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On the Efficiency of Solar Energy in the Tropics

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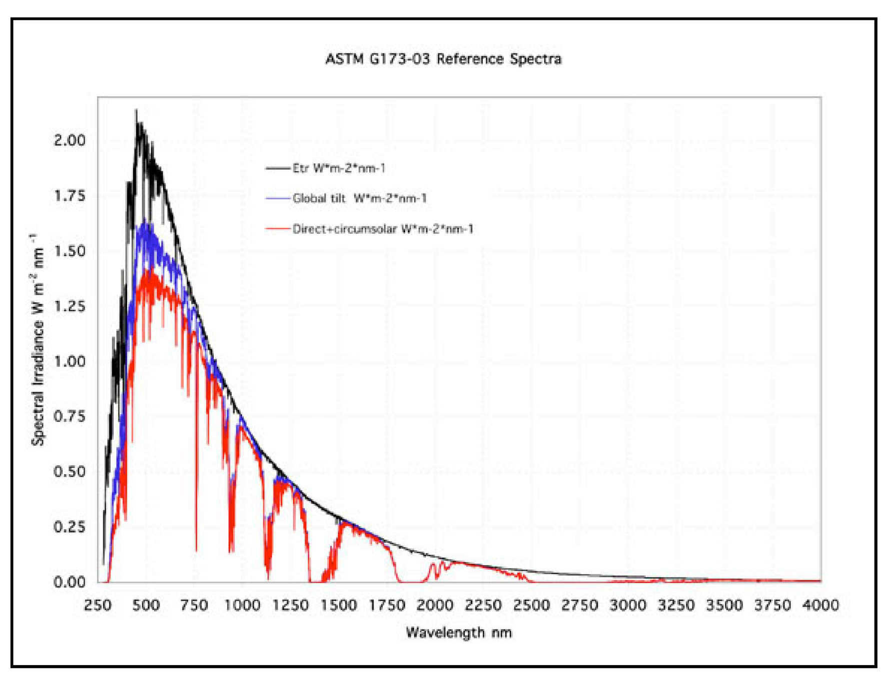
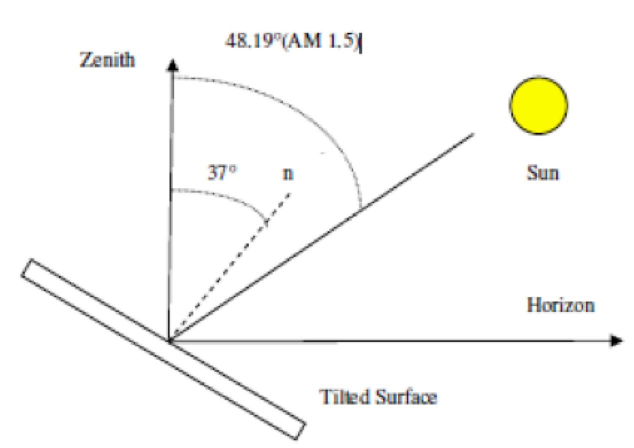
Abstract

There are numerous meteorological factors that limit the efficiency of solar energy systems in the tropics. Depletion of available solar energy at the surface by increased water vapor, cloudiness, temperature of the solar panel system, pollution, are sometimes overlooked, because engineering specifications for design are often based upon midlatitude continental air masses. The typical tropical atmospheric reduction factors are reviewed in this paper, using a state-of-the-art solar energy model. In addition, meteorological variability can be quite extreme in the tropics and many engineering studies on feasibility of renewable energy sources in general are often based upon "typical" year criteria, rather than longer term climatologies. It is suggested that climatological data be utilized to more accurately portray the variability of output to be expected at a typical installation. Many of these variables are already widely available from a combination of surface and upper air meteorological stations, as well as remote sensing data from satellites. We will demonstrate the sources for these data as well as strategies for teaching about solar energy efficiency using routine observations from school-based weather stations.

Background

Reference spectra are used by end-users and manufacturers - typically involving a US midlatitude reference spectrum (Gueymard et al. 2002) valid at a mean latitude and solar zenith angle.





Typical Meteorological and Surface Factors Affecting Calculations of Available Solar Energy Potential Tropics)

Variable	Surrogate/Description	Symbol	Range/Typical Values
Aerosol optical depth	aerosol optical depth	σ	
Air mass factor		AM	0-10 (1.5)
(latitude ϕ, zenith angle ζ)			
Air temperature	Dry-bulb temperature	T_a	0-40°C
Albedo		α	0.05 - 0.95
Barometric pressure		p	700-1040 hPa
Carbon dioxide	Ground concentration CO_2		370 (~390) ppm
Cloud cover	Cloud fraction (reduced set)	cc	0-1.0 (in tenths or oktas)
Irradiance		I	
Land surface type			Lookup table
Panel temperature	Brightness temperature	T_B	0-50°C
Precipitable water	Relative humidity, Dew point	PW	0-70 mm
Total ozone	(Column Total)		344 DU (0.344 atm cm)
Visibility	Runway visual range	VR	0-50 km
Wind speed		V	0-25 m s^{-1}

Sample Models for Surface Irradiance

Myers & Gueymard (2004) – SMARTS version 2.9

$E(\lambda) = E_0(\lambda)T_R(\lambda)T_o(\lambda)T_{mg}(\lambda)T_{tg}(\lambda)T_w(\lambda)T_a(\lambda)$; $I = \int E(\lambda)d\lambda$, where (e.g.) $T_x(\lambda) = \exp[-m_x u_x A_x(\lambda)]$, and m is an optical mass correction for extinction process x, u is the abundance for absorber x, and A is the absorption coefficient for x.

Seo & Krarti (2007) – Regression Model

$$I = \{I_0 \sin(h)[c_0 + c_1(cc) + c_2(cc)^2 + c_3(T_n - T_{n-3}) + c_4(RH) + c_5(V)] + d\}/k$$

Testing Procedures for Significance of Meteorological Factors

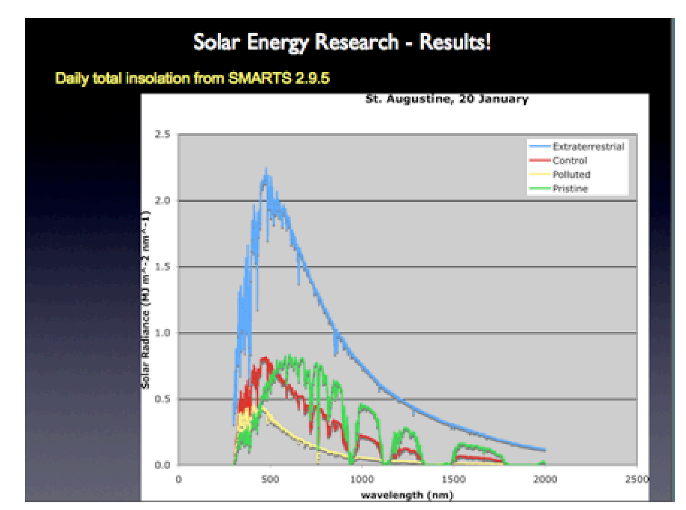
In a study at FSU, Case et al. (2008) designed a series of experiments with different photovoltaic modules under a variety of meteorological conditions. A Davis Vantage Pro2 weather station was used to monitor most of the meteorological conditions.

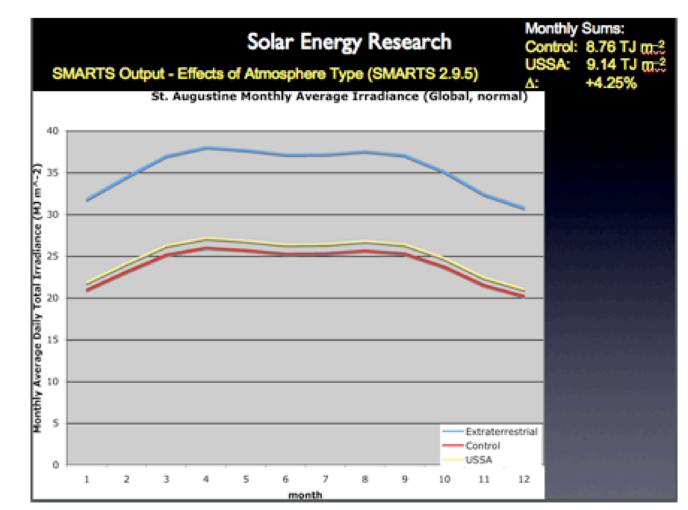
From Case (2007).

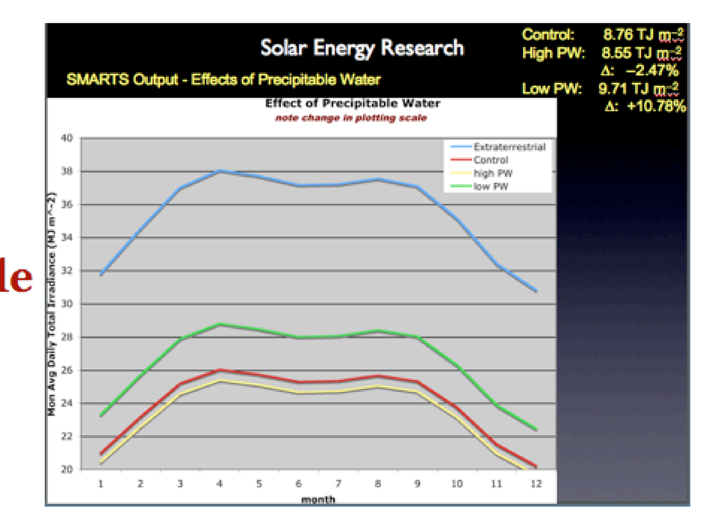
Statistical Testing - Volt-Amperes Generated

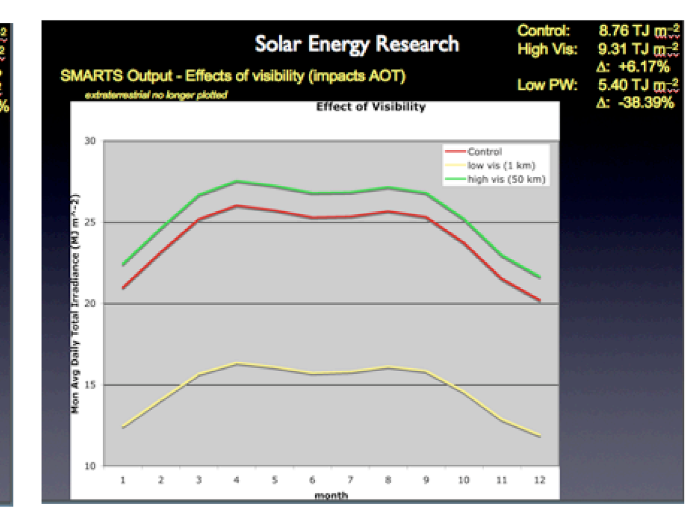
Variable Tested	Significant?	p-value
p	No	0.27
RH	Yes	0.02
T_a	No*	0.06
V	Yes	0.001
I	Yes	0.000
cc	Yes	0.000

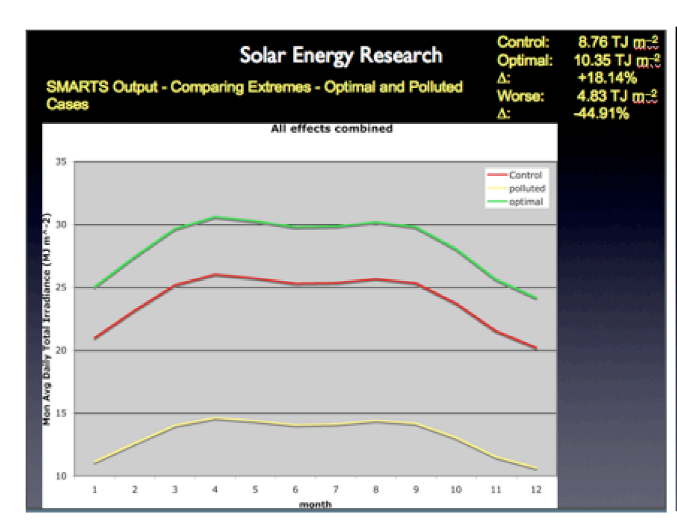
*some modules tested were significant

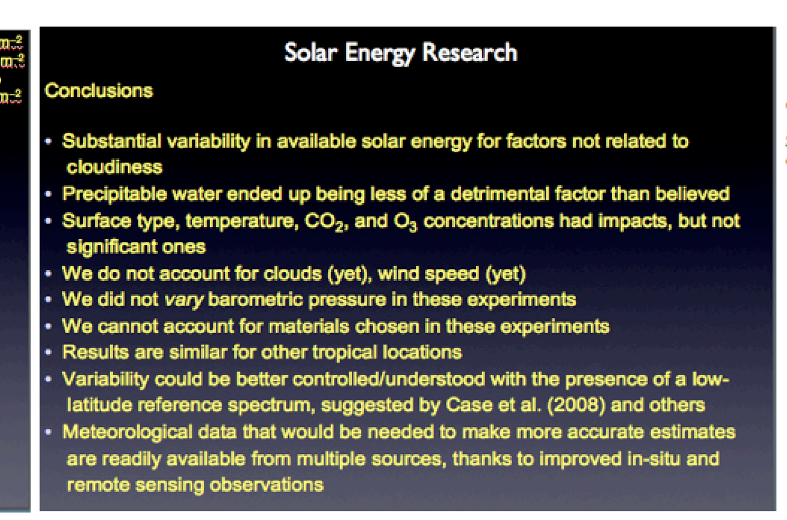


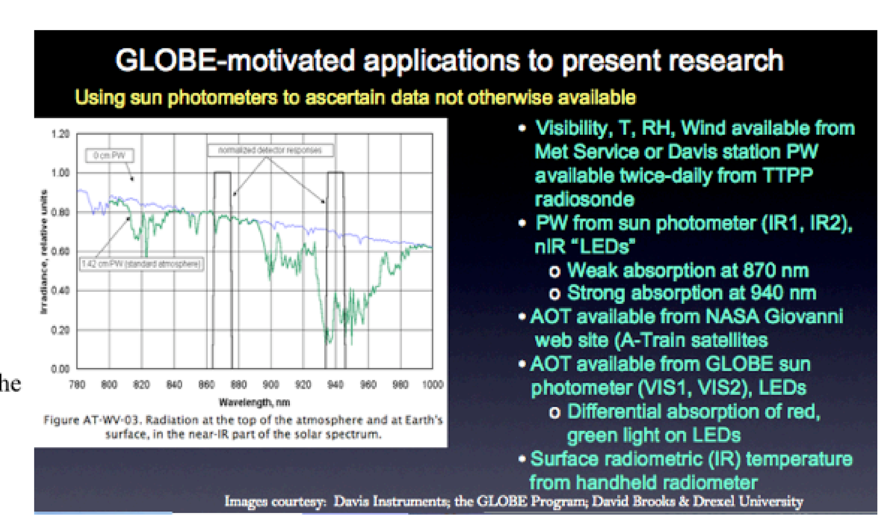


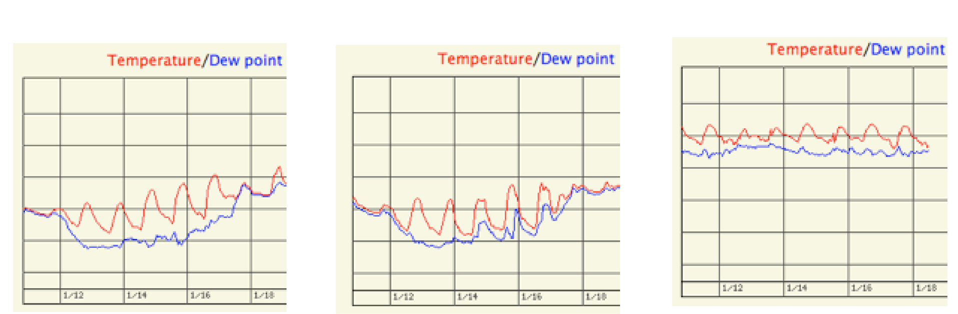












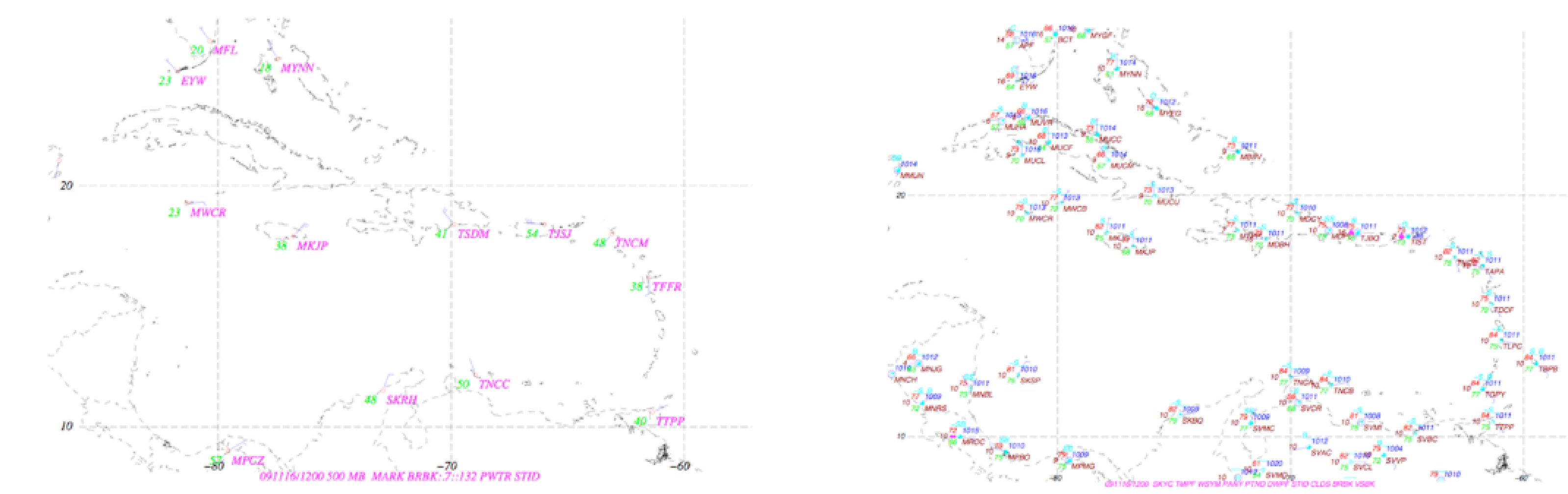
Real-time data monitoring is available from various mesonet/voluntary APRS/CWOP related sites feeding data to MesoWest and NOAA, including findu.com (see left). Can you guess which site is for St. Augustine (T&T), St. Teresa (FSUCML), and which is for Tallahassee (FSU) (FSUMET, CW4103, DW6407, respectively? The same time period is shown for each station

Real-time remote monitoring is important so that we can visualize solar radiation Received as well as dew point, which is sometimes correlated with precipitable water.

Available Surface and Upper Air Data

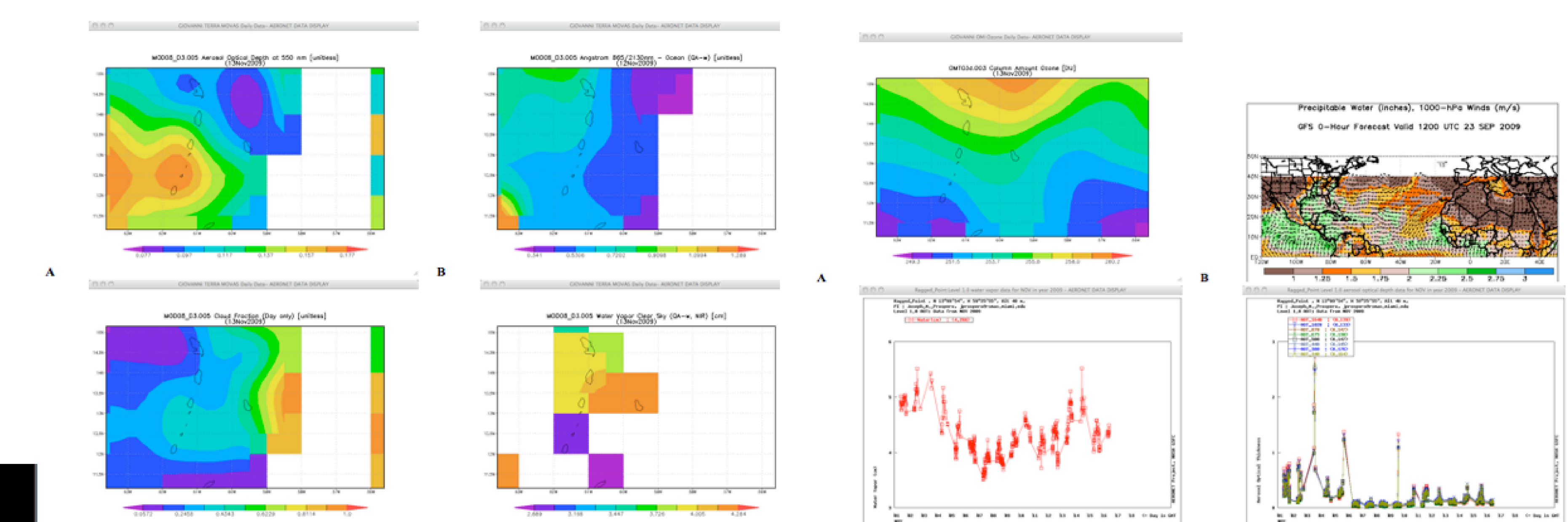
Conventional rawinsonde data provide in situ observations of precipitable water (PW) on a routine basis (twice daily at 00 & 12 UTC). Unfortunately these times do not correspond to times of peak demand. However in other developing nations in the tropics, soundings are taken near solar noon (~12 UTC in Africa; ~00 UTC across parts of Asia) - these data can provide useful estimates that allow for daily estimates of this important control variables.

Surface data are also available routinely hourly at most METAR stations. Important variables include barometric pressure, air temperature, wind speed, visibility, and cloud cover. Sample upper-air (left) and surface (right) charts created by GEMPAK are shown below.



Available Remote Sensing Data

Operational surface and rawinsonde data are insufficient to estimate daily meteorological factors - fortunately, NASA's A-Train satellite constellation and other resources have been deployed, along with special ground-based networks, to allow for real-time estimation of necessary parameters required for quantification of realizable solar energy. The tropical atmosphere is plagued, however, with constituents that reduce efficiency compared to drier midlatitudes.



Samples of satellite-derived products for 13 November 2009, from NASA's Aeronet/Giovanni web site. A) aerosol optical depth; B) Ar coefficient; C) cloud fraction; D) clear sky total water vapor. http://aeronet.gsfc.nasa.gov/cgi-bin/bamgomas_interactive.

A) Satellite retrieval of total ozone from OMI. B) NCEP AMMA Precipitable Water Product. C) Aeronet Barbados surface measurement of precipitable water vapor. D) As in (C) except for aerosol optical depth at various wavelengths.

Setting Up New Observation Programs

Schools will be valuable partners in establishing increased ground-truthing for the remote sensing observations. Using GLOBE science protocols, we are working with partners in Jamaica (University of Technology, Kingston and National Meteorological Service), Trinidad & Tobago (University of the West Indies, St. Augustine and the GLOBE program), and elsewhere in the Caribbean Basin to deploy automated weather stations and GLOBE radiometric measurements to facilitate a deeper understanding of the realizable solar energy potential across the region, and then into other parts of the world. We are using SMARTS 2.9.5 to help us assess the variations that will be expected from a theoretical source. Our first two stations, DW6406 and DW6407, are up and running as of January 2011, and report to NOAA MADIS (Patty Miller et al., NOAA GSD).

Images courtesy: Davis Instruments; the GLOBE Program; David Brooks & Drexel University

Key References & Sources & Acknowledgements

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