Integrated modelling systems in Australia

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Motivated to explore air pollution in complex geographic settings, in 1986 Bill Physick coupled the Pielke mesoscale meteorological model (Colorado State University) with McNider's Lagrangian particle model (University of Alabama) in off-line mode. After replacing the meteorological model with one developed locally (by John McGregor), speeding up the particle model near boundaries, and adding a new advanced display system, the result was LADM, used in numerous coastal industrial air pollution settings (Physick *et al*., 1994).

Seeing the strengths and weaknesses of the LADM approach, Peter Hurley built a test bed to explore various turbulence schemes, non-hydrostatic effects, and further ideas for speeding up Lagrangian particle models; by 1999 these had come together on a PC platform as the GUI-driven in-line integrated mixed-Lagrangian/Eulerian modelling system TAPM (Hurley 1999a,b).

TAPM uses the fundamental equations of atmospheric flow, thermodynamics, moisture conservation, turbulence and dispersion, wherever practical. For computational efficiency, it includes a nested approach for meteorology and air pollution, with the pollution grids optionally able to be configured for a sub-region and/or at finer grid spacing than the meteorological grid, which allows a user to zoom-in to a local region of interest quite rapidly. The meteorological component of the model is nested within synoptic-scale analyses/forecasts that drive the model at the boundaries of the outer grid. The coupled approach taken in the model, whereby mean meteorological and turbulence fields are passed to the air pollution module every five minutes, allows pollution modelling to be done accurately during rapidly changing conditions such as those that occur in sea-breeze or frontal situations. The model incorporates explicit cloud microphysical processes. The use of integrated plume rise, Lagrangian particle, building wake, and Eulerian grid modules, allows industrial plumes to be modelled accurately at fine resolution for long simulations. Similarly, the use of a condensed chemistry scheme also allows nitrogen dioxide, ozone, and particulate mass to be modelled for long periods.

TAPM has become an important integrated modelling system in Australia and abroad, evolving to the present Version 3 (Hurley, 2005a,b): we have 154 active licences, involving 18 countries around the world. It is successful because of its ease of use, and this in turn is because of some self-imposed limitations that make it very practical:

- its application is limited to a few thousand kilometres, so major inter-continental transports are not accommodated

- because we are focussed on air pollution problems, high-impact weather is rarely of concern, so its simplified approach to deep convection, absence of a stratosphere (maximum altitude is 8 km), and its explicit but simplified rain processes, are not significant
- it includes wet and dry deposition processes and a simplified photochemical smog mechanism that is only applicable to regional and urban pollution.

The most striking thing about TAPM for most applications by its target user group is that it only requires information on pollutant emissions — datasets of the important inputs (e.g., terrain, land use and 3D synoptic meteorology) needed for meteorological simulations are provided with the model, allowing model set up for any region, although user-defined databases can be connected to the model if desired — in fact TAPM has been shown to give very good results without any recourse to local meteorological data. Many demonstrations of the veracity of this claim have been made: see Hurley *et al.*, (2005b) for an extensive set of case studies, and more recent literature referenced at the CMAR Library Web address given already.

A major learning for Australian conditions is that recirculation of pollutants in the sea breeze is an important feature of coastal cities: the spatial resolution required of the meteorological model needs to be adequate to resolve the sea breeze phenomenon. Resolutions substantially finer than 10 km are required – 2–5 km seem adequate.

Using a high quality emissions dataset, TAPM performance is very good for the prediction of extreme pollution statistics, important for environmental impact assessments, for both non-reactive (tracer) and reactive (nitrogen dioxide, ozone and particulate) pollutants for a variety of sources (e.g. industrial stacks and surface or urban emissions) — see Luhar and Hurley (2003); Hurley *et al.*, (2005a). A study, with the attention to detail that makes a big difference, is by Luhar *et al.*, (2006a).

Other findings include:

- correctly specifying landuse and vegetation improves the meteorological predictions and has flow-through benefits for the air quality predictions
- the vertical temperature profiles in standard synoptic analyses often have poor detail below 1000 m. For example, extra-stable layers between 200 m and 400 m can be non-existent in the forecast model analyses that have only a few levels below 1000 m. This can greatly affect our air quality predictions.
- it is important to use wind data only from well-sited anemometers for evaluating model performance, or for assimilating during a run.

Characteristics of urban areas that can affect flow properties include roughness length, building characteristics, thermal properties of the surface and anthropogenic heat flux. As Luhar *et al.*, (2006b) showed by comparison with the Swiss BUBBLE data, although TAPM in particular accounts for these effects with a varying degree of complexity, the land-surface scheme in the model needs improvement to resolve the urban canopy layer and the roughness sublayer. The topic of urbanisation of meteorological models is an area of increasing interest, and has been a focus of COST728. But there are also important new developments for rough boundary layers in which shedding shear layers slow the flow markedly (Harman and Finnigan, 2007). These may have implications for understanding flows in and above urban canopies.

As TAPM was being developed, the opportunity arose to integrate its chemical transport component with Australian Bureau of Meteorology's weather forecasting system to provide real-time weather and air pollution forecasts. TAPM already had been using historical six-hourly BoM global analyses to initialise that model, so the extension was natural. In collaboration with the BoM and the major environment authorities of Australia, we developed the Australian Air Quality Forecasting System (AAQFS) in time to be run operationally for the 2000 Sydney Olympic Games. See Cope *et al.*, (2004), Hess *et al.*, (2004) and Tory *et al.*, (2004). The major emphasis for Sydney was on predicting urban ozone (Cope *et al.*, 2005a). It has been run twice daily ever since, producing hourly forecasts for the next 36 hours for 21 chemical species on a 1 km grid for the major cities of Australia. We have learnt a lot and have made many improvements.

- A big learning was that it is best to have as much of the emissions inventory as possible on-line, described by algorithms that respond where appropriate to the forecast meteorology, and calibrated by relevant observational data. We now have emissions from motor vehicles, vegetation (Azzi *et al.*, 2005; Kirstine & Galbally 2004), soils, wind-blown dust, bushfires, sea-salt spray, domestic wood heating, and some industry handled this way.
- As with the finer-scale TAPM experience, it is vitally important to accurately include biogenic emissions. In Australia, concentrations of up to 60 ppb ozone are measured in country areas with no evident industry or vehicle sources.
- Intrusion of bushfire smoke is a major cause of exceedences of air quality standards, particularly for ozone, in Australian cities. This is an extreme example of biogenic emissions, and is a major driver for the next point:
- Australia-wide forecasts are now done for wind-blown dust (e.g., Wain *et al.*, 2006) and for bushfire smoke. Size-segregated dust is emitted and transported depending on historical land-use, soil-type and seasonal LAI. For bushfires, we use the Sentinel outputs of hotspots to locate emissions. Sentinel currently obtains MODIS data from the NASA EO Satellites Terra and Aqua. See http://sentinel2.ga.gov.au/acres/sentinel.

AAQFS provided the impetus to further explore complex chemistries for air pollution predictions, something we had been doing for special projects in and around Australia (e.g, Cope *et al.*, 2003; Malfroy *et al.*, 2005). We are currently gaining experience with the Carbon Bond 2005 mechanism and have incorporated this into a new Chemical Transport Model that runs optionally in both TAPM and AAQFS (it is called TAPM-CTM). This complexity is essential for addressing policy questions of urban planning and around the veracity of new transport fuels such as ethanol blends, and the effects of pollutants such as formaldehyde and benzene. Pollution by ozone and fine particles, particularly secondary particles, are the main questions ultimately being addressed, though air toxics and personal exposure and the interaction with indoor air pollution are also questions increasingly being asked.

Recognition that personal exposure is the really relevant air pollution question for human health has led to a lot of work on near-road air quality, both experimentally and by modelling. The Lagrangian Wall Model (the LWM: Lilley and Cope, 2005; Cope *et al.*, 2005b), a complex chemical transport model of a wall that is advected downwind of nominated anchor points can resolve pollution concentrations to 10 m. The model runs within a TAPM grid cell. Some thirty or so walls can be set up and tracked at once from a GUI, giving high resolution results for the effects of individual roads, intersections and terrain on the air quality. Other relevant work integrates the results of environmental monitoring data, high resolution modelling of pollution fields and hospital admissions to seek to improve understanding of pollutant exposure to increases in asthma (Physick *et al.*, 2006; Physick *et al.*, 2007).

On a wider front, for downscaling from large-scale climate models we have developed CCAM, a global model that has spatially varying resolution (McGregor, 1997; McGregor and Dix, 2005). It is initialised from a single global analysis or climate change prediction to predict scenarios of weather down to a kilometre for hours to months.

Embedding TAPM off-line and with the possibility of using TAPM-CTM in-line in CCAM gives us a powerful GUI-driven integrated weather and air pollution forecasting system that has wide application.

Our current direction is to merge our research with Australian Bureau of Meteorology. A particular development underway is ACCESS, the Australian Community Climate and Earth System Simulator, based in large part on HADGEM in collaboration with the UK Hadley Centre (Martin, 2004; John, 2004). CCAM is expected to become an alternative dynamical core (McGregor, *et al.*, 2007), and AAQFS will be unified into the system. For air quality applications, ACCESS will play the major role, but TAPM and LWM will continue to develop in parallel, providing very convenient test beds for process and algorithm developments before they are considered for incorporation into ACCESS and possibly HADGEM.

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