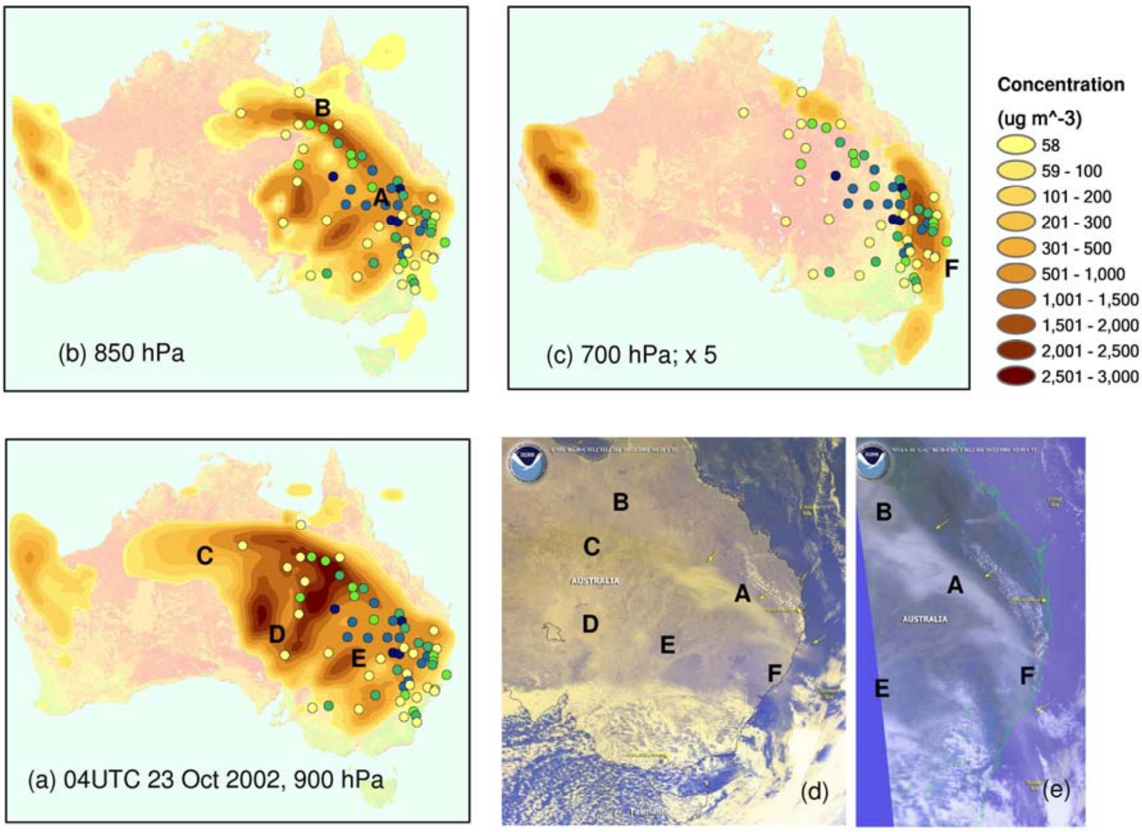


Figure 10. Simulated dust concentration on 900 hPa at 04UTC 23 Oct 2002; dots represent the surface weather record for the period between 00UTC and 06UTC 23 Oct 2002; dots in deeper colour indicate higher dust concentration; (b) as (a), but for 850 hPa; (c) as (a), but for 700 hP; (d) GMS image for 04:26UTC 23 Oct 2002; and (e) NOAA16 image for 03:50UTC 23 Oct 2002. To facilitate comparison, dust-cloud sections are marked with A, B, C, D, E and F

Figure 11 shows the simulated near-surface wind field and dust concentration for 18UTC 22 Oct 2002. Comparisons with the weather data confirm that the wind field is well simulated. At that time, the cold front was an arc-shaped narrow region stretching from NSW to WA, as can be seen from the dense temperature contours (for simplicity only five contours are drawn). Strong south-westerly wind (maximum 12 m s^{-1}) prevailed behind the cold front resulting in strong erosion and high dust concentration. The dust entrained from the post-frontal areas was carried north-eastward by the south-westerly to converge to the frontal area, causing high dust concentration there. The dust was then transported north-westwards and south-eastwards along the front. Due to the converging (normal to front) and diverging (along front) flow pattern, the dust storm affected a large area, although the area of dust emission was much smaller.

In eastern Australia, the dust front was advancing rapidly north-eastwards (90 km hr^{-1}). At 00UTC 23 Oct, dust was wide spread, although the maximum concentration was somewhat lower than that at 18UTC 22 Oct. According to the surface observations, at about 00UTC 23 Oct, the dust front passed over Sydney reducing visibility at the Sydney airport to 6 km. The model did not quite correctly predict the very southern section of the dust front.

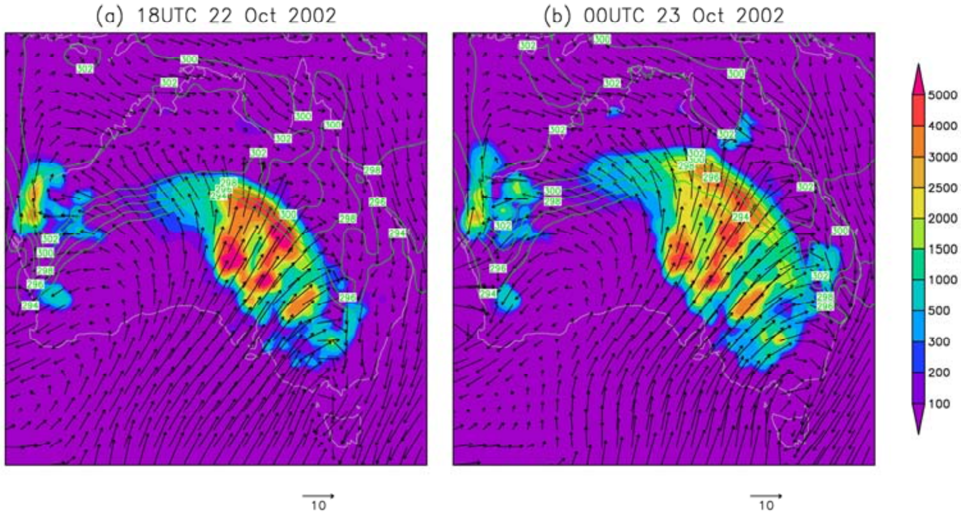


Figure 11. Near surface velocity field, dust concentration [μg m^{-3}] and temperature [K] for 18UTC 22 Oct 2002; (b) as (a), but for 00UTC 23 Oct 2002

The flow field and dust-concentration field on surface, 950 hPa, 850 hPa and 600 hPa are shown in Figure 12 for 20UTC 22 Oct 2002. On 600 hPa, dust concentration was rather low. This flow pattern enabled the dust particles entrained in SA and central Australia to be transported in three directions: in south-east Australia, dust was were carried by the cyclonic flow towards the centre of the cyclone, as indicated by the relatively high dust concentration over Tasmania; near the surface, dust was transported from central Australia north-westward along the front towards WA; and in the upper levels (e.g. 850 hPa and 600 hPa) over the same area, flow was mainly south-westerly and dust was transported mainly north-eastwards. These features revealed from the model are identifiable from the satellite images shown in Figure 10.

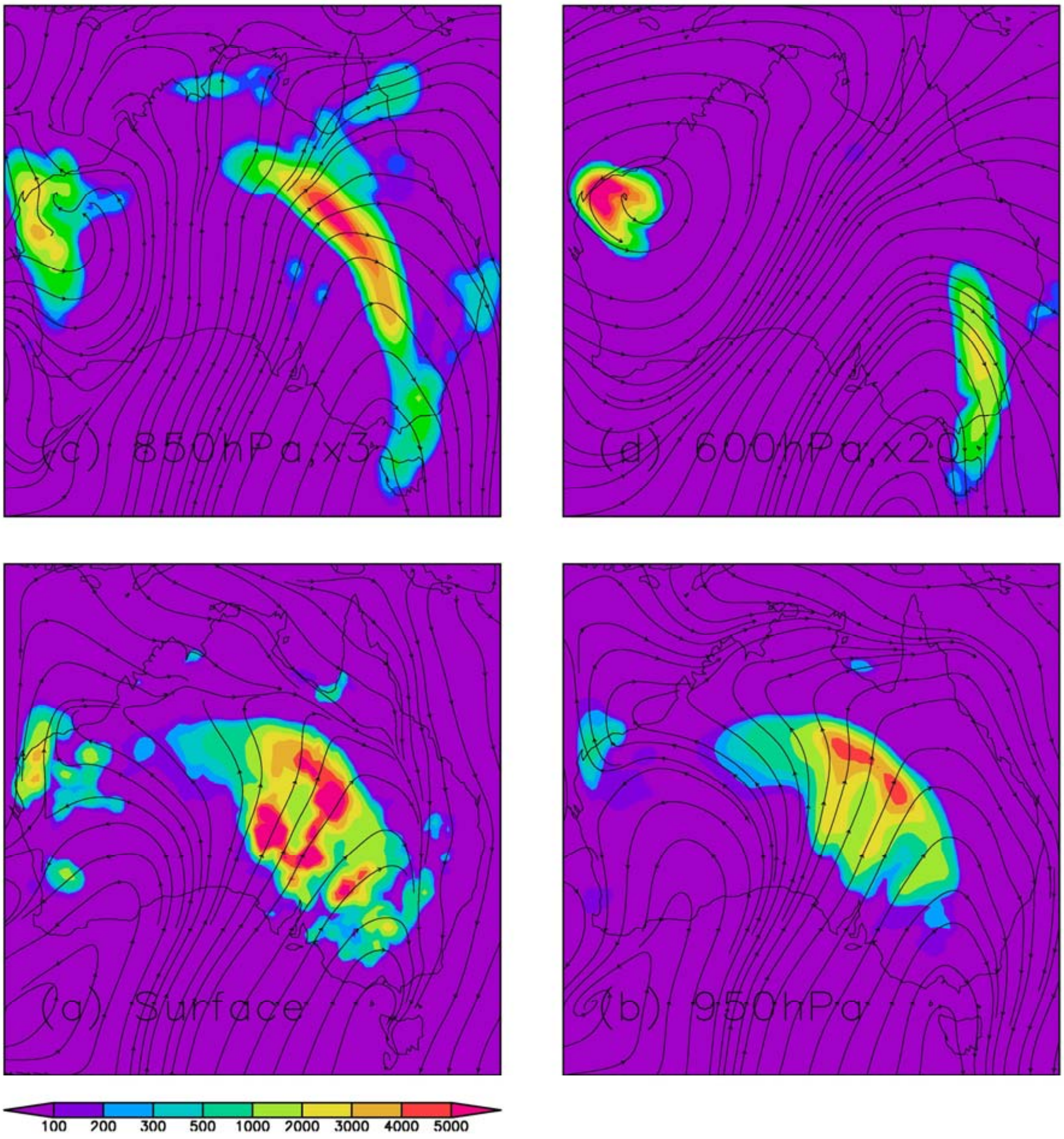


Figure 12. Streamlines and dust concentration at (a) surface; (b) 950 hPa; (c) 850 hPa and (d) 600 hPa. For visualisation, dust concentrations on 850 hPa and 600 hPa are multiplied by 3 and 20, respectively

Suppose dust emission rate is F_S and dust deposition rate is F_D, then net dust emission (F_N) can be defined as:

$$F_N = F_s - F_D \quad (1)$$

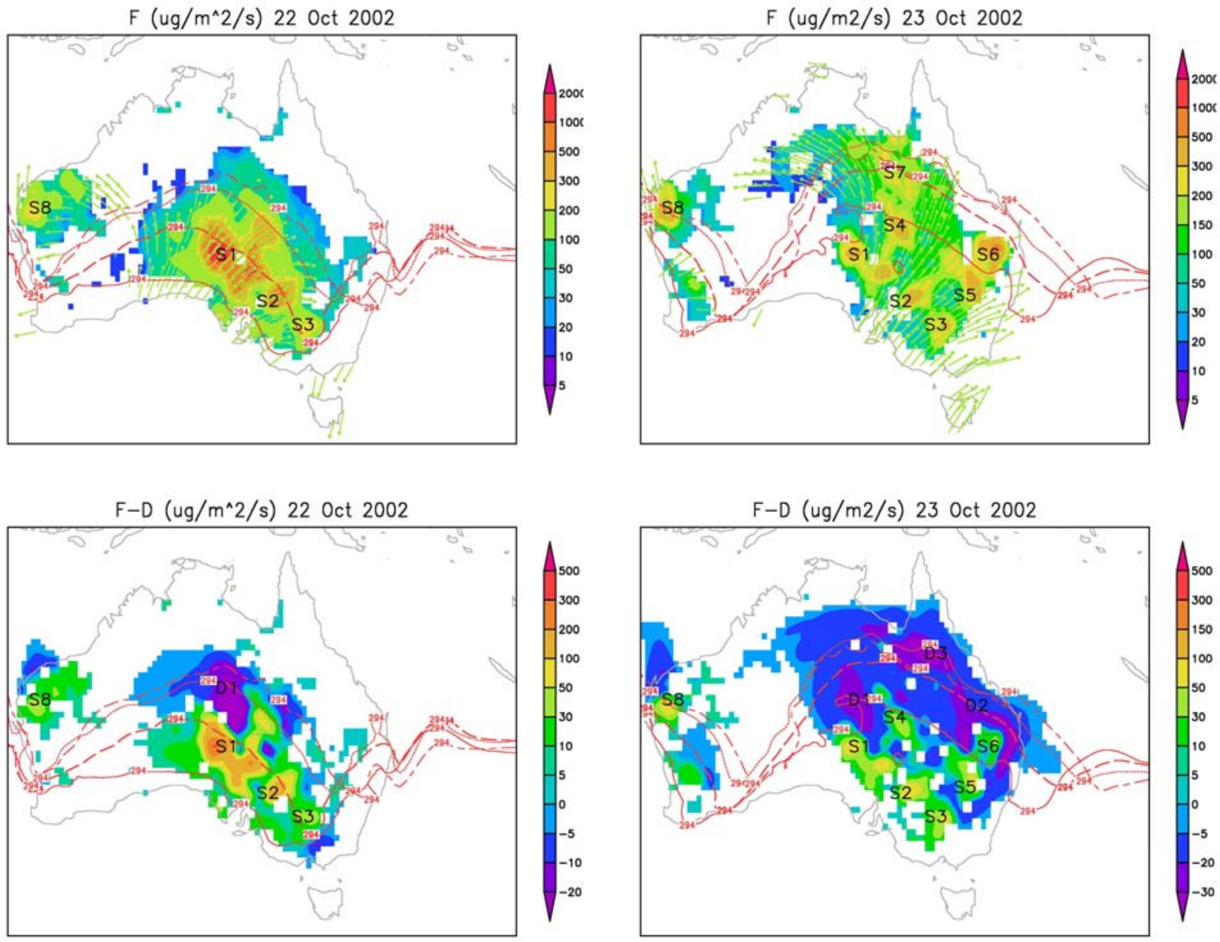


Figure 13. *(a) Averaged dust emission rate in μg m^{-2} s^{-1} over the period of 00-24UTC 22 Oct 2002. The 294 K temperature contours at 06UTC (thin solid line), 12UTC (thick solid line), 18UTC (dotted line) and 24UTC (dashed line) of 22 Oct 2002 are drawn to show the approximate location of the cold front. Main dust sources are marked with S1, S2 etc. Wind vectors with speed exceeding 6 m s^{-1} are drawn; (b) as (a), but for 23 Oct 2002; (c) As (a), but for net dust emission; and (d) as (b), but for net dust emission.*

Both F_S and F_D are calculated by the model. F_S averaged over a 24 hour period for 22 and 23 Oct 2002 is shown in Figure 13a and b. Figure 13 shows that on 22 Oct, the main dust sources were the desert areas in northern SA (S1), the grazing lands in western NSW (S2, with mining areas near Cobar and Broken Hill) and the farming areas in NSW and Vic (S3). Net dust emission also occurred in WA (S8). S1 was the strongest source with the maximum dust emission rate exceeding 2000 μg m^{-2} s^{-1}. Dust emissions from S2 and S3 were weaker. Apart from the dust source in WA (S8), dust emission occurred mainly behind the cold front where wind speed exceeded 6 m s^{-1}. Overall, on 22 Oct, dust emission dominated. On 23 Oct, dust emission was spread much wider but weaker in intensity. New dust sources S4, S5 and S6 emerged in NSW, Qld and NT. S4, S5 and S6 correspond to the Channel Country (near Birdsville), northern NSW floodplains (near Moree) and western Darling Downs. All these regions are open grasslands or farms with little perennial vegetation. During droughts, vegetation cover in these regions diminishes faster than regions with perennial bush or tree cover. The Channel Country is a known source area, while the Moree and Darling Downs are known to be dusty in dry years. The fine sediments of loams and self-mulching clays in these three areas provide favourable conditions for dust emission. In NT, to the north of S4, there was a large area of weak dust emission (S7).

F_N, averaged over a 24 hour period for 22 and 23 Oct 2002 is shown in Figure 13c and d. Net dust emission is smaller than dust emission. The magnitude of maximum F_N is about half that of F_S. On 22 Oct, regions of significant net dust deposition (i.e., negative F_N) were confined, but to the north of S1, a region of substantial dust deposition (D1) can be found. On 23 Oct 2002, net dust emission was much weaker. Surrounding the dust sources to the north, north-east and north-west were regions of significant dust deposition, D1, D2 and D3. The latter almost covered the entire eastcoast of Australia. Dust from S8 was deposited in the Indian Ocean.

The total net dust emission I_N is computed by integration of F_N over the domain surface

$$I_N = I_S - I_D = \int F_S ds - \int F_D ds \qquad (2)$$

Likewise, the total dust load M can be obtained by integration of dust load over the domain. Figure 14a shows the time series of I_S (in Mt hr^{-1}) and I_D (in Mt) and Figure 14b shows the time series of I_N (in Mt hr^{-1}) and M (in Mt) for the four-day time period of 22 - 25 Oct 2002. I_S and I_D were of similar order of magnitude. The maximum of I_S and I_D occurred at around 06 - 07UTC 23 Oct 2002. Positive net dust emission occurred over a period of 32 hours between 01UTC 22 and 08UTC 23 Oct 2002 (Figure 14b). After 08UTC 23 Oct 2002, net dust emission was negative, implying that dust deposition exceeded dust emission. During the dust episode, there existed two distinct peaks of net dust emission, one on 22 Oct 2002 and the other on 23 Oct 2002. Both peaks occurred during the day (local time). In the night, net dust emission was substantially weaker. The maximum net dust emission from Australia was found to be around 0.4 Mt hr^{-1} which occurred at around 06-08UTC 22 Oct and 06UTC 23 Oct 2002. At 06UTC 23 Oct, the intensity of dust emission was not strong, but the area of dust emission was large. Because of the positive net dust emission, the total dust load was increasing until the maximum was reached at 08UTC 23 Oct. From that time, M decreased. The magnitude of the maximum total dust load is comparable with the estimate of McTainsh *et al*. (2005). Their estimated total dust load falls between 3.35 and 4.85 Mt but dust in WA was not included. We have also calculated the total net dust emission and total dust load with WA excluded (Figure 14a). Then, the model-estimated maximum total dust load is 5 Mt. This is remarkably close to that of McTainsh *et al.* (2005), although the methods used in the two studies are completely different.

Deposition dominated the later stages of the dust episode. Strong net deposition occurred between 11 and 23UTC 23 Oct 2002 (20EST 23 - 08EST 24, night), with maximum exceeding 0.2 Mt hr^{-1}. This was accompanied by a rapid decrease in dust load. In the two days to follow, net deposition continued although at a lower rate and dust load continued to decline. Dust load was below 2 Mt by 00UTC 26 Oct 2002, much of the dust was floating in the atmosphere over the ocean.

The total net dust emission during the 01UTC 22 - 08UTC 23 Oct 2002 Australian dust event is estimated to be about 6 Mt, of which 1 Mt from WA and 5 Mt from the rest of Australia. These estimates are consistent with the maximum dust load which occurred at 08UTC 23 Oct. The 6 Mt dust is the residual of 66.7 Mt dust entrainment and of 60.7 Mt dust deposition.

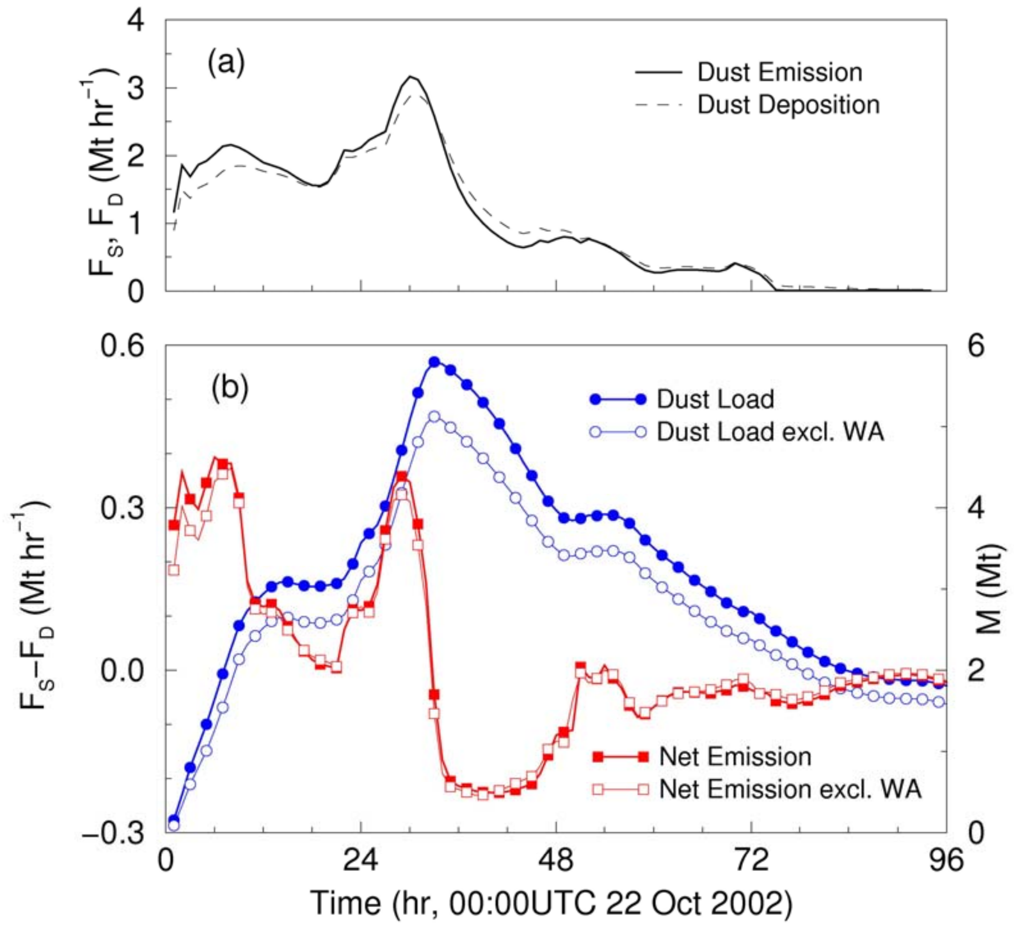


Figure 14. (a) Time series of total (domain surface) dust emission and deposition, both in Mt ^{1}, starting from 00UTC 22 Oct 2002; (b) Time series of total net dust emission in Mt hr^{-1} and total (domain volume) dust load in Mt.

A portion of the dust is deposited in the ocean. Dust emitted from the east of Australia, including SA, Vic, NSW, Qld and NT was deposited mainly in the Pacific to the east of Australia and the Gulf of Carpentaria. Dust from WA was deposited in the Indian Ocean to the north-west of Australia. Figure 15 shows the distribution of dust load and deposition averaged over 00-24UTC 23 Oct 2002. On 22 Oct, dust load and deposition over the oceans surrounding Australia were very low (not shown). On 23 Oct, a significant dust load over the Pacific Ocean can be seen along the entire north-eastern coast, as well as over the Indian Ocean. The highest dust load exceeded 1000 mg m^{-2} off the coast of Brisbane, the NW Cape and the Gulf of Carpentaria (Figure 12a). High dust depositions also occurred in these three areas, as seen in Figure 15b. Further analysis shows that 95.8 Mt dust was emitted into the atmosphere, but 93.67 Mt (97.8%) was deposited to the continent and 2.13 Mt (2.2%) was deposited in the ocean.

a) Load (mg/m^2) 23 Oct 2002 b) Deposition (μg/m^2/s) 23 Oct 2002

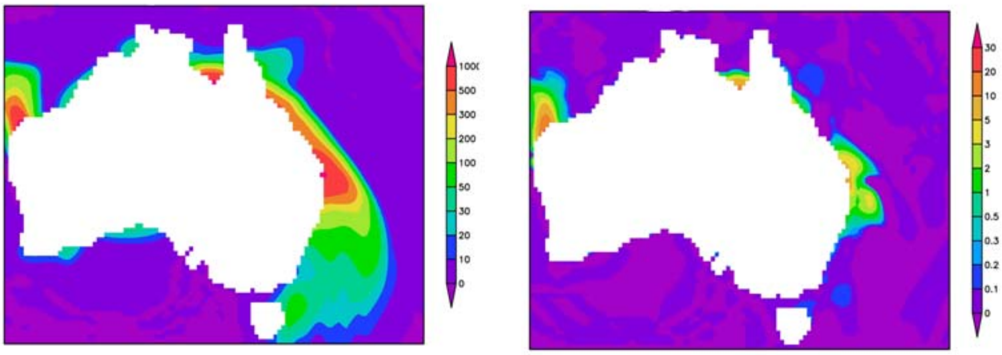


Figure 15. (a) Average dust load over the ocean (mgm^{-2}) and (b) average dust deposition in the ocean (μgm^{-2}s^{-1}). Average is over 00-24UTC 23 Oct 2002

Monthly and yearly application

Configuring the model and running it on a yearly basis is computational, storage and labour intensive. However, it is possible to link the modelling to other indicators, such as the Dust Storm Index (DSI), thus reducing the need to model full years. For example, the DSI (Figure ***16***) shows that in 2002 the major dust activity occurred in September–December. In particular, Figure 16 indicates that October and November had the largest dust activity. The value is not surprising given the large event that occurred on 22–24 October, however the November-December result suggests that a large proportion of the continent was still being actively eroded. Modelling these months using CEMSYS can provide details on when and where these dust events were occurring.

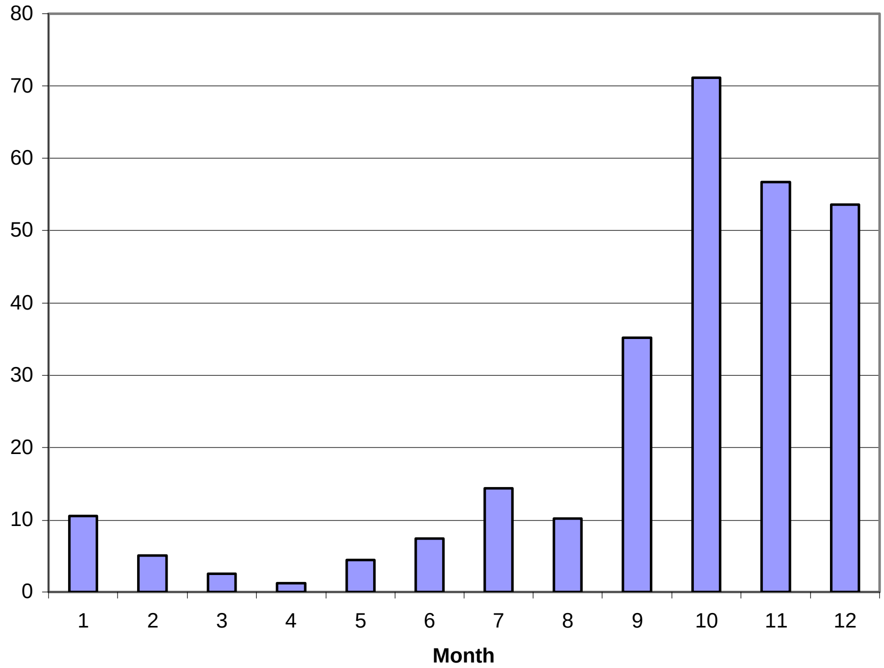
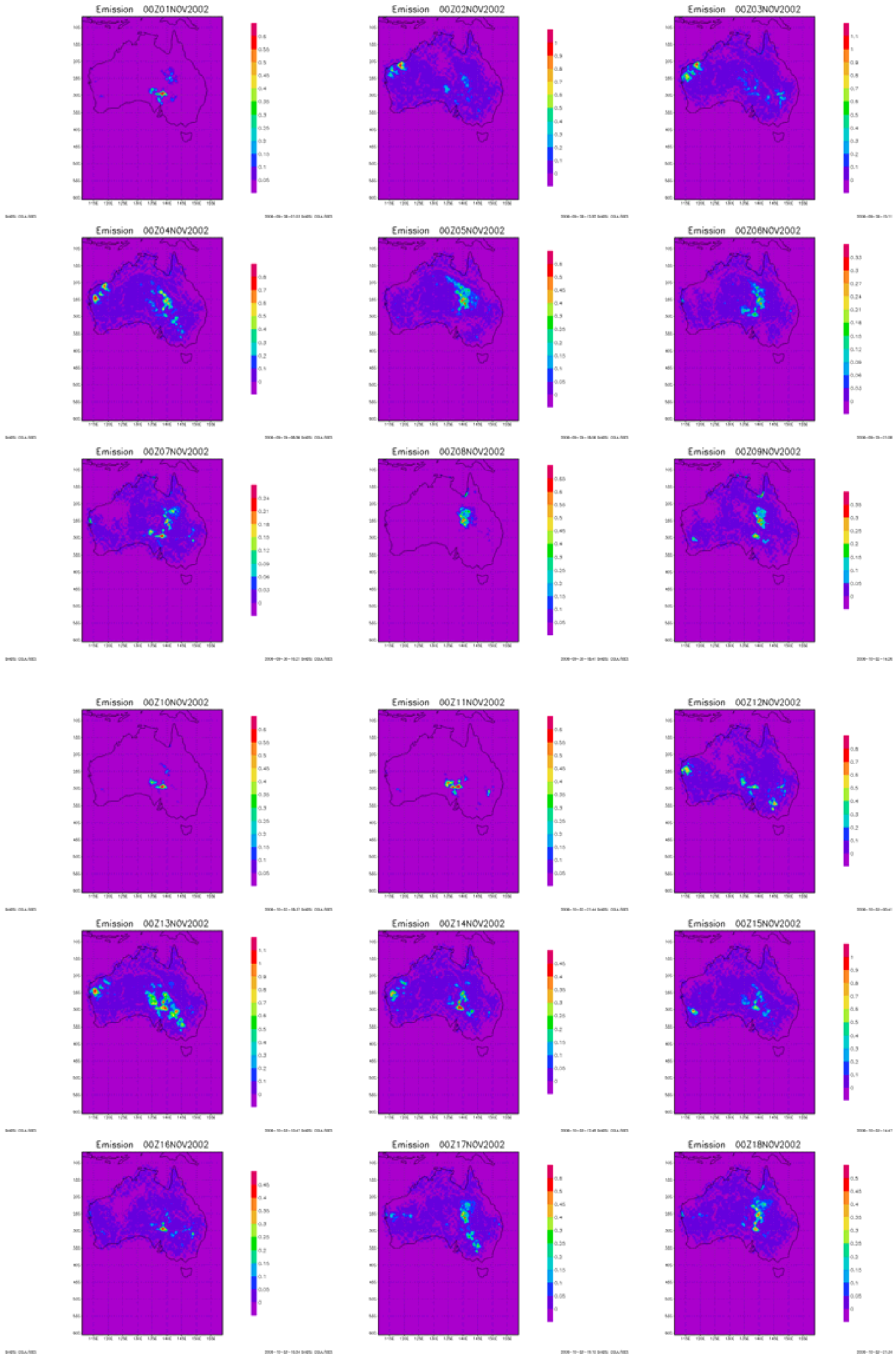


Figure 16. Monthly DSI (Dust Storm Index) for 2002

Figure 17 shows the 6 hr average dust flux for each CEMSYS simulated day in November 2002. This figure highlights the spatial and temporal variability in surface erodibility and emissions depending on both atmospheric and surface conditions. Other results not shown here indicate that there are significant wind erosion events at night. These events often are not captured in visibility observations which are routinely made during daylight hours. Other wind erosion variables such as *dust load, dust concentration* and *deposition rate* can be also simulated and mapped in a similar fashion to highlight the spatial and temporal variability in these properties. These maps provide a unique insight into the spatial and temporal variability associated with the wind erosion process.



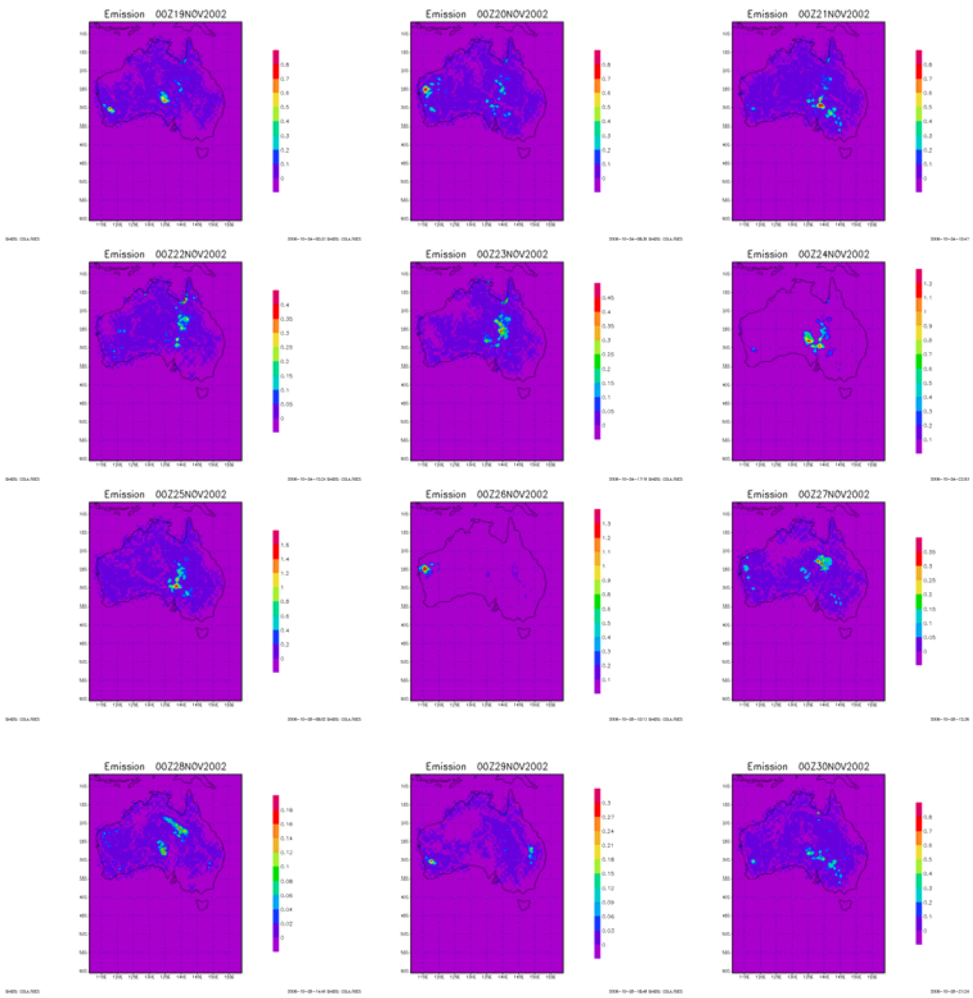


Figure 17. Six hour average dust flux ($\mu g/m^2/s$) at 0:00 GMT for November 2002

These maps can also be re-analysed to produce spatial maps for either daily or monthly averages. Thus, the choice of averaging period is crucial, and requires consultation between the modeller and client as to what averaging period is most suitable to their requirements.

While it is computationally, and human resource intensive to model yearly periods, it is still important to use CEMSYS to model specific years. For example, Figure 18 shows that 2002 was one of the dustiest years on record. When coupled with Figure 16, this indicates that most of the dust activity occurred in September–December. Figure 18 also indicates that the dust activity had more than halved by 2004. This prompts several questions, as to reasons for this drop, such as, was ground cover and land management better in 2004 or was it just a favourable year in terms of weather and frontal systems? Modelling enables the simulation of different atmospheric weather and cover scenarios, thus providing some of the tools to begin addressing the fundamental question of what impact does land management practices have on wind erosion.

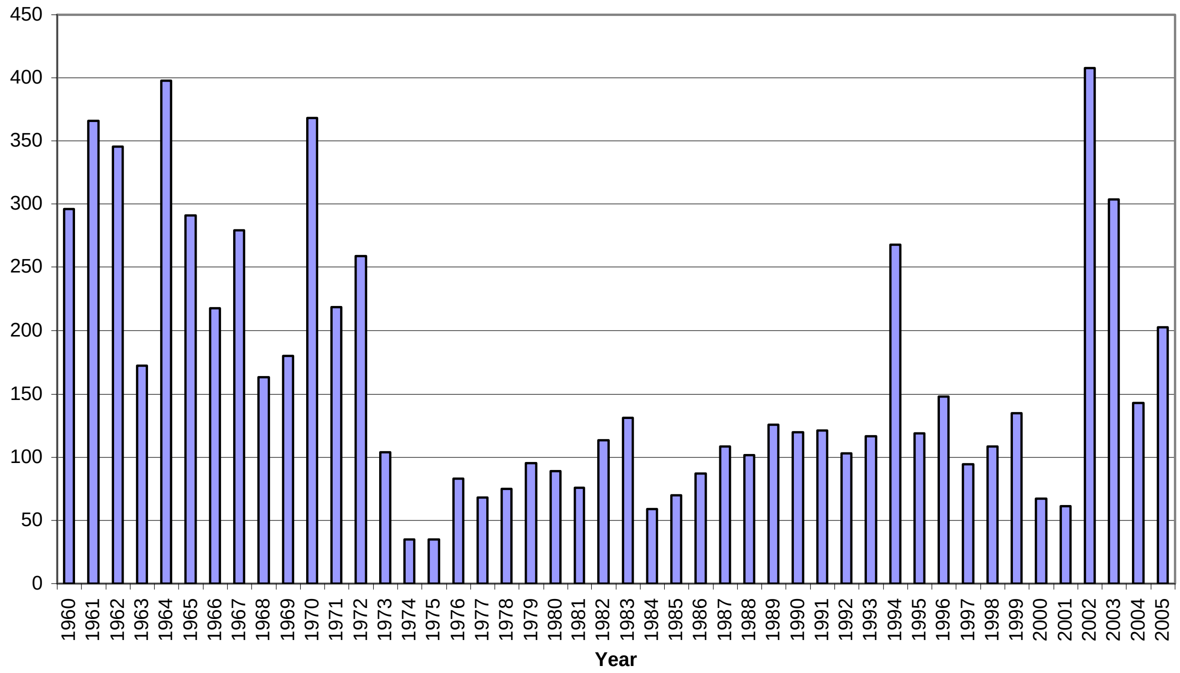


Figure 18. Annual DSI values for 1960–2005

3.3 Confidentiality

CEMSYS is run by the University of Southern Queensland under contract to NSW DECC and Griffith University. Intellectual Property rights are shared equally by the collaborators.

Output maps and statistics are produced for each model run, and can be made available on request for use by external clients provided the model has been run for the period requested and the collaborating funding groups agree. However, the model and raw binary output data will remain the intellectual property of Y. Shao and H. Butler, and their various collaborating institutions (currently NSW Department of Environment and Climate Change (DECC), Griffith University). Currently Dr Butler at the University of Southern Queensland is the custodian of the archived modelling data.

Product definition statement

Product Name	CEMSYS Data Products
Jurisdiction	Australia
Custodian	Australian Centre for Sustainable Catchments, University of Southern Queensland
Contact details	Dr H Butler, Australian Centre for Sustainable Catchments, University of Southern Queensland, Toowoomba 07 4631 5524, butler@usq.edu.au
Description	An indicator of the frequency and intensity of wind erosion across Australia

Source data name and ASDD link	As outlined in section 2.8
Source data attributes used	Sea surface temperature, NCEP atmospheric data, Vegetation structure and coverage, Vegetation Index (NDVI), Soils and Topographical data
Processing of source data	CEMSYS is run using the data outlined above. The result data is post processed using either ARCinfo or GRADS to produce the spatial maps and time series illustrated.
Description	An indicator of the frequency and intensity of wind erosion across Australia.
Source data attributes used	Sea surface temperature, NCEP atmospheric data, Vegetation structure and coverage, Vegetation Index (NDVI), Soils and Topographical data
Processing of source data	CEMSYS is run using the data outlined above. The result data is post-processed using either ARCinfo or GRADS to produce the spatial maps and time series illustrated in section 3.2.

Status	Currently exists
Coverage	80-100%
Recency	2005-1990
Trend	Yes, very good in this respect.
Usability scale	Regional
Availability	Restricted/licence
Delivery	Digital data Electronic document
Content type	Mixture of real & modelled data
Update	Frequently

4. Discussion

4.1 Current national activities

CEMSYS has been under development since the early 1990s (Shao, Raupach & Leys 1996; Shao & Leslie 1997; Shao & Lu 2000; Shao 2003). It has been used to model several large scale wind erosion events, the latest being October 2002 (Shao *et al.* 2007). Currently, it is being run at the University of Southern Queensland in conjunction with Griffith University and DECC, to evaluate wind erosion activity in New South Wales. It is also being used to estimate dust deposition into the oceans. Currently, the raw output data and research products are archived at the University of Southern Queensland. The proposed use of CEMSYS, and future development products as a subindicator of wind erosion within the National Monitoring and Evaluation Framework is a logical extension of the applications outlined in this report. The CEMSYS products described can be provided on a fee-for-service basis, depending on the client. The overall annual running costs would be $100,000, comprising $80,000 for a scientist plus $20,000 in operating costs.

4.2 Future developments

Database improvements: As mentioned the modelling results are only as reliable as the input data on which they are based. Consequently, there is a need to improve the GIS databases for soil properties (e.g. particle-size properties of soil etc.), vegetation cover, and land management practices. It is crucial given the spatial and temporal variability of wind erosion that these databases capture spatial and temporal changes in these properties. These databases have to be ground-truthed to ensure the accuracy (i.e. it is essential that the result of roadside surveys, site-based wind erosion assessment using WEAM and CEMSYS5 are linked in this regard). These improved databases need to be incorporated into CEMSYS as soon as they become available. It would be practical to separate the model into two different versions: one being a production version and the other a development (research) version. By separating, it is possible to ensure the continued availability of the CEMSYS5 output, while ensuring that the model is continuously upgraded. It also essential that production and research CEMSYS outputs be compared to ensure consistency before switching to a new version; and if necessary, critical periods should be remodelled to ensure consistency.

Further research: At present CEMSYS5 assumes that there is an unlimited sediment supply. Consequently, it tends to overestimate the amount of sediment available for erosion and transportation. This issue needs dedicated resources to address in future versions. Further work also needs to undertaken to establish NDVI/u_{*t} for additional land and vegetation types. Finally, additional field data are required at the correct scale to further validate and extend the model.

Linkages: A process that establishes linkages between CEMSYS output and the other indicators has to be established. In particular, there is a need to look at the relationship between the Dust Storm Index Spatial (DSIS) Maps and the dust emission and concentration maps produced via CEMSYS. If a relationship can be established between these indicators, then it should be possible to develop a methodology which would enable CEMSYS simulations to be made of periods for which no remote sensing data exists. This methodology would most likely use the DSI maps to validate the choice of available remote sensing data used to approximate the land and surface conditions for the period being modelled.

Computer resources: Given that the computers currently being used to run CEMSYS are likely to be replaced with 64-bit machines in the next couple of years, there is a need to port CEMSYS to these 64-bit architectures in the near future. Such porting will take several months to complete and test due to the complexity of the model. It is recommended that if this methodology is adopted that this porting be undertaken as a matter of priority.

A consequence of this change in architecture is that the GIS and meteorological databases have to be converted to formats compatible with the new architecture. These databases, along with the model outputs should be archived for future use and to enable comparison with future versions of the model. However, each month takes approximately 10 Gb of storage[2]. Consequently, yearly data requires approximately 120 Gb of storage. If yearly model simulations are to be archived for later use by research and other end users, there will be a need to increase the online/offline data storage for the project.

Human resources needs: Funding needs to be provided to ensure that these human resources are in place to complete these CEMSYS simulations in a timely fashion; especially if the modelling products are going to be published and used by end users on a regular basis.

4.3 *Links to other indicators*

The above discussions highlight the links between the modelling, field, and remote sensing data (see Figure 19). In particular, it has shown that the modelling can add valuable interpretation information to both field measurements and remote sensing data, while the field and remote sensing data are extremely important in validating the inputs and output produced as part of the model processes. Therefore, to maximise the effectiveness of all three approaches it is crucial to establish channels via which this information can be readily exchanged.

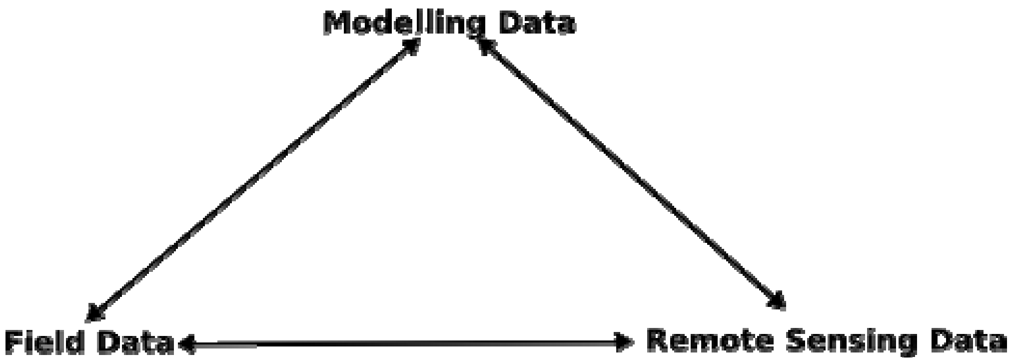


Figure 19. Schematic showing the feedback cycle between model, field, and remote sensing data

[2] This assumes that only 6 hourly averages are stored for further analysis. The actual storage space depends on the averaging period, the shorter the time the larger the files.

In terms of CEMSYS, this feedback cycle indicates that CEMSYS cannot be used alone, but rather has to be used in conjunction with a suite of other approaches to maximise its potential. In particular, there is a clear need to establish the following links to other indicators:

- DSI, as a means of validating and extending CEMSYS to periods when input data is unavailable
- Roadside Surveys and WEAM, as means of improving CEMSYS inputs regarding spatial and temporal variability in vegetation cover and land management practices
- DustWatch as a means of involving the community and sharing education and science outcomes. For example, visibility information reported by DustWatch observers can be used to compare CEMSYS products against field conditions.

These linkages would also improve the performance of the sub indicators within WESCI. A recent paper by Shao et al (2007) describing the dust storm of 23 October, 2002 is a good example of the utility of using dust concentration data from the Dust Event Database (DEDB) (used to calculate DSI) to test the CEMSYS model. The outcome of this testing was particularly encouraging. The CEMSYS modelled total dust load for the event was 5 million tonnes and the measured load, based on the DEDB data was 4.85 million tonnes. This study provides an excellent indication that the suite of methods proposed within WESCI will provide reliable monitoring information products.

5. Further information

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6. Glossary

CMA – Catchment Management Authority

CEMSYS - Computational Environmental Management System

DECC – NSW Department of Environment and Climate Change

DNR – NSW Department of Natural Resources

Dust Concentration - measure of the amount of dust in the air [mass/unit volume]

DustWatch Node - Dust watch station with instrumentation for measuring dust concentration

DSI - Dust Storm Index

GRADS -Grid Analysis and Display System software (developed by Centre for Ocean-Land-Atmosphere Studies, Institute of Global Environment and Society)

NCST - National Committee for Soil and Terrain

NRM - Natural Resource Management

NLWRA - National Land and Water Resources Audit

Saltation – bouncing grains blown by wind across the surface, that is not held in suspension

Sand flux - represents the mass of material that blows off a site as saltation

7. Appendices

Appendix 1. Soil mapping units and properties

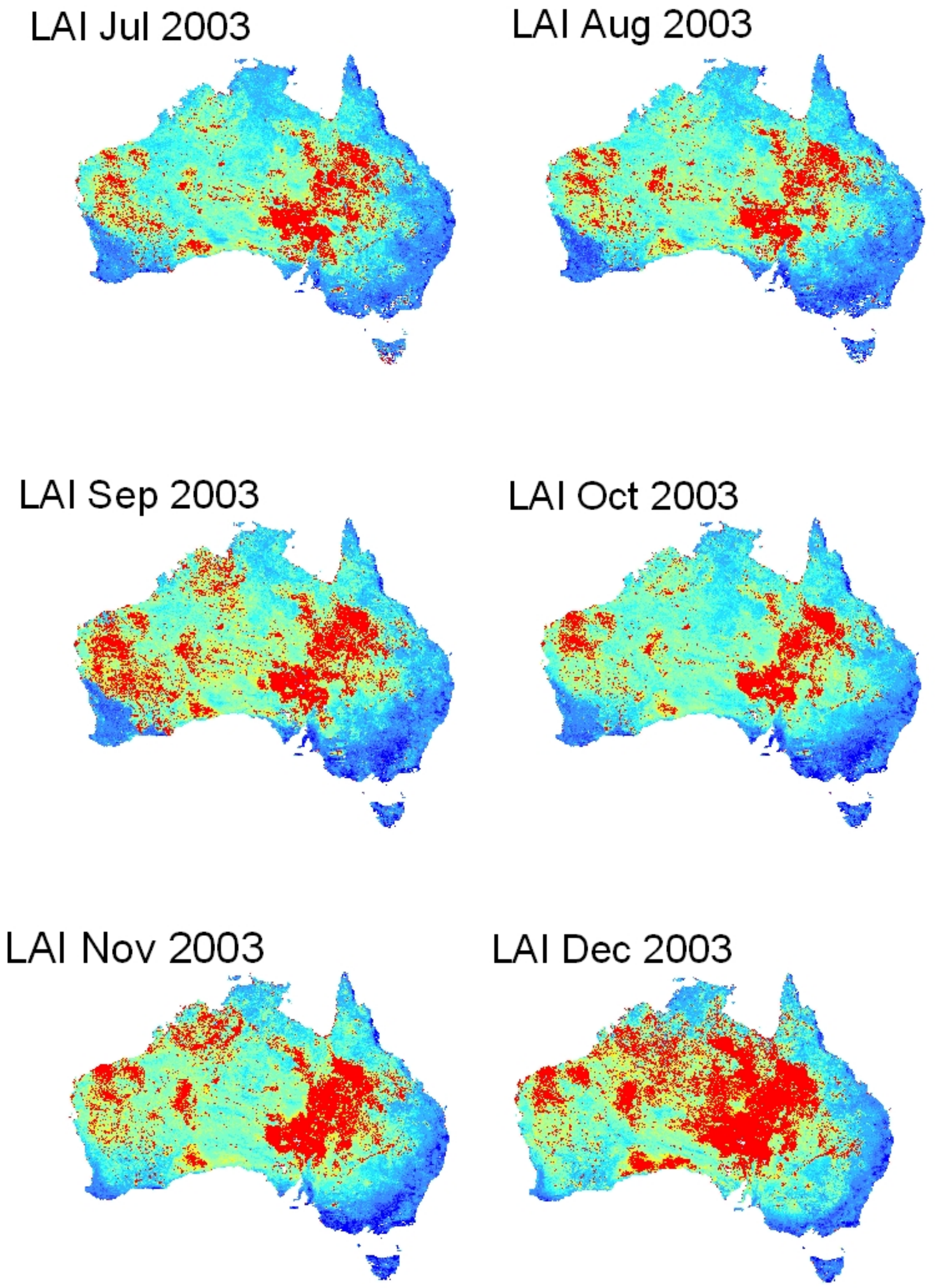
Table 1: A summary of soil mapping units and soil properties. Note that the descriptions of the soil properties are extracted from more detailed descriptions given in the *Atlas of Australian Resources*, Vol. 1, Soils and Land Use (Division of National Mapping, Canberra, 1980). The corresponding USDA soil texture classes are also listed.

Mapping Class	**Mapping Units**	**Soil properties**	**USDA Classes**
1	A1	Deep loam soils	Loam
2	A2	Deep duplex soils	Clay Loam
3	Ba1	Deep highly structured loams	Sandy clay loam
4	Ba2	Deep highly structured clays	Silty clay loam
5	Ba3	Deep highly structured earths	Sandy loam
6	Bb1	Deep massive porous loams	Sandy clay loam
7	Bb2	Acid organic loam soils	Sandy loam
8	Bb3	Similar to Bb1, with unknown clays	Silty clay loam
9	Bb4	Deep massive earths	Clay loam
10	Bb5	Duplex soils, large amounts of gravels	Clay loam
11	Bc1	Deep calcareous sands	Sand
12	Bc2	Calcareous earths	Loam
13	Bd1	Young loam soils	Silty loam
14	Bd2	Clay soils, highly saline	Clay
15	Bd3	Red duplex soils	Heavy clay
16	Ca1	Sandy soils	Sand
17	Cb1	Cracking clay	Silty clay
18	Cb2	Cracking clay	Silty clay
19	Cc1	Duplex soils with thin surface soils	Clay
20	Cd1	Sand soils with hardpans	Sand
21	Cd2	Duplex soils with surface soil ranging from sand to loam	Silty clay loam
22	Ce1	Clay soils with gleyed subsoils	Clay
23	Ce2	Duplex gley soils	Clay
24	Cf1	Sand soils	Sand
25	Cf2	Sandy soils	Sand
26	Cf3	Shallow depth loam soil	Loam sand
27	Cf4	Friable clay soils	Sandy clay
28	Cf5	Quaternary basals with pockets of organic debris	Heavy clay
29	Peren Lake		
30	Peaty Sand		
31	Saline Lake		

Table 2: Summary of vegetation mapping units. See *Atlas of Australian Resources*, Vol. 6 for details.

Mapping Class	**Mapping Unit**	**Canopy Height (m)**	**Description**
1	T4	40	Tall closed forest
2	T3	35	Tall open forest
3	T2	35	Tall woodland
4	M4	25	Closed forest
5	M3	10	Open forest
6	M2	0.5	woodland
7	M1	7.5	Open woodland
8	L4	7.5	Low closed forest
9	L3	7.5	Low open forest
10	L2	3.0	Low woodland
11	L1	0.5	Low open woodland
12	S4	3.5	Closed shrub
13	S3	3.5	Open shrub
14	S2	2.0	Tall shrubland
15	S1	0.4	Tall open shrubland
16	Z4	1.0	Closed heath
17	Z3	0.8	Open heath
18	Z2	0.5	Low shrubland
19	Z1	0.05	Low open shrubland
20	H2	0.25	Hummock grassland
21	G4	0.5	Closed tussock grassland or closed sedgeland
22	G3	0.5	Tussock grassland or sedgeland
23	G2	0.25	Open tussock grassland
24	G1	0.025	Sparse open tussock grassland
25	F4	0.2	Dense sown pasture
26	F3	0.15	Sown pasture
27	F2	0.075	Open herbfield
28	F1	0.015	Sparse open herbfield
29		10?	Peren lake
30			Peaty sand
31			Saline lake

Appendix 2. Leaf area index maps of Australia



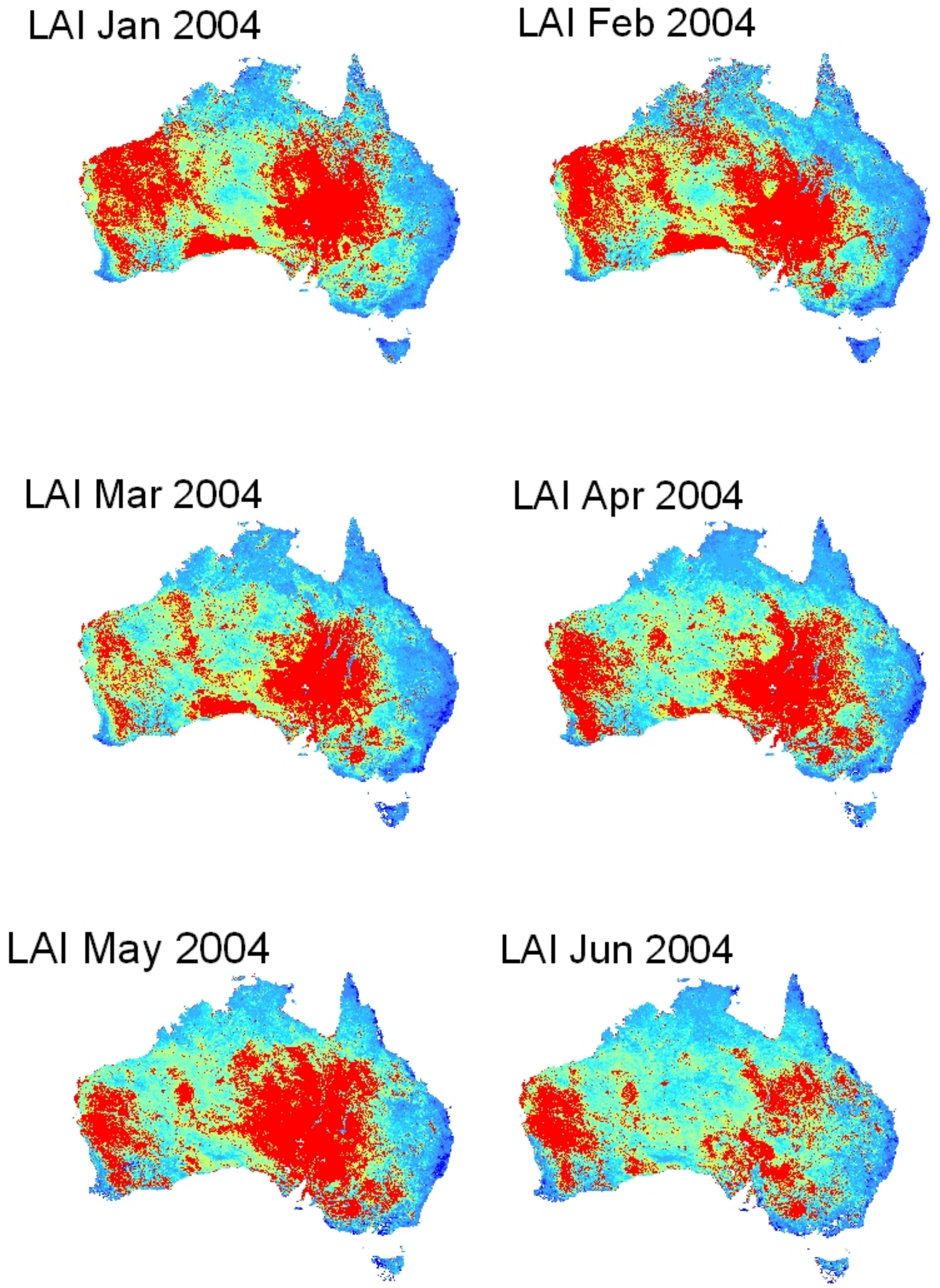


Figure 20.   LAI maps for Australia for July 2003~June 2004