A Cloud Hydrology and Albedo Synthesis Mission (CHASM)

India-United States Conference on Space Science, Applications and Commerce
21-25 June, 2004

Roger Davies

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

Cloud: arguably the weakest link in our understanding of the climate system

Hydrology: where is the missing mass of cloud liquid water?

Albedo: determines the energy that drives the climate system

Synthesis: cloud albedo must be related to cloud water in a consistent way

Mission: to reconcile observed and theoretical cloud water amounts and relate these to cloud albedo

- the main motivation for CHASM is that there is something seriously wrong with our current understanding of cloud liquid water amounts
- correct cloud water amounts are absolutely crucial to modeling precipitation variability in the hydrological cycle and cloud radiative feedback in the climate system
- our hypothesis is that significant amounts of cloud water are contained in vertically extensive clouds, which have been inadequately measured due to saturation effects
- our knowledge of cloud water amounts can be fundamentally improved by CHASM
- CHASM uses proven technology, but in a novel combination, to overcome current measurement limitations

- the paradox of missing water
- limitations of conventional remote sensing
- multiangle optical solutions
- liquid/ice determination
- limitations of conventional passive microwave
- dual angle microwave solution
- comparison and synergy with other programs
- summary of scientific strategy
  - measurements
  - validation
- summary of scientific requirements

Missing mass of global cloud water?

- satellite observations traditionally yield low optical depths
- ISCCP* estimates the global average cloud optical depth,

$$\tau \approx 3.7$$

  - **this is equivalent* to an average liquid water path (LWP), $w \approx 25$ g m^{-2}**

- theoretical estimates* of global cloud water are very different, getting instead

$$w \approx 388 \text{ g m}^{-2}$$

  - **this is equivalent to an optical depth, $\tau \approx 57$**

- these estimates differ by a factor of ≈15!
- if the finding of CHASM is that there is no missing mass (unlikely), then the theory of the global hydrological cycle will have to be completely revised, with a much shorter average lifetime of cloud liquid water before precipitation
- more probably, CHASM will find the missing mass, improve the theoretical estimates, and permit totally new parameterizations, such as the dependence of LWP on temperature, to be developed

Impacts of LWP uncertainty

- precipitation models: coalescence rates depend on cloud liquid amount and residency times of clouds
  - the theoretical estimate of global mean cloud liquid residency is ≈3.5 hrs
  - the satellite estimate of LWP corresponds to ≈13 min (too short for coalescence)

- climate models: cloud radiative feedback to climate change depends strongly on the response of cloud albedo to changes in temperature and surface evaporation rate
  - low amounts of liquid water overestimate the albedo response, and cause parameterizations of liquid water dependence on temperature to have the wrong sign

- aerosol models: affected by mean residency times of clouds
  - evaporated clouds are a significant distributed source of atmospheric aerosol
  - average aerosol has been recycled by cloud several times
    - with resulting changes to its size distribution and chemical composition
  - a low liquid water content reduces the volume of aerosols recycled and gives insufficient reprocessing of the background size distribution

Vapor cycle

- the following slide shows an animated example of the difference between the theoretical estimates (on left) and current satellite estimates (on right)
  - note the vapor cycling (once per 9 days) is common to both

theoretical estimate

satellite estimate

diameters ≈ global mean column amounts

rotation rate ≈ mean residency times

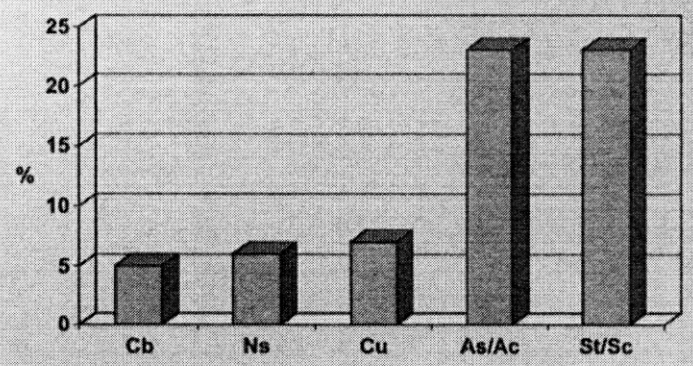
The missing mass of cloud water?

- candidate explanations for why the satellite observations underestimate global mean cloud LWP:
  1. traditional optical techniques underestimate the mass of bright clouds
  2. traditional microwave techniques have large uncertainties in cloud liquid water amount over land due to surface emissivity effects
  3. deep convective clouds over land contain the most moisture but are often missed by sun-synchronous orbits
     - late-afternoon continental clouds are the largest and wettest of all clouds (Nesbitt *et al.*)
- CHASM has remedies for each of these points
  - side scan optical
  - dual-angle microwave
  - precessing orbit

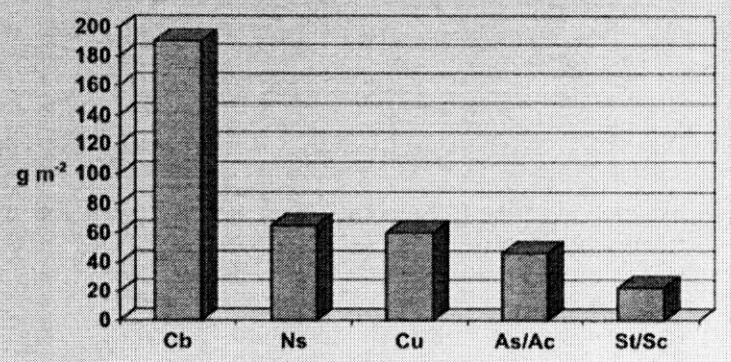
Estimates of global cloud types

- the planetary albedo, and the frequency distribution of cloud optical depth, is dominated by thin stratiform clouds, which are (relatively) well measured
- the hydrological cycle is dominated by cumulonimbus and nimbostratus clouds, which are (relatively) poorly measured

global cloud fractions

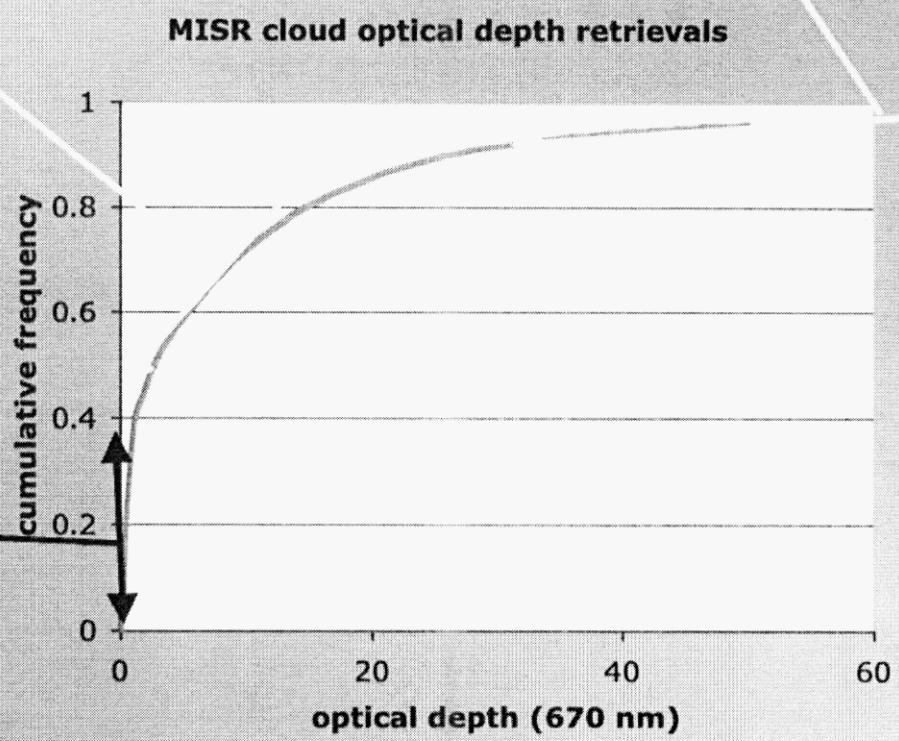


mean liquid water content



1D retrieval of cloud optical depths from MISR nadir radiances (14 Terra orbits) truncated at τ=50

most hydrologically important clouds are in this range



non-cloud

remote sensing considerations

- limitations to conventional (nadir-view) retrieval of cloud optical depth
  - because albedo (or reflected radiance) depends nonlinearly on optical depth, all clouds exceeding a certain thickness appear bright when viewed from above
  - there is thus little to distinguish a 1 km from a 10 km thick cloud by measuring visible reflectance at the cloud top from a single direction
  - optical depths greater than ≈60 are typically not retrieved
  - 1D radiative transfer is used to get τ , which assumes that clouds are plane parallel (not realistic for most global clouds)

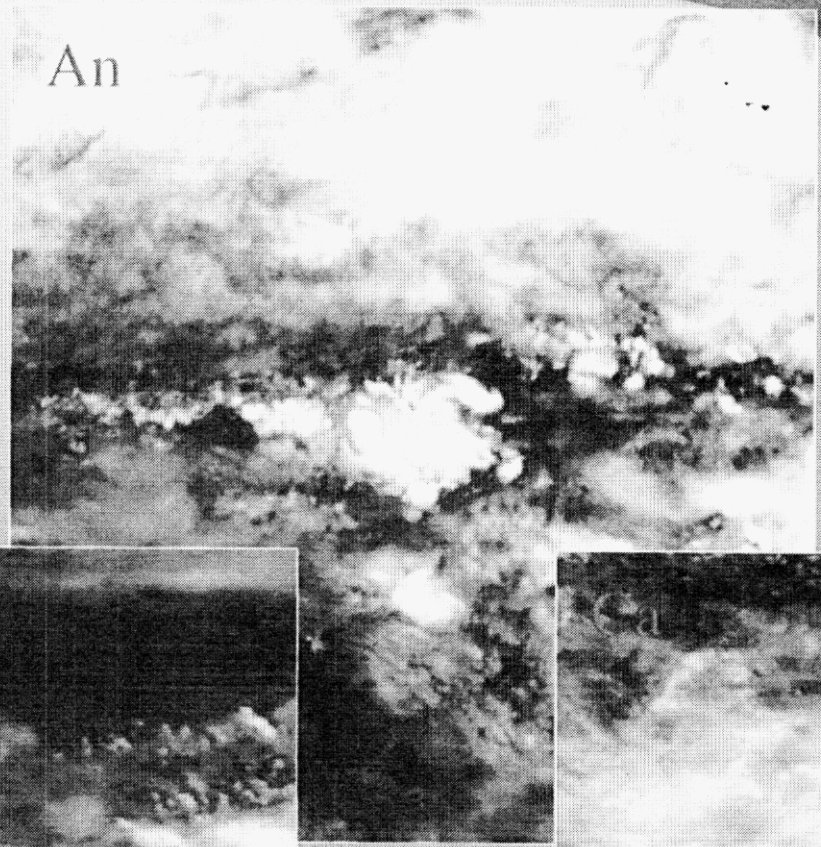
Remote sensing considerations

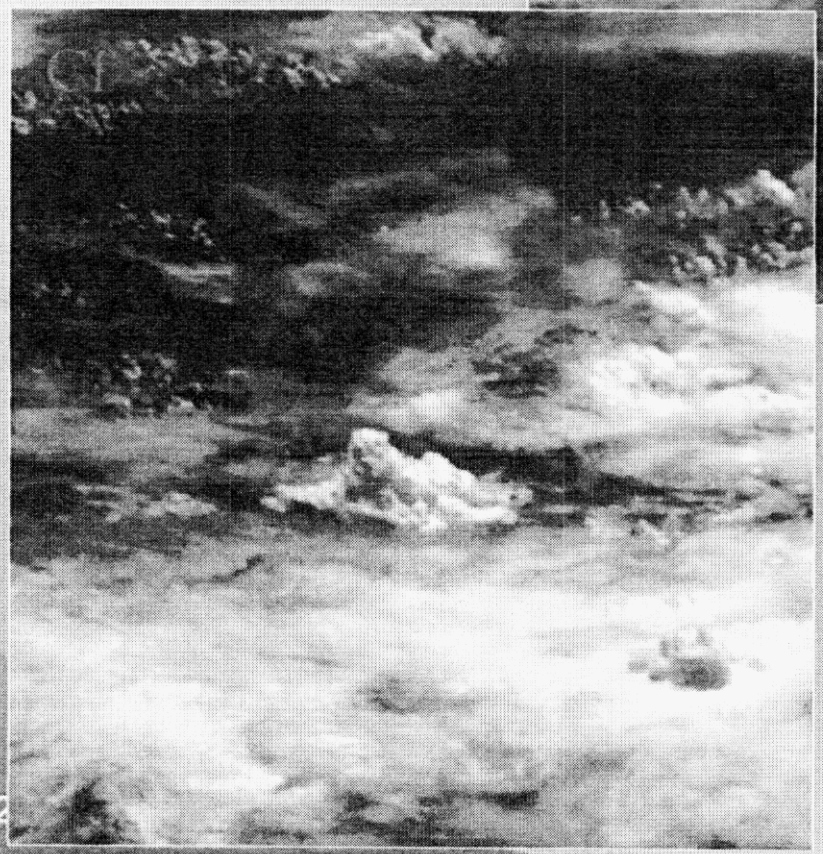
- CHASM's solution using multiple views from 5 pushbroom cameras
  - use the near-nadir cameras to provide geometrical cloud-top heights and side geometry by stereo matching
  - measure radiances at high resolution (100 m) down the sides of deep convective clouds with the oblique (60°) views, when the sides are visible
  - match against 3D radiative transfer models and integrate over height to get optical depth values without saturation
  - detect homogeneous conditions (≈10% of cases) for accurate 1D retrievals using the angular dependence measured by all cameras
  - improve the retrieval of non-saturated τ for heterogeneous cases using the angular information from all cameras, and 3D radiative transfer theory

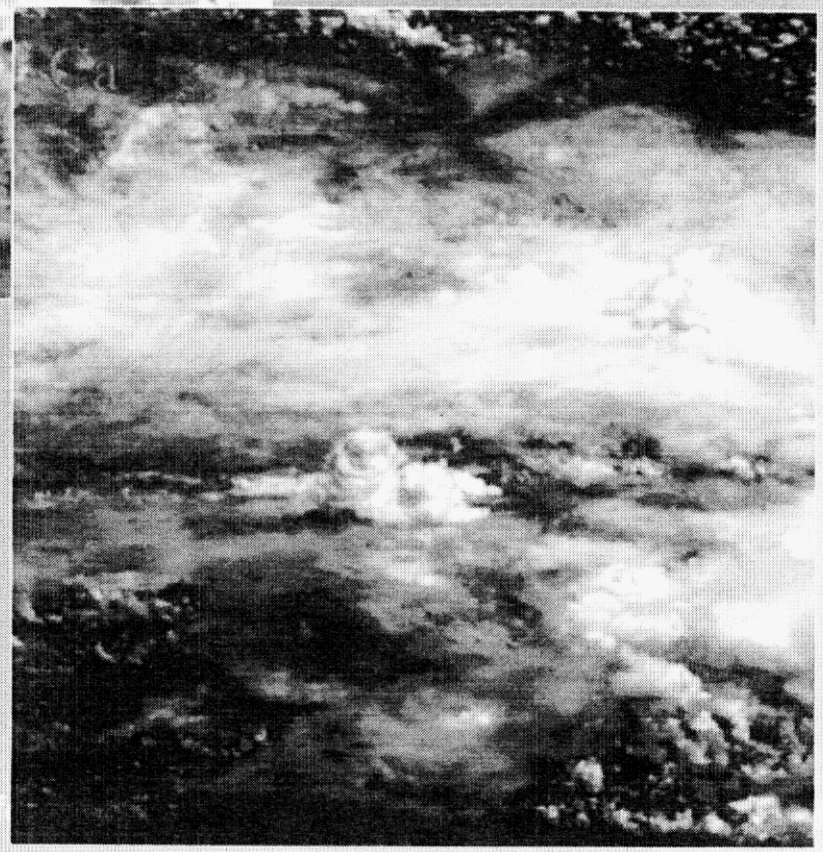
the use of side views from MISR

- the following slide shows an animated flyover of a convective cloud
  - the first views are from the forward MISR cameras approaching the cloud
  - the nadir image is then flipped,and the remaining views are from the aft cameras leaving the cloud
  - note the additional visual information available in the oblique views
  - the Ca and Cf views correspond to CHASM, but it will have higher resolution

- Ca is the sunlit side



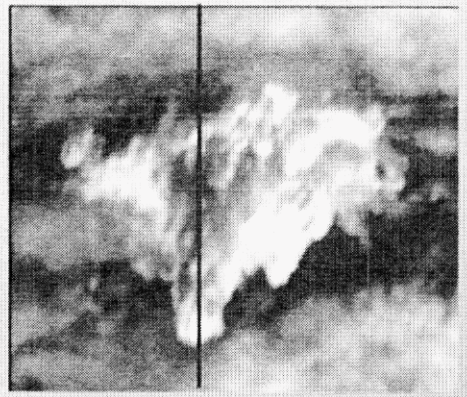


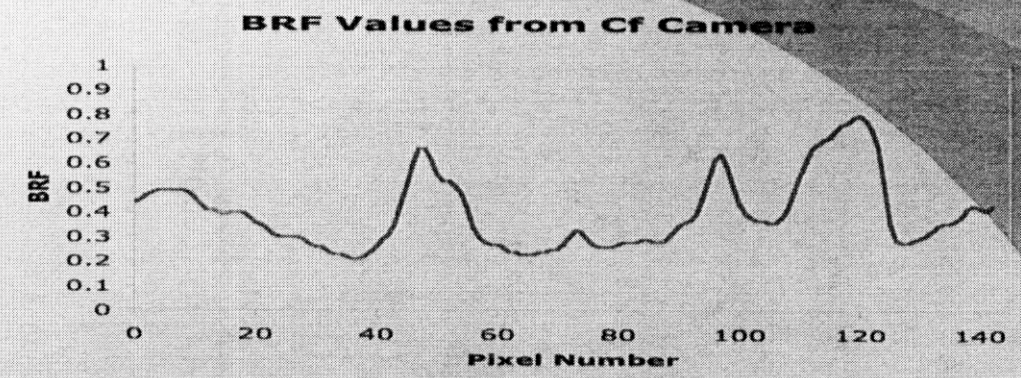


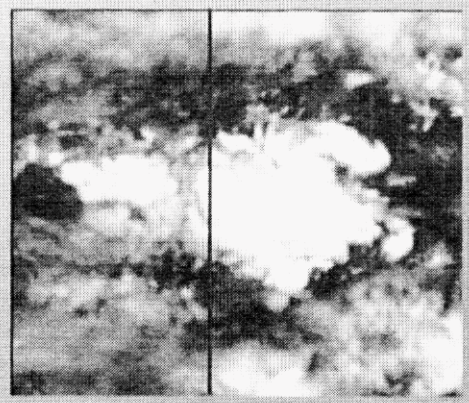
Radiance cross-sections

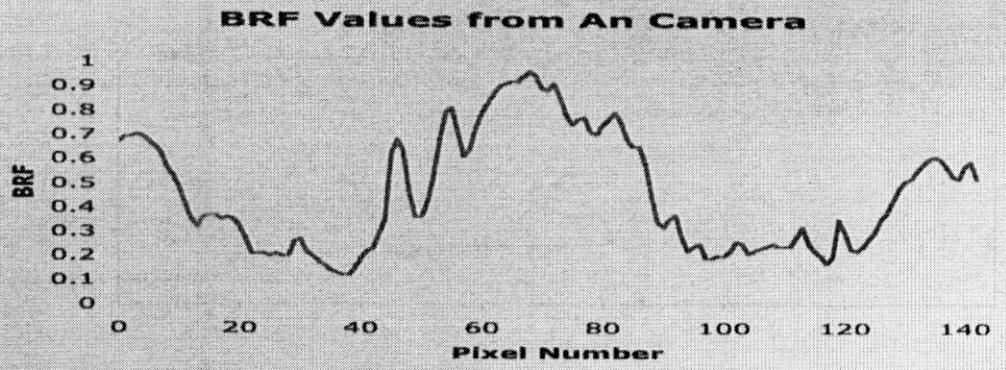
- the following slide shows the radiance cross-sections through the previous cloud
  - expressed as brf's (i.e. a brf of 1.0 implies an albedo of 100%, for isotropic reflection)
  - note how close the nadir brf's are to saturation in the middle of the cloud
  - the table below summarizes the analysis of the oblique views using TIPA*, compared to a nadir view only

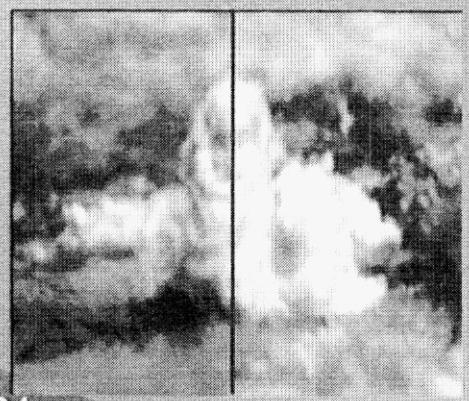
	nadir only	nadir+60°
cloud vertical extent	no information	10.5±0.8 km
extinction coefficient	no information	8–22 km^{-1} (higher at base)
cloud optical depth	> 60	150±30

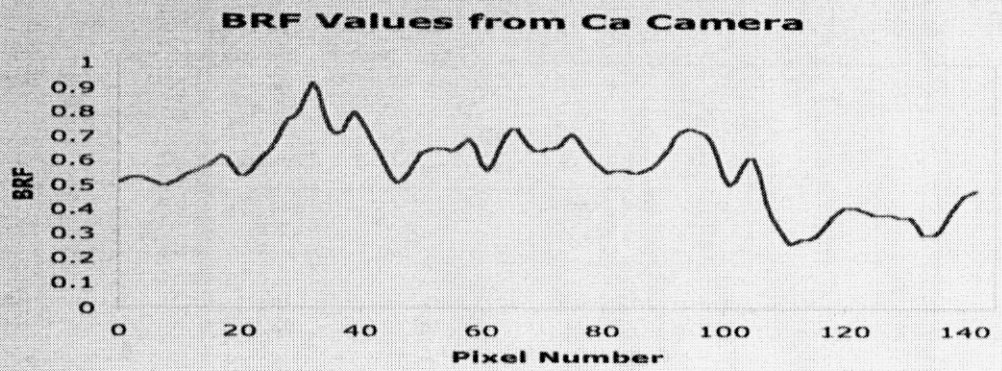



BRF Values from Cf Camera
BRF
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
Pixel Number



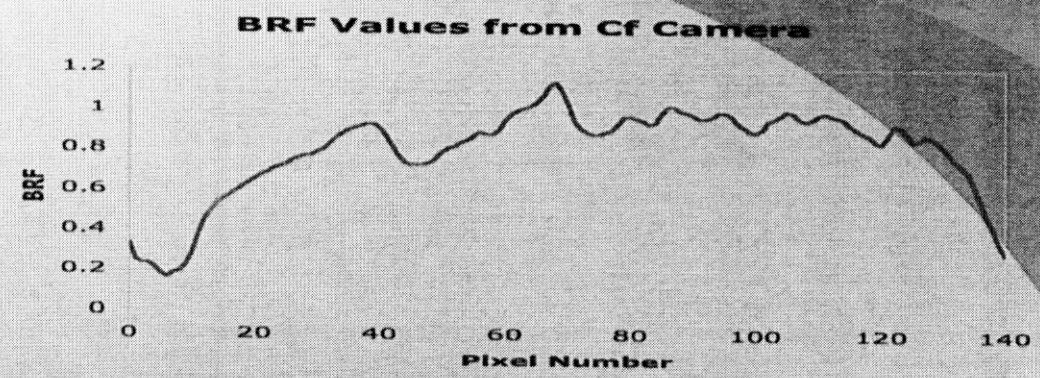

BRF Values from An Camera
BRF
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
Pixel Number

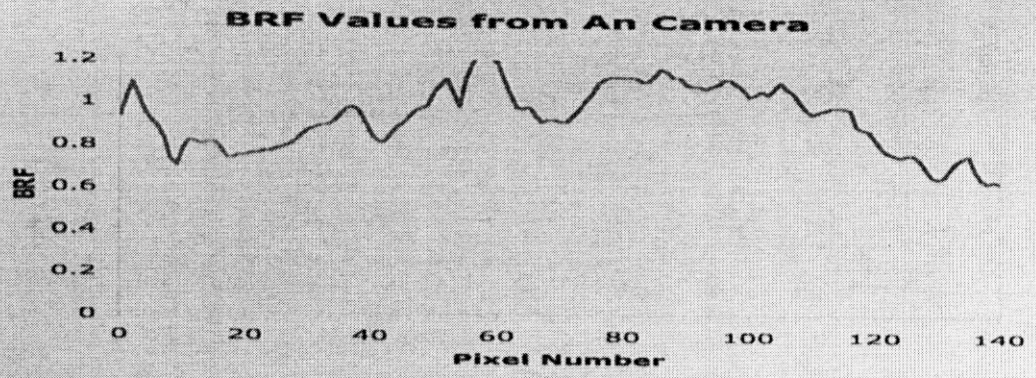


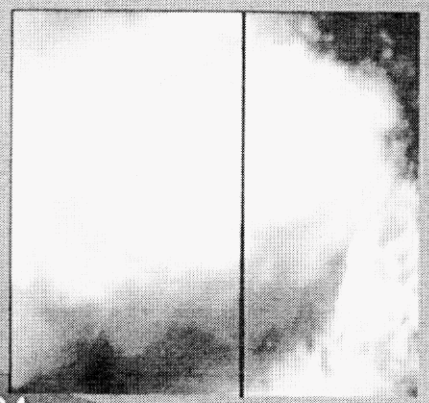

BRF Values from Ca Camera
BRF
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
Pixel Number

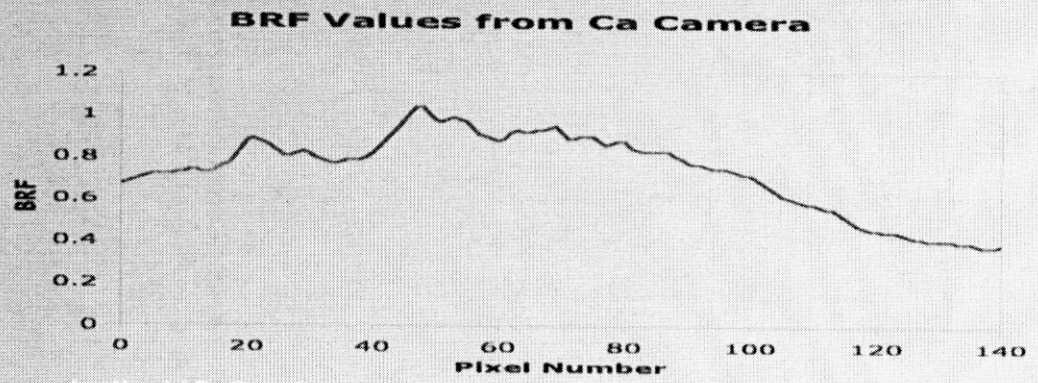
another cloud example

- the previous case was reasonably tractable
- the following cloud is more challenging
  - note the very high brf values, requiring a 3D radiative transfer treatment
  - the cloud vertical extent is again about 11 km
  - it is considerably brighter (even though it is located only 200 km east of the previous cloud)
  - a preliminary 3D analysis indicates an optical depth for this case in excess of ≈300
  - nadir view alone simply indicates an optical depth > 60


BRF Values from Cf Camera
BRF
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
140
Pixel Number


BRF Values from An Camera
BRF
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
140
Pixel Number

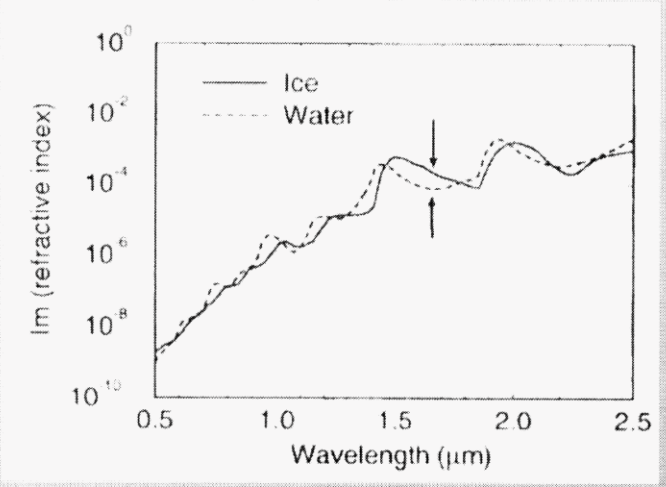


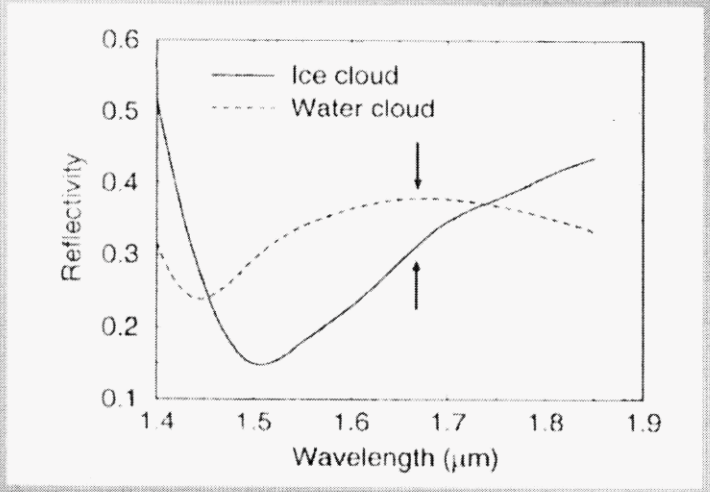

BRF Values from Ca Camera
BRF
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
140
Pixel Number

Importance of cloud phase

- most deep convective clouds are glaciated
- the extinction coefficient and scattering phase function for water and ice differ significantly
- accurate retrieval of LWP (or ice water path) requires knowledge of the vertical transition region between the phases
- supercooled liquid is frequently present, so that temperature-phase relations are not reliable between 0°C and –40°C (even if the brightness temperature and emissivity are known)
- CHASM will detect ice vs. liquid phases using a split spectral band in the solar infrared and use the distinction in cloud phase to derive the correct LWP

Use reflectivity to detect phase





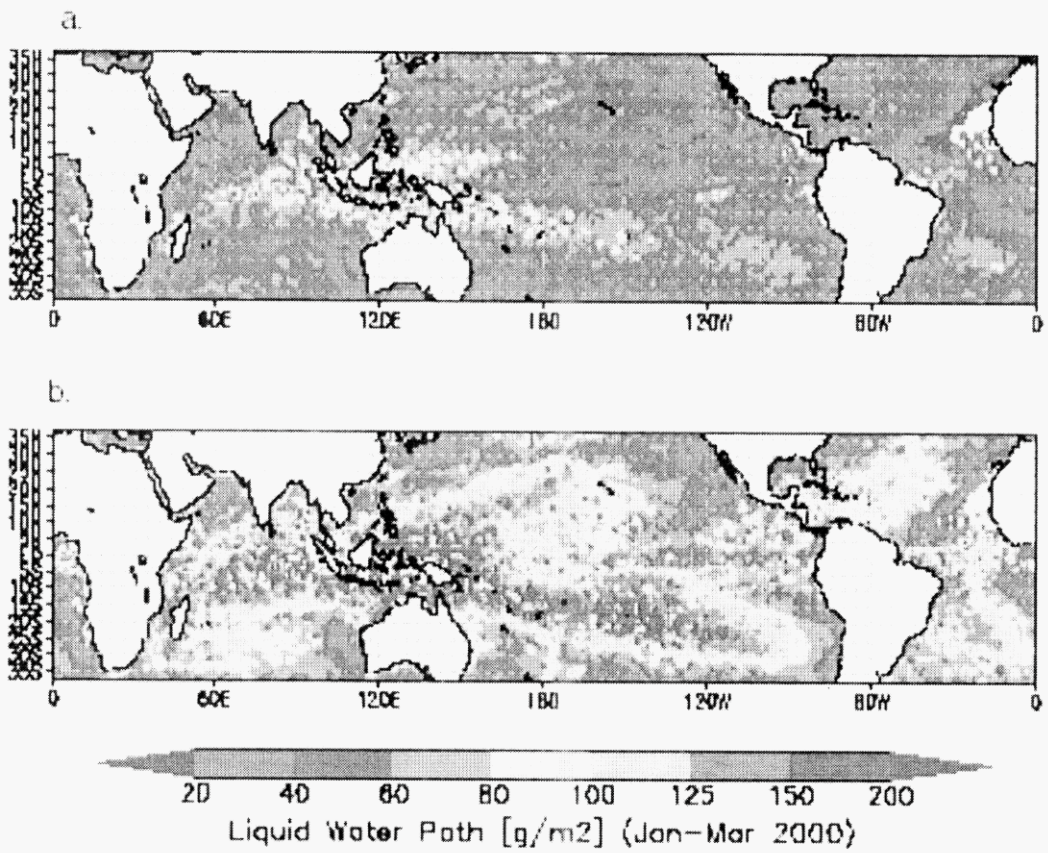
- the imaginary index of refraction for liquid water has a turning point at ≈1670 nm, whereas the index for ice changes steadily with wavelength
- the above figures, from Knap et al. 2002, show the effect on cloud reflectivity
- Knap* has demonstrated that this can be used as a useful detector of cloud phase, using spectrally resolved radiances around 1670 nm
- CHASM will measure spectral reflectivity in two adjacent bands (1655 nm and 1685 nm)

microwave remote sensing considerations

- limitations to conventional microwave remote sensing of LWP
  - passive microwave retrievals are traditionally not attempted over land due to first order effects of high surface emissivity
  - cloud radar is very sensitive to drop-size distribution
    - radar reflectivity increases as r^6 and is strongly affected by the presence of precipitation
  - over ocean, the surface emissivity is much lower, but is polarized, and depends on surface wind speed
    - LWP is typically retrieved based on climatological regression, tuned to average conditions, and has a significant uncertainty for deep convective cases
    - see following example from Masunaga

Example of passive microwave retrieval over ocean (next slide)

- from Masunaga *et al.*, 2002 using TRMM microwave imager (TMI) and visible/infrared scanner (VIRS) to enhance the microwave retrieval of liquid water path
  - VIRS corrects the beam-filling efficiency of TMI (9-63 km footprint) by measuring the cloud fraction at moderate resolution (2 km)
  - VIRS provides an estimate of cloud-top temperature
- note the significance of the cloud fraction correction, and the larger values of LWP that are obtained for this maritime case (three-month average)
- their technique works over ocean only, and may underestimate LWP for deep clouds by ignoring scattering
  - higher resolution visible measurements would improve the retrieval by more accurately measuring the cloud fraction



cloud liquid water from TRMM (a) without and (b) with corrections for subpixel cloud fraction (adapted from Masunaga et al. 2002)

Microwave remote sensing considerations

- CHASM's approach
  - passive microwave radiometer based on JMR*
  - two channels at 23.8 GHz and 34.0 GHz single V-polarization
  - two view angles at nadir and 60°
    - near-simultaneous views of the same 50 km diameter footprint
    - apply Masunaga's enhancement to improve the microwave retrievals
      - this uses knowledge from the optical sensors to account for beam filling and cloud top heights from stereo
  - first order effects of surface emissivity are removed using dual angle views
  - column water vapor from the 24 GHz channel
  - cloud liquid water from the 34 GHz channel

Impact of surface microwave emissivity on MW retrieval

	Traditional	CHASM
land	not attempted due to the high value of land surface emissivity	dual angle approach removes first order effects of surface emissivity over both land and ocean – see next slide for theory – cf. ATSR dual angle IR retrieval of sea surface temperature
ocean	requires dual polarized 18.7 GHz channel to account for the ocean emissivity – emissivity varies with surface wind speed	insensitive to first order effects of wind speed – two channels and one polarization suffice – see simulations that follow

dual angle microwave equations

(all symbols are defined in the notes, *N* and *O* are the nadir and oblique brightness temperatures, *f* is either 23.8 or 34.0 GHz)

$$N_f = \varepsilon_s T_s \tau_f + (1-\varepsilon_s) T_d (1-\tau_f)\tau_f + T_a(1-\tau_f)$$ at nadir

$$O_f = \varepsilon_s T_s \tau_f^2 + (1-\varepsilon_s) T_d (1-\tau_f)\tau_f^2 + T_a(1-\tau_f^2)$$ at 60°

the surface terms involving ε_s can therefore be eliminated, giving

$$O_f - \tau_f N_f = T_a(1-\tau_f)$$

or

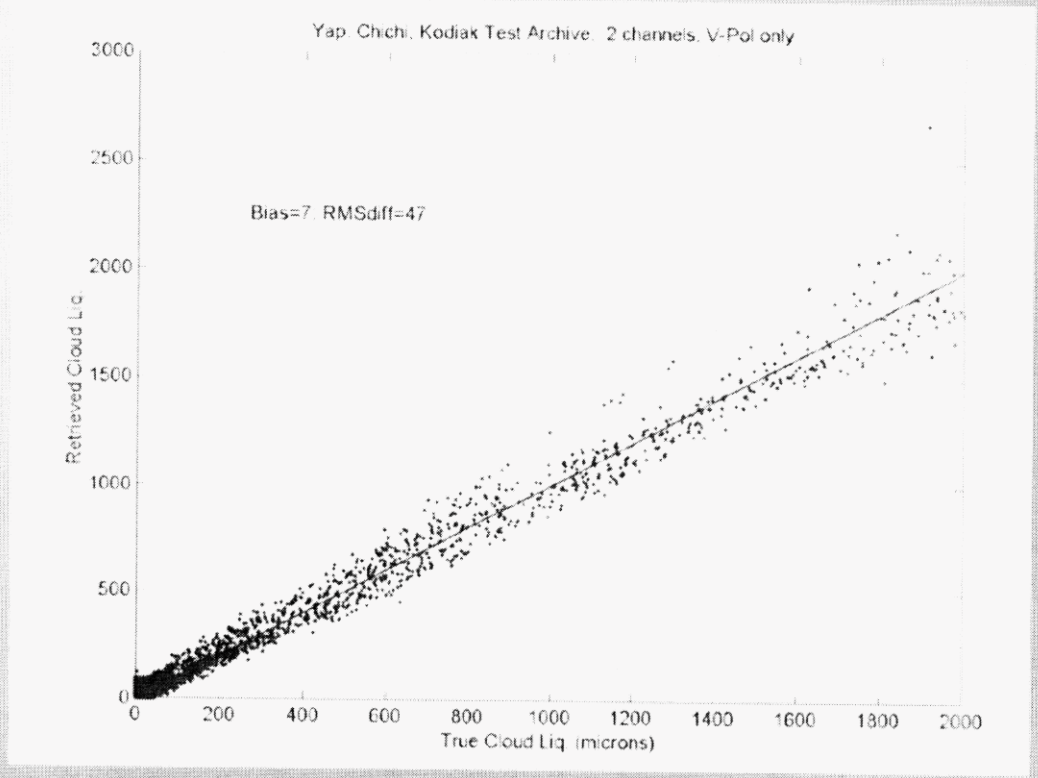
$$\tau_f = \frac{1 - O_f / T_a}{1 - N_f / T_a}$$

which is (to first order) independent of the surface emissivity and surface temperature

Initial CHASM microwave retrievals of cloud liquid water over ocean

- conducted independently by Steve Keihm
- based on current regression approach used by the Jason and TOPEX radiometer algorithms*
- applied to the two-channel nadir and 60° views of CHASM
- using a statistical archive of sounding data representative of low-, mid-, and high-latitude conditions over ocean
- non-precipitating clouds
- retrieved microwave cloud liquid water compared against 'true' radiosonde-computed values
- following results are for a 2-channel, dual view, V-polarization only case (CHASM)

Retrieval versus radiosonde



The figure shows an rms retrieval error of 47μm (g m^{-2}) in LWP for non-raining oceanic clouds using a conventional regression algorithm applied to the simulated CHASM microwave measurements. Only by using a full suite of measurements can SSM/I achieve a smaller error in LWP (nominally 25 μm rms for average conditions). The SSM/I errors would be much larger than this for deep convection.

Relate to other missions

- CHASM makes unique measurements that do not duplicate existing or proposed missions
- CHASM will capitalize on the GPM mission by flying in formation with a GPM core satellite in order to make use of the GPM precipitation and ground validation measurements
- CHASM will provide essential and different information about vertically extensive clouds:
  - these contain the bulk of global cloud water
  - they are beyond the saturation threshold of MODIS/VIRS/ISCCP optical techniques, and the attenuation limit of CloudSat
  - the precessing orbit of CHASM includes sampling of late afternoon convection (which is dominant over land)

Relevance to GPM

- GPM will use a combination of active, dual frequency radars, and passive, multichannel microwave radiometers on a constellation of satellites, starting in 2007
- the core satellite(s) have a nominal altitude of ≈400 km and inclination of ≈65°, precessing through all local times with a period of ≈103 days
- by flying in constellation with a GPM core satellite, CHASM can:
  - make use of GPM's precipitation measurements to improve the LWP retrievals of precipitating clouds
  - compare with GPM's multichannel LWP retrievals over ocean for validation purposes
  - piggyback on the data collection from GPM's ground validation sites for additional validation

Relation to CloudSat

- CloudSat will use a 94 GHz radar to obtain reflectivity profiles at a resolution of ≈500 m (vertically) and ≈2 km (horizontally), at 1:30 pm local time
- the radar reflectivity, which increases as r^6, makes CloudSat a sensitive detector of precipitation water, even drizzle from boundary layer clouds
- the LWP retrieval by CloudSat is limited by attenuation in vertically extensive clouds, and also relies on traditional optical retrievals which saturate for thick clouds
- synergy of CloudSat with other instruments on the A-train (notably MODIS on Aqua and CALIPSO) provides relations between optical properties and precipitation water, especially for thinner clouds where the optical properties do not saturate
- CHASM's focus is instead on the vertically extensive clouds for which the conventional optical and passive microwave techniques fail and which contain the bulk of the global cloud water
- CHASM provides the added benefit of sampling late afternoon clouds, which often have the greatest vertical development

- MISR provides stereo cloud heights and cloud albedos
  - resolution of C cameras (275 m across-track, 550 m along-track) allows rough calculation of optical depth down cloud sides
  - cannot separate optical depths between liquid and ice water
  - 10:30 am orbit misses all the deep convection over land
- CHASM provides higher spatial resolution measurements
  - improved integrations down cloud side
  - improved stereo height retrievals of cloud top and cloud base
  - improved cloud fraction and 3D radiative transfer calculations
- CHASM provides differential 1670 nm measurements
  - needed for phase, separating ice water path from LWP
- CHASM has precessing orbit
  - captures diurnal range of convective activity
  - the deepest clouds tend to form in the late afternoon over land
- CHASM includes simultaneous microwave measurements
  - needed for full diurnal range
  - needed when cloud sides are obscured
  - provides effective radius retrieval for unobscured cloud sides

Summary of science strategy

- the first novelty is the determination of the optical depth of vertically extensive clouds by measuring reflected radiance as a function of height down the visible sides of clouds from an angle of 60°
  - stereo retrievals of cloud-top and cloud-base altitude provide geometrical information about the cloud
  - top-leaving (nadir view) and side-leaving (oblique view) radiance as a function of position, coupled with 3D radiative transfer models, yields the local extinction coefficient
  - differential spectral reflectivity at 1670 nm provides cloud phase information, to partition ice water from liquid water
- the second novelty is the concurrent determination of liquid water path for dual angle passive microwave measurements at 23.8 GHz and 34.0 GHz, over both land and ocean
  - the dual angle view eliminates the first order effects of surface emissivity
  - the high spatial resolution information from the optical measurements is used to correct for beam filling effects on the microwave (cf. Masunaga)
  - comparisons between the microwave and optical retrieval of liquid water path for the same scenes with visible cloud sides are used to retrieve effective radius of the cloud drops
  - the microwave measurements alone are used to extend the liquid water path retrievals to deep clouds with obscured sides
- statistical compilation of liquid water paths over a two year mission, classified by cloud type and meteorological context (air mass thunderstorms, frontal thunderstorms, mesoscale convective complexes, etc.) will answer the global question of where the missing mass of cloud water is predominantly located