A-Train formulation with the arrival of CloudSat and CALIPSO as motivated to a large degree by a desire to better understand clouds and aerosols and their impact on the radiation budget and hydrological cycle.
A-Train Sensor Diversity – when data are combined new insights on important processes are revealed

An example of the diversity
A-Train science is having a profound impact. There is a large & growing number of A-Train papers in the peer reviewed literature.

- Two CloudSat based papers were the #1 (Suzuki et al) and #2 (Riely & Mapes) downloaded papers of 2012 in AMS and a third AIRS paper was #7
- One multi-sensor A-Train paper was the #6 most downloaded JGR papers of 2012 (Jiang et al., 2012)

A-Train data are also impacting model development.

The value of A-Train data will only increase in time as the data record lengthens.
What are some new science achievements enabled by the A-Train?

Integration across different observations platforms & sensors leads to:
(i) Richer validation of key products and expansion to fill in voids
(ii) Extraction of new products from combinations of different matched observations,
(iii) Combination products to yield new insights on processes
(iv) With (i)-(iv), provide a more integrated view of Earth far beyond that which had been possible.

What has made A-Train multi-disciplinary science possible?

(i) Public availability of Level 1 and 2 data,
(ii) Public availability of key documents (instrument descriptions, ATBDs, open documentation of known problems, etc),
(iii) Easy data access of data & sharing of data
(iv) Open science team meetings
(v) Careful management of constellation flying (e.g. MOWG)

What are some other advantages?

Ability to share calibration and validation efforts across missions (e.g. C3VP=Cloudsat+CALIPSO+GPM, LpVex)
IMPORTANT MESSAGE Mar 16, 2013  Scheduled Maintenance on March 16th, 2013
There will be planned maintenance on a GSFC network from Saturday, March 16th from 8am until 6pm ET. The GES DISC website (http://disc.sci.gsfc.nasa.gov) may not be accessible during this maintenance window.

A-Train Data Depot

IMPORTANT MESSAGE Feb 04, 2013  CloudSat/Collocated subsets
1) Issues with the CloudSat spacecraft in 2011 resulted in collocated subsets gap for the period June 29, 2011 - May 14, 2012. This is a reference gap period for the purposes of A-Train Data Depot, using MODIS-collocation criteria. Concerning OMI, because of its wider swath and orbit-long granules, the collocated subset data gap may be smaller.

Users should be very considerate of the location of CloudSat with respect to Aura (OMI, MLS, TES, HIRDLS), Aqua (MODIS, AIRS, AMSR-E, CERES), and CALIPSO. During the gap, the CloudSat satellite drifted off and was not in formation flying with these A-Train satellites.

2) The OMI products, OMNO2 and OMTO3, require revisions to the subset production software. While we are searching for an appropriate solution, we regret the production of the OMNO2_CPR and OMTO3_CPR subsets is halted until further notice, and data past 2011 are not available.

The A-Train Data Depot (ATDD) has been developed to process, archive, allow access to, visualize, analyze and correlate distributed atmospheric measurements from A-Train instruments. The ATDD portal provides easy on-line data access and services for science, applications, and educational use so that users get exactly the data they want, and not large files of data which would take much time and effort by individuals to be co-registered and refined.

On September 15, 2009, the A-Train formation happened to fly over the super-typhoon Choi-wan. Just one such event can yield enormous amounts of data of various science contented from the diverse A-Train sensors. Fittingly...
Selected highlights with a little illustration of AMSR-E A-Train science

Science highlights - the A-Train *constellation* science has two flavors

- Science that results specifically from matching individual level 1 ‘footprint’ data & integrating to produce new products
- Science that results from matching level 2 (and level 3) product data more broadly to examine relations between variables

• The iconic A-Train result due to formation flying creating a virtual observatory
• Combining data for new insights on convection
• Combining data for new insights on aerosol/cloud/precipitation
• Enhancing global precipitation products
A-Train demonstrated how formation flying can create a virtual 2 satellite radar-lidar observatory. Matching footprints yielded important new products.
Cloud and precipitation frequency (Fig. 7.4, Chapter 7 of IPCC AR5) and ice and water contents adding truly a new dimension this could not have been possible without the careful matching of footprints that resulted from formation flying.
Example of combining data CloudSat, MODIS & the convective process

A super-cell t’storm over Wyoming
The classic Riehl and Malkus (1958) paper introduced the concept of "hot towers".

Abstract

The equatorial trough zone receives the latent heat accumulated by the lower trades, lifts and converts the energy, balancing radiation losses, and exports the residue poleward aloft in the form of sensible heat and potential energy.
The classic Riehl and Malkus “hot towers”
How tall are these hot towers (CloudSat/CALIPSO)?
How cold are their tops (MODIS)?
How many hot towers?

(i) \( T_{\text{parcel}} - T_{\text{env}} = \text{bouyancy} \)

(ii) \( h = C_p T + gz + Lq \)
\( h, h_{\text{env}} = \text{entrainment} \)

Cloud top height = \( z \)
Cloud top temperature (MODIS 11 \( \mu \text{m} \) TB) = \( T_{\text{parcel}} \)
CPR profile = identifies convective tower
Entrainment rate

Buoyancy

Deep convection:
$B < 0 \& \lambda < 10\%/km$

"Terminal" cumulus congestus:
$B < 0 \& \lambda$ up to 50%/km

"Transient" cumulus congestus:
$B > 0 \& \lambda \sim 10\%/km$

$\Delta T = T_{\text{parcel}} - T_{\text{env}}$ (K)

Luo et al. (2010)

The combination of entrainment and buoyancy provides a tool to identify hot towers.
The first global map of hot towers

0.08% of tropics occupied by ‘hot towers’
A-Train reveals important insights on aerosol effects on cloud reflection – an example of how we infer processes by connecting data.
Aerosol indirect effects

The Twomey Effect

Ship tracks are an example of how aerosol interact with clouds. They are analogs for both the more global effects of aerosol on clouds and for geo-engineering concepts for modifying the albedo.
Aerosol effects on clouds – largest uncertainty in climate forcing and these too is shaped by the thermodynamic properties of the boundary layer/free troposphere.
The buffering of cloud albedo

More aerosol does not always make clouds brighter

We have developed an A-Train ship track inventory that consists of Cloudsat, AMSR-E, CALIPSO, CERES and MODIS sensor data.

- Differences in liquid water path primarily determine the sign and strength of the cloud albedo response.
- Humidity above cloud tops is responsible for the differences in LWP.
- E-PEACE aircraft observations results agree with A-train observations.

Chen, Christensen, Seinfeld & Stephens, 2012
The more global picture from the A-Train

AMSRE-E and MODIS (GEMS)

Correlation between AMSR-E lwp and aerosol
Drier RH_{ft} imply a decrease in LWP (through entrainment); yet higher LTS (more stable) inhibits entrainment restricting.

Globally, dry areas with low RH_{ft} correspond to areas of high LTS (where stratocumulus are prevalent). This confounds our ability to infer how LWP changes.

More aerosol is associated with less liquid water implying a positive AIE

More aerosol is associated with more liquid water implying a negative AIE

Chen, Christensen, Seinfeld and Stephens, 2013
A- Train Precipitation
Precipitation

Rain Fraction (CPR)

January-December 2007

CloudSat and TRMM
Insight on the rain process - seeing rain form using combinations of CloudSat, MODIS, AMSR-E

A-Train observations


Dreary state of precipitation in global models

Graeme L. Stephens,1 Tristan L’Ecuyer,1 Richard Forbes,2 Andrew Gettleman,3 Jean-Christophe Golaz,4 Alejandro Bodas-Salcedo,5 Kentaroh Suzuki,1 Philip Gabriel,1 and John Haynes6
Three different 20th century climate change experiments by the NOAA GFDL climate model group - the only difference is the strength of the AIE – and the A-Train can tell us which one is more correct.
Global Precipitation – combining different sources of to gain a more representative global view

MCT* = TRMM+ CloudSat + AMSR-E + diurnal cycle (Behrangi et al, 2012)

Global mean
MCT* - GPCP ~ 5%

| MCT* - GPCP | ~10%

Behrangi et al., 2013
Snowfall observations:
CloudSat provides the 1\textsuperscript{st} real spaceborne global observations (IPWG) further adding valuable information about precipitation

CloudSat global snowfall product – the only real global product but how good is it? It’s a challenge to retrieve and a challenge to validate.
Summary

(i) New science continues to emerge as the A-Train data record continues to grow.

(ii) OCO is to join soon and it offers quite unique information about important components of the climate system IN ADDITION TO CO2

(iii) Steve Volz (HQ) has asked us to plan a 3rd A-Train science conference. Planning is underway.
The mass increase (red) is equivalent to about 10% of the annual sea level rise.

The mass increase is consistent with CloudSat snowfall accumulation.

The ice mass gain through snowfall is a consequence of the change in circulation and storm trajectory in 2009/2010.
Figure 2. (a, c, e, and g) Maps of CS₄ rain frequencies, corresponding to the footprint size of each studied sensor. (b, d, f, and h) Maps of fraction of missed rainfall (Fₑ₆) for each sensor, calculated from equation (1) using its corresponding map of CS₄ rain fraction. From top to bottom the rows represent maps for PR, AMSR-E, MHS, and IR, respectively. The results are based on 3 years (2007–2009) of rainfall data.

Figure 7. Maps of (a, c, e, g, and i) mean rain rate (MRR) and (b, d, f, h, and j) MRR differences for different sensors. The maps are constructed by calculating MRR or MRR difference in each 4° × 4° grid cell. The maps of MRR differences are plotted after subtracting sensors MRR maps from the MRR map of CloudSat. Cells with MRR difference equal or less than zero are shown as white.
Comparison of level 2 products

Assessment of global models

Figure 4: Scatter plots of tropical (30°N-30°S) oceanic multi-year means: H2O versus IWC at 100 and 215 hPa, H2O versus LWC at 600 and 900 hPa. Results from each AR5 models and from A-Train observations are shown. The grey area and the dotted lines indicate the observational uncertainty. The dashed lines at 600 and 900 hPa indicate CloudSat noPcp values as discussed in the text.
Insights on storms and climate change

Key modes of variability include MJO (interseasonal), El Nino (internannual)
CloudSat-CALIPSO-AMSR-E data document sensitivity of tropical convection to humidity during the Madden-Julian Oscillation

Observations

Left panels: A-train data show transition from shallow to deep convection at intermediate column water vapor amounts (50-68 mm), but with all depths possible at these values depending on details of the humidity profile.

Right panels: GISS GCM shallow-deep convection transition occurs too soon when too little dry air is entrained into clouds, but gets the correct transition with strong entrainment.

Context: GCMs poorly simulate the MJO because their convection schemes are insensitive to tropospheric humidity. CloudSat/CALIPSO/AMSR-E provides the first global direct detection of convection depth, while AMSR-E gives simultaneous water vapor. GEOPROF-LIDAR data were accumulated over the developing phase of 10 MJOs.

Del Genio et al. (2012), Journal of Climate
Figure 4: Fractional differences $\Delta$ for small mode optical thickness $\tau_1$ between AERONET observations/retrievals and MODIS only retrievals (left) and between AERONET observations/retrievals and GOSAT only retrievals (right).

Figure 6: Same as figure 4 but for the small mode single scattering albedo $\omega_1$.

McGarragh & Stephens, 2013
Multi-sensor fusion - new insights on planets major storms

Tropical Cyclone Choi-Wen ...

(Imagery Courtesy Naval Research Laboratory, Marine Meteorology Division, Monterey CA)
Access to Information

• Public availability of key documents
  ▪ Mission and instrument descriptions
  ▪ Algorithm Theoretical Basis Documents (ATBDs)
  ▪ Data Catalogues and data set examples
  ▪ Data Quality Summaries
• Open and advertised A-Train Data Policy
• Open and advertised Science Team meetings
• Public availability of Level 1 and 2 data products soon after start of operations (beta or provisional data quality)
  ▪ Better to keep data formats simple
  ▪ Near real-time access
• Creation of fused data sets (slow to develop for A-Train)

Example - initial data release for CALIPSO & CloudSat within first 6 months
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*Example - initial data release for CALIPSO & CloudSat within first 6 months*
NASA ESD Operating Missions
(LDCM not shown, Launched 11 Feb 2013)
NASA ESD Operating Missions
(LDCM not shown, Launched 11 Feb 2013)
## Anticipated A-Train highlights

<table>
<thead>
<tr>
<th>Sensor data used</th>
<th>What is provided</th>
<th>Why useful</th>
<th>Interesting tidbits</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CloudSat &amp; CALIPSO</strong></td>
<td>Vertical profiles of cloud occurrence, new definitions of high thin cloud, cloud base, cloud layering, etc</td>
<td>This vertical structure is required for many weather and climate related processes</td>
<td>Multiple layering is prevalent in tropics (60%), total cloud cover ~76%</td>
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<tr>
<td><strong>MLS, CloudSat, AIRS</strong></td>
<td>Ice water content and path comparison and relation to UTH</td>
<td>Important climate feedbacks revolve around high, thin ice clouds - agreement between these two data sets confirms validity of products</td>
<td>Connection to water vapor implies processes. Gross errors in the relation between UT ice and vapor in climate models -</td>
</tr>
<tr>
<td><strong>AIRS, MODIS Cloudsat, AMS RE &amp; CALIPSO</strong></td>
<td>Cloud &amp; precipitation information from different sensors can be tested including cloud liquid water path of raining/non-raining clouds</td>
<td>Can calibrate longer time records of other sensor data, like cloud top heights, precipitation, – useful for other applications like cloud track winds</td>
<td>Major biases in cloud/radiance climatologies exposed, AMSR-E precip occurrence is ~ 2X less than CloudSat, exposes large uncertainty in mid alt precipitation</td>
</tr>
<tr>
<td><strong>AMSR-E, CERES, CloudSat, MODIS &amp; CALIPSO</strong></td>
<td>More integrated view of aerosol indirect effects on observed cloud albedos</td>
<td>Large uncertainties in AIE is one of the principle tools that constrain our ability to predict climate warming.</td>
<td>AIE are inferred to be small composed due to combination of processes that buffer one another. Production of precipitation grossly influences AIE</td>
</tr>
<tr>
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<tr>
<td>MODIS IR, CloudSat, CALIPSO</td>
<td>Convective buoyancy, entrainment</td>
<td>Provides unique, global information that is beginning to revolutionize model convection parameterization</td>
<td>Verified hot tower hypothesis – 0.02% of tropics contain undilute convective cores</td>
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<tr>
<td>AMSR-E, CALIPSO</td>
<td>Surface wind from lidar surface reflection</td>
<td>CALIPSO surface wind sees in between clouds and is less contaminated by cloud effects</td>
<td>1m/s rms, near zero bias compared to AMSR-E</td>
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<tr>
<td>CloudSat &amp; CALIPSO</td>
<td>Aerosol optical depth via PIA – radar</td>
<td>AOD much less sensitive to aerosol model assumptions that plague all other methods</td>
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<td></td>
<td>surface reflectivity is used to define lidar surface reflection</td>
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# A-Train Serendipity

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</thead>
<tbody>
<tr>
<td>MODIS vis, nir,</td>
<td>Correlation between radar reflectivity and MODIS particle size</td>
<td>Provides unique identification of the transition from cloud to rain and</td>
<td>Time scale is much longer in nature than is assumed in models</td>
</tr>
<tr>
<td>CloudSat,</td>
<td></td>
<td>time scale of rain formation</td>
<td></td>
</tr>
<tr>
<td>OMIi, CloudSat,</td>
<td>Inferred cloud top heights fro UV scattering matched to cloud profiles</td>
<td>Impacts ozone estimation above clouds</td>
<td>Considerable UV multiple scattering makes OMI cloud tops appear many kms low</td>
</tr>
<tr>
<td>CloudSat &amp; MODIS</td>
<td>A confirmation of MODIS particle size and its relation to precipitation</td>
<td>Passive measures particle size of low clouds can be used to characterize</td>
<td>Drizzle is so persistent in oceanic clouds that it measurably affects the mean</td>
</tr>
<tr>
<td></td>
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<td>drizzle/precio occurrence.</td>
<td>particle size</td>
</tr>
<tr>
<td>CloudSat &amp; CALIPSO</td>
<td>Identification of thin winter time ice clods and precipitation</td>
<td>Explosive development of precipitation altered by aerosol affecting the</td>
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<td></td>
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<td>rate of dehydration of polar clouds</td>
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A-Train Science Concepts

4 slides from:

“ESA-NASA Constellation Management Workshop
May 17, 2011
Saint-Hubert, Quebec, Canada

Perspectives on Maximizing Science Return

Chip Trepte, CALIPSO Project Scientist, NASA/LARC”
Common Interests

- A-Train formulation motivated to a large degree by a desire to better understand clouds and aerosols and their impact on the radiation budget and hydrological cycle
- Prior to A-Train international science community was already engaged in collaborative research efforts across multiple fronts, for example:
  - climate and weather forecast modeling (GEWEX)
  - field measurement campaigns (Pinatubo eruption)
  - remote sensing research: vis/ir sensors, polarimeters, lidar, radar
- Deep seeded desire for global observations – time was ripe
- Recognition that multiple measurement approaches are needed

Example – large volume of publications using A-Train observations (Aqua > 500, CloudSat >300, CALIPSO >350, Aura >500, Parasol >150; may be some duplication between missions)
Leadership

- Mission leads (Principal Investigators, Project Scientists, Project Managers, Program Scientists, Agency Leads) recognize the value of collaborative efforts at an early stage
  - collaborations between missions and discipline communities evolved on their own
  - no centralized approach; self-organizing
- Effective communication to the science community
  - well articulated expectations
  - routine meeting opportunities
  - strive to provide clearer messages to the public
- Effective Mission Operations Working Group
  - tight connection between science needs and capabilities
  - operates under clear and established procedures
  - Routine communication across management, science, and engineering sectors
- Funding for cross discipline/mission and multi-sensor research
- Supportive of new and young scientists
Access to Information

• Public availability of key documents
  ▪ Mission and instrument descriptions
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• Creation of fused data sets (slow to develop for A-Train)

*Example - initial data release for CALIPSO & CloudSat within first 6 months*
Open Validation

• Sustained calibration and validation efforts
  ▪ Formulation of pre-launch plans
  ▪ Data processing effort includes iterative processing to capitalize on improved calibration/validation approaches
  ▪ Committed funding from sponsoring agencies
• Coordinated comparison field missions
  ▪ Optimizes resources (instruments, aircraft, ground systems)
  ▪ Brings more eyes to a set of issues
  ▪ Promotes additional interest
• Independent assessments

Example – ozone trend studies in late 1980: TOMS, SBUV, SAGE, HALOE, NDSC

Example – Cirrus optical thickness: CALIPSO lidar and IIR, MODIS, PARASOL, CloudSat, in situ measurements, CPL
Convective core cloud

- Generally defined as **moist buoyant updrafts** in LES studies used to develop convection parametrizations (e.g. Siebesma & Cuijpers, 1995).

- **Area** (and hence radiative effect) of core is relatively small – probably less than 0.1 in typical global model grid.

- Currently ignored in UM but test show it **does have an impact** (e.g. US surface temperature).

- A good regime indicator for inhomogeneity?
Identifying core cloud

Tested several methods but using method based on Luo et al 2009.

A column is designated as a core if:

- less than 5 layers between 0 dBZ echo top height and cloud top
- less than 9 layers between 10dBZ echo top height and cloud top
- at least 3 layers between cloud base and 10dBZ echo top

A convective cloud observed by CloudSat on 19/11/2009 at about 5:20 UTC above Brazil.

Battaglia et al (2011)
Using convective core information

% of columns with cores

Observed liquid FSD
### TOA Budget

**Observations**

- **SW in**: 340.2 ± 0.1
- **SW out**: 100.0 ± 2
- **LW out**: 239.7 ± 3.3

**CMIP5**

- **Min**: 338.6, 96.4, 232.4
- **(Mean)**: (343), (102.2), (238.6)
- **Max**: 343.7, 106.5, 243.5

**TOA Imbalance**: 0.6 ± 0.4

### Surface Budget

**Observations**

- **SW down**: 188 ± 6
- **SW up**: 23 ± 3
- **SH**: 24 ± 7
- **LH**: 88 ± 10
- **LW up**: 398 ± 5
- **LW down**: 345.6 ± 9

**Surface Imbalance**: 0.6 ± 17

**CMIP5**

- **Min**: 181.9, 21.1, 17.6, 78.4, 391.9, 326.4
- **(Mean)**: (190.3), (24.9), (20.9), (85.8), (397.5), (339.7)
- **Max**: 196.2, 30.3, 27.8, 93.6, 398.1, 347.0
A-Train Constellation Evolution

- Aqua (May 2002)
- Aura (July 2004)
- PARASOL (Dec 2004; lowered orbit Dec 2009)
- CALIPSO (April 2006)
- CloudSat (April 2006; battery management; orbit lowering June 2011, re-entered train May 2012)
- GCOM-W1/Shizuku (May 2012)
- OCO-2 (~July 2014)

- Glory launch failure on 4 March 2011
- OCO launch failure on 24 Feb 2009
Aerosol effects on clouds – largest uncertainty in climate forcing and these too is shaped by the thermodynamic properties of the boundary layer/free troposphere.