An Abbreviated History of the IRF Working Group: 1992 -2005

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Outline

- Where did the IRF originate?
- Birth of the IRF – first workshop information
- Summary of workshop locations and developments
- Some major thrusts – LBL- QME, Water Vapor IOP, Anomalous Absorption – ARESE, Diffuse SW problems, BBHRP, CLOWD –Instrumentation, IOPs, and extensive analyses – New parameterizations
- Some offshoots as well – I3RC
- Reports along the way – 97, 2000, 2001, 2003 and 2006
- Current make up and primary thrusts – Surface and atmospheric properties, 3-D clouds, Instrumentation

IRF Predecessor - ICRCCM Intercomparison of Radiation Codes in Climate Models

- Initiated and funded by the U.S. DOE
- Sponsored by the International Radiation Commission (IRC) and the World Climate Research Programme (WCRP)
- Began in 1983 as a series of short- and long-wave radiation model comparisons
- International workshops in 1984 and 1988
- JGR Special edition in 1990 summarized the results
- Recommended a major field experiment to test models (SPECTRE 1991), the plan for which evolved into the ARM Program Plan

State of the Science 1990 - ICRCCM Conclusions - Longwave

- There is a clustering of many models in the ±2% flux range relative to line-by-line models. This is in the marginal range to meet the accuracy (relative) requirements of major climate programs.
- Uncertainties in the physics of line wings and in the proper treatment of the water vapor continuum make it impossible for line-by-line models to provide an absolute reference.
- The large discrepancies revealed by the model comparisons can only be resolved by well calibrated *spectral* observations because *the uncertainties associated with broadband observations are the same magnitude or larger of the discrepancies between models (5% or 20 W m^{-2}).*

State of the Science 1990 - ICRCCM Conclusions - Shortwave

- Different parameterizations for H2O absorption may lead to significant differences between band model results.
- If the discrepancies attributable to various water vapor transmittances are removed, flux calculations at the surface generally agree to within 1%.
- Provided that the Rayleigh optical thickness is adequately parameterized, climate model codes appear to simulate clear-sky fluxes in reasonable correspondence with results from the high-resolution codes.
- More definitive recommendations will emerge only from comparisons of high resolution calculations with high precision observations.

IRF Info from the First Science Plan

- **Programmatic Objective**: ***Develop and test radiation parameterizations at the accuracy required for climate studies***
- **Scientific problems presented as a series of *"Grand Hypotheses"* covering a variety of *important* clear-and-cloudy sky radiation problems that might be solved through comparison of observations with calculations**
- **Example:**

Common Assumption	Current Understanding
H2O absorption inside clouds is well understood	H2O absorption has never been measured in the laboratory at relative humidities above about 70% ...

Evolution of the IRF - Workshop Dates, Venues and Important Developments

Year	Host/Location	
1992	PNNL, Richland, WA	
1994	UM, College Park, MD	↔ H2O IOP group
1996	UM, College Park, MD	
1997	UM, College Park, MD	↔ IRF SOS Report for Science Plan
1998	LLNL, Pleasanton, CA Joint with Cloud and SCM	
1999	SUNY Albany, NY	↔ IRF White Paper
2001	PNNL, Richland, WA	↔ IRF reorganization ↔ BBHRP initiated
2002	SUNY Albany, NY	
2003	SUNY Albany, NY	↔ Input to Science Plan
2004	UC Santa Barbara, CA	↔ CLOWD initiated
2005	Annapolis, MD (with Cloud)	
2006	Washington, DC	↔ Nuggets

First IRF Workshop - November 4-6, 1992, Richland, WA

General Goals For The First IRF Workshop

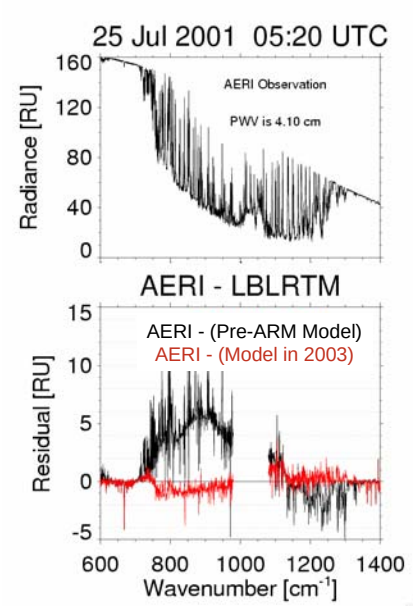
- To discuss the status of the Southern Great Plains CART site, currently and in the near term.
- To ascertain the extent to which the measurements available from CART are sufficient to support the research goals of the Science Team projects.
- To foster communication between IRF projects concerning research issues of joint interest, and to develop plans to acquire the measurements necessary to address these issues.

IRF focus through 1996 Was on the 'Clear-sky Longwave Problem'

- ICRCCM identified problems associated with errors in flux measurements, lack of spectral detail, and the H2O continuum
- Instrumentation was relatively mature - particularly the Wisconsin interferometer - AERI
- Could build on initial efforts from SPECTRE
- Necessary step prior to major advancement on cloudy-sky problems

From 1997 State of Science Report

AERI Observations at Southern Great Plains Improve Infrared Radiative Transfer Models



- AERI observations used to evaluate clear sky IR radiative transfer models
- Long-term comparisons have improved
  - Spectral line database parameters
  - Water vapor continuum absorption models
- Reduced errors in computation of downwelling radiative IR flux by approx 4; current uncertainty is on the order of 1.5 W/m^2

1 RU = 1 mW / (m^2 sr cm^{-1})

Turner et al., JAS, 2004

•One of the goals of the ARM program is to improve radiative transfer models.

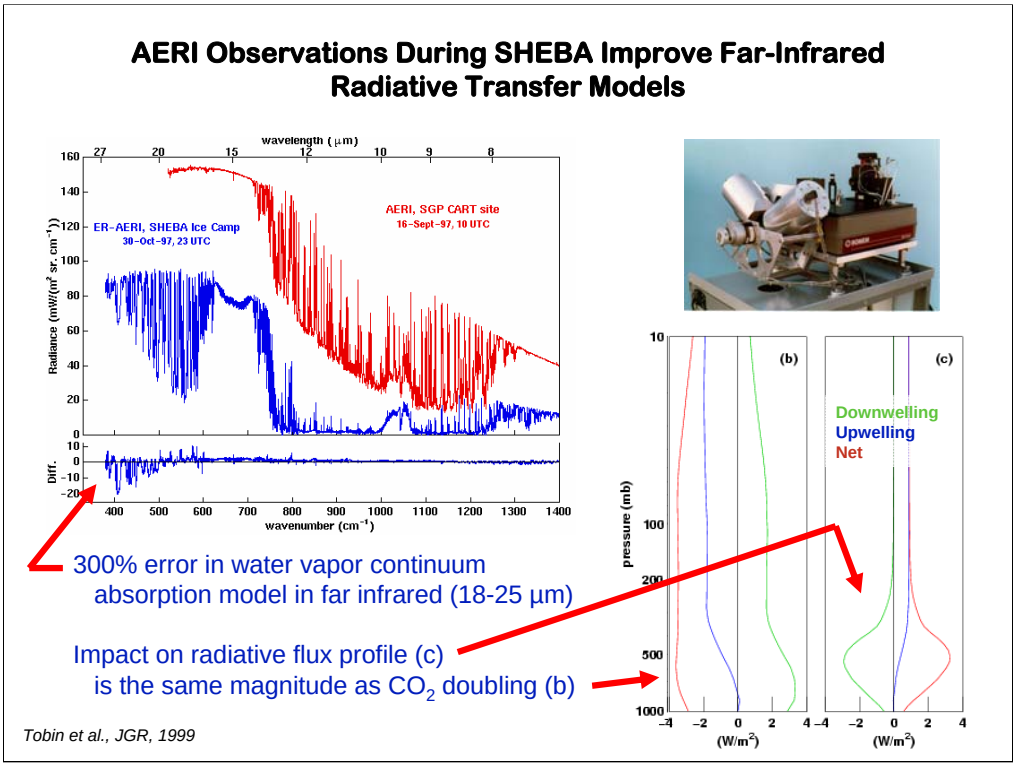
•Observations from the Atmospheric Emitted Radiance Interferometer (AERI) are critical to evaluate and improve these models

•AERI observations at the Southern Great Plains site over the last decade have lead to improvements in both spectral line absorption parameters and in the water vapor continuum (a spectrally broad feature).

•The current (2003) model has approximately 4 times less error in the computation of downwelling IR flux compared to models used in the early 1990's.

•These observations led to a significant and important change of the radiative transfer models used by ARM, and hence by the climate community.

•Published by D.D. Turner et al. in J. Atmos. Sci., 2004.



•One of the goals of the ARM program is to improve radiative transfer models.

•Observations from the Atmospheric Emitted Radiance Interferometer (AERI) are critical to evaluate and improve these models

•AERI observations during the Surface Heat Budget of the Atmosphere (SHEBA) demonstrated a 300% error in the water vapor continuum model in the far-infrared.

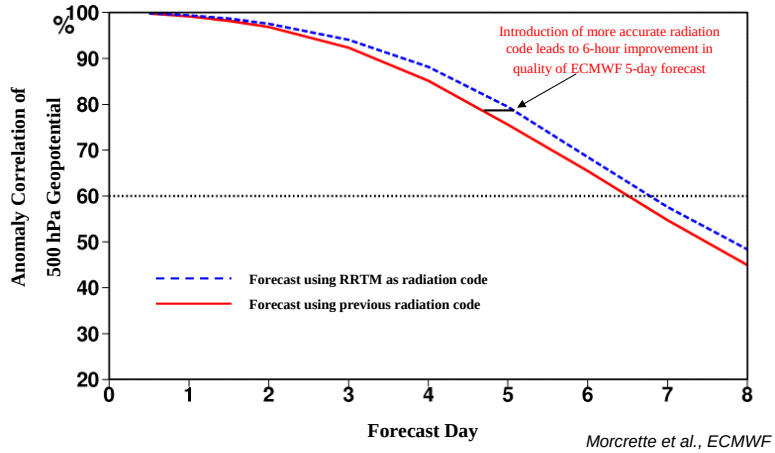
•This error has the same magnitude as CO2 doubling (in terms of radiative flux), although that distribution in the atmosphere is significantly different.

•These observations led to a significant and important change of the radiative transfer models used by ARM, and hence by the climate community.

•Published by D.C. Tobin et al. in J. Geophys. Res, 1999.

ARM-Developed Radiation Code Improves Weather and Climate Prediction

- Radiation code 'RRTM' developed at AER, Inc., *with ARM funding and using ARM data*, has been implemented in a number of forecast models, including:
  - NCEP Global Forecast System (GFS)
  - ECMWF Forecast Model
  - PSU/NCAR Mesoscale Model (MM5)



Morcrette et al., ECMWF Memo, 1998

The anomaly correlation of the 500 hPa geopotential is a commonly used metric for weather forecast quality. This plot shows the improvement in forecast quality when the ARM-developed longwave radiation code RRTM replaced the previously used code. For example, the quality of the forecast at 5 days when the model used RRTM is equal to the quality the previous version attained at 4 3/4 days. This improvement in forecast quality can be directly attributed to ARM measurements and funding.

References:

Morcrette, J.-J., S.A. Clough, E.J. Mlawer, and M.J. Iacono, Impact of a validated radiative transfer scheme, RRTM, on the ECMWF model climate and 10-day forecasts, ECMWF Research Department Tech. Memo No. 252, 47pp, 1998.

Mlawer, E.J., S.J. Taubman, P.D. Brown,/\ M.J. Iacono and S.A. Clough: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res.*, **102**, 16,663-16,682, 1997

ARM IRF-related Observational Accomplishments

- **Implementation of the 'Super Satellite on the Ground' with instrument accuracy and precision at or approaching the level required for many IRF studies**
- **Operationally infer downwelling longwave fluxes with the AERI for homogeneous scenes to better than 5 W m^{-2} - a reduction of observational uncertainty by about a factor of 4.**
- **Simultaneous operation of the AERI and pyrgeometers allows an accurate check of the pyrgeometer data for homogeneous conditions, thereby assuring accurate flux estimates for all scenes.**
- **The SGP CART site has become a satellite validation location and is being used by many different agencies (NASA, NOAA, DOD, and groups using GPS)**

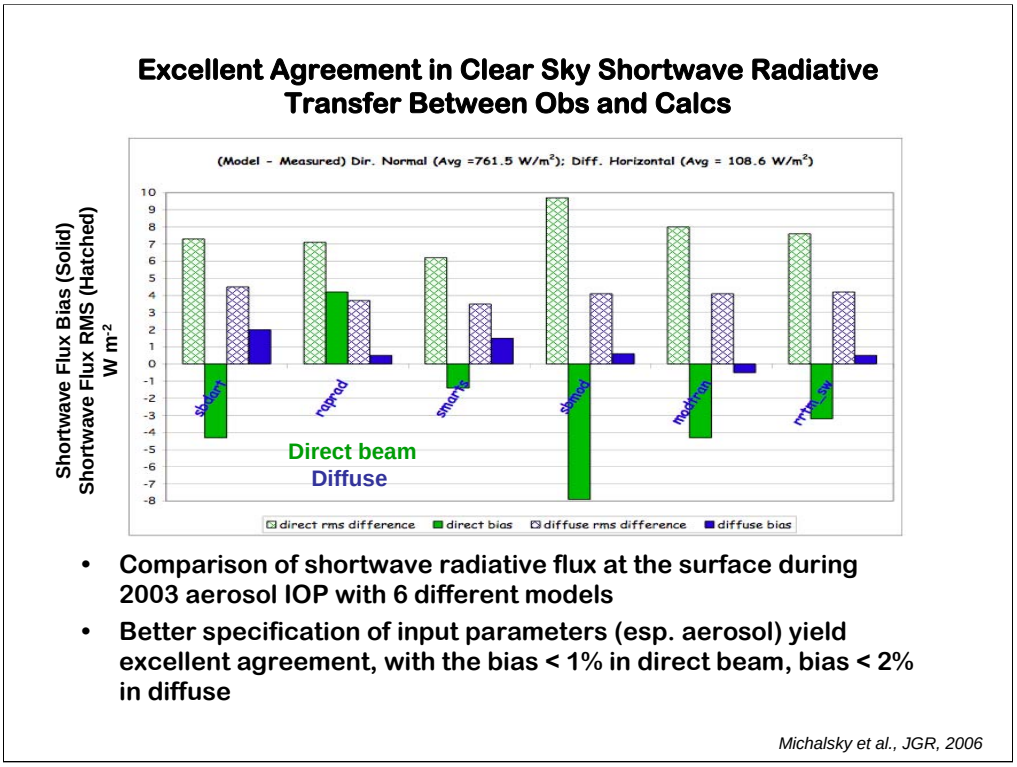
From 1997 State of Science Report

1997 - 2000 Period

- Foci shifted more to Shortwave Radiation, particularly the diffuse field, cloud-radiation problems and the development of GCM parameterizations
- Led to development of an IRF White Paper in 2000 (available from the ARM website) which highlighted the views of where the IRF should focus its activities
- Led to a reorganization of the IRF into a set of focus groups, ones that very much remain the same today

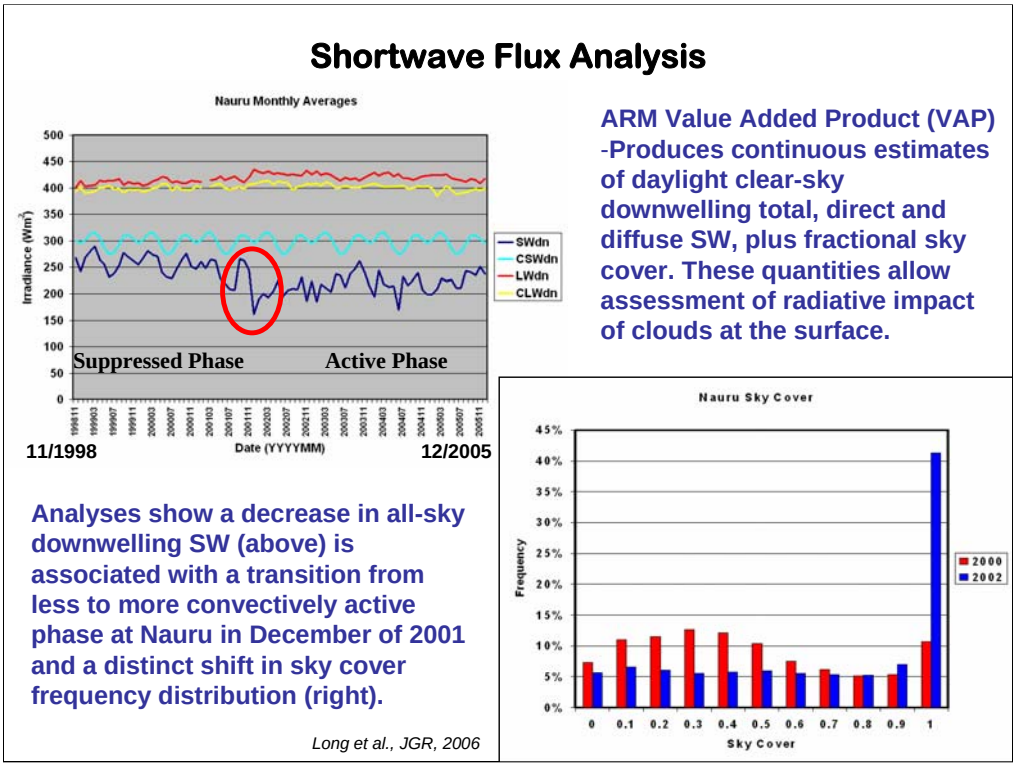
1997- 1999 Workshops

1997	UM, College Park, MD	H2O WV_IOP Summary Shortwave Radiation Status of instrumentation Microwave measurement PWV at the NSA Longwave Clear-and-Cloudy Radiative Transfer
1998	Pleasanton, CA Joint with Cloud and SCM	Recent Issues Regarding Measurement and Calculation of Diffuse Radiation Development of a strategy for parameterization of radiation for climate models Results from Recent Analyses/IOPs ARESE Follow-on - A call for ideas
1999	SUNY Albany	Shortwave Radiation - Measurement and modeling activities Atmospheric State - T, q and clouds ARESE revisited Shortwave Spectral radiation Longwave Radiation Spectral Modeling Discussion and Formulation of New IRF Activities Use of models in discovery



The Atmospheric Radiation Measurement (ARM) program sponsored a large aerosol intensive observation period (AIOP) to study aerosol during the month of May 2003 centered on the Southern Great Plains (SGP) Climate Research Facility (CRF) in north central Oklahoma. Redundant measurements of aerosol optical properties were made using different techniques at the surface as well as in vertical profile with sensors aboard two aircraft. One of the principal motivations for this experiment was to resolve the disagreement between clear-sky models and measurements of diffuse horizontal broadband shortwave irradiance at the surface, especially for modest aerosol loading. This paper focuses on using the redundant aerosol and radiation measurements during this AIOP to compare direct beam and diffuse horizontal broadband shortwave irradiance measurements and models at the surface for a wide range of aerosol cases that occurred during 30 completely clear-sky periods on 13 days of May 2003. Models and measurements are compared over a large range of solar-zenith angles. Six different models are used to assess the relative agreement among them and the measurements. Better agreement than previously achieved appears to be the result of better specification of input parameters, especially asymmetry parameter and spectral surface albedo, and better measurements of irradiances than in previous studies. Biases between modeled and measured direct irradiances are less than about 1%, and biases between modeled and measured diffuse irradiances are less than 2%. These differences are considerable less than the the combined uncertainties of the models and measurements.

Figure. Bias and root-mean-squared differences of six models compared to measurements for 30 cases during the AIOP. Solid bars are model biases in W/m^2 for direct (green) compared to an average measured direct of 761.5 W/m^2 and in diffuse (blue) compared to an average measured diffuse of 108.6 W/m^2. Hatched



The ARM Shortwave Flux Analysis (SWFA) Value Added Product (VAP) is based on the work of Long and Ackerman (2000) and Long et al. (2006). Time series of downwelling total and diffuse SW measurements are analyzed to detect periods of clear (i.e. cloudless) skies. The detected clear-sky data are used to fit functions, and the fit coefficients are interpolated for cloudy periods in order to produce a continuous estimate of clear-sky values, and then estimate the fractional sky cover during daylight periods. As described in Long and Gaustad (2004), the SWFA VAP is used to operationally process surface radiation measurement data from all ARM Central and Extended Facilities.

In monitoring of the surface radiative energy budget, we note changes on various time scales. Analyses using the SWFA can not only document changes in the effect of clouds on the surface radiation budget, but assess what about the nature of the cloudiness might have changed to produce the radiative changes. An example is shown here, where a distinct shift in monthly average downwelling all-sky SW has been produced by a shift to a more convectively active phase of the Walker circulation for the Nauru area. The increase in convective activity is documented as a shift in the frequency distribution of sky cover from one where most often the skies are partly cloudy to one where almost half the time the skies are overcast.

Long, C. N. and T. P. Ackerman, (2000): Identification of Clear Skies from Broadband Pyranometer Measurements and Calculation of Downwelling Shortwave Cloud Effects, JGR, 105, No. D12, 15609-15626.

Long, C. N. and K. L. Gaustad, (2004): The Shortwave (SW) Clear-Sky Detection and Fitting Algorithm: Algorithm Operational Details and Explanations, Atmospheric Radiation Measurement Program Technical Report, ARM TR-004, Available via http://www.arm.gov/publications/techreports.stm.

Long, C. N., T. P. Ackerman, K. L. Gaustad, and J. N. S. Cole, (2006): Estimation of fractional sky cover from broadband shortwave radiometer measurements, JGR, 111, D11204, doi:10.1029/2005JD006475.

IRF Science Philosophy/Vision and Foci

- Fix the focus and process of implementation within ARM on a very, very short list of high profile science questions
- Focus more attention on the direct and indirect effects of aerosols
- Focus more attention on cloudy sky work – 3–dimensional clouds
- Focus more attention on cloudy sky work – ice and mixed phase clouds
- Focus more attention on cloudy sky work

Recommendations from the 2000 white paper

Revised ARM IRF Working Group

Major Components

- **Steering Committee** (Bob Ellingson, Bill O'Hirok, Chuck Long, Joe Michalsky, and Andy Vogelmann)
  - **Arbitrates priorities from subgroups and makes recommendations to STEC & ARM management**
- **IRF Focus Groups**

Overarching goal - the solution of major ARM-related problems - not the solution of individual PI projects

- make recommendations for ARM acquisitions to meet programmatic goals
- subgroups determine the major ARM subgroup problems to be studied and set the priorities for their solution

2001 -2006 Period

Focus shifted to

- 3-D radiative transfer
- Cooperative work with other working groups leading to new focus groups, namely
  - BBHRP (Broad Band Heating Rate Profile) - overarching with aerosol, CPM and CP WGs
  - CLOWD - Clouds with Low Optical Water Depth - overarching with CP WG

Remote Sensing of Cloud Properties Using Measurements of Zenith Radiance

Cloud optical thickness is the most fundamental optical variable in any cloud-resolving model, including the ones used in super-parameterization. If we cannot confidently and unambiguously measure it, we will never be able to validate such models.

ARM accomplishment:
We have recently pioneered in the development of a new cloud optical thickness retrieval algorithm that accounts for a fully 3D cloud structure including broken clouds. This method uses the new ARM ground-based passive two-channel narrow-field-of-view (2NFOV) measurements. In addition to cloud optical thickness, an *effective* cloud fraction is also provided.

2NFOV

Microwave radiometer (MWR)

Marshak et al., JAS, 2004
Chiu et al., JGR, in press 2006

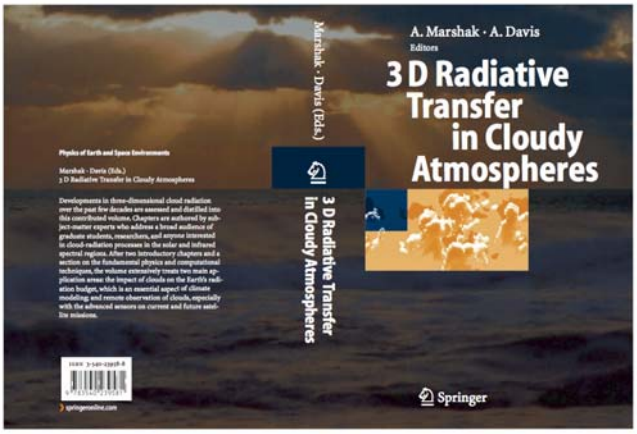
References:

Marshak, A., Knyazikhin, Yu., Davis, A., Wiscombe, W., and Pilewskie, P., 2000. Cloud – vegetation interaction: use of Normalized Difference Cloud Index for estimation of cloud optical thickness. *Geophys. Res. Lett.*, 27,1695-1698.

Marshak, A., Knyazikhin, Yu., Evans, K.D., and Wiscombe, W.J., 2004. The "RED versus NIR" plane to retrieve broken-cloud optical depth from ground-based measurements. *J. Atmos. Sci.*, 61, 1911-1925.

Chiu, J. C., A. Marshak, Y. Knyazikhin, W. J. Wiscombe, H. W. Barker, J. C. Barnard, Y. Luo, 2006. Remote sensing of cloud properties using ground-based measurements of zenith radiance. *J. Geophys. Res.* (in press).

New book has been published by Springer

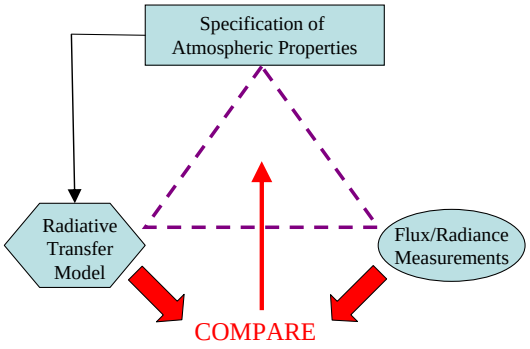


3D cloud radiative community has matured enough to prepare a volume on 3D radiative transfer in cloudy atmosphere. More than half of the authors of the book chapters are from ARM science team

The objective of the book was to capture and preserve much of the best ARM 3D cloud radiation work, and bring it to better maturity as authors took special care to explain their discoveries and advances to a larger audience. The book starts with the basic 3D radiative transfer problem, describes its solutions and models, discusses the effects of cloud inhomogeneity for remote sensing, addresses climate problems in realistic atmosphere and studies cloud-vegetation interactions.

Major Expansion of ARM Radiative Closure Studies:
Broadband Heating Rate Profile Project (BBHRP)

Since the beginning of ARM, *radiative closure studies* have been instrumental in the evaluation and improvement of radiation codes and ARM measurements.

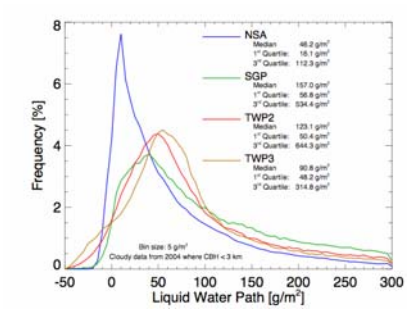


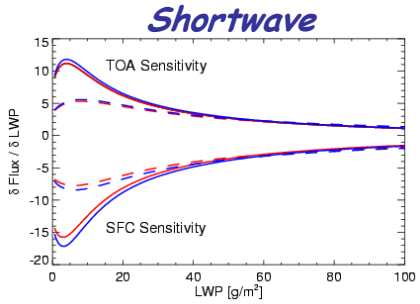
Main objective of BBHRP - Generation of long-term dataset of radiative heating rate profiles at all ARM Climate Research Facilities:

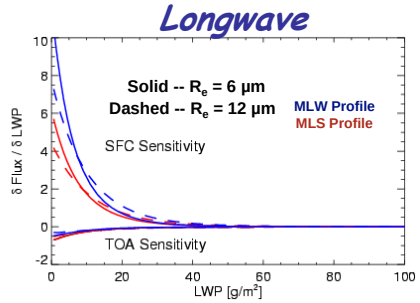
- accomplished for SGP and NSA
- in progress for TWP and ARM mobile facility deployments

Some background: Radiative closure studies involve the comparison of observed radiances (or irradiances) with corresponding calculations from a radiative transfer model, where the model has been provided with atmospheric profiles obtained from in situ or remotely sensed measurements. In such a closure study, when there is a disagreement between the measurement and model, careful analysis can often determine whether the cause of the discrepancy is the quality of the model (especially spectroscopic parameters), the radiometric observation, or a component of the atmospheric profile. This analysis is best performed if the measurement and calculation are spectrally resolved, which has been the case in a decade-long radiative closure study performed at the ARM SGP site (i.e. the AERI/LBLRTM Quality Measurement Experiment). Recently ARM has embarked on major extension of the scope of the program's radiative closure efforts, called the Broadband Heating Rate Profile project. This extension is in multiple directions: broadband measurements and calculations; shortwave radiation as well as longwave; cloudy atmospheres; top-of-the-atmosphere comparisons as well as surface-based; and all ARM Climate Research Facilities (ACRFs) will be analyzed. This project is very comprehensive and involves all ARM working groups. The main objective of the project is the production of long-term continuous datasets of radiative heating rate profiles at all ACRFs, which will, as a result of the closure study, be based on validated (with measurements) radiative transfer calculations.

Radiative Importance of "Thin" Liquid Water Clouds







- **Thin clouds occur very frequently in Arctic, mid-latitudes, and tropics**
- **Radiative fluxes are very sensitive to small changes in liquid water path (LWP) when LWP <100 g/m²**

Turner et al., BAMS, 2006 (accepted), Sengupta et al., J Climate, 2003

•Determined the (surprisingly) large importance of thin, liquid-water clouds to global climate.

•From the tropics to the Arctic, nearly 50% of the liquid-water bearing clouds are optically thin, having less than about 100 g m-2 of liquid water.

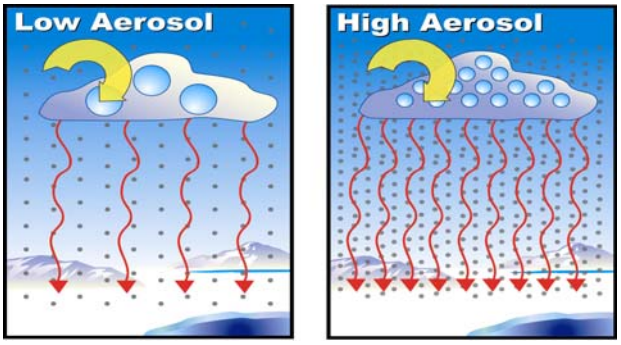
•Liquid water path (LWP) is the total amount of liquid water in a column of air (i.e., the vertical integral of cloud liquid water content)

•The Earth's radiative energy balance is particularly sensitive to small changes in the properties of these thin clouds, where small variations can easily affect changes in the local radiative energy balance in excess of that for global warming.

•Thus, particularly accurate observations are required to understand the impact of these clouds on the Earth's energy balance and their possible response in global warming scenarios.

•References: Turner et al., BAMS, 2006 (accepted for publication), Sengupta et al., J. Climate, 2003

Indirect Effect of Arctic Aerosols in the Infrared



- In a process known as the first aerosol indirect effect, enhanced aerosol concentrations cause the droplets in a cloud to be smaller and more numerous within a cloud of fixed water amount.
- 6-yr analysis at NSA found that this process can make clouds more opaque and emit more thermal energy to the surface.
- Significant for the Arctic energy balance

Lubin and Vogelmann, Nature, 2006

The warming of the Arctic climate and decreases in sea ice area and thickness observed over recent decades are believed to result from greenhouse gas warming. The Arctic region also experiences significant periodic influxes of anthropogenic aerosols, which originate from the industrial regions in lower latitudes. Six-years of ARM data from the DOE ARM Climate Research Facility in Barrow, Alaska were used to determine that enhanced aerosol concentrations increase the amount of thermal energy
emitted by many Arctic clouds to the surface, which would augment that by greenhouse gas warming. The increase found is comparable to the surface warming effect from established greenhouse gases, suggesting that it is significant to the Arctic energy balance.

Journal Reference: Lubin, D., and A.M. Vogelmann, 2006: A climatologically significant aerosol longwave indirect effect in the Arctic, Nature, 439, 26 January, 453-456, doi:10.1038/nature04449.

IRF Structure

Three Primary IRF Focus Groups

Instrumentation

Chuck Long

Atmospheric/Surface Properties and Modeling

Bob Ellingson
&
Dave Turner

3-D RT

Andy Vogelmann

Overarching Groups

BBHRP
Eli Mlawer &
Many Others

CLOWD
Dave Turner &
Andy Vogelmann

Measurement of Radiation Quantities and the Atmospheric State - 1

- Learn to do continuous 24/7 shortwave radiometry under any conditions in the field
- Nail down the extraterrestrial solar spectrum
- Move to trap detectors to maintain the irradiance scale
- Find a replacement for the Eppley PSP for diffuse flux measurements
- Develop an instrument that can act as a reference for standard pyranometers
- Reprocess past ARM broadband shortwave data to remove thermal offsets by an IRF-consensus algorithm (rather than having this algorithm decided off-line from the IRF)

Recommendations from the 2000 white paper

Measurement of Radiation Quantities and the Atmospheric State - 2

- Produce a weekly surface albedo product for the ARM sites, especially when surrounded by vegetation
- Measure O3 column multiple times a day with the Microtops instrument
- Convert the SWS to radiance mode
- Purchase and/or develop fast AERIs, ASTIs and or spectral radiometers
- Create a position of ARM instrument czar
- Develop direct links from the ARM website to instrument mentors
- Put some resources in

Recommendations from the 2000 white paper

ARM IRF Longwave Accomplishments

- **Line-by-line model calculations of downwelling longwave fluxes show agreement with AERI data to within 2 W m^{-2} RMS for clear-sky conditions. Uncertainties in the routine water vapor observations provide the current limitation on these comparisons.**
- **Refinements made in line-by-line radiative transfer models, particularly the water vapor continuum (e.g., LBLRTM). *SHEBA providing very exciting new information.***
- **Development of a rapid radiative transfer model for use in climate models (agrees with LBLRTM to 1 W m^{-2}).**
- **The GCM modeling community has begun incorporating the modeling developments supported by the ARM measurements in their radiation models. (GFDL, GSFC to some extent, British Met Office, ECMWF, and others)**

From 1997 State of Science Report

ARM IRF Shortwave Accomplishments

- ARESE highlighted difficulties in making absorption measurements, uncertainties in model calculations in the presence of clouds, lack of standards for making SW spectral and total flux comparisons.
- Clear-sky closure studies have bounded calculation errors of direct beam solar irradiance for a limited set of cases.
  - • MODTRAN Comparisons with active cavity radiometers data show agreement to within (-0.18 ± 0.94)% (~ -1.5 ± 7.9 W m^{-2}). Uncertainty in the aerosol optical depth is the major source of error in the calculations.
  - • LBLRTM comparisons with ASTI indicate flux errors of < 1 W m^{-2} in the 500 to 10000 cm^{-1} region (no evidence for Gas X, water vapor dimers, or water vapor clusters).
- Several extensive case-study data sets collected during the First ARM Shortwave IOP - September 1997.

From 1997 State of Science Report