The DAWEX field campaign to study gravity wave generation and propagation

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Abstract. A field campaign studying aspects of the atmospheric dynamics from the ground to the lower thermosphere was conducted in Australia during October-December 2001. This Darwin Area Wave Experiment (DAWEX) involved participation from 9 institutions in the USA, Japan and Australia, and focused on studying wave perturbations in the middle atmosphere in conjunction with detailed observations of tropospheric moist convection. The experiment involved extended deployment of 5 airglow imagers, medium-frequency radars and a boundary layer wind profiler. Tropospheric convection was observed by meteorological radars including the Australian Bureau of Meteorology Research Centre C-band polarized radar. This paper provides an overview of the experimental setup, and also discusses the basic meteorological fields during the experiment, including some examples of convective activity near Darwin. Wind and temperature fields extending up into the lower thermosphere were constructed on the basis of campaign observations and the UKMO global meteorological analysis. These fields can be used for the modeling of gravity wave propagation through the middle atmosphere.
1. Introduction

A fundamental difficulty in understanding and modeling the climate system is the range of spatial and temporal scales that are strongly coupled. An important example of this concern is provided by moist convection, for which individual elements typically occur on horizontal scales of at most a few km. These elements may be organized into complexes on scales of 10-1000 km, and the dynamical and physical processes in the convection have profound influence on atmospheric composition and circulation even on the global scale.

Of particular interest for modeling stratospheric circulation and chemistry is the role of convection in forcing vertically-propagating inertia-gravity waves (IGWs). Such waves can propagate to stratospheric and higher levels, and they act as catalysts for the transfer of mean horizontal momentum between the lower and middle atmosphere (MA). In the extratropics the IGW transports of mean momentum are believed to drive the MA mean meridional circulation and thus help determine the overall thermal structure and zonal-mean zonal wind distribution of the extratropical middle atmosphere [e.g., *Lindzen*, 1981; *Garcia and Boville*, 1994; *Hamilton*, 1996; *Alexander and Rosenlof*, 1996]. In the tropics vertical transports of mean momentum associated with IGWs are generally believed to play an important role in forcing both the quasi-biennial oscillation (QBO) and semiannual oscillation (SAO) of the zonal-mean flow in the stratosphere and mesosphere [e.g., *Sato and Dunkerton*, 1997; *Dunkerton*, 1997; *Alexander and Holton*, 1997; *Baldwin et al.*, 2001]. In addition, part of the spectrum of the IGWs propagating upward through the mesosphere will reach F-layer heights, where the gravity waves account for temporal and spatial variability in electron density. Electron density, in turn, can affect aspects of radio
wave propagation. Gravity waves in the equatorial F-region may also trigger large-scale ionospheric instabilities which cause the “spread-F” phenomenon [e.g., McClure et al., 1998].

There have been a very large number of published studies reporting on gravity wave observations in the MA. Typically such studies describe observations taken with a single observing system that profiles the MA winds or temperatures (e.g., balloons, rockets, radars, lidars) near a single geographical location. In some instances such MA profile observations have been related to meteorological conditions in the troposphere, including the occurrence of strong convection [e.g., Clark and Morone, 1981; Taylor and Hapgood, 1988]. In the last decade the development of airglow imaging techniques has allowed a somewhat broader view of the wave field to be obtained from a single station, although such imagers produce data relating only to disturbances within fairly thin emission layers, typically near the mesopause.

The limitations of single station observations of middle atmospheric IGWs have been appreciated for some time and the need for coordinated field campaigns is clear. Notable in this respect were the ALOHA-90 and ALOHA-93 campaigns which were conducted in the central tropical north Pacific in 1990 and 1993 [e.g., Hostetler et al., 1991; Gardner et al., 1995; Swenson et al., 1995].

Discussions subsequent to the ALOHA campaigns led to the conclusion that further coordinated campaigns focussed on tropical IGWs and their relation to tropospheric convection would be valuable. Planning for another such campaign was spearheaded by the Gravity Wave Processes Working Group of the WCRP SPARC Project and the Dynamics Working Group of the SCOSTEP EPIC Initiative. This planning resulted in the ex-
periment now known as the Darwin Area Wave EXperiment (DAWEX) which was held October-December 2001 in Australia. A brief report on the initial plans for DAWEX was given in Hamilton and Vincent [2000]. The experiment field involved contributions from scientists at 9 institutions in Australia, the USA and Japan, and colleagues at other institutions have been involved in related analysis and modeling work.

This paper presents an overview of the DAWEX campaign and related background material. It serves as an introduction to the more detailed reports that appear in this special issue. Section 2 describes the typical meteorology of the Darwin area and the rationale for designing an experiment focussed on this region. Section 3 briefly describes the experiment itself, including the instruments deployed. Section 4 discusses the meteorological conditions prevailing during DAWEX and descriptions of the convection observed. Section 5 describes the observations of temperature and prevailing wind during the experiment and places them in context of the global meteorological analyses for the period. Section 6 summarizes the significance of the experiment and briefly considers the possibility of future campaigns.

2. Meteorological Background

A number of factors led to the choice of the Darwin area in the Austral spring as the focus for the field campaign. The period of the experiment, mid-October to mid-December, was coincident with a predictable change in the dominant meteorology from pre-monsoon to summer monsoon conditions, with a consequent dramatic increase in the typical extent and intensity of deep convection. The basic goal of DAWEX was to observe the IGW field from the tropopause to the thermosphere and to relate the results to the tropospheric convection, particularly deep convection. A natural choice then was to schedule DAWEX
for a region and period in which the convection could be expected to vary systematically from little deep convection to widespread deep convection.

In addition, the Tiwi Islands north of Darwin feature an interesting diurnal convection regime in the transition to the summer monsoon period. Figure 1 shows the geography of the Darwin area and the sites where a number of instruments used in the experiment were located. In the late pre-monsoon period there is a diurnal cycle of intense convection over the Tiwi Islands [e.g., Keenan et al., 1990; Keenan and Carbone, 1992; Carbone et al., 2000] This phenomenon is driven by the sea breeze circulation and is so regular as to have earned the local nickname of “Hector”. Hector is generally initiated by interaction of convectively-driven cold pools and sea breeze fronts and builds into a bundle of intense thunderstorms reaching the tropopause in mid-afternoon, then finally moving off-shore to the west of Bathurst Island where it dissipates by mid-evening. Updrafts as strong as 40 ms$^{-1}$ and cloud tops to 20 km (more typically 17-18 km) have been observed during Hector.

The interesting character of the convection in the area led to the Tiwi islands being chosen as the focus for the Island Thunderstorm Experiment (ITEX) in spring 1988 [Keenan et al., 1989], and the Maritime Continent Thunderstorm Experiment (MCTEX) conducted in November and December 1995 [Keenan et al., 2000]. The earlier experiments provide a very valuable base for understanding the tropospheric convection in the region.

The MCTEX observations showed that the diurnal evolution of the convection over the Tiwi Islands generally takes one of two paths. In about 20% of the cases (Type A) the convection is largely initiated by the collision or merging of inward-penetrating sea breeze fronts. This leads to development of somewhat weaker convection (or convection...
peaking later in the day) than in the more common (Type B) cases. In the Type B development (about 80% of cases) the organized convection is initiated before the actual merging of sea breeze fronts by interaction between cold pools (from early less-organized convection) and the sea breeze fronts. This Type B evolution generally results in the strongest fully-developed Hectors.

Hector is largely forced by the locally-driven sea-breeze circulation and so, on some days, the convection can be somewhat isolated from other deep cloud systems. Also very significant is the fact that the locally-forced nature of Hector makes the job of detailed numerical simulation much more feasible than for more random, weakly-forced convection. Indeed, there has already been some considerable success in simulating the development of Hector as observed on some individual days during MCTEX [Crook, 1997] and DAWEX [Stenchikov and Hamilton, 2004, in this issue].

The expectation, based on numerical simulations, is that the convection penetrating the tropopause will excite a broad spectrum of gravity waves at the base of the stratosphere that will then propagate upward and outward from the source [e.g., Holton and Alexander, 1999; Horinouchi et al., 2002]. In the absence of mean wind effects, the orientation of the group velocity of gravity waves is related simply to the frequency. High-frequency waves propagate more vertically. Higher-frequency waves also tend to have higher magnitude of group velocity. Thus, the convection should excite high-frequency waves that propagate nearly vertically to the mesopause in a time interval of the order of an hour. As time progresses, the wave field at mesopause levels will be dominated by lower-frequency waves that have propagated further horizontally. So, for example, during the sunset-to-dawn observation period for airglow imagers, waves from a late afternoon source may be seen
at the mesopause many hundreds of kilometers away. Even longer distance horizontal propagation may be possible if conditions are suitable for wave ducting in the lower thermosphere.

3. DAWEX Description

DAWEX was organized around three intensive observational periods (IOPs): IOP1 during October 13-18, IOP2 during November 15-20, and IOP3 during December 11-16. However, many of the instruments were deployed for considerable periods before and after the IOPs.

The list of ground-based instruments deployed for DAWEX is given in Table 1, and the associated geographic coordinates in Table 2. In addition, the Bureau of Meteorology Research Centre (BMRC) operated its polarimetric radar (C-Pol) at Gunn Point about 20 km north of Darwin [see Keenan et al., 1998 for details]. This instrument was important for characterizing convection and its intensity.

The C-Pol radar runs a “volume scan” once every 10 minutes. These scans consist of a series of conical sweeps at a sequence of increasing elevations. Data are sampled every 300 m out to a range of 150 km (shown by the circle in Figure 1). This builds up a three-dimensional picture of cloud systems. Note that at 150 km the minimum detectable signal with the radar is about 0 dBZ, so the radar does see substantial amounts of non-precipitating cloud. The volume scan data is then interpolated onto a Cartesian grid. The analysis for the October IOP utilizes the BoM operational radar located at Berrimah near Darwin as C-Pol was not operational at that time.

The C-Pol radar data is used to produce estimates of the microphysical properties of the precipitation echoes as described by Straka et al. [2000] and Keenan [2003].
hydrometeor species can be defined using this approach. The present paper makes use of a gridded reflectivity and a derived classification product rather than the raw data. Note that 2 km horizontal resolution grids are used here and this means that the maximum echo height seen in the analyses is slightly underestimated.

The Bureau of Meteorology also has a network of operational radars across northern Australia. These radars operate in a variety of scan modes, but all include a long range surveillance scan out to a range of 512 km. These radars are increasingly being used for quantitative precipitation estimates, but note that the spatial resolution of the radar at these long ranges is poor and the beam is well above the ground even at very low radar elevation angles because of the Earth’s curvature. These characteristics give the radars a limited utility for quantitative rainfall measurement at these long ranges, but they do give a qualitative indication of the position of intense convection across a much wider region than the C-Pol volume data provides.

As well as the Doppler and weather radars, Darwin has other infrastructure for weather-related research, including three different raingauge networks on different scales [Keenan and Manton, 1996].

Wave responses in the vicinity of the mesopause were observed by a total of six airglow imagers deployed during the experiment. The contours in Figure 2 show the estimated useful fields-of-view near 90 km altitude for five of the imagers. The imagers were arranged so that the imagers located at Wyndham, Katherine and Darwin had overlapping fields of view with the aim of studying wave propagation and identification of sources in the vicinity of Darwin. The imagers located at Alice Springs and Adelaide give insight into the nature of waves that appear to propagate poleward from sources in the tropics and which
may be ducted in the lower thermosphere [Walterscheid et al., 1999]. The imager located at Tanjungari in Indonesia provides information on wave propagation and properties at a location equatorward of northern Australia. Details of the instruments used may be found in Hecht et al. [1997], Taylor et al. [1997], Tang et al. [2002], Otsuka et al. [2002] and Nakamura et al. [2003].

Three-hourly balloon soundings of the wind and temperature were made during each of the IOPs at Pirlangimpi, Darwin (130 km south) and Katherine (400 km south and east). The soundings were made with larger balloons than those used for normal routine soundings (800 g vs 350 g) in order to reach as high an altitude as possible. In practice over 75% of the IOP soundings reached 25 km and over 65% reached 30 km.

A boundary-layer (BL) radar that profiled the three components of the wind up to about 8 km height was installed at Pirlangimpi on the Tiwi Islands. This system was based on the radar described in Vincent et al. [1998a], but had a higher transmitter power (7 kW) and larger antennas for transmission and reception. This radar provided wind measurements with a time resolution of 1-2 min and was used to provide observations of the mean wind field and its evolution during the IOPs as well as to study gravity waves in the vicinity of Hector.

In order to measure horizontal winds in the mesosphere/lower thermosphere at altitudes observed by the airglow imagers a medium-frequency radar was installed at Katherine. This was a small system, similar to that described in Vincent and Lesicar [1991]. A more powerful MF radar located at Buckland Park near Adelaide was also used to provide mesospheric winds at the southern end of the observing region.
4. General Conditions and Characteristics of Convective Storms

The three IOPs sampled a wide range of conditions. These include the early phase of the build up to the Australian monsoon where there is deep convection in the area during most afternoons, the mature phase when the convection tends to be deeper and more intense, with squall lines also being common, and, finally, the early phase of the monsoon. A surface streamline analysis for IOP1 shows there was no sign of the monsoon through the maritime continent as the cross-equatorial flow was still southerly. A monsoon trough extended across the tropical north Pacific region. There were south-westerlies across the western part of Indonesia. Easterlies dominated the flow over northern Australia. This is typical of conditions in the early phase of the build up. In November there was still southerly flow across the equator, but the monsoon trough in the North Pacific had disappeared. There was a symmetric disturbance to the north of Cape York. These are commonly associated with westerly wind bursts and the occurrence of “twin” tropical cyclones. There was a low across New Guinea and the flow across northern Australia was still dominated by strong easterlies. The surface streamlines during the third IOP reveal a quite different flow regime. There was now northerly flow across the equator over the maritime continent and a south-west to north-east oriented trough line across northern Australia. There was some debate amongst the forecasters whether this was a “real onset” of the monsoon, but certainly large scale wind regime, the characteristics of the convection and the low level westerly winds at Darwin were consistent with this being a true monsoonal period [Holland, 1986; Drosdowsky, 1996]. Note that the eastern part of tropical Australia was still in westerly conditions.
These transitions are evident at Darwin in the mean soundings for the 3 IOPs (Figure 3). The mean boundary layer temperature and humidity increases between October and November, while the boundary layer temperature drops and the moisture becomes much deeper with the reversal of the low level flow with the monsoon conditions in December. Below 5 km the static stability also systematically increases in December. In all cases, Katherine (not shown) was warmer and drier, reflecting its inland location. The near-surface winds were westerly throughout, consistent with the heat trough to the south, but the steering easterlies were clearly seen in the first two IOPs, with November being stronger than October. The monsoon trough was nearly centered on Katherine in the third IOP, and this is evident by the weak average zonal wind compared with the two northern sites.

The temperature and winds near the tropopause did not vary much across the three radiosonde sites. There were however distinct differences among the three IOPs. The easterly wind maximum moved consistently lower during the experiment, with 20 ms$^{-1}$ easterlies as low as 16 km by the December IOP. The tropopause height itself only varied slightly during the experiment and across the sites, but was slightly higher during the November IOP compared with the others. This is probably a reflection of the deeper convection. The coldest tropopause temperatures were also seen during the November IOP, with the minimum temperature about 5°C less than during October. The monsoonal December soundings were midway in between.

As discussed above, the focus of the experiment was on the generation of gravity waves by deep convection. Before any specific examples are discussed, some metrics of convective activity in the area and significant events during the IOPs will be discussed. The first of
these is the percentage area of reflectivity greater than 5 and 40 dBZ (Figures 4, 5, 6). These thresholds represent the detectability limit at large range for no noisy data and a nominal threshold for active convective cells respectively. The data from IOP1 shows just a few convective events and these do not reach to great altitudes. There was a significant island thunderstorm on October 15, but in the main this IOP is characterized by limited convective activity.

The conditions in the second IOP were far more convectively active (Figure 5). During IOP2, several days show a double peak or broad peak. These correspond to about 06 UTC (1530 LT) when the afternoon convective storms occurring near the coastal areas maximize and a second peak in the early evening when squall lines propagating from the east move into the radar region. By this time the squalls are beginning to decay, but it is seen in the upper panel of Figure 5 that these squall lines cover significantly more area than the isolated afternoon convection. In general, these do not occur every day, but were frequent during this IOP. A second feature that can be seen on close examination is a local minimum in cloud cover between 5 and 10 km. The low level maximum occurs earlier and includes the shallow convection and the upper level includes significant anvil cloud from the very deep cases (and leaves a local minimum in between). The maximum cloud height and the intensity of convection within these lines may be as great as the intense Hector storms over the Tiwi Islands.

The summary of the radar data for IOP3 is shown in Figure 6. There are several features that are quite different from IOP2. The cloud tops are not as high, the maximum reflectivities are lower (Figure 7) and decrease much more rapidly with height above the freezing level, but the areas of intense rainfall are similar. The diurnal signature is now
much weaker with maxima in activity spread throughout the day. This weakening of the diurnal cycle and a shift towards night is consistent with the much more maritime characteristics of the convection seen during the Australian monsoon [e.g. Keenan et al., 1989]. IOP1 shows generally small rainfall amounts tied very closely to the coastal regions. The totals during IOP2 are much higher, with significant totals falling off-shore as the Hector storms moved off the Tiwi Islands and squall lines traversed the area. By IOP3, with the monsoonal conditions, the rainfall is generally wide-spread with the maximum accumulations off-shore.

The vertical profiles of reflectivity are also very different between the latter two IOPs (Figure 7). In the build-up season the profile of the maximum reflectivity generally has more intensity and decreases more slowly with altitude. In particular, the reflectivity drops off quite abruptly above the freezing level in the monsoon case (IOP3), indicating weaker vertical motions. This is very characteristic of oceanic convection and is also seen by significantly less lightning activity during monsoonal flow conditions [Petersen et al., 1996]. Another consistent feature among Figures 4 to 7 is that the highest altitude of the echoes is a maximum during the build up (IOP1 and 2) and drops with the onset of the monsoon (IOP3).

There is a clear contrast in the modulation of convective activity between IOP2 and 3. There is a distinct diurnal modulation of convection in the former, while the diurnal signatures are much weaker in the monsoon case; so much so that a diurnal composite is not statistically meaningful for the latter case as the record is too short and singular events would bias the results. However, the diurnal variation of convection during IOP1 and IOP2 was so strong that several interesting features are apparent in a diurnal composite.
Figure 8 shows such a composite of the area covered by reflectivities greater than a 5 dBZ threshold for IOP2; the pattern for IOP1 is very similar although the areas are smaller (not shown). In IOP2, the afternoon peak is smaller in the cloud area than the early evening peak in convection corresponding to the squall line passages and area of active convection. The first peak in the active convection is from afternoon thunderstorms, such as Hector, while the latter peak in area is associated with squall lines entering the area in the early evening, local time. This figure also clearly shows the lag between the maximum in convective activity and subsequent stratiform rain and remnant cloud. The squall lines cover the region with a much more extensive cloud cover than the afternoon convection. A smaller peak is also evident in the morning local time (∼15-20 UTC). This is associated with relatively weak and shallow convection that forms offshore.

To conclude this section, a sample of radar results from a single day typical of IOP2 are presented. Figure 9 displays the maximum reflectivity as a function of height as Hector developed over the islands on 15 November. There is a distinct stepwise character to the increases in storm height. The initial convection is relatively shallow with storm tops between about 7 and 10 km. Note that this is after the even earlier cumulus congestus phase prior to the onset of intense precipitation [e.g. Carbone et al., 2000]. The rapid growth to very deep storms occurs after the merger of storm cells. This is an integral part of the Hector lifecycle [Simpson et al., 1993] and results in very rapid increases in storm intensity as measured by maximum reflectivity, storm height and area. The step-wise growth shown in this figure was seen in all the Hector cases in the first two IOPs. The duration of the most intense convection is of the order of an hour. In this example there is a second maximum in storm height. This was associated with a group of cells that
developed along the sea breeze on the south coast to the east of the main complex (Figure 10).

The storm structure in the mature phase on 15 November shows a major convective complex on the western end of the islands (Figure 10). The reflectivities reached $\sim 60$ dBZ and the major merged cell complex was about 15 km across. At this time the storm tops were reaching to about 19 km (Figure 11) and an extensive anvil cloud had developed, primarily on the south side (the upper level winds were northerly to augment the strong divergence at the top of the storm). This anvil cloud eventually extended all the way to Darwin. There is also a clear over-shoot in the storm top at this time, consistent with the very strong vertical motions in this storm. An indication of the presence of large amplitude updrafts is the extensive region of a rain/hail mixture detected in the C-Pol classifications. This is only seen when the vertical motions near the freezing level exceed about 10 ms$^{-1}$ [May and Keenan, 2003].

In terms of the potential for the initiation of large gravity waves, the horizontal scale of the heating was of the order of 10 km. Rapid vertical development through the depth of the troposphere occurred over periods of $\sim 15$ min. This type of rapid development and intensification was also documented in detail by May et al [2002] for non-Hector storms developing on sea breeze convergence lines.
5. DAWEX Wind and Temperature Observations and Concurrent Meteorological Analyses

Since the prevailing wind and mean temperature structure can have profound effects on the generation and propagation of IGWs, the observations of temperature and prevailing wind from radiosondes and the BL and MF radars during DAWEX will be described here. These results are compared with concurrent global troposphere-MA analyses from the United Kingdom Meteorological Office (UKMO). For the purposes of illustration, results from IOP2 are used. This coincided with the most intense Hector events.

5.1. Boundary-layer radar

The boundary layer radar operated in two height modes. The low mode used a 0.75 µs pulse length, equivalent to a 100 m height resolution, to cover the lowest 3.5 km of the atmosphere. Data were sampled every 100 m. The high mode used a 3 µs pulse (600-m resolution) with data oversampled every 300 m. This mode covered the region above 2 km, with measurements often extending to 10 km in the humid atmosphere.

As an example of the BL radar observations, Figure 12 shows zonal winds formed by compositing hourly winds over the whole IOP2 period. In the lowest 700 m of the atmosphere the winds were eastward with a mean velocity of \( \sim 1-2 \text{ ms}^{-1} \), although during the period 20 to 5 hr UT (6 to 12 LT) the speed was essentially zero. Above 700 m the zonal component was westward with a mean shear of \(-6.5 \text{ ms}^{-1} \text{km}^{-1}\) so that the zonal component peaked at \(-15 \text{ ms}^{-1}\) at an altitude of 3 km.

The mean meridional winds (not shown) during IOP2 were northward and weak, rarely exceeding 2 ms\(^{-1}\). However, in a 1 km thick layer centered at an altitude of 4 km the meridional component reached 6 ms\(^{-1}\).
5.2. Radiosonde and UKMO comparisons

The radiosonde observations from Pirlangimpi, Darwin and Katherine had excellent height resolution (\(\sim 5\)–\(10\) m) and usually extended to above \(30\) km. While the radiosonde data are excellent for studying waves in the vicinity of these sites it is desirable to extend the wind and temperature fields to higher altitudes and a wider range of latitudes so that gravity wave ray tracing and full wave calculations can be undertaken. As the basis for an overall climatology for the IOPs, winds and temperatures derived from the UKMO analyses were compared with the radiosonde data. The UKMO data are supplied on a \(2.5^\circ \times 3.75^\circ\) latitude–longitude grid for each day at \(12\) UT at \(22\) pressure levels extending from \(1000\) hPa to \(0.31\) hPa (\(\sim 56\) km). UKMO data averaged over the each IOP interval and corresponding to a longitude of \(131^\circ\)E were compared with the observations made at each of the three sonde sites. Figure 13 gives an typical example of a comparison for IOP2 at Darwin. The temperatures agree extremely well, deviating by only few degrees at most. The zonal winds also agree well, although in the troposphere the UKMO values are \(\sim 3\) ms\(^{-1}\) more eastward than the radiosonde values. In the lower stratospHERE the UKMO winds also underestimate the peak amplitude of the easterly and westerly jets that are associated with the QBO; this is a common bias seen in global meteorological analyses. The meridional winds (not shown) in the UKMO analyses were very small, in agreement with the radiosonde observations.

5.3. Wind and temperature climatologies

The overall good agreement seen in this example and in the other IOPs shows that the UKMO data are suitable for constructing wind and temperature climatologies up to near the stratopause. Extending these fields up to heights above \(100\) km is more difficult as
there are no meteorological analyses available on a daily basis for the mesosphere/lower thermosphere. To extend the UKMO data it was decided to use the wind climatology from the Upper Atmosphere Research Satellite (UARS) atmospheric reference project (URAP) \cite{Swinbank and Orland, 2003}. URAP combines winds measured by the High Resolution Doppler Imager (HRDI) on UARS in the mesosphere and lower thermosphere with winds from the ground to near the stratopause derived from the UKMO assimilations. Monthly mean zonally-averaged winds are provided at the SPARC data center (http://www.sparc.sunysb.edu) for the period November 1991 to December 1999. For each IOP the historical URAP dataset was searched to find months where the winds best matched the DAWEX period UKMO data in the stratosphere and the DAWEX MF radar observations in the mesosphere. For example, in November 1995 the QBO was in a very similar phase to that observed in November 2001 for IOP2, and also the URAP winds at 35°S agreed well with the observed mean wind profile from the Adelaide MF radar during IOP2. To construct a mean wind climatology for IOP2 the URAP data were first interpolated onto the same height and latitude grid as the UKMO assimilation data and the URAP data from 0.1 hPa and above then merged with the UKMO data for IOP2. A similar procedure was used to obtain a temperature cross-section using the November zonal-mean COSPAR reference climatology, CIRA-86, for the heights above those for which UKMO data are available. The resulting latitude-height plots are shown in Figure 14. Here the heights are given in log-pressure coordinates, \( z = H \ln(1000/p) \), with \( H = 7 \) km.

Atmospheric tides become important above a height of about 70 km, and dominate at airglow altitudes near 90 km. It is therefore important to include tidal effects in
the climatologies, especially for the meridional wind component which otherwise would be very small. The MF radars provide coverage of the tidal winds at Katherine and Adelaide and show that, in general, the diurnal tide is dominant. In IOP2 for example, amplitudes of $\sim 35 \text{ ms}^{-1}$ and $\sim 40 \text{ ms}^{-1}$ at an altitude of 86 km were found at Adelaide and Katherine, respectively. The phase change with height indicated a vertical wavelength of approximately 25 km, indicative of the (1, 1) mode.

The Global Scale Wave Model (GSWM00) [e.g. Hagan et al., 1999] was used to incorporate tidal effects into the climatology. This model in general agrees well with tidal parameters measured in the subtropics and tropics using MF radars, especially for the diurnal tide [Vincent et al., 1998b]. First, the radar results were used to 'calibrate' GSWM by adjusting the amplitudes and phases to match the radar values. In practice the adjustment in phase was only 2-3 hr, but the observed amplitudes were approximately double the model amplitudes. Then climatologies were produced as a function of time, height and latitude by combining the modified GSWM output with the basic climatologies described above. It is recognized that non-migrating tides might cause longitudinal variations in tidal parameters [e.g. Hagan and Forbes, 2003], but nevertheless these climatologies provide reasonably robust wind and temperature fields to study gravity wave propagation and ducting during DAWEX.

To illustrate the results of merging the tides with the mean wind and temperature fields we show latitude-height plots corresponding to the sunset-to-dawn period from 1800 LT (0830 UT) to 0600 LT (2030 UT), which encompasses the airglow observations. Figures 15 and 16 show the zonal and meridional wind components and Figure 17 the temperatures at these times. In the latitude band of interest between $10^\circ S$ and $30^\circ S$ the effects of the tide
on temperature are either to strengthen or to weaken the vertical temperature gradients in the MLT, thereby modulating the local buoyancy frequency. However, because the (1, 1) tidal winds reach their maximum amplitude in this region, wind filtering effects are likely to play a more important role in determining which waves reach the MLT and their propagation characteristics within the MLT. In particular, waves propagating southward (poleward), as are often seen in summer near 85-90 km [Walterscheid et al., 1999], will encounter quite different conditions near sunset than at dawn. Figure 16 shows that at 1800 LT the meridional winds are northward near 85 km, so that southward propagating waves will be Doppler shifted up in frequency. Near dawn, when the winds in this region are southward, southward propagating waves will be shifted down in frequency and so are more likely to encounter critical levels.

In summary, the composite middle atmosphere wind and temperature fields deduced for the three IOPs can be used to deduce the intrinsic properties of waves observed in airglow and for ray-tracing studies to investigate possible source regions and wave ducting.
6. Discussion and Outlook

The field campaign was successful in obtaining most of the expected observations. The simultaneous deployment of six airglow imagers within a single region was unprecedented.

Many of the data taken during DAWEX are already available to the community. The results of individual balloon soundings in each IOP, the wind data from the Katherine radar, and figures produced from nightly airglow imager data at Katherine and Darwin can all be found at http://hermes.physics.adelaide.edu.au/atmospheric/dawex/links.html.

The data taken during DAWEX are now being analyzed and the first fruits of this analysis are discussed in the papers in this Special Issue. The DAWEX data have also stimulated detailed numerical modeling work, and once again some initial results are presented in papers in this issue.

There is interest among DAWEX participants in designing and conducting future field campaigns focussed on convection and MA IGWs. Such experiments might be performed in a number of locations throughout the world, but the DAWEX participants feel that there is scope for a more ambitious campaign focussed once again on Northern Australia during the monsoon transition period. DAWEX was a somewhat modest experiment in terms of resources employed. A future experiment would benefit greatly by extending the observational capabilities available for DAWEX. Valuable additions would be provided by Rayleigh lidars to obtain information about wave fluctuations in the 30-70 km height range, and also by deployment of airglow imagers on aircraft to allow a broader geographical coverage of the airglow observations. An experiment that could extend over a long period of time would also be useful, as it would allow sampling of days with a wide variety of weather situations. It is noteworthy, for example, that the Austral spring season of 2002
featured at least one day with a strong Hector storm that was rather isolated from any other significant convection, a situation that did not occur so clearly during the DAWEX IOPs in 2001.

The unique character of the pre-monsoon Hector convection over the Tiwi islands could also serve as a focus for a much more ambitious experiment with broader scientific aims. The predictable and somewhat isolated nature of the Hector convection makes it reasonably straightforward for aircraft to sample both the entrained air at the base of the convection and the outflow in the cloud anvil in the upper troposphere. Thus Hector might serve as a case study of the effects of deep tropical convection on atmospheric transport, chemistry, microphysics and radiation, as well as on wave dynamics.

Acknowledgments. The contributions of students and staff from a number of institutions in support of the DAWEX campaigns are gratefully acknowledged. The efforts of Ross Christmas for his support of the radiosonde launches are especially appreciated, as are those of Ken Glasson for his work in support of the radar operations. This work was supported in part by grant A1003317 from the Australian Research Council. The International Pacific Research Center is sponsored in part by the Frontier Research System for Global Change. Part of this work was supported by the US DOE Atmospheric Radiation Measurement (ARM) Program.

References


Crook, N.A., Simulation of convective storms over the Tiwi Islands and comparison with observations from MCTEX. *Australian Bureau of Meteorology Rep. 64* (P.J. Meighen and J.D. Jasper, eds), 7-10, 1997.


Figure 1. Map of the Darwin region. The circle shows the approximate coverage of the Bureau of Meteorology’s C-Pol radar.

Figure 2. Map showing the location of airglow imagers. The ovals show the approximate coverage of each imager at an altitude of 90 km.
Figure 3. Profiles of the mean temperature (top panels), relative humidity (middle) and zonal wind component (bottom) taken from the Darwin soundings during DAWEX. Data from IOP1 (October) is dotted, IOP2 (November) is solid and IOP3 (December) is dot-dashed.
Figure 4. Time-height series of the area within a hundred km radius of Darwin with reflectivity exceeding 5 dBZ for IOP1 given as a percentage of the total area (top). This demonstrates the large areas of cloud generated by afternoon convection and squall lines. The lower panel shows a time series of the reflectivity exceeding 45 dBZ at a height of 2 km, highlighting the most intensely convective periods.

Time is in UTC (LT is UTC+9.5).
Figure 5. As for Figure 4, but for IOP2.

Figure 6. As for Figure 4, but for IOP3.
Figure 7. The maximum reflectivity at each height and time has been calculated and the 95 percentile of the distribution of reflectivities with time computed. There are profiles of the 95 percentiles of the maximum reflectivity for IOP1 (dotted), IOP2 (solid) and IOP3 (dash-dotted).

Figure 8. Diurnal composite of the data presented in Figure 5 showing the diurnal variation in cloud cover and convective activity. The scale is in percentage of the total area covered by reflectivity greater than 5 dBZ within a radius of 100 km from the radar. Local noon is at 02:30 UTC.
Figure 9. Time-height cross-section of the maximum reflectivity observed over the Tiwi Islands on 15 November 2001. Note that this includes any cell so this is NOT the life cycle of a particular convective element, but rather the summary of the most intense elements at any one time. The onset of deep convection is seen just after 0300 UTC (1230 LT) with very deep convection beginning about 0510 UTC (1440 LT).
Figure 10. Constant altitude ($z = 3$) km cross-section of the radar reflectivity calculated from the radar volume scan over the Tiwi Islands at 0620 UTC, 15 November 2001 (1550 LT). The scale is in km from the radar at Gunn Point. The reflectivity units are dBZ.

Figure 11. RHI cross-sections through a Hector at 0610 UTC, 15 November 2001. The top panel is the reflectivity and the bottom panel represents a summary of the microphysical classification. The number of types is reduced for clarity. Type 1 is rain, 2 is snow and 3 is graupel, hail and rain-hail mixtures. Most of type 3 in this case is hail and rain-hail mixtures.
Figure 12. Hourly average zonal winds during IOP2 derived from VHF boundary layer radar. The dashed lines indicate negative (westward) winds. High mode (top), low mode (bottom)
Figure 13. Comparison of mean temperature and zonal winds derived during IOP2 from radiosonde (dashed) and UKMO assimilation (solid) during IOP2.
Figure 14. Top: Latitude-height cross-section of zonal winds for IOP2. Dashed lines indicate negative (westward) winds. Bottom: Latitude-height cross-section of temperature for IOP2
Figure 15. Estimated zonal winds including tides. Right: 1800 LT (0830 UT). Left: 0600 LT (2030 UT).

Figure 16. As for Figure 15, but for the meridional wind component.
Figure 17. As for Figure 15, but for temperature.
### Table 1. Instruments used during DAWEX.

<table>
<thead>
<tr>
<th>Institution (PI)</th>
<th>Instrument</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>U Adelaide (Vincent)</td>
<td>VHF boundary layer radar</td>
<td>Pirlangimpi</td>
</tr>
<tr>
<td>U Adelaide (Vincent)</td>
<td>MF radar</td>
<td>Katherine</td>
</tr>
<tr>
<td>U Adelaide (Vincent)</td>
<td>MF radar</td>
<td>Adelaide</td>
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<tr>
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<td>Airglow imager (OH, O$_2$)</td>
<td>Alice Springs</td>
</tr>
<tr>
<td>Aerospace Corp (Hecht)</td>
<td>Airglow imager (OH, O$_2$)</td>
<td>Adelaide</td>
</tr>
<tr>
<td>U Illinois (Swenson)</td>
<td>All-sky imager (OH, O$_2$)</td>
<td>Katherine</td>
</tr>
<tr>
<td>U Nagoya (Shiokawa)</td>
<td>Mesosphere/Thermosphere imager (OH, O)</td>
<td>Darwin</td>
</tr>
<tr>
<td>Utah State U (Taylor)</td>
<td>All-sky imager (OH, O$_2$)</td>
<td>Wyndham</td>
</tr>
<tr>
<td>U Kyoto (Nakanura)</td>
<td>All-sky imager (OH)</td>
<td>Tanjungsari</td>
</tr>
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### Table 2. Location of observing sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
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<td>Tanjungsari</td>
<td>(6.9°S, 107.9°E)</td>
</tr>
<tr>
<td>Pirlangimpi</td>
<td>(11.4°S, 130.5°E)</td>
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<tr>
<td>Darwin</td>
<td>(12.5°S, 130.9°E)</td>
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<tr>
<td>Gunn Point</td>
<td>(12.3°S, 131.0°E)</td>
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<tr>
<td>Katherine</td>
<td>(14.5°S, 132.3°E)</td>
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<tr>
<td>Wyndham</td>
<td>(15.3°S, 128.1°E)</td>
</tr>
<tr>
<td>Alice Springs</td>
<td>(23.4°S, 133.5°E)</td>
</tr>
<tr>
<td>Adelaide</td>
<td>(34.4°S, 138.3°E)</td>
</tr>
</tbody>
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