The CSIRO AVHRR time series, and the best practice tools to process that data is the result of many years work by past and current colleagues within CSIRO, including: Alan Pearce, Alex Held, Bob Cechet, Chris Rathborne, Damian Barrett, David Jupp, Dean Graetz, Denis O'Brien, Fred Prata, Harvey Davies, Hua Lu, Iain Hume, Ian Barton, Ian Grant, Jeff Kingwell, Jenny Lovell, Mac Dilley, Matt Paget, Mary Edwards, Mike Raupach, Murray Wilson, Paul Tildesley, Peter Briggs, Peter Turner, Ross Mitchell, Sonja Nikolova, Steven Clift, Susan Campbell

Also many other agencies involved in acquiring and providing the current AVHRR data including: Australian Bureau of Meteorology (operate Darwin); Curtin University and Western Australia Department of Land Information (jointly operate Perth); Geoscience Australia (operate Alice Springs); and James Cook University and Australian Institute of Marine Science (jointly operate Townsville)
Physical Basis for Linking Water Balance with Thermal Remote Sensing

- $\text{ET}_a =$ Actual Evapotranspiration (either mm day$^{-1}$ or W m$^{-2}$)
- $\text{ET}_p =$ Potential Evapotranspiration (either mm day$^{-1}$ or W m$^{-2}$)
- Moisture Availability (Ma) = $\text{ET}_a / \text{ET}_p$

- Water Balance Models take the form $\frac{dS}{dt} = P - \text{ET}_a - Q$
  - $\frac{dS}{dt} =$ Change in storage; $P =$ Precipitation; $Q =$ Runoff
  - Dimensions are length per time, with common units being mm day$^{-1}$

- Energy Balance Models take the form $R_n - G = \text{AE} = H + \text{ET}_a$
  - $R_n =$ net radiation (the incoming and outgoing balance of shortwave and longwave), $G =$ ground heat flux, $\text{AE} =$ available energy; $H =$ sensible heat flux
  - Dimensions are energy per area, with common units being W m$^{-2}$
  - $H = p.C_p[(T_s - T_a)/(r_a + r_{ex})]$ where $p =$ air density; $C_p =$ specific heat of air; $T_s =$ Surface temperature; $T_a =$ Air temperature; $r_a =$ aerodynamic resistance; $r_{ex} =$ so called extra resistance (accounts for difference in momentum and heat transport from roughness elements differ)
  - Measuring $T_s$ from remote sensing allows $\text{ET}_a$ to be calculated as the residual
Previous Scientific Directions

- Monteith and Szeicz (1962) related Canopy – Air temperature ($T_c - T_a$) to Available Energy (AE), Vapor Pressure Deficit (VPD), aerodynamic resistance ($r_a$) and canopy resistance ($r_c$).

- Stress-Degree-Days (SDD) based on $T_c - T_a$ was used to define empirical correlations with yield (Walker and Hatfield 1979), many others reported increases in foliage temperature for water stressed vegetation in late 1970s / early 1980s.

- Crop Water Stress Index (CSWI)
  - Developed by Isdo and Jackson in the early 1980’s, is daily measure of water stress.
  - Provides more mechanistic insights than the SDD approach.
  - When canopy cover is partial it does not work well, as only using a one-source REBM.

- Water Deficit Index (WDI)
  - Developed by Moran and Jackson in the mid 1990’s.
  - Uses both reflective and thermal remotely sensed data.
  - Improves formulation for partial canopies.
  - Heavily reliant on interpolated daily meteorological data for input, not sensible when using rainfall in a highly convective environment.
Previous Scientific Directions

- The WDI led to many researchers looking at the relationships between reflective and thermal data, the data is described as forming a triangle or a trapezoid.

- The Ts-NDVI approach needs a wide range of conditions observed in a scene, also the location of Y is dependent on local meteorological conditions. That is, need some met data (i.e. at least Ta) to relate YZ/XZ to ETa/ETp.

- Have been difficulties extending both the WDI and Ts-NDVI analysis due to issues involved in spatially distributing met data.

- Normalised Difference Temperature Index (NDTI)
  - Based on the principles of the CSWI, implemented as both a one-source or a two-source REBM (later better allows for partial canopies to be modelled – a constraint is needed)
  - Based on specific time-of-day scene modelling.
Normalised Difference Temperature Index (NDTI)

- Removes seasonal and daily variation from daytime $T_s$ measurements, is a specific time-of-day scene based modelling approach

$$ NDTI = \frac{(T_\infty - T_s)}{(T_\infty - T_0)} $$

where:

- $T_\infty$ - modeled surface temperature, where the surface is assumed ‘dry’
  [ infinite surface resistance (ETa=0) ]

- $T_s$ – remotely sensed surface temperature (e.g., observed by AVHRR, MODIS, (E)TM, TIMS or another other sensor with thermal capacity)

- $T_0$ - modeled surface temperature, where the surface is assumed ‘wet’
  [ zero surface resistance (ETa = ETp) ]


Time series of $T_\infty$, $T_s$ and $T_0$

- Using the REBM to calculate the envelope $T_\infty$ and $T_0$
- Specific time-of-day met data is temporally estimated from daily met data
- The changes in time-of-day of satellite observation, due to changes from older satellites with decaying orbits and to new satellites (there can be up to a 3 hour difference) can be catered for by the method

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McVicar, King, Schmidt, Jupp and Van Niel: Applications and Developments of CATS
How to ‘go spatial’ - use the best quality of each data source

- Met data has relatively high temporal density (daily) and relatively low spatial density (stations are 10s to 100s km apart)
- Remote sensing has relatively low temporal density (10-day to monthly) and relatively high spatial density (for specific conditions it is a census)

\[
\begin{array}{ccc}
A & B & C \\
0.3 & ? & 0.6 \\
0.3 & 0.45 & 0.6 \\
0.3 & 0.22 & 0.6 \\
\end{array}
\]

At each meteorological station $T_{\text{max}}, T_{\text{min}}$ and rainfall is recorded daily

$Y = f(x)$

X (Time or Distance)
Focus study area for initial NDTI generation is central-western NSW, in the middle of the Murray-Darling Basin.

RLPBs are the base geographic area for drought assessment in NSW.

States must have declared drought prior to the Commonwealth considering areas for exceptional circumstances funding.
Example of two dates of NDTI

NDTI Image Spring Wet

NDTI Image Summer Dry

0

Moisture Availability

1.0

Met station

McVicar, King, Schmidt, Jupp and Van Niel: Applications and Developments of CATS
Annual Anomaly Images linked to NSW Dept Ag Drought

- Note the similarities between the NDTI and NDVI anomaly images for 89/90 and 90/91, yet there are substantial differences between the two in 91/92 and 92/93.

- Commonwealth is currently revising its policy on drought, with submissions recently closing to the Drought Review Task Force.

- In the new policy the “nowcasting”, within the historical context (the “hindcasting”) of 23-years of EO data is seen as an attractive monitoring tool.

- Wanting to remove some of the ad-hoc decision making, and have less reliance on daily spatially interpolated met data, especially rainfall.

McVicar, King, Schmidt, Jupp and Van Niel: Applications and Developments of CATS
Anomalies (variations from monthly average) for the period June 2002 to May 2003

Physical Basis for Estimating Vegetation Cover with Reflective Remote Sensing

- Green vegetation absorbs red light and cell structure reflects NIR light
- Positive correlations exist between state variables of vegetation condition (e.g. % vegetation cover and Leaf Area Index (LAI)) and reflective remote sensing transformations
- % Vegetation Cover better estimated using the NDVI (NDVI = \([\text{NIR-Red}] / [\text{NIR+Red}]\))
- LAI better estimated using the Simple Ratio (SR = NIR / Red)
- Field work needed to provide validation data sets
March 1990 woody field sampling (transect across the MDB)
1995 northern Victoria herbaceous field sampling

- Relate 1 m field samples to 30m TM data, to provide a scaling relationship to estimate LAI for the entire TM image
- Relate the 30m TM-based LAI estimate to 1km resolution AVHRR data
- An example of up-scaling using the inherent high spatial density of remotely sensed data
- The 1990 MDB woody vegetation transect and 1995 N-Vic TM exercise are the basis for validating continental vegetation attribute mapping conducted using the Lovell and Graetz (2001) GAC AVHRR dataset
Just north of Bendigo
- Dryland crops (reds / yellow)
- Irrigated crops (blue / pink)
- Fallow fields (browns)

Feb = Blue
Aug = Green
Oct = Red

Plate 3: TM LAI Estimates

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Percent Herbaceous Cover – Monthly Averages

January  
February  
March  
April  

Herbaceous Cover (%)  
- < 2.5  
- 2.5 - 7.5  
- 7.5 - 12.5  
- 12.5 - 20  
- 20 - 40  
- 40 - 60  
- 60 - 80  
- > 80  

May  
June  
July  
August  

September  
October  
November  
December  

McVicar, King, Schmidt, Jupp and Van Niel: Applications and Developments of CATS
(A) Applications: Summary and outlook

- Thermal and reflective data, in combination with suitably complex process modelling and meteorological data can be used to map $M_a$ and $ET_a$

- The output from the site specific modelling is interpolated using remote sensing based covariates (this avoids using daily interpolated rainfall surfaces)

- The NDTI provides an avenue to use thermal remote sensing to monitor national water resources. Many applications would benefit from spatially distributed near-real time estimates of $M_a$ and $ET_a$, these include drought, agricultural management (e.g., is there enough water to establish a wheat crop), erosion modelling, C modelling, biodiversity assessment (e.g., avian fauna habitat mapping)

- Vegetation attributes (LAI and % Veg Cover) can be obtained from broad-band time series remote sensing – field validation is important

- How do operational users and other researchers gain access to this time series data? Stay tuned for (B) Current Developments introducing the Web-CATS project
(B) Developments of CSIRO AVHRR Time Series

- Established a front end Web-site for data delivery

- Development of a fully automated method to perform post-launch sensor calibration

- Establishing the computing environment to perform the processing

- On-going implementation of automating atmospheric correction, BRDF normalisation, scene stitching, geometric correction and cataloguing
  King, Paget, Lovell and Campbell undertaking this activity

- Assessment of the accuracy of the geometric accuracy of the satellite state vector calculations using the method developed by Clift et al. from CMAR Hobart
(B) Web-CATS Progress to-date

- CATS = CSIRO AVHRR Time Series

- IDEA:
  - Provide a “useful” dataset
  - Full archive of the Australasian region
  - Processed within one system: CAPS
  - With state of the art “standardised” algorithms
  - On user demand
  - Outsourced processing
  - Usable for experts and non-experts
  - Fully automatic
  - Version control

- Web-CATS provides an easy to use front end to CATS via CAPS as the backend processing system
  - Accessible via the web
  - Operated with non commercial freely available software (Apache, PHP, MySQL)
  - Linux RedHat, CAPS (Common AVHRR Processing Software)
The AVHRR archive in the EOC

- Acquisition of HRPT data at several receiving stations (Perth, Darwin, Hobart, Alice Springs, Townsville)
- Stitching, archiving and indexing in an relational database (MySQL)
- Data volume is reaching 100,000 satellite overpasses (approx. 7 Tbyte)
- Holding the AVHRR data online on a LINUX computer cluster
- Backup on tapes (in ASDA format)
Correction for sun and view geometry (BRDF)

Before

Channel 1 (red)

Channel 2 (NIR)

After
Setup and organisation

Web interface → Web Server (Apache) via PHP/HTML

LINUX Cluster

User request

User

Data delivery

FTP

Dynamic product generation (CAPS)

Metadata

Database (MySQL)

Data ingestion (Tapes)
Computer cluster

- 18 machines to hold the 8 TB of original AVHRR data on-line
- Cluster software in final developed and under testing stages
- Hard disks need to be populated with AVHRR data (~500 GB per machine)
- Separate FTP server with ~1.5 TB capacity
3. Choose a job-name
Each time you visit this web-service you will be asked to insert a job-name for the data search. This will be your reference to the data and the performed data search. You can either insert a new job-name or continue a job (if it was completed and accept button was pressed at the end of a former session) and upload former job details. The system will generate another version of this job-name for you.
If this is your first visit you'll have to insert a new job-name.

In the case of a re-visit and if the option of an upload of a former job-version was chosen, a submenu allows you to either upload the same data parameters as in a former session and search the whole database again (in case there might be new data) or to use the same data as in a former search.

4. Spatio-temporal search
After registration, you are directly guided to the product selection page or asked to specify parameters for a new spatio-temporal search. In the spatio-temporal search page, you are asked to define your geographic region of interest and your temporal search window. On the same page you have the option to either search for all available data (default) or to specify which particular satellites (currently: NOAA-6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 17) interest you. The overpass direction (ascending or descending orbit) or time of day can also be selected as parameters to narrow the search down. 
Dependent on the length of the given time interval this data search can take several minutes (see [http://www.eoc.csiro.au/cats/search-performance.html](http://www.eoc.csiro.au/cats/search-performance.html) for the currently estimated search times).
You are provided with the option to manually browse through the list of satellite images and de-select scenes, that you want to exclude from the processing. The default is to include all scenes that match you defined search criteria!

5. Product selection
A range of different products and processing strategies have been implemented to enable as wide a choice as possible. Select products from the shown list. The products will be delivered either as separate files or layers (in HDF format).
WWW frontend

- Spatio-temporal search
  - Spatial polygon search (Lat/Lon)
  - Satellite
  - Date
  - Overpass

McVicar, King, Schmidt, Jupp and Van Niel: Applications and Developments of CATS
Automatic Sensor Calibration of AVHRR Chns 1 and 2

- There is no on-board sensor calibration for AVHRR Channels 1 and 2
- Classical approaches use Pseudo-Invariant Features (PIFs)
  - Never truly invariant
  - Need modelling of the surface changes through the year and monitoring of rainfall events etc.
  - Outlier statistics require editing/check
- Previous methods for determining on-board calibration are all operator based
  - Clouds over Oceans (e.g. Vermote & Kaufmann, 1995)
  - Ice caps (e.g. Tahnk & Coakley, 2001)
  - Cross calibration against other sensors (e.g. Heidinger et al., 2002)
  - Calibration measurement campaigns (e.g. Abel et al., 1993)
  - Desert targets (e.g. Rao et al., 1999)
- Alternative (statistical) method to derive “true” No Change Pixels (NCPs), based on the MAD (Multivariate Alternate Detection), Nielson, 1998.
Image selection and pre-processing

- All image pairs in used in range $n \ 365.25 \pm 20$ days, where $n = 0, 1, 2, 3$, are presented to the MAD algorithm
- Subtraction of space-count values: $DS = DN - C_0$
- Scaled by the earth-sun distance
- Adjusted for solar zenith angle variation
- Cloud impacted pixels identified by CLAVR & 10 pixel buffer around each cloudy pixel
- Equatorial crossing path must be $\pm 1$ degree longitude
- NCP are within $\pm 10$ degrees sub-track satellite view angle

Left: 12 Jan 1996
Right: 06 Jan 2000
MAD NCP Selection Performed Over Central Australia

- NCPs
- Ground tracks
- View angle limitation (10 deg.)

Ground track 1
orbit nr. 5329
12 Jan. 1996

Ground track 2
orbit nr. 25860
6 Jan. 2000

1800 km
1100 km
100 km
Time series of the slope of the sensor calibration
Assessing the order of the polynomial

- For channel 1 and 2 there were 2486 and 2349 image-pair comparisons, respectively available for curve fitting.
- Order of the polynomial assessed by minimising the predictive error (leaving one out lemma).
- Coefficients determined by minimising using sum-of-squares and assuming that at time zero, i.e., $P(0) = 1$.

$P_{\text{ch1}}(t) = S_{\text{ch1}}(1 + 2.4228 \times 10^{-4} t - 6.2293 \times 10^{-7} t^2 + 1.0535 \times 10^{-9} t^3 - 6.3554 \times 10^{-13} t^4 + 1.2650 \times 10^{-16} t^5)$

$P_{\text{ch2}}(t) = S_{\text{ch2}}(1 + 4.0991 \times 10^{-4} t - 6.2425 \times 10^{-7} t^2 + 4.7478 \times 10^{-10} t^3 - 1.1478 \times 10^{-13} t^4)$

$t \leq 1700$
Assessing the sensitivity of the method - Chn 1

- Bootstrapping 100 iterations of 1500 random samples of $m_{12}$ from the 2486 available.
Assessing the sensitivity of the method - Chn 2

● Bootstrapping 100 iterations of 1500 random samples of $m_{12}$ from the 2349 available
Difference between measured and fitted data
Differences between the fitted data and measured data
Comparison to previous published methods

McVicar, King, Schmidt, Jupp and Van Niel: Applications and Developments of CATS
Impact of sensor degradation - Chn 1
Impact of sensor degradation - Chn 2
Assessment of Geometric Correction (hot off the press)

- Collection of Ground Control Points (GCPs) in the vicinity of Darwin and Spencer Gulf from a number of images with different viewing geometries

- As a function of satellite view angle calculate both the internal errors (RMSE) and external errors (either predictive error or some difference vector)

- Mean error shown in the red line, with mean + 2 SD in blue revealing that within ±35 degrees of nadir the internal error is within 1 pixel
Web-CATS: Summary and outlook

- The 25-year AVHRR archive for the Australia is a vital record of landscape and ocean state and variability

- The EOC holds a best-practice AVHRR record for 1981 to present and ongoing; data are available in near-real time (from the Alice Springs receiving station)

- CAPS (Common AVHRR Processing software) is improving new algorithms can/will be included

- Data can be generated dynamically for user specific needs using Web-CATS

- The data are/will be made available to maximise the
  - Use of the record
  - Novel applications

- A lot of effort has been put in the establishment of this dataset.... we are almost ready to ‘go live’ on the Web
Thanks to many contributors to CSIRO’s AVHRR archive

- The CSIRO AVHRR time series, and the best practice tools to process that data is the result of many years work by past and current colleagues within CSIRO, including:
  - Alan Pearce, Alex Held, Bob Cechet, Chris Rathborne, Damian Barrett, David Jupp, Dean Graetz, Denis O'Brien, Fred Prata, Harvey Davies, Hua Lu, Iain Hume, Ian Barton, Ian Grant, Jeff Kingwell, Jenny Lovell, Mac Dilley, Matt Paget, Mary Edwards, Mike Raupach, Murray Wilson, Paul Tildesley, Peter Briggs, Peter Turner, Ross Mitchell, Sonja Nikolova, Steven Clift, Susan Campbell
  - With thank them all (and any we have forgotten who worked on the data prior to our involvement with it) for the valuable part each has played in necessary *a priori* research that Web-CATS is based upon

- There are also many other agencies involved in acquiring and providing the current AVHRR data including: Australian Bureau of Meteorology (operate Darwin); Curtin University and Western Australia Department of Land Information (jointly operate Perth); Geoscience Australia (operate Alice Springs); and James Cook University and Australian Institute of Marine Science (jointly operate Townsville)
Thanks to those leading and supporting the EOC

EOC was an 11-year very successful cross Divisional Program with CSIRO, and as importantly (arguably more importantly), developed strong scientific links external to CSIRO both Nationally and Internationally.

The two Science Leaders, David Jupp and Mike Raupach, most likely undertook many thankless tasks on behalf of the EO Crew (CSIRO is sometimes csirO instead of cSIRo).

On behalf of the EO Crew – THANKS!

Rowena, Louisa, Irenke and Cheryl – who over the 11-years of the EOC have been the backbone of the tremendous organisational, administrative and financial support.

On behalf of the EO Crew – THANKS!
National Oceanographic and Atmospheric Administration (NOAA) satellites are polar-orbiting with the AVHRR sensor first launched on TIROS-N on 13 Oct 1978, NOAA-6 was launched June 1979, and NOAA-N’ (or NOAA-19) is planned for launch in 2008.

AVHRR is a 5 channel instrument acquiring data in 2 reflective channels, 2 thermal channels, and one channel influenced by both. Data is 1.1 km at nadir, and degrades to ~5.5 km at the edge of the 55° swath. There is NO on-board calibration (compare with MODIS that is well calibrated).

The NOAA series of satellites are part of the US operational meteorological service, this means if a satellite fails another will be launched as soon as possible (compare this with TERRA and AQUA [that both carry MODIS] are one-off [happening twice] scientific missions).

Currently NPOESS (National Polar Operational Environmental Satellite System) is planned for launch in early 2009. NPOESS will subsume the current role performed by both MODIS and AVHRR, there will be a significant period of overlap (at least 2 years) between the three sensors. NPOESS will run until at least 2020.
Significance and use of the AVHRR record

- AVHRR record for Australia
  - Nearly continuous for 23 years
  - Each satellite acquires data over all Australia and surrounding oceans 2 times a day (night and day) at 1.1 km resolution at nadir
  - Currently there are 3 operational NOAA satellites

- Uses
  - **Land Surface Temperature** related to regional water balance
  - **Vegetation condition monitoring** (e.g., LAI and %VegCov for yields, growth and curing)
  - **Climate variability** and its effect on landscapes
  - **Sea Surface Temperature** variation and structure
  - **Land use change**
  - **Fire** behaviour, modelling, role in carbon cycle
  - **Fire detection** in near real time (with MODIS in the Sentinel system)
  - **Cloud** dynamics and properties
  - **Modelling** of water balance, plant growth, nutrient dynamics (testing, calibration)
BPAL data 8 km spatial resolution, from 1981 to current, for different pre-defined spatial units.

Number of pixels for spatial average: 60815