SCOUT-O3/ACTIVE High-altitude Aircraft Measurements around Deep Tropical Convection

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A multinational field campaign in Australia studied the effect of deep convection on the composition of the tropical tropopause layer.

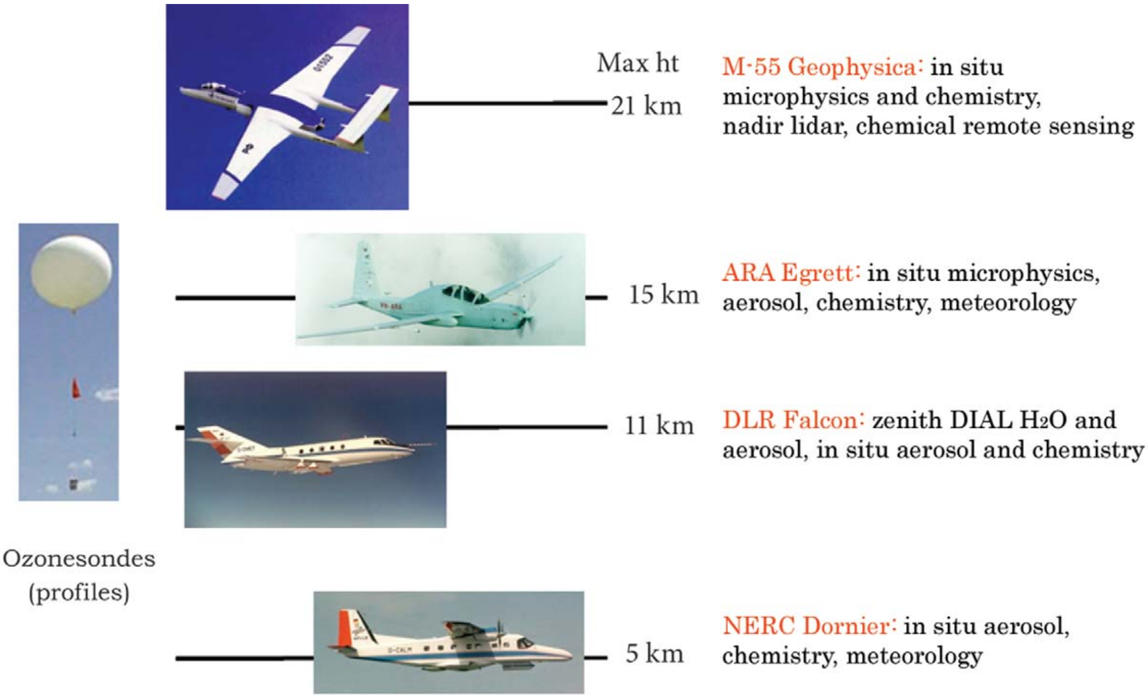

FIG. 1. Montage showing the aircraft used in the campaign, with a brief description of their function and altitudes of operation.

This article describes the Stratospheric–Climate Links with Emphasis on the Upper Troposphere and Lower Stratosphere (SCOUT-O3) and Aerosol and Chemical Transport in Deep Convection (ACTIVE) field campaign conducted in Darwin, Australia (12.47°S, 130.85°E), from 10 November to 10 December 2005, to investigate the transport of water vapor, aerosols, and chemicals into the tropical upper troposphere and lower stratosphere (UTLS). The campaign involved four aircraft (Fig. 1) equipped with a variety of in situ and remote sensing instruments, with ancillary measurements from ozonesondes. These observations were supported by an extensive network of ground stations, including a polarimetric weather radar (Keenan et al. 1998) and a lightning interferometer network (Betz et al. 2004). Measurements were made in the vicinity of deep convection (the so-called Hector storms, which appear most days over the Tiwi Islands, north of Darwin), and also in clear air well away from convection. Aircraft flight patterns ranged from direct penetrations of convective turrets and anvils to long survey flights in air well away from convection. The ground-based support data provided information on the intensity and microphysical structure of the parent convection.

The thermal structure of the tropical troposphere is determined by radiative–convective equilibrium up to 12–14 km, which is the level of maximum outflow from convective storms (Folkins 2002). Above this level, convective outflow drops off with altitude, and at the cold point tropopause, the outflow is very much reduced (Highwood and Hoskins 1998; Thuburn and Craig 2002). The layer of the tropical atmosphere between the main convective outflow and the cold point tropopause is known as the tropical tropopause layer (TTL). At some altitude within it, the net radiative heating changes from cooling to warming. This is around 15 km in clear air, though it depends quite sensitively on the cloud cover in and below the TTL. Above this altitude, large-scale dynamics dominate and the corresponding vertical diabatic transport is a slow background on top of which rapid adiabatic oscillations occur. Air will tend to ascend slowly into the tropical middle stratosphere, although there is some isentropic exchange with the extratropical lowermost stratosphere (Chen 1995; Levine et al. 2006). This part of the TTL forms the base of the Brewer–Dobson circulation, determining the eventual composition of the global stratosphere.

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There has been considerable discussion over the years as to whether a globally significant amount of air is transported into the stratosphere through deep convection (e.g., Newell and Gould-Stewart 1981; Danielsen 1993; Sherwood and Dessler 2001; Holton and Gettelman 2001). Some studies show that a subset of the most intense cells reaches the height of the surrounding cold point and frequently appears to have significant overshoot (e.g., Liu and Zipser 2005; May and Ballinger 2006). One of the aims of the SCOUT-O3/ACTIVE campaign was to identify air that remained in the stratosphere following such deep overshooting convection. Quantifying the contribution of air lofted in convection compared to that transported over much longer distances in the TTL is important for understanding the water vapor and trace gas budgets in the stratosphere.

Below the level of zero net radiative heating, convective transport becomes increasingly dominant. Convection is fast and chemical reactions take place in cloud droplets or on ice crystals; thus, air transported by deep convection to the TTL has distinctive chemical properties. Measurements of trace gases with a wide range of lifetimes (from hours to decades) can be used to understand the dynamical and chemical processes that govern their distribution and input into the stratosphere. Short-lived chemicals originating near the surface can be deposited virtually unchanged at high altitudes, for example, the source gases for halogen radicals (particularly bromine and iodine), which may destroy ozone in the TTL and the lower stratosphere (see chapter 2 of WMO 2002). Lightning in deep convection generates copious amounts of NO_x (Huntrieser et al. 2002), which, with hydrocarbons and CO lifted from a polluted boundary layer, can generate ozone in the TTL. The ACTIVE and SCOUT-O3 missions were designed to investigate both convective and large-scale transport and to distinguish their relative contribution to TTL composition. The missions were complementary, but had somewhat different foci as follows:

i) The transport of water (as vapor and ice) into the stratosphere was a key focus of the SCOUT-O3 Darwin campaign. One minor, but indispensable, channel of the global hydrological cycle occurs in the TTL, where cirrus clouds form and water is transported across the tropopause. Tropical thunderstorms inject relatively moist air into the TTL. This moist air moves away from storm centers in the readily recognizable anvils of the storms, which can exist for hours after the initiating storm has dissipated. Most, but by no means all, of this moist air injection occurs at the base of the TTL, as we have just discussed. Studies using global reanalysis datasets suggest that the tropical west Pacific–Maritime Continent region in Northern Hemisphere winter is a "hot spot" for air entering the TTL, for air crossing the tropical tropopause, and for air encountering the coldest temperatures (Fueglistaler et al. 2004, 2005). Generally the lower the temperature experienced by an air parcel the lower its water content will be.

ii) The transport and transformation of aerosol by deep convection was a major focus of the ACTIVE component of the campaign. Soluble aerosol is removed by precipitation during convective uplift, but not all aerosol is soluble. Trace gases transported into the anvil may be oxidized to nucleate new ultrafine particles (Raes et al. 2000); indeed, Twohy et al. (2002) found condensation nuclei concentrations more than an order of magnitude greater within a thunderstorm anvil than outside it. Cirrus clouds in the TTL region have a substantial impact on the Earth's radiation budget, and their properties depend on the nucleating aerosol population. ACTIVE/SCOUT-O3 addresses the scarcity of systematic measurements of aerosols in and around tropical convective outflow.

iii) Of importance to both ACTIVE and the SCOUT-O3 Darwin experiment was the nature of clouds observed in the TTL. ACTIVE's focus was on the main convective outflow and the nature of particles observed therein as a function of convection type (whether isolated deep thunderstorms or more extensive maritime convection). SCOUT-O3's focus was on how cirrus clouds (injected by convection or formed in situ) change the transport of tracers through the TTL (e.g., by changing the height where the net radiative heating changes from cooling to warming).

These investigations were complemented by the campaign conducted by ACTIVE and the Tropical Warm Pool International Cloud Experiment (TWP-ICE) in the monsoon period after Christmas (May et al. 2008).

THE EXPERIMENT. The rationales of both ACTIVE and the SCOUT-O3 campaign spoke strongly in favor of the investigation of tropical convection in a region where i) the convection is regular, ii) the convection is isolated, iii) aspects of the convection have already been documented, and iv) a good infrastructure exists to support the measurements. In the premonsoon period (mid-November–mid-December), convection in the Darwin area is dominated by single isolated storms. Spectacular examples occur over the Tiwi Islands north of Darwin (Fig. 2), due to convergence of sea

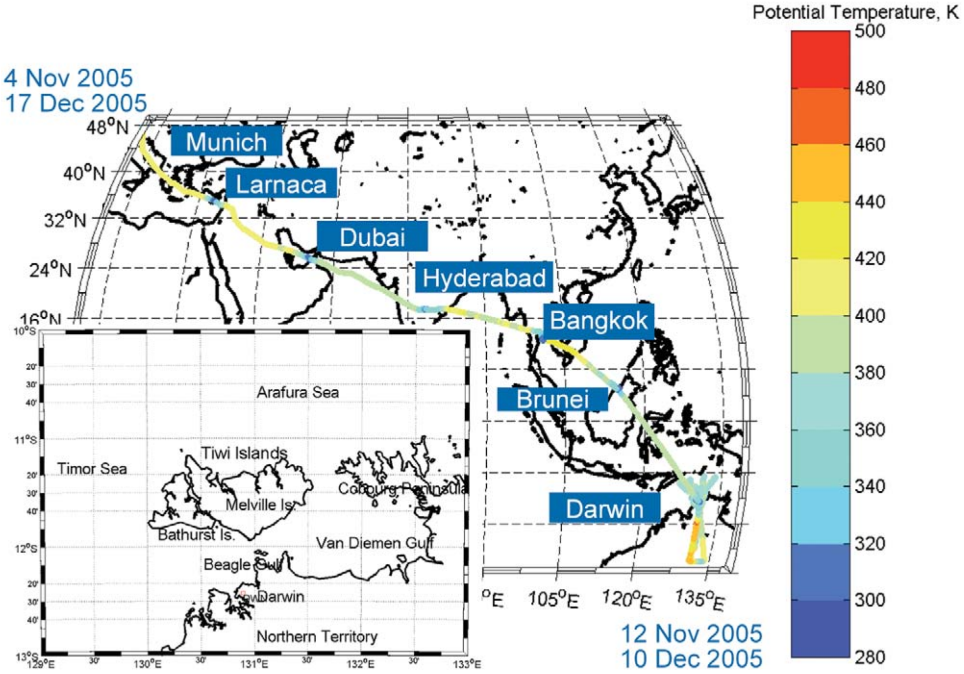


Fig. 2. Map of Darwin area, superimposed on the track taken by the Geophysica and Falcon on the transit flight from Germany and local flights from Darwin. Color shows the potential temperature of the Geophysica during flight.

breezes over the islands (Carbone et al. 2000). These are the Hector storms, which occur regularly over the islands in the afternoon or early evening. These giant thunderstorms reach (and sometimes penetrate) the synoptic tropopause at 17 km, thus directly injecting air into the TTL and tropical lower stratosphere (TLS). Their predictability and isolation also make them excellent natural laboratories for comparing the aerosol–chemical input to, and output from, the TTL, and for studying the transport of water near the tropopause. Aircraft can easily cross or circumnavigate the storms; coordinated flying is easier because pilots can often see the storm center and edges, and modeling the storms on the mesoscale is not such a formidable task as for more extensive, or less topographically locked, convection. Darwin also has excellent facilities to support a campaign of this type, including advanced radar systems operated by the Australian Bureau of Meteorology. This infrastructure is described more fully in the companion article (May et al. 2008).

The SCOUT-O3/ACTIVE campaign was first to study Hector storms in the premonsoon period with aircraft that observed the full altitude range from the bottom of the convective inflow to the top of the outflow. However, a number of previous campaigns in the Darwin area have investigated the nature of the convective storms and their impact on the TTL and TLS. In January–February 1987 (during the monsoon period), the National Aeronautics and Space Administration (NASA) ER-2 aircraft was deployed in Darwin for the Stratosphere–Troposphere Exchange Project (STEP) tropical experiment (Russell et al. 1993). This campaign found that air of recent tropospheric origin was transported into the stratosphere and dehydrated to water vapor concentrations consistent with local cold point tropopause temperatures (Russell et al. 1993; Danielsen 1993 and accompanying papers). More meteorological in focus was the Australian Monsoon Experiment (AMEX) (Holland et al. 1986), which coincided with STEP, the Island Thunderstorm Experiment (ITEX) in 1988 (Keenan et al. 1989), and the Maritime Continent Thunderstorm Experiment (MCTEX) in 1995 (Keenan et al. 2000). Measurements of the aerosol and chemical background in the Darwin area during the dry season were made during the Biomass Burning and Lightning Experiment (BIBLE) in 1998 and 1999 (Kondo et al. 2003). Of direct importance to the present campaigns was the Egrett Microphysics Experiment with Radiation, Lidar, and Dynamics in the Tropics (EMERALD-2) experiment conducted in Darwin in November 2002 to study the nature of cirrus clouds in the outflow of Hector. These experiments established the conditions that cause deep convection and showed that a multiaircraft experiment of the type described here was both feasible and likely to be scientifically fruitful when conducted from Darwin.

The ACTIVE component. ACTIVE is a consortium of eight institutions led by the University of Manchester and funded by the U.K. Natural Environment Research Council (NERC). Its main focus is on measurements of aerosol and chemical species in the inflow and outflow of deep tropical convection, and its secondary aim is to map out the overall distribution of these constituents in the Darwin region. To this end the following two aircraft were used: the NERC Airborne Research Facility Dornier-228 for low-level measurements (up to 4 km) in clear air around the storm base, and Airborne Research Australia's Grob G520T Egrett aircraft for measurements in the anvil outflow at 12–14 km. Details of the payloads of these two aircraft are given in Tables 1 and 2. The Dornier's instrument package made comprehensive measurements of aerosol size spectra and composition, meteorological variables, and chemical species, while the Egrett carried cloud physics probes in addition to determine the nature of ice particles in the anvil. Supporting measurements were made by 23 ozonesondes launched from the Darwin meteorological station during the campaign, giving ozone profiles into the stratosphere.

The specific scientific objectives of ACTIVE are as follows:

i) To relate measurements of aerosol and chemical species in the outflow of deep convection, and in the surrounding TTL, to low-level sources;
ii) to determine how deep convection modifies the aerosol population reaching the outflow, and thus evaluate its impact on cirrus nucleation in the TTL;
iii) to compare the concentration of aerosol and chemical tracers (with a range of lifetimes and origins) in the outflow with that in the background TTL, and therefore determine the contribution of convection to the composition of the TTL over Darwin;
iv) to use latitudinal surveys of tracers, together with high-resolution global models, to determine the contribution of large-scale transport to the composition of the TTL;
v) to compare the effects of isolated very deep convection with that of widespread but less penetrative convection on the composition of the TTL;

TABLE 1. Egrett payload.

Instrument	Measurement	Principal investigator
Basic meteorology and position	Pressure, temperature, wind, GPS (1 Hz)	Jorg Hacker, Airborne Research Australia
Droplet measurement technology (DMT) single-particle soot photometer (SP-2)*	Aerosol particle size distribution (0.2–1.0 μm), light absorbing fraction and composition	Hugh Coe, University of Manchester
2 × TSI-3010 condensation particle counter (CPC)	Total condensation particles > 10 and > 100 nm	Martin Gallagher, University of Manchester
DMT cloud, aerosol and precipitation spectrometer (CAPS)	Cloud-droplet spectrum, aerosol/small particle asymmetry, aerosol refractive index (diameter 0.3–2000 μm)	Andy Heymsfield, NCAR
DMT cloud-droplet probe (CDP)	Cloud particle size distribution (diameter 2–62 μm)	Martin Gallagher, University of Manchester
SPEC cloud particle imager CPI-230	Cloud particle/ice CCD images, (diameter 10–2,300 μm)	Martin Gallagher, University of Manchester
Buck Research CR-2 frost-point hygrometer	Ice-point temperature (0.05 Hz, ± 0.1°C)	Reinhold Busen, DLR
Open-path tuneable diode laser hygrometer	Water vapor concentration (1 Hz, ±1 ppmv)	Jim Whiteway, York University, Canada
Closed-path tuneable diode laser hygrometer	Water vapor concentration (1 Hz, ±1 ppmv)	Geraint Vaughan, University of Manchester
Vacuum UV fluorescence CO analyzer	Carbon monoxide (1 Hz, ± 2 ppbv)	Andreas Volz-Thomas, Forschungszentrum (FZ) Jülich
Miniature gas chromatograph	Halocarbons (Cl, Br, I; 3–6 min, ±5%)	Neil Harris, University of Cambridge
TE-49C UV ozone sensor	Ozone concentration (± 2 ppbv, 10 s)	Reinhold Busen, DLR
Automatic tube sampler (ATS); 15 samples per flight	C4–C9 nonmethane hydrocarbons, monoterpenes, OVOCs	Alastair Lewis, University of York, United Kingdom
NO and NO_2 chemiluminescent detector*	±200 ppt at 10 Hz; ± 30 pptv with 4-s integration	Andreas Volz-Thomas, FZ Jülich

*Alternates (only one flown at any time).

TABLE 2. Dornier payload

Instrument	Measurement	Principal investigator
Aventech AIMMS-20 probe	GPS position, pressure, temperature, relative humidity, winds, 1 Hz	David Davies, ARSF
Aerodyne aerosol mass spectrometer	Aerosol size and composition (30–2000* nm)	Hugh Coe, University of Manchester
TSI3010 condensation particle counter	Aerosol concentration > 10 nm, 1 Hz	Martin Gallagher, University of Manchester
Grimm optical particle counter model 1.108	Aerosol size distribution (0.3–2* μm, bins 0.1–0.2 μm, 0.16 Hz)	Martin Gallagher, University of Manchester
Ultra-high-sensitivity aerosol spectrometer	Aerosol size distribution (0.1–0.8 μm, 7.5-nm bins, 1 Hz)	Martin Gallagher, University of Manchester
DMT aerosol spectrometer probe ASP-100	Aerosol size distribution (0.2–2* μm, bins 0.03–0.5 μm, 0.1 Hz)	Martin Gallagher, University of Manchester
Forward scattering spectrometer probe (FSSP)	Aerosol and cloud-droplet size distribution (0.5–32 μm, bin 0.8 μm, 0.1 Hz)	Martin Gallagher, University of Manchester
Particle soot absorption spectrometer (PSAP)	Black carbon concentration (aerosol) (± 1 $\mu g\ m^{-3}$, 0.2 Hz)	Andreas Minikin, DLR
Filters	Coarse aerosol composition, whole flight accumulation	Keith Bower, University of Manchester
2B technologies model 202 ozone monitor	Ozone concentration (±2 ppbv, 0.1 Hz)	Alastair Lewis, University of York, United Kingdom
Aerolaser AL5003	Carbon monoxide concentration (± 1 ppbv, 1 Hz)	Alastair Lewis, University of York, United Kingdom
Automatic tube sampler (ATS), 15 samples per flight	C4–C9 nonmethane hydrocarbons, monoterpenes, oxygenated volatile organic compounds (OVOCs)	Alastair Lewis, University of York, United Kingdom
Chemiluminescence/catalysis	$NO/NO_x/NO_y$	James Lee, University of York, United Kingdom
Miniature gas chromatograph	Halocarbons (Cl, Br, I; 3–6 min, ±5%)	Neil Harris, University of Cambridge

*Upper bound limited by inlet efficiency.

vi) to determine the contribution of deep convection to the NO_x and O_3 budget in the TTL; and
vii) to measure how much black carbon reaches the outflow regions of the storms.

ACTIVE participated in both Darwin field campaigns, with SCOUT-O3 before Christmas and TWP-ICE afterward in January and February. Details of the latter are given by May et al. (2008), but the aim was to study isolated island convection in the first campaign and more widespread monsoon convection in the second. In fact, both monsoon and isolated convection were experienced in the second campaign and ACTIVE will be able to compare the Hector storms from the premonsoon and monsoon break periods.

The SCOUT-O3 component. The SCOUT-O3 Tropical Aircraft Experiment Darwin 2005 (hereafter SCOUT-O3 Darwin) is part of the SCOUT-O3 Integrated Project of the European Commission (online at www.ozone-sec.ch.cam.ac.uk/scout_o3/). The overarching aim of SCOUT-O3 as a whole is to predict the evolution of the coupled chemistry–climate system, with emphasis on ozone change in the lower stratosphere and the associated UV and climate impact. SCOUT-O3 Darwin feeds into the following three aspects of this overarching aim:

- to understand the tropical mechanisms of troposphere-to-stratosphere transport (TST),
- to understand past changes in stratospheric trace gas concentrations and humidity, and
- to enable a prediction of future stratospheric trace gas concentrations and humidity.

This, in turn, led to the following objectives for the SCOUT-O3 Darwin experiment:

i) How does air undergo TST?
ii) Where is air transported from the troposphere to the stratosphere?
iii) How is air processed during its passage through the TTL and what is its composition?
iv) How is air dehydrated during TST?
v) How well do numerical weather prediction models represent mesoscale and large-scale transport processes in the tropical Pacific/Maritime Continent region?

Meeting these objectives requires measurements of the chemical composition of air in the TTL and in the TLS, particularly where air is just entering the TTL and where air is just entering the TLS. As already mentioned, large-scale modeling studies suggest that the tropical west Pacific/Maritime Continent is an important region for such transport into, and out of, the TTL; it is the region of coldest temperatures globally at these altitudes. During the campaign the lower-stratospheric winds were basically from the east so that air passing over Darwin area at tropopause level was from this region of coldest temperatures, giving the SCOUT-O3 aircraft the chance to sample air that recently entered the stratosphere. In addition, the vigorous island convection near Darwin provides a direct route for rapid injection of boundary layer air to the TLS (Danielsen 1993). Contrasting measurements made close to convection with those from farther away will allow the relative importance of convective and large-scale transport into the TLS to be assessed.

The SCOUT-O3 Darwin deployment consisted of the M-55 Geophysica aircraft and the DLR Falcon, flying out from central Europe to meet a small support team for logistics, weather prediction, and more general modeling. The transfer flights from Europe to Darwin represent an integral part of the campaign, extending the measurement coverage and permitting extra science missions. The aircraft payloads were somewhat different on transfer flights and local sorties; these are detailed in Tables 3 and 4, for the Geophysica and the Falcon, respectively. During the transfer flights, priority was given to remote sensing measurements of the TTL: water vapor measurements by upward-looking differential absorption lidar (DIAL) from the DLR Falcon, lidar aerosol measurements from the Falcon (zenith) and the Geophysica (nadir), and limb-scanning chemical measurements from the Geophysica. On the outward transfer flight, the Geophysica and Falcon were accompanied by a Swiss Lear jet, carrying a microwave spectrometer for the retrieval of stratospheric profiles of water vapor and ozone. Coverage of the tropical UTLS by the SCOUT-O3 Darwin transfer flights is summarized in Fig. 3, and discussed briefly at the end of "First results from two selected missions." During the local flights, priority was usually given to in situ measurements of water vapor, particles, reactive chemical species and tracers, at or just below the main anvil outflow altitude (Falcon), and from anvil top through the TTL to the lower stratosphere (Geophysica).

Satellite data were used to place the localized aircraft measurements in a larger-scale context. Most notably, the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) experiment onboard the European research satellite ENVISAT was operated in a special mode for the period and location of the SCOUT-O3 flights from Darwin and during

Table 3. Geophysica payload.

Instrument	Measurement	Principal investigator
Basic meteorology (UCSE)	Pressure, temperature, wind, position	Myasishchev Design Bureau, Zhukovsky, Moscow, Russia
Meteorology probe (TDC)	Temperature, wind (10 Hz, 0.5 K, 1 m s^{-1})	Genrikh Shur, Central Aerological Observatory (CAO), Dolgoprudny, Moscow, Russia
Microwave temperature profiler (MTP)	Vertical profile of temperature and potential temperature	Mike Mahoney, Jet Propulsion Laboratory, California
FOZAN chemiluminescence ozonometer	Concentration of ozone (1 Hz, 0.01 ppmv)	F. Ravegnani, Consiglio Nazionale delle Richerche (CNR), Bologna; A. Ulanovski, CAO
FISH fluorescence hygrometer	Concentration of total water (1 Hz, 0.2 ppmv)	Cornelius Schiller, FZ Juelich
FLASH fluorescence hygrometer	Concentration of water vapor (8 s, 0.2 ppmv)	Vladimir Yushkov, CAO
ACH frost-point hygrometer	Concentration of water vapor (60 s)	Vladimir Yushkov, CAO
SIOUX chemiluminescence detector	Concentration of NO, NO_y, particle NO_y (1 Hz, 10%)	Hans Schlager, DLR
HALOX chemical conversion fluorescence detector	Concentration of ClO and BrO (20/100 s, 20%/35%)	Fred Stroh, FZ Juelich
HAGAR gas chromatograph and IR absorption	Concentration of N_2O, F11, F12, halon 1211, SF_6 (90 s, 2%/4%); CO_2 (5 s, 0.5%)	Michael Volk, University of Frankfurt
ALTO tunable diode laser spectrometer	Concentration of CH_4 (3 s, 10%)	Francesco D'Amato, CNR
COLD tunable diode laser spectrometer	Concentration of CO (4 s, 9%)	Silvia Viciani, INOA
Whole-air sampler	Long- and short-lived source gases, trace gas isotopes	Thomas Röckmann, University of Utrecht
COPAS condensation nuclei counter	CN concentrations in three size bins, nonvolatile CN	Stephan Borrmann, University of Mainz
Forward scattering spectrometer probe (FSSP300 and FSSP100)	Size-speciated particles 0.4–40 μm	Stephan Borrmann, University of Mainz
Cloud particle imager	Particles > 100 μm	Stephan Borrmann, University of Mainz
Multiwavelength aerosol scatterometer (MAS)	Aerosol optical properties and concentration	Francesco Cairo, CNR
Microjoule lidar (MAL)	Aerosol and cloud profile below aircraft altitude	Valentin Mitev, Obs. Neuchatel
MIPAS infrared limb sounder	Vertical profile of H_2O, CH_4, N_2O, O_3, F11, HNO_3, and others, clouds	Cornelis Blom, FZ Karlsruhe
CRISTA-NF infrared limb sounder	Vertical profile of H_2O, O_3, F11, HNO_3, and others, clouds	Martin Riese, FZ Juelich
MARSCHALS microwave limb sounder	Vertical profile of H_2O, CO, and O_3	Brian Kerridge, Rutherford Appleton Laboratory, United Kingdom

the transfers from and to Europe, with enhanced coverage in the North Australian/Indonesian region. ENVISAT measures a large number of atmospheric trace gases and cloud parameters in the upper troposphere, stratosphere, and mesosphere with quasi-global coverage (Nett et al. 2001).

Flight patterns. The aim of the Dornier flight program was to characterize the aerosol and chemical input into deep convection. Because the focus of the field campaign was on Hector, most of the Dornier flights were conducted around the Tiwi Islands. Typically, the Dornier took off around midday, before the deep convection started, and measured profiles of composition and meteorological variables from 100 to 3200 m upwind, downwind, and north and south of the islands (consistent with the seabreeze circulation, temperature profiles north and south of the islands were consistently warmer than off the east and west coasts). This took about 2 h, after which time the remaining 2 h of the flight were used to fly around and across the island at constant altitudes chosen by

TABLE 4. Falcon payload.

Instrument	Measurement	Principal investigator
Basic meteorology [inertial navigation system (INS), GPS, five-hole probe, Rosemount]	Position, wind (1 m s^{-1} horizontal, 0.3 m s^{-1} vertical), temperature (0.5 K)	Andreas Giez, DLR
Lidar	Aerosol and cloud (backscatter and polarization) profile above aircraft (1 s, 10%)	Andreas Fix, DLR
Differential absorption lidar (DIAL)	H_2O profile above aircraft (60 s, 10%)	Andreas Fix, DLR
Absorption hygrometer	Concentration of total water (1 Hz, 0.3 g m^{-3})	Andreas Giez, DLR
FISH fluorescence hygrometer	Concentration of total water (1 Hz, 6%)	Cornelius Schiller, FZ Juelich
OJSTER tunable diode laser spectrometer	Concentration of water vapor (10 Hz, 10%)	Cornelius Schiller, FZ Juelich
Chemiluminescence detector (with converter for NO_y)	Concentration of NO and NO_y (1 Hz, 2 and 5 pptv)	Hans Schlager, DLR
Vacuum ultraviolet (VUV) fluorescence detector	Concentration of CO (5 s, 3 ppbv)	Hans Schlager, DLR
Chemical ionization mass spectroscopy	Concentration of SO_2	Hans Schlager, DLR and F. Arnold, University of Heildelberg
CN counter	Condensation nuclei (1 Hz, 10%)	Andreas Minikin, DLR
Filter sampler	Aerosol composition and size distribution	Martina Krämer, FZ Juelich

the on-board mission scientist to probe any distinctive layers (constant-altitude flight legs were the optimum choice for the aerosol mass spectrometer). Three survey missions were also conducted—two over Arnhem Land and a third around the Cobourg Peninsula, at the end of which an intercomparison leg was conducted at 3200 m flying in close formation with the Egrett.

Most of the Egrett flights concentrated on the outflow from Hector, typically flying reciprocal legs across the anvil outflow at three to four altitudes between 12,800 and 14,300 m, with a final along-anvil leg. Flights were designed to measure in clear air as well as in-cirrus cloud, to sample the transition between recently uplifted and background air. At the end of the campaign two survey flights were conducted—one to measure the NO_x left behind after the passage of a huge MCS, and one to measure the properties of aged, thin cirrus remaining in the TTL well away from convection.

The aim of the Falcon flight program was to characterize the TTL upwind of cirrus outflow, the TTL cirrus itself, and the aerosol and chemical output from deep convection. The first two of these targets were addressed remotely using the aerosol and water DIAL system; the output from deep convection was

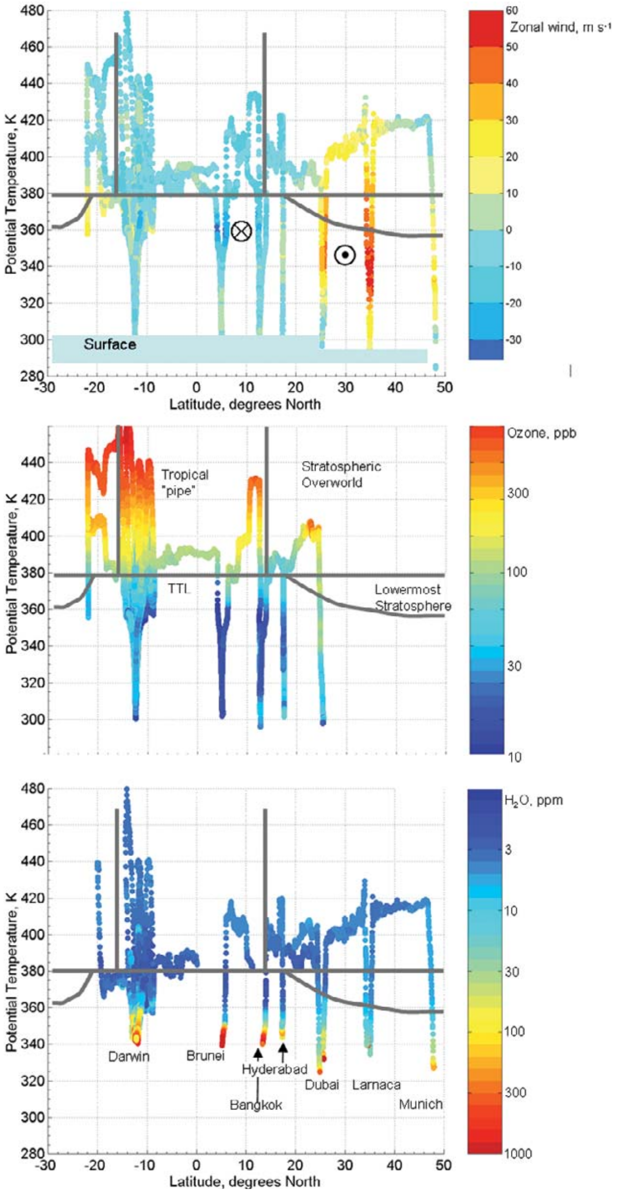


FIG. 3. Lat–potential temperature coverage of the SCOUT-O3 flights, with a schematic of atmospheric compartments overlaid. (top) Data points colored by wind speed. The Geophysica was in the region of the westerly subtropical jet between Lanarca (35°N) and Dubai (25°N; circle–dot symbol), and in the region of an equatorial easterly jet (circle–cross symbol) at Brunei (5°N). (middle) Data points colored by ozone mixing ratio (ppbv), and (bottom) data points colored by total water mixing ratio (ppmv).

investigated using in situ measurements complementary to those on the Dornier. Falcon flight patterns typically consisted of ascent to a holding pattern upwind of the Tiwi Islands at 11,600-m altitude, held until convection was well established, and then transects below the developing anvil followed by entry into the anvil itself.

The aim of the Geophysica flight program was to characterize the TTL under quiescent conditions and above convection. To characterize quiescent conditions, flights consisted of long cross-wind (i.e., north–south) flight segments between 14,600 and 18,400 m, often with final ascents to the operational ceiling of the aircraft of 20,000 m. For characterization of convection, sorties generally began with ascent to a holding pattern upwind of the Tiwi Islands, held until the convection was reaching its most intense phase, and then ascent to an altitude above the highest convective tower followed by slow descent toward, and penetration of, a tower. Sorties of this kind generally involved two or three of these tower interceptions; see Fig. 10 for an example of a Geophysica flight to characterize the TTL above convection. For all Geophysica flights, ascent and descent rates were made at 7.5 m s^{-1}, or less, giving time for accurate vertical profiles to be measured.

METEOROLOGICAL CONDITIONS. For most of the field campaign, the low-level flow around Darwin was dominated by strong easterly winds at 700 hPa originating in confluence along the Queensland coast (Fig. 4a). This easterly flow reached up to around 300 hPa. Near the surface, strong sea breezes developed during the morning, serving to initiate convection along lines parallel to the coast. The strong steering level flow advected these storms to the west, so that the Darwin area generally experienced thunderstorms in the evening. In addition, sea breezes from the Gulf of Carpentaria to the east of Darwin often developed into squall lines (extensive organized regions of convection, or mesoscale convective systems). Westward passage of these systems over Darwin, usually during the night, left behind a cooled and stabilized boundary layer, delaying the onset of convection the following day. Typical convective available potential energy (CAPE) values of 2000–4000 J kg^{-1} indicate a convectively unstable troposphere, while convective inhibition (CIN) of ~100–300 J kg^{-1} allows energy to build up in the boundary layer to be released in deep convection.

As previously mentioned, the Hector storms on the Tiwi Islands were a particular focus of the campaign. These deep storms develop through the interaction between sea breezes advancing from north and south of the islands with cold pools set up by earlier convection (Carbone et al. 2000). Visible satellite imagery depicts the development of these storms: early in the day (around 0900 LT) isolated boundary layer convection occurs all over the islands. As the sea breezes advance, the convection is swept into bands oriented east–west, and deepens. From midday onward, usually around 1400 LT, the interacting

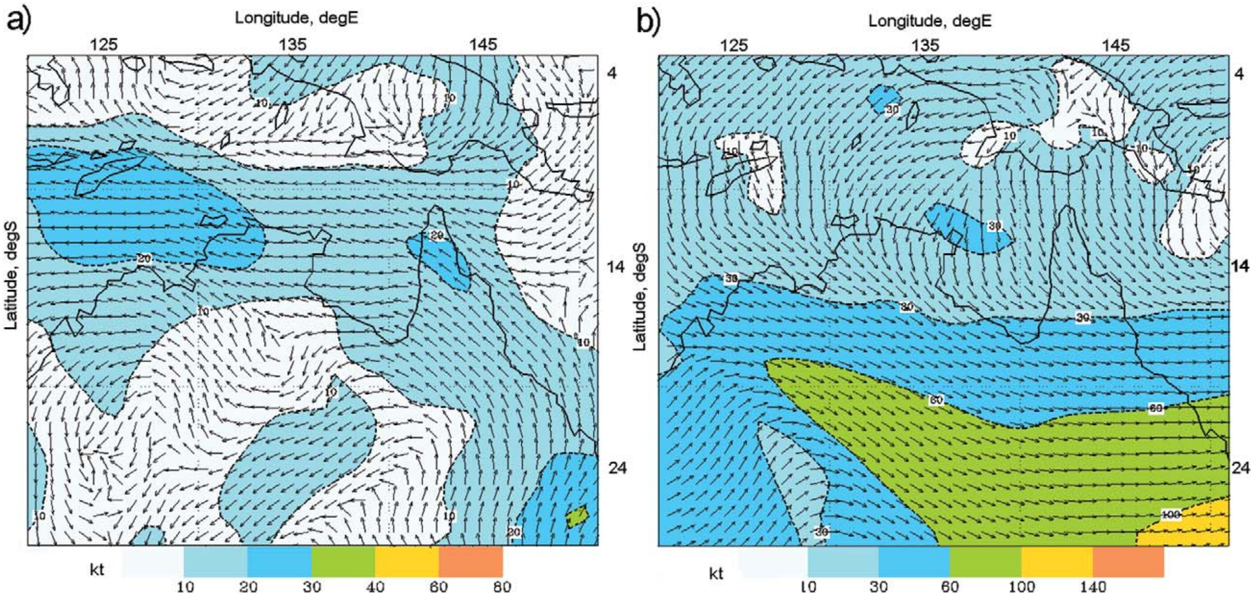


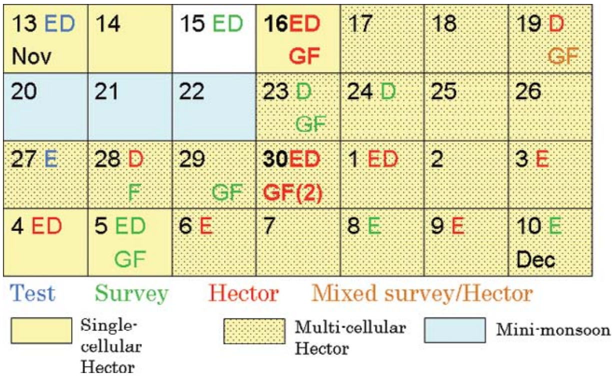
Fig. 4. Flow over Northern Australia (a) 700 hPa (the steering level) and (b) 200 hPa (the main convective outflow level) at 0000 UTC 16 Nov 2005. Colors denote wind speed (kt). Analyzed fields are from the Bureau of Meteorology's Extended Limited Area Prediction System (TXLAPS) model.

cold pools provide enough impetus to overcome the convective inhibition and initiate Hector.

In early November the very strong easterly winds at the steering level meant that the deepest convection was found over Bathurst Island, with isolated single-cell Hectors blown rapidly out to sea, where they decayed. The detached anvil resulting from such a case was intensively studied by the four aircraft on 16 November. Later in the season deep convection occurred all over the islands and multicellular storms were the norm, organizing into squall lines that propagated across the islands. The intensive case study of 30 November was of this type, when the Geophysica penetrated the tops of the convective turrets (at 18 km) and the Egrett probed the anvil outflow. Both of these days are further described below. A summary of the meteorological conditions during each day of the campaign, together with the flights of each aircraft, is given in Fig. 5.

For most of the field campaign the subtropical jet stream was well south of Darwin (Fig. 4b), and easterly winds increased in strength with altitude above 100 hPa. At the altitude of the main convective outflow (150–200 hPa) conditions were more complex. For the first half of November northerly winds prevailed (Fig. 4b), blowing the Hector anvils south toward the Darwin area. In December conditions were more variable, with some days having almost no background wind at these levels; the anvils on such days spread in all directions like mushrooms. An exception to these conditions was experienced during the period of 18–24 November, when pronounced Rossby wave activity occurred along the subtropical jet stream, pushing filaments of midlatitude air deep into the tropics over Darwin. At the same time the Queensland ridge retreated eastward, bringing westerly winds at middle levels over Darwin and monsoonal conditions at the surface with oceanic convection. Ozonesonde ascents during this period revealed ozone-rich layers of stratospheric origin around 7 km, contrasting markedly with the very uniform profiles measured the following week (Fig. 6).

An important feature of the premonsoon period was revealed by the Dornier aerosol and chemistry measurements. During the dry season, and extending into November, widespread biomass burning characterizes the top-end region (Russell-Smith et al. 2000); it is a custom of the native people to burn off surplus vegetation during this season, and other fires are started by lightning. As the season pro-



13 ED Nov	14	15 ED	16ED GF	17	18	19 D GF
20	21	22	23 D GF	24 D	25	26
27 E	28 D F	29 GF	30ED GF(2)	1 ED	2	3 E
4 ED	5 ED GF	6 E	7	8 E	9 E	10 E Dec

Test Survey Hector Mixed survey/Hector

Single-cellular Hector | Multi-cellular Hector | Mini-monsoon

Fig. 5. Table showing the type of convection occurring on the Tiwi Islands each day of the campaign, with the days that each aircraft flew. Joint missions of all four were performed on 16 and 30 Nov; D = Dornier 228, E = Egrett, F = DLR Falcon, and G = Geophysica. The Falcon and Geophysica made two flights on 30 Nov. Letters are colored according to the kind of flight undertaken on that day.

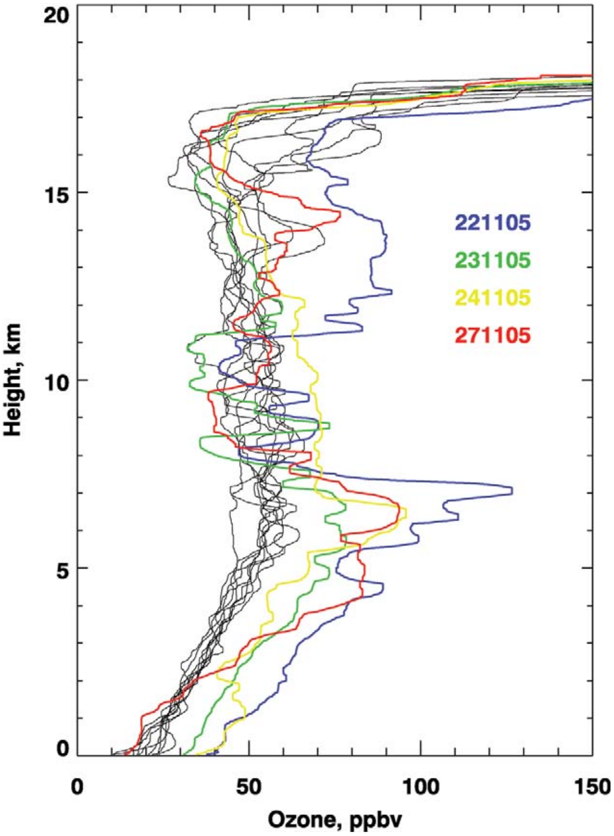


Fig. 6. Ozonesonde profiles measured from Darwin between 22 Nov (marked 221105) and 6 Dec. The nine profiles measured between 30 Nov and 6 Dec are shown in black; they show a remarkably consistent profile below 14 km with some variation in the TTL. The four colored profiles show the influence of Rossby wave breaking to the south of Darwin, with elevated ozone around 7 km and (on 22 Nov) in the TTL also. A profile measured on 13 Nov was consistent with the black profiles.

gressed, biomass burning abated, and by the second campaign, during the TWP-ICE experiment, very low aerosol concentrations were observed (less than 1 particle per cubic centimeter, for sizes > 300 nm). This change from polluted conditions at the beginning of November to very clean conditions in February (when meteorological conditions were similar to those of the premonsoon) offers us an unprecedented opportunity to study the impact of aerosols on deep convection and is one of the main avenues of research being pursued within ACTIVE.

Another remarkable feature of the meteorology was the large variation in tropopause temperatures over Darwin. A warm phase between 9 and 15 November was followed by a cold phase lasting up to 21 November with tropopause temperatures about 4°–6°C colder than before and with absolute values near −87°C. A preliminary analysis shows the presence of a large-amplitude Kelvin wave over the equatorial region with possibly important effects on cirrus formation and on the dehydration of air entering the stratosphere (Fujiwara et al. 2001). The effects of the wave were likely seen on the flights on 19 and 23 November, which showed particularly low H_2O mixing ratios at the hygropause of well below 2 ppmv. Further analysis of these observations, combined with the detailed measurements of aerosol and cirrus particles, should lead to new insights into the processes affecting dehydration in the TTL and the role of Kelvin and other waves causing temperature fluctuations on various scales.

FIRST RESULTS FROM TWO SELECTED MISSIONS. Of the 14 Egrett and 12 Dornier missions, 7 were joint Hector experiments, with the Dornier flying around the storms at low level while the Egrett flew in and around the anvils. A further four Hector missions were flown with the Egrett alone. In addition to three survey missions with the Dornier and one with the Egrett, two test flights of both aircraft were conducted at the beginning of the campaign. There were eight sorties of the Geophysica, of which five were directed at Hector, and nine sorties of the Falcon, of which again five were directed at Hector, but usually contained a substantial element of larger-scale survey. The objectives of the other SCOUT-O3 flights were larger-scale surveys (making use of the longer range of these aircraft), synoptic-scale cirrus investigations, and study of a mesoscale convective system, which had developed over the Northern Territory.

On two days—16 and 30 November—joint flights were conducted with all four aircraft. These two days present a contrast between two extreme cases of Hector—a single cell producing a rapidly detached anvil in the TTL, and an extensive convective complex producing a much longer-lived storm and an anvil covering the whole island. Here we present a short overview of these two days with a flavor of some of the results obtained.

On 16 November, strong easterly steering-level winds (Fig. 4) pushed the deep convection to Bathurst Island, where a single-cell Hector blew up around 1510 LT (Fig. 7). Its anvil soon detached and was advected southward over the Timor Sea by the prevailing northerly winds at 150–200 hPa (Fig. 8). Transects of this anvil were made by the Egrett at 13,100 and 13,700 m and by the Falcon at 12,600 m, as shown in Fig. 8. The Geophysica concentrated on the top of the storm, descending from above. Dornier measurements on this day, flying around the Tiwi Islands, revealed extensive biomass-burning residue above 550 m. This burning probably contributed, along with lightning, to the elevated NO (in excess of 220 pptv) measured by the Falcon while flying at the height of the main Hector anvil, and measured by the Geophysica at 15,500–16,400-m altitude (or 360–370-K potential temperature).

On 30 November Hector was much larger, beginning over east Melville Island at around 1330 LT. Deep convection developed all over Melville Island, arranging itself into a squall line propagating southward (Fig. 7). Light upper-level winds meant the anvil flowed radially out from the storm complex, with a slight northeastward drift. The Dornier again flew around the Tiwi Islands, measuring profiles between 550 and 3200 m. Biomass burning was still influencing the lower atmosphere on this day, but the pollution was waning. With such an extensive anvil, the Egrett and Falcon could only sample one part of it in detail, and the Egrett concentrated on the radial flow over northeast Melville Island. It flew seven legs across the outflow between 11,600 and 14,000 m, remaining in cloud throughout, with a final radial run toward the convective core at 13,000 m (Fig. 9). The Falcon surveyed three sides (north, south, west) of the Tiwi Islands and flew a triangular pattern with an east–west leg about 150 km north of the islands. Cirrus was observed throughout the flight, at altitudes between about 14 and 17 km; close to the convection this cloud deck expanded to cover altitudes between 9 and 18 km (although the deck was usually too thick for the lidar to penetrate so the morphology of the cloud top is difficult to determine). The Geophysica probed the tops of collapsing convective turrets over south Melville Island (Fig. 10).

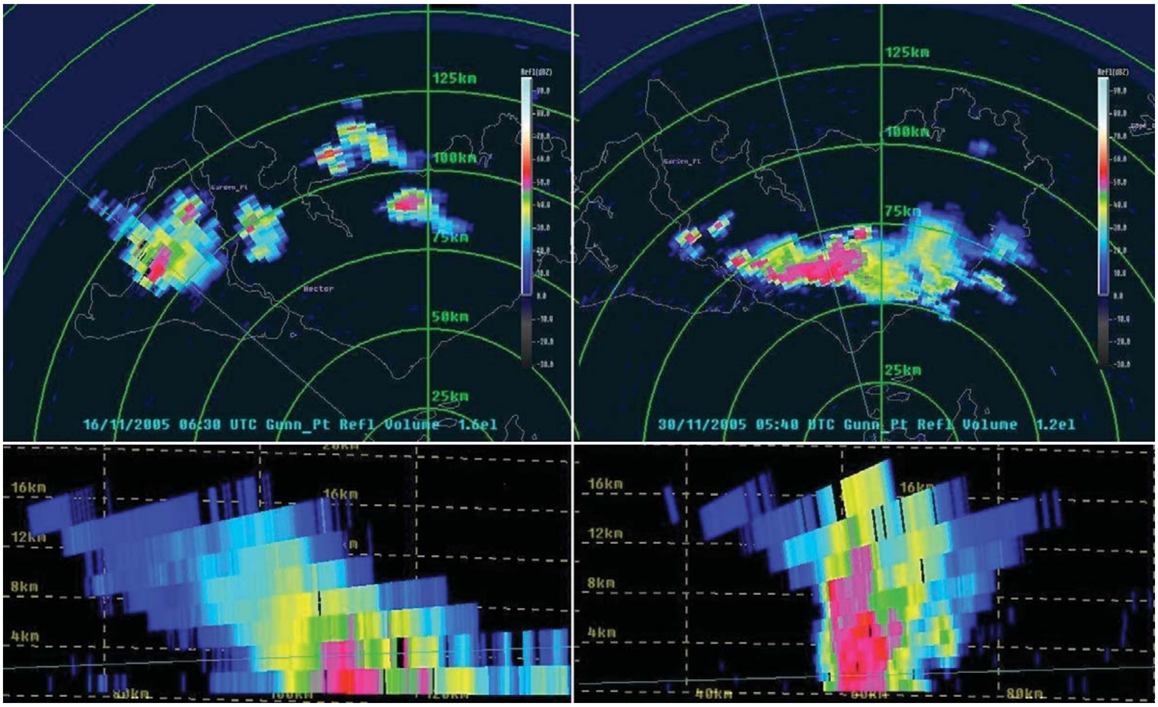


Fig. 7. Reflectivity measured by the c-band dual-polarization Doppler radar (C-Pol) at Gunn Point, just north of Darwin (left) at 0630 UTC (1600 LT) 16 Nov 2005, and (right) at 0540 UTC (1510 LT) 30 Nov 2005. (top) The results of azimuthal scans, and (bottom) elevation scans along the lines shown in the corresponding volume scan are shown. Convection on 16 Nov was limited due to short-lived intense towers reaching ~16 km; that on 30 Nov was more extensive, more organized, and longer-lived, and reached up to 18 km. Colors in each image denote radar echo intensity (dB*Z*), with bright red around 60 dB*Z*.

Nadir-pointing lidar data corroborate the 18-km cloud-top near the storm center, surrounded by anvil with cloud top 1 km lower.

Later on the evening of 30 November, less than 4 h after landing, the Falcon and Geophysica took off again in an attempt to resample the air masses lofted by Hector. Because tropopause-level winds were light, the aircraft were able to perform zigzag survey maneuvers close to the Tiwi Islands; however, the light winds also made the position of the outflow from Hector uncertain. Both aircraft observed extensive cirrus decks covering an area of approximately 60,000 km^2 just north of Darwin. Evidently, cirrus clouds remnants of Hector, and the other sea-breeze-initiated convection of the afternoon (see Fig. 9), had coalesced to form a nearly uniform deck between 12- and 16-km altitude, with much thinner ribbons of cloud, disconnected from the main deck, at altitudes up to 18 km. The trace gas mixing ratios

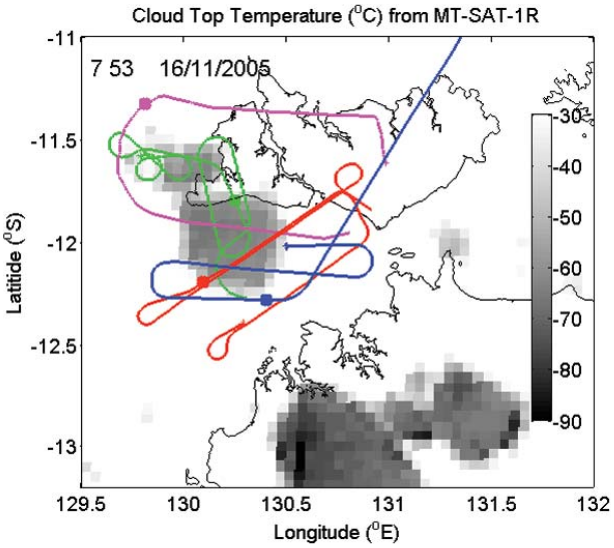


Fig. 8. Images of aircraft flight tracks on the MTSAT image, 16 Nov. This image is at 1723 LT: Geophysica (green; probing the convective cores), Egrett (red, probing outflow), Falcon (blue), and Dornier (magenta). Solid circle denotes exact position of plane at the time of the image; Geophysica and Falcon tracks are shown at 20 min on either side of this time and Egrett and Dornier at ±40 min. Note the storm is blown off the island to the west while the anvil has gone south, allowing a clear separation of the Hector anvil from the massive system over the Top-End mainland (13°S).

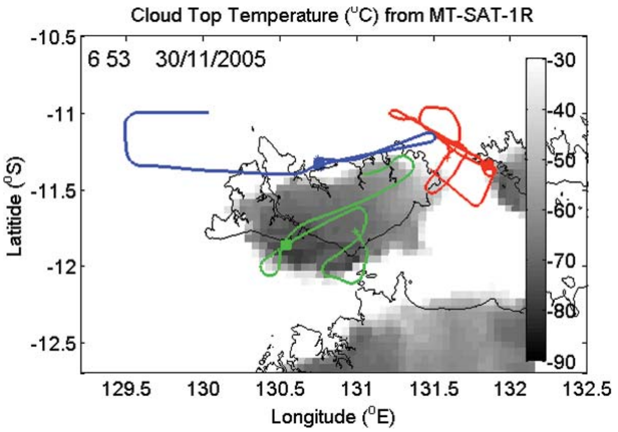


Fig. 9. Images of aircraft flight tracks on MT-SAT IR image, 30 Nov. This image is at 1623 LT. Geophysica (green; probing the convective cores), Egrett (red; probing outflow), and Falcon (blue; probing upwind region). Solid circle denotes exact position of plane at the time of the image; Geophysica and Falcon tracks are shown at 20 min either side of this time and Egrett at ±40 min. Very thin cloud at the edge of the anvil does not show up in this image, hence the Egrett and Falcon appear to be sampling out of cloud.

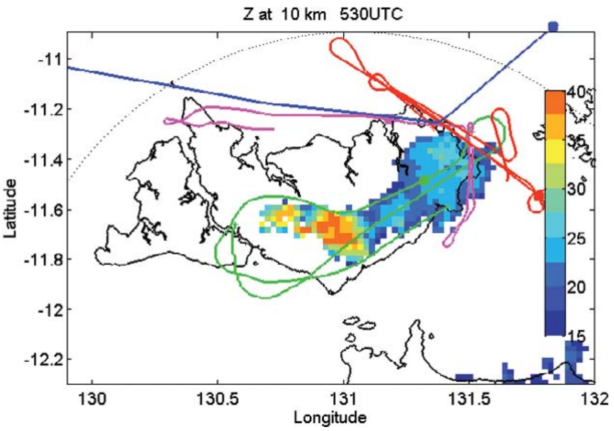


Fig. 10. Aircraft flight tracks superimposed on radar reflectivity (dBZ) at 10 km, for 0530 UTC (1500 LT) 30 Nov. Geophysica (green; probing the convective cores), Egrett (red; probing outflow), Falcon (blue), and Dornier (magenta). Solid circle denotes exact position of plane at the time of the image; Geophysica and Falcon tracks are shown at 20 min on either side of this time and Egrett and Dornier at ±40 min.

at tropopause level showed high degrees of variability; for example, CO mixing ratios showed 15%–20% variability around the mean, which is about twice as large as the variability observed at these altitudes on the survey flight of 23 November (Fig. 11). This larger variability at tropopause levels on 30 November is indicative of pools of air recently lofted by convection to the TTL.

SCOUT-O3 TRANSFER FLIGHTS.

As well as the local flights from Darwin, the transfer flights of the SCOUT-O3 aircraft from and to Europe were conducted as fully instrumented measurement flights. The aircraft required five intermediate stops for refuelling and/or instrument maintenance, in Larnaca (Cyprus), Dubai (United Arabian Emirates), Hyderabad (India), U-Tapao (Thailand), and Brunei on Borneo Island. Coverage of the tropical and subtropical UTLS by all the SCOUT-O3 flights is summarized in Fig. 3; the transfer flights sampled across 62° latitude and 120° longitude. The Geophysica was in the region of the subtropical jet between Larnaca (35°N) and Dubai (25°N; circle–dot symbol), and in the region of an equatorial easterly jet (circle–cross symbol) at Brunei (5°N). Strong westerly winds extended into the wintertime (northern) extratropical stratosphere. Above 400 K, ozone mixing ratios were highly correlated with potential temperature; below 400 K, the deep tropical ozone profiles (south of Dubai) show a high degree of variability, with markedly low ozone mixing ratios throughout the troposphere above Brunei. An increase in ozone with altitude through the TTL (i.e., 340–380 K), as described previously by Folkins et al. (1999), is present in the profiles above Hyderabad, Bangkok, and Brunei, but is not shown clearly above Darwin, probably as a result of the targeted flight around Hector. Above Dubai the profile becomes more typical of the extratropics, with evidence of a midtropospheric intrusion of stratospheric air, and a chemically defined tropopause ("chemopause") at about 360 K. Water mixing ratios were low throughout the stratosphere, but somewhat higher in the most poleward measurements. This poleward increase in water mixing ratios along an isentrope is consistent with the Brewer–Dobson circulation bringing down air in which methane has been oxidized to water. At the base of the TTL (340 K), the air is much moister than at the same potential temperature in the subtropics; convection, that is, the upward branch of the Hadley circulation, is an efficient source of moisture to the bottom of the TTL. Moving upward through the TTL, the water mixing ratios decrease by about two orders of magnitude although, again, because of the focus on flying around Hector, this decrease is not so evident in the Darwin profiles as presented in this figure.

The influence of midlatitude Rossby wave breaking on the ozone profiles around Darwin during the period of 22–27 November has already been noted (Fig. 6). Away from this period the ozone profiles show values of around 20 ppbv at the surface, rising to

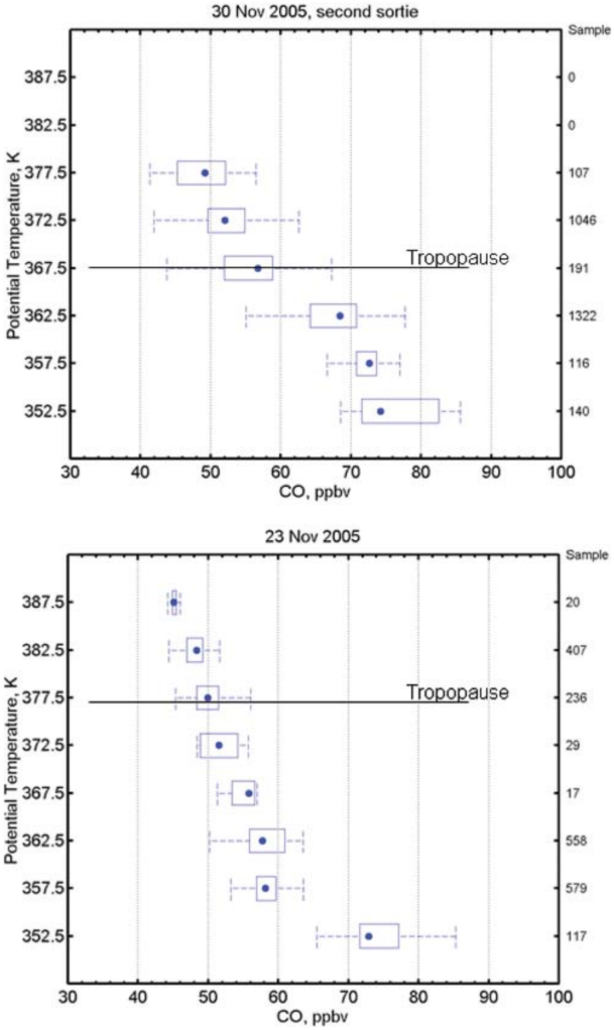


Fig. 11. Box-and-whisker plots for 5-K potential temperature bins of CO data on the survey flight of 23 November 2005 (top panel) and the second sortie of 30 November 2005 (bottom panel). The average position of the tropopause on these sorties is also shown. The boxes and whiskers show median (asterisk), 25th- and 75th-percentiles (box edges) and the adjacent values (whiskers). Adjacent values are the highest (lowest) values inside the fences defined by the quartile plus (minus) 1.5 times the interquartile range.

55 ppbv between 6 and 10 km before falling to around 40 ppbv at 14 km, with considerable variability up to the tropopause at ~17 km. This is consistent with the TTL climatology presented by Gettelman and Forster (2002).

CONCLUSIONS. The ACTIVE/SCOUT-O3 campaign in Darwin was a resounding success, with excellent data being measured by aircraft, sondes, and ground-based systems. Twelve science missions by the Egrett and Dornier, and nine by the Geophysica and Falcon in addition to the transit flights, collected a wealth of in situ data on the background atmosphere and in the vicinity of deep convection. Final datasets from all the instruments are still being prepared, but it is already clear that the missions were very successful and will allow us to address the project objectives effectively. Highlights identified so far are as follows:

a) Clear midlatitude stratospheric layers were measured in the midtroposphere by the ozonesondes due to Rossby wave influences.
b) The transition from polluted to clean conditions at low levels was observed as the biomass burning abated.
c) The TTL above Darwin and in the inflow region over Indonesia during November and December 2005 were characterized by very low temperatures down to −87°C, with modulations by Kelvin waves. A persistent layer of cirrus was observed between about 14 and 16 km. In addition, a layer of very thin cirrus was present just below the cold point tropopause for much of the time. Accordingly, low water vapor mixing ratios below 2 ppmv were observed close to the cold point.
d) Perturbations in the concentrations of a number of trace gases were observed in the anvil outflow; for example, increased NO$_x$ produced by lightning and enhanced NO$_x$, H$_2$O, and CO from uplift.

These results are currently being prepared for publication, and considerable progress is also being made on the impact of aerosol on deep convection; the overshooting of convective turrets into the stratosphere, and the consequent transport of water vapor and short-lived halogen compounds across the tropopause; and the impact of deep convection on the aerosol population of the TTL.

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