# CLOUDY SKY VERSION OF BIRD'S BROADBAND HOURLY CLEAR SKY MODEL

Daryl R. Myers
National Renewable Energy Laboratory
1617 Cole Blvd
Golden CO 80401
daryl_myers@nrel.gov

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Renewable Energy Key to Climate Recovery

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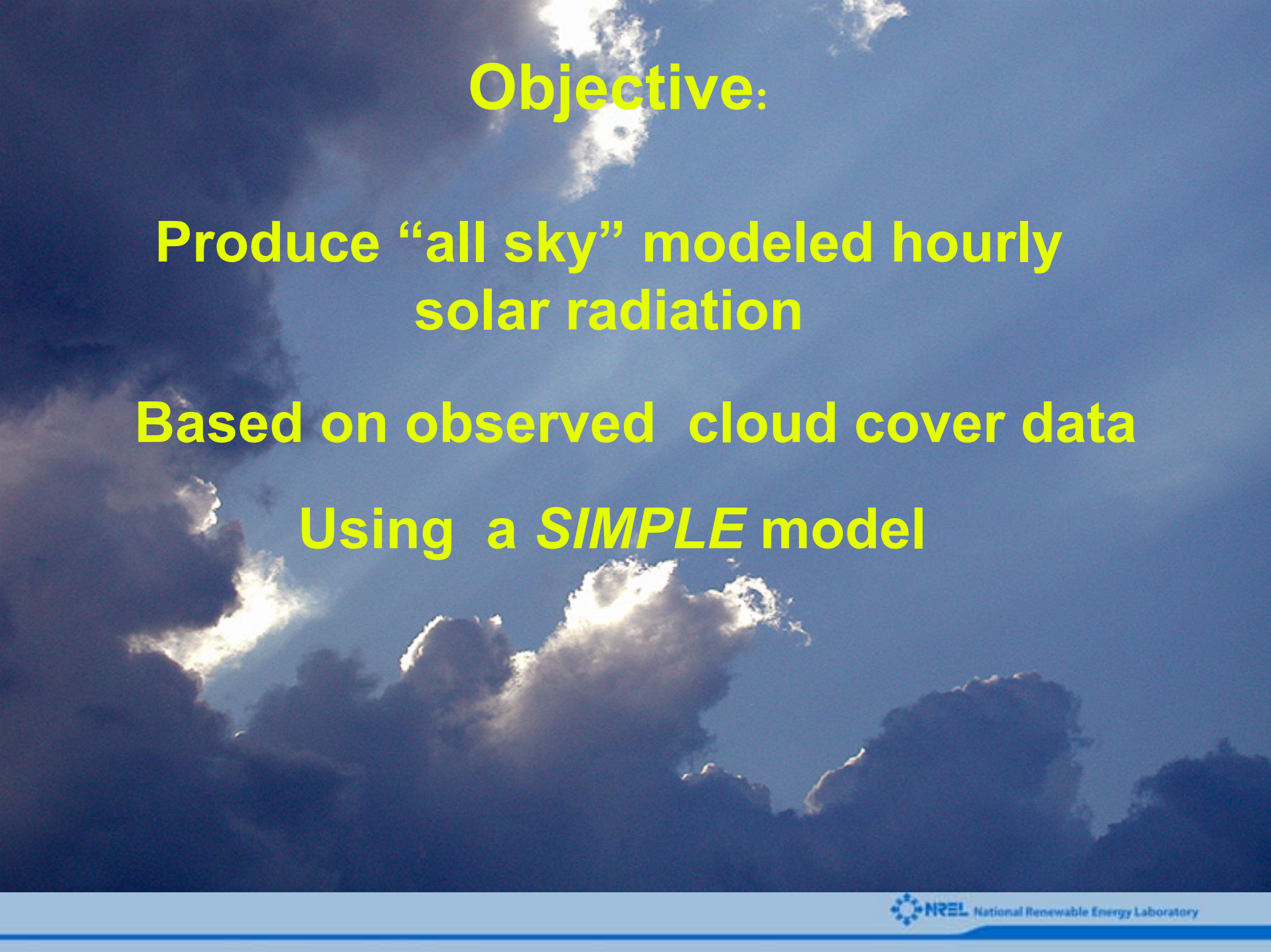
# Acknowledgments

The pioneering work of Dr. Richard Bird has stood the test of time, and still reverberates in the solar modeling community.


**Dr. Richard E. Bird**
**★ 1 February 1942**
**–**
**† 18 April 2002**


This work is but an editing of his contribution.


Objective:
Produce “all sky” modeled hourly solar radiation
Based on observed cloud cover data
Using a *SIMPLE* model

# Bird's Clear Sky Model


SERI TR-761

**Table 2-6. EQUATIONS FOR TOTAL DOWNWARD IRRADIANCE FOR THE BIRD MODEL**

Basic Equations

$$I_d = I_o (\cos Z)(0.9662)\, T_R T_o T_{UM} T_w T_A$$

$$I_{as} = I_o (\cos Z)(0.79)\, T_o T_w T_{UM} T_{AA} [0.5(1 - T_R) + B_a (1 - T_{AS})]/[1 - M + (M)^{1.02}]$$

$$I_T = (I_d + I_{as})/(1 - r_g r_s)$$

Transmission Equations

$$T_R = \exp\{-0.0903 (M')^{0.84}[1 + M' - (M')^{1.01}]\}$$

$$T_o = 1 - 0.1611 X_o (1 + 139.48 X_o)^{-0.3035} - 0.002715 X_o (1 + 0.044 X_o + 0.0003 X_o^2)^{-1}$$

$$X_o = U_o M$$

$$T_{UM} = \exp[-0.0127 (M')^{0.26}]$$

$$T_w = 1 - 2.4959 X_w [(1 + 79.034 X_w)^{0.6828} + 6.385 X_w]^{-1}$$

$$X_w = U_w M$$

$$T_A = \exp[-\tau_A^{0.873} (1 + \tau_A - \tau_A^{0.7088}) M^{0.9108}]$$

$$\tau_A = 0.2758 \tau_{A,0.38} + 0.35 \tau_{A,0.5}$$

$$T_{AA} = 1 - K_I (1 - M + M^{1.06})(1 - T_A)$$

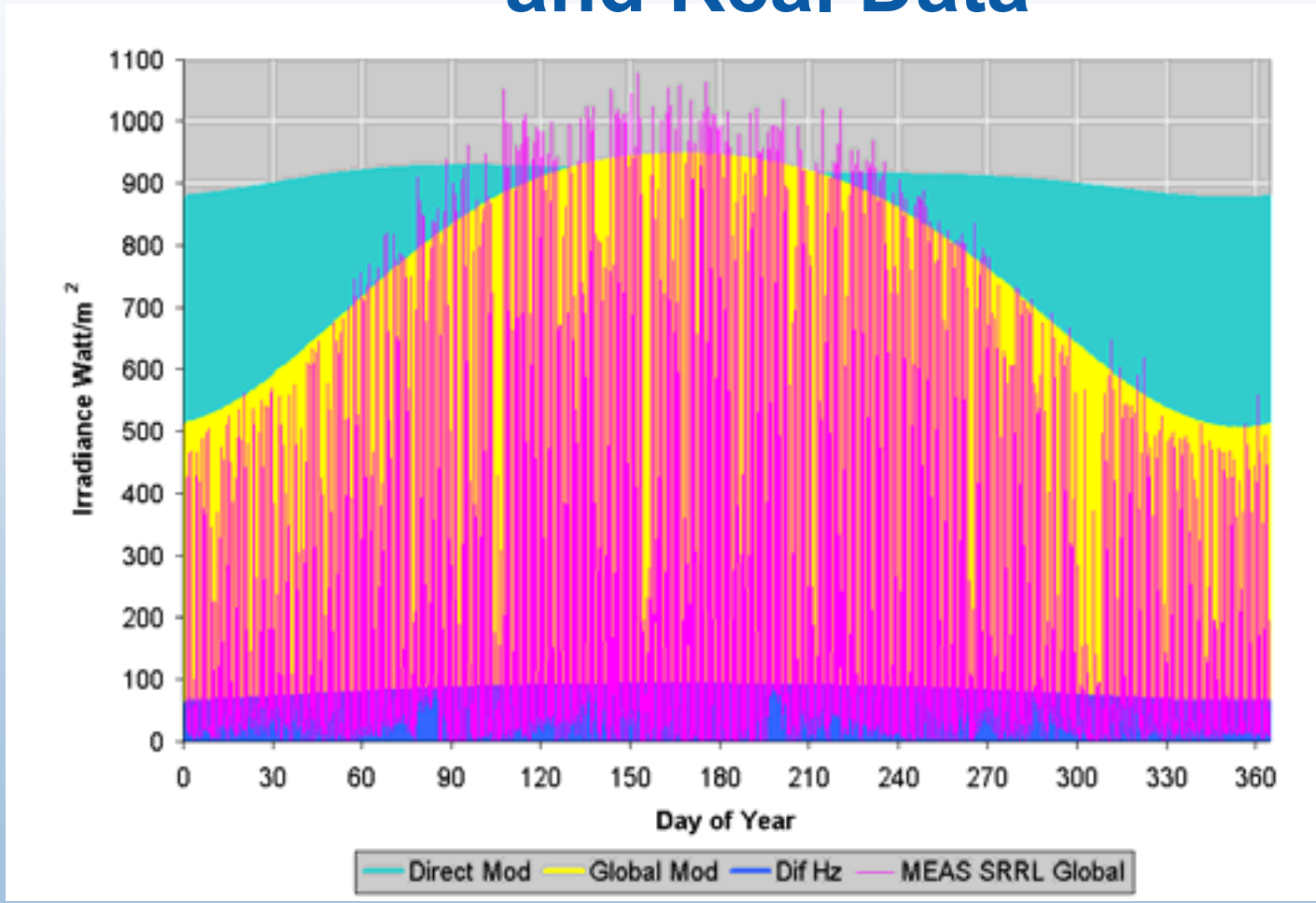
$$T_{AS} = T_A / T_{AA}$$

$$r_s = 0.0685 + (1 - B_a)(1.0 - T_{as})$$

$$M = [\cos Z + 0.15(93.885 - Z)^{-1.25}]^{-1}$$

$$M' = MP/1013$$

# 8760 Hour Clear Sky Profile (Climatological Aerosol, Water, Ozone) and Real Data



# The (Long Standing) Problem--Clouds

Cloud Type?

Layers?

Height?

Thickness?

Density?

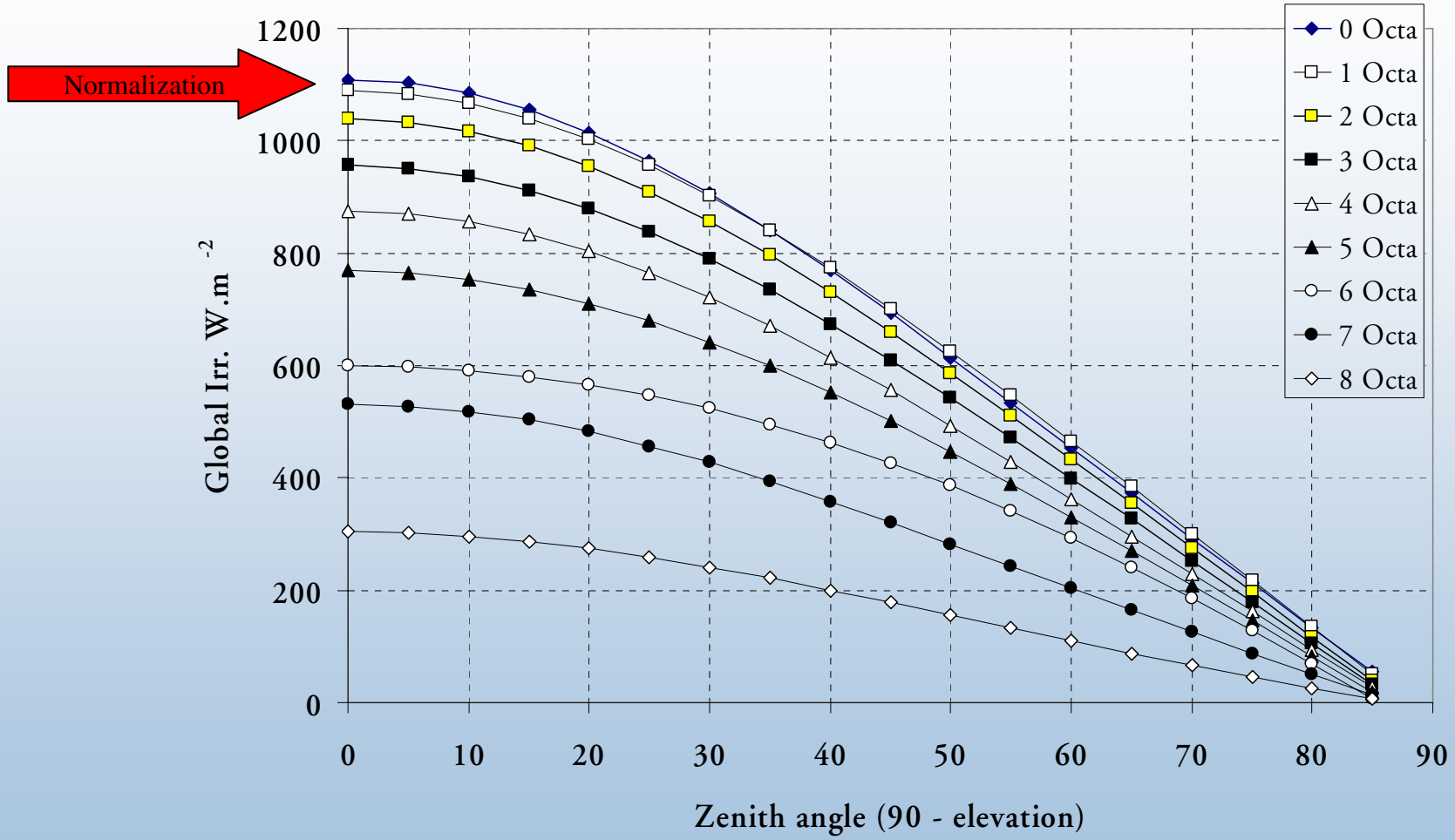
Distribution?

Empirical:
*Measured* solar data *and* cloud information

Stochastic:
Need statistics!

"Fuzzy" and AI Models:
Require "training" with real data

# Nielsen's Irradiance Vs CC Reported by Ehnberg

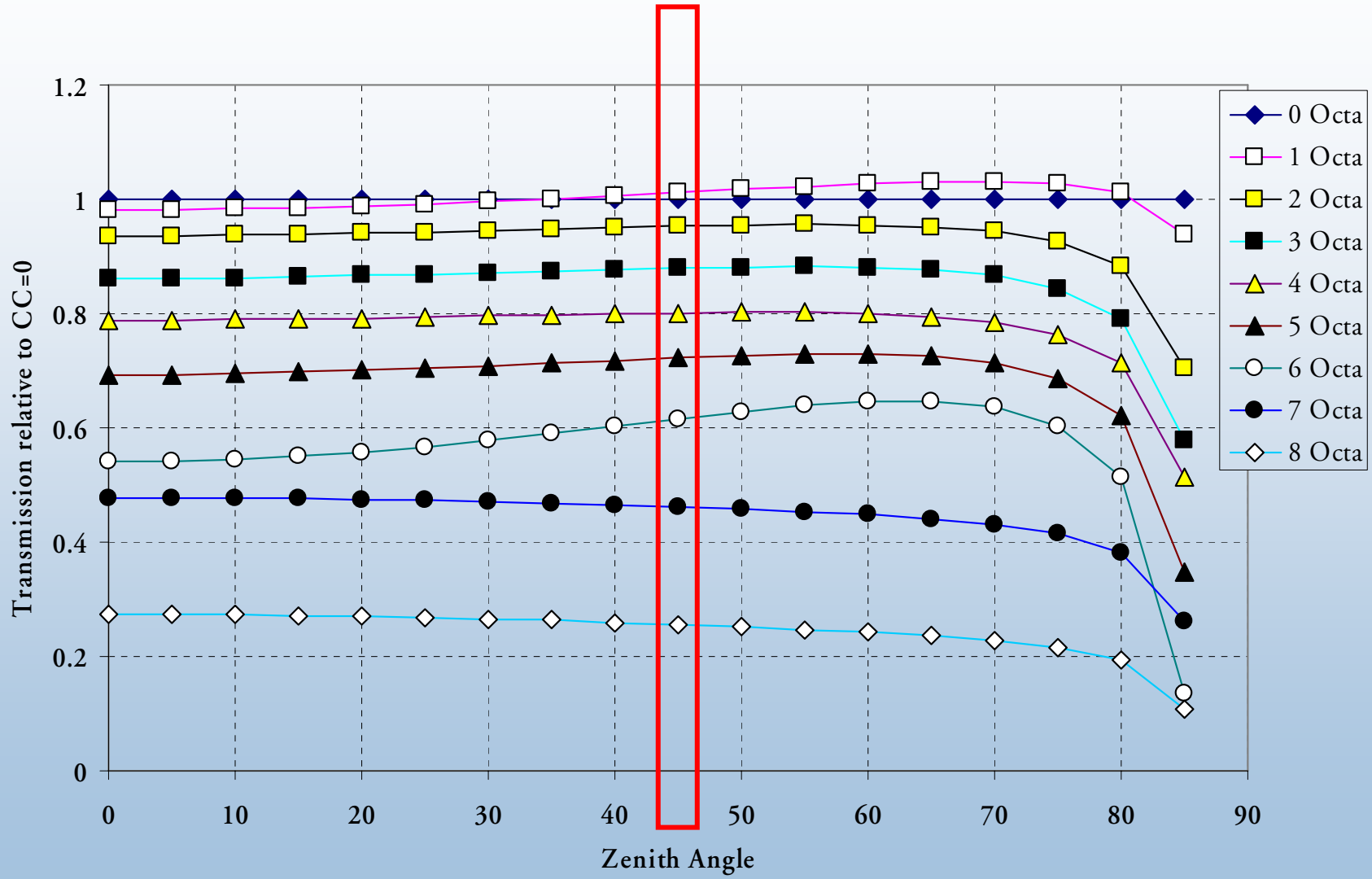




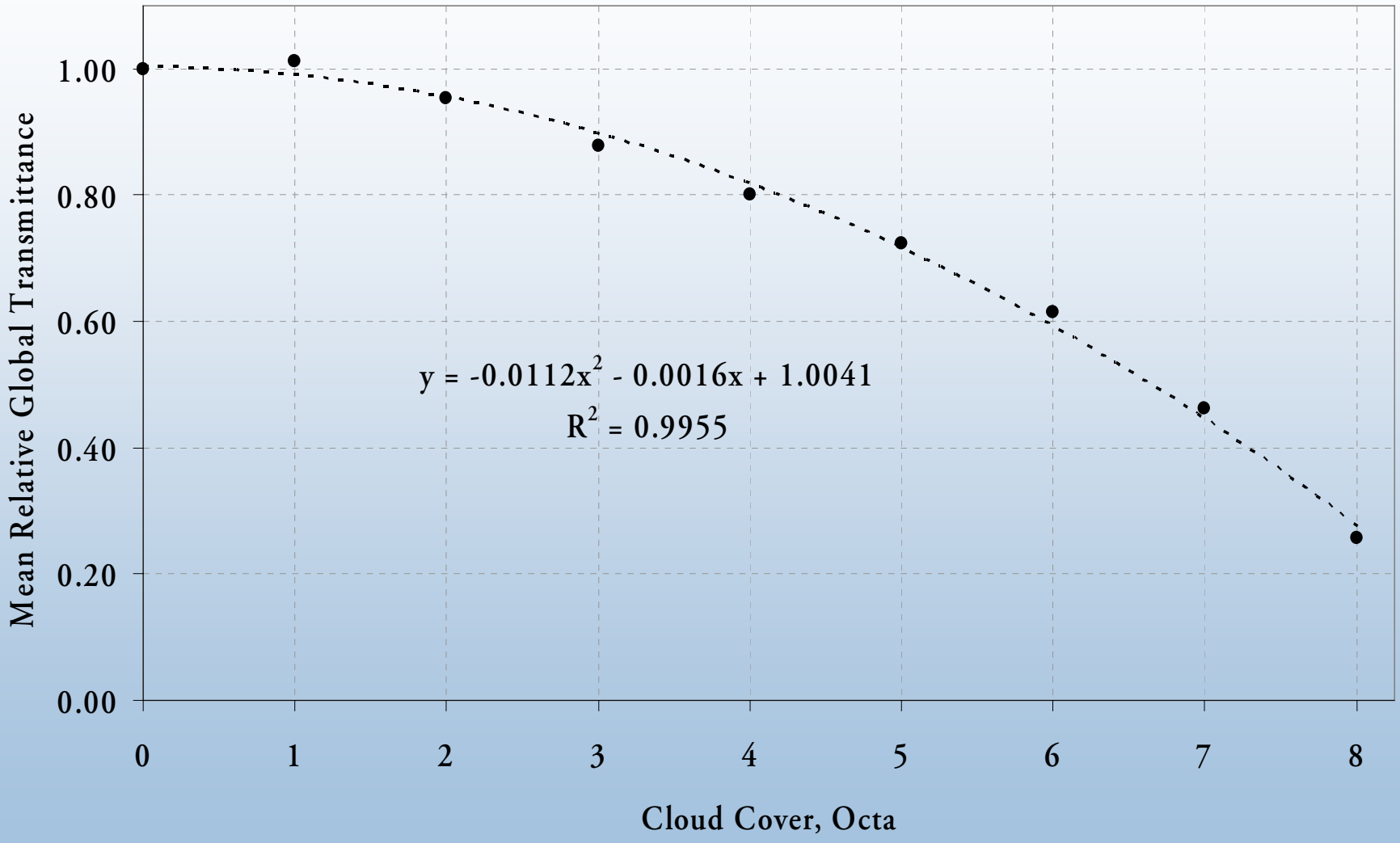
Nielsen, L., et al. Net Incoming Radiation Estimated from Hourly Global Radiation and/or Cloud Observations. *Journal of Climatology*, I, p. 225-272, 1981

Ehnberg, J.S.G., and M.H.J. Bollen, Simulation of Global Solar Radiation Based on Cloud Observations, *Solar Energy* Vol 78, p. 157-162, 2005

# Normalized Cloud Transmittance Vs Z and CC



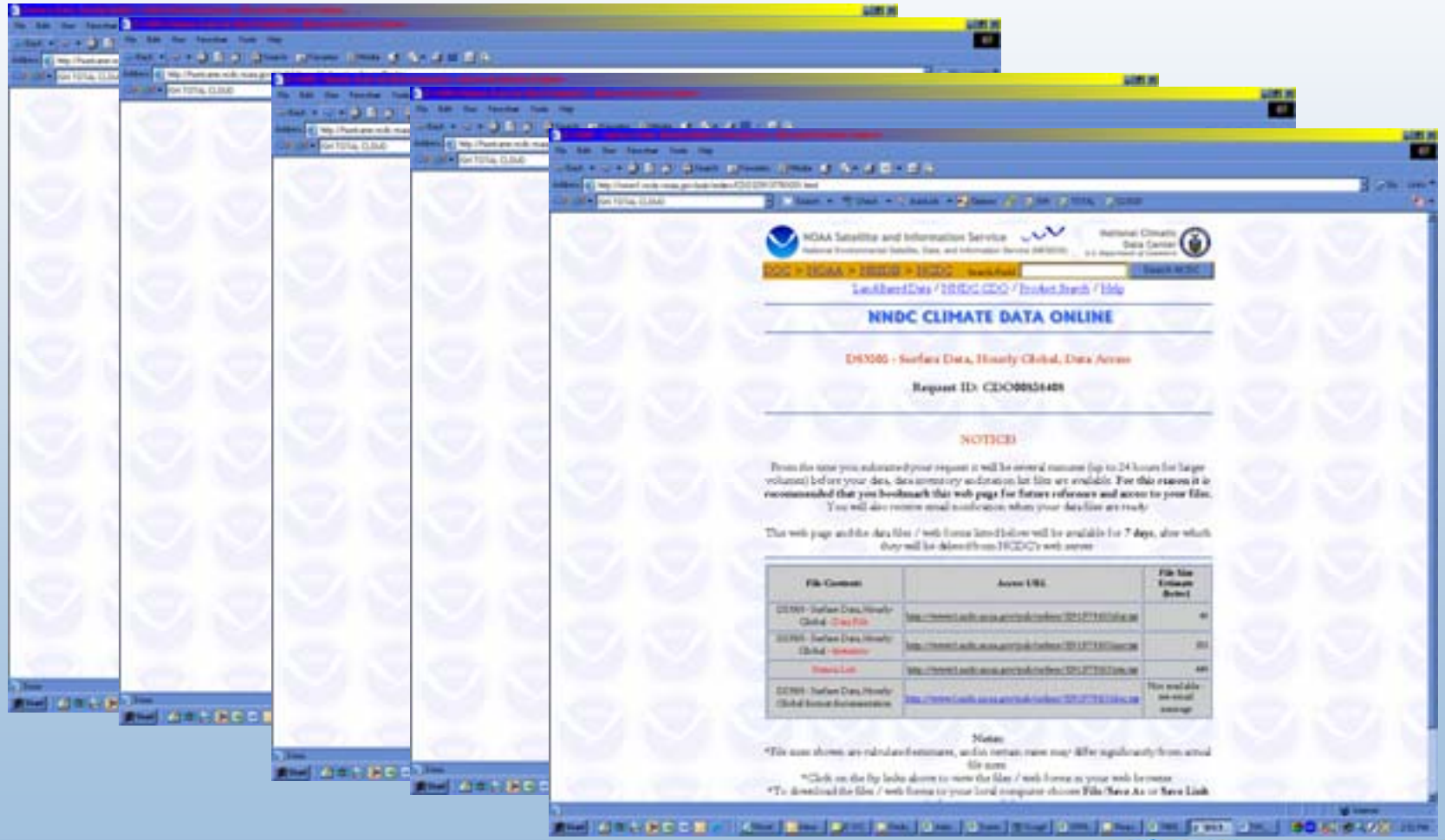
# 45° Z Normalized CC Transmittance



# Let's Try It with Real Data: 30 Sites, 2 Years Measured CC & Solar Data

# National Climatic Data Center Integrated Surface Hourly (ISH) Online Data

- http://lwf.ncdc.noaa.gov/oa/mppsearch.html
- http://www5.ncdc.noaa.gov/cgi-bin/script/webcat.pl
- http://hurricane.ncdc.noaa.gov/pls/plclimprod/poemain.accessrouter?datasetabbv=DS3505



# Excel Model Implementation

| AA | AG | AH | AI | AJ | AK | AL | AM | AN | AO | AP | AQ | AR | AS | AT | AU | AV | AW | AX |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | -0.0112 | Square | | Rand Scale > | -0.05 | NOTE: | | | | | | | | | | | | |
| | -0.0016 | Linear | | | | | | | | | | | | | | | | |
| | 1.004 | Cons ant | | | | | | | | | | | | | | | | |
| | 0.4 | Base 3/8 Transmittance | | | | | | | | | | | | | | | | |
| | Measured | Inte polated | | | | | MEASURED DATA | | | | | | | | | | | |
| | ISH Total Cloud | TOT | | Tg(N) | G*tGN | DfromG! | Global Gr | Direct Ground | | Dec Date | G-Mod-err | | | | | | | |
| | -9900 | 0 | | 0.986 | 0 | | 4 | 0 | | 1.042 | 1 | Mod Avg | 158.0407 | | | | | |
| | 0 | 0 | | 0.995 | 0 | | 0 | 0 | | 1.083 | | Meas Avg | 153.2398 | | | | | |
| | 8 | 8 | | 0.269 | 0 | | 0 | 0 | | 1.125 | | | | | May be edited to remove | | | |
| | 7 | 7 | | 0.435 | 0 | | 0 | 0 | | 1.167 | | Dif Avg | -14% | | months large missing data | | | |
| | 2 | 2 | | 0.918 | 0 | | 0 | 0 | | 1.208 | | | | | | | | |
| | 7 | 7 | | 0.418 | 0 | | 0 | 0 | | 1.250 | | | | | Model(AK) | Meas(AM) | Delta % of MEAS | |
| | 0 | 0 | | 0.986 | 0 | | 0 | 0 | | 1.292 | | | | Jan | 45.2 | 40.4 | -12.0 | |
| | 0 | 0 | | 0.966 | 0 | | 8.3 | 0 | | 1.333 | 1 | | | Feb | 98.7 | 91.1 | -8.4 | |
| | 0 | 0 | | 0.977 | 108.2922 | | -9900 | 0 | | 1.375 | 1.010939 | | | Mar | 132.9 | 157.0 | 15.4 | |
| | 4 | 4 | | 0.817 | 201.9983 | | 319.4 | 0 | | 1.417 | 0.36757 | | | Apr | 204.5 | 187.5 | -9.1 | |
| | 7 | 7 | | 0.421 | 145.699 | | 322.2 | 0 | | 1.458 | 0.547799 | | | May | 230.2 | 242.0 | 4.9 | |
| | 2 | 2 | | 0.908 | 360.0676 | | 361.1 | 0 | | 1.500 | 0.002859 | | | Jun | 270.7 | 266.9 | -1.4 | |
| | 0 | 0 | | 0.964 | 380.7627 | | 447.2 | 0 | | 1.542 | 0.148563 | | | Jul | 269.9 | 260.0 | -3.8 | |
| | 0 | 0 | | 1.001 | 341.4476 | | 380.6 | 0 | | 1.583 | 0.10287 | | | Aug | 214.4 | 210.3 | -1.9 | |
| | 7 | 7 | | 0.409 | 98.1732 | | 233.3 | 0 | | 1.625 | 0.579198 | | | Sep | 173.3 | 164.5 | -5.3 | |
| | 0 | 0 | | 0.961 | 98.10479 | | 102.8 | 0 | | 1.667 | 0.045673 | | | Oct | 99.4 | 91.6 | -8.5 | |
| | 0 | 0 | | 0.997 | 0 | | 5.6 | 0 | | 1.708 | 1 | | | Nov | 75.7 | 77.9 | 2.8 | |
| | 0 | 0 | | 0.993 | 0 | | 0 | 0 | | 1.750 | | | | Dec | 55.8 | 31.6 | -76.6 | |
| | 0 | 0 | | 0.993 | 0 | | 0 | 0 | | 1.792 | | | | | | | | |
| | 0 | 0 | | 0.968 | 0 | | 0 | 0 | | 1.833 | | | | TOTAL | 1870.8 | 1820.9 | -2.7 | |
| | 0 | 0 | | 0.957 | 0 | | 0 | 0 | | 1.875 | | | | | | | | |
| | 0 | 0 | | 0.978 | 0 | | 0 | 0 | | 1.917 | | | | | | | | |
| | 0 | 0 | | 0.965 | 0 | | 0 | 0 | | 1.958 | | | | | | | | |

0.2

```
C ------- Bird Clear sky Model -----------
      IF (Am.gt.0.) THEN
C Rayliegh
      Tr=(1.0+AMp-AMp**1.01)
      Tr=Tr*(-0.0903*AMp**0.84)
      Tr=EXP(Tr)
C Ozone
      Ozm=Oz*AM
      Toz=1-0.1611*Ozm*(1.+139.48*Ozm)**(-0.3035)
     +       -(0.002715*Ozm)/(1+0.044*Ozm+0.0003*Ozm**2)
C Mixed Gases
      Tm=EXP(-0.0127*AMp**0.026)
C Water vapor
      Wm=AMp*W
      Tw=1-2.4959*Wm/((1+79.034*Wm)**0.6828 + 6.385*Wm)
C Daily Turbidity !
      IF (ITs.eq.1) THEN
      Ta5 = A*SIN((dan-B)*0.01745)+C
      Else
      Ta5=C
      end if
      Ta3=Ta5+.1
      Tau=0.2758*Ta3+0.35*Ta5
      Ta=EXP((-Tau**0.873)*(1.+Tau-(Tau**0.7088))*Am**0.9108)
      TAA=1-0.1*(1-Am+AM**1.06)*(1-Ta)
      TAs=Ta/TAA
      Rs=0.0685+(1-.85)*(1.0-TAs)
C
C Compute Clear irradiances
C    Direct
      Id=Io*.9662*Tr*Toz*Tm*Tw*Ta
C direct on HZ
      Idh=Id*COS(Z* 0.01745)
C Diffuse( scattered)
      Ias=0.79*Io*COS(Z*0.01745)*Toz*Tm*Tw*TAA
      Ias=Ias*(0.5*(1-Tr)+0.85*(1-Tas))/(1-AM+AM**1.02)
C Total dir + dir on Hz
      Itot=(Idh+Ias)/(1-Ab*Rs)
      Idif=Itot-Idh
C
C compute Cloud cover correction
        CALL Random_number(X)

       Tcld=-0.0112*Tc**2-0.0016*Tc+1.004+0.15*X
c compute cloudy GH
      Itc=Itot*Tcld
```

# FORTRAN Program Process 30 Sites

**INPUTS**

- Latitude
- Longitude
- Year
- Month
- Day
- Hour
- Pressure
- Aerosol OD @ 550 nm
- AOD @ 380 nm
- Total Water Vapor
- Total Ozone
- Albedo
- **Total Cloud Cover (8ths)**

| | Hourly mean Global $Wm^{-2}$ | MBE $Wm^{-2}$ | RMS $Wm^{-2}$ | MBE % | RMS % | # Hours |
|---|---|---|---|---|---|---|
| FSE | 357.5 | -2.9 | 129.4 | -0.8 | 36.2 | 8458 |
| TAL | 341.7 | -74.8 | 161.6 | -21.9 | 47.3 | 7977 |
| CLE | 341.7 | 13.3 | 132.6 | 3.9 | 38.8 | 9245 |
| OVE | 323.3 | -91.2 | 163.5 | -28.2 | 50.6 | 9590 |
| EDI | 353.0 | -112.7 | 177.9 | -31.9 | 50.4 | 9553 |
| COR | 345.5 | -82.7 | 158.8 | -23.9 | 46.0 | 9581 |
| LAR | 401.5 | 6.6 | 112.0 | 1.6 | 27.9 | 9161 |
| AUS | 343.7 | -5.5 | 115.4 | -1.6 | 33.6 | 9336 |
| DEL | 378.6 | -69.8 | 132.6 | -18.4 | 35.0 | 9299 |
| ABI | 385.9 | -75.3 | 142.1 | -19.5 | 36.8 | 9577 |
| ELP | 391.9 | -24.4 | 161.0 | -6.2 | 41.1 | 5890 |
| SGP | 355.6 | 35.5 | 140.3 | 10.0 | 39.4 | 9545 |
| CAN | 380.6 | -70.6 | 140.1 | -18.5 | 36.8 | 9485 |
| ALB | 427.2 | 36.1 | 116.4 | 8.4 | 27.3 | 8435 |
| DES | 426.9 | -5.3 | 122.0 | -1.2 | 28.6 | 9618 |
| HAN | 393.3 | -62.7 | 114.1 | -15.9 | 29.0 | 8529 |
| STE | 305.9 | 15.2 | 113.5 | 5.0 | 37.1 | 8472 |
| BLU | 305.2 | 23.6 | 131.0 | 7.7 | 42.9 | 9481 |
| SRR | 345.8 | 21.9 | 135.8 | 6.3 | 39.3 | 9587 |
| PEN | 283.9 | 21.0 | 121.6 | 7.4 | 42.8 | 9575 |
| ANY | 282.2 | -53.7 | 143.0 | -19.0 | 50.7 | 8140 |
| BON | 308.9 | -42.9 | 127.5 | -13.9 | 41.3 | 9488 |
| SAL | 357.3 | 60.1 | 149.9 | 16.8 | 41.9 | 8531 |
| KLA | 315.1 | 28.8 | 102.6 | 9.1 | 32.6 | 5666 |
| MAD | 287.2 | -45.6 | 121.0 | -15.9 | 42.1 | 8960 |
| BUR | 347.4 | -43.6 | 121.4 | -12.5 | 35.0 | 9597 |
| EUG | 283.5 | -8.9 | 132.3 | -3.2 | 46.7 | 9435 |
| BIS | 294.4 | -27.5 | 132.7 | -9.4 | 45.1 | 8494 |
| FTP | 291.0 | -60.7 | 146.1 | -20.9 | 50.2 | 9620 |
| SEA | 240.1 | 0.2 | 113.2 | 0.1 | 47.1 | 8574 |
| **MEAN** | **339.9** | **-23.3** | **133.7** | **-6.9** | **40.0** | |

# Hourly Mean Errors (ANNUAL)

**MBE 23 $Wm^{-2}$**

**-80 $Wm^{-2}$ <MBE<+60 $Wm^{-2}$**

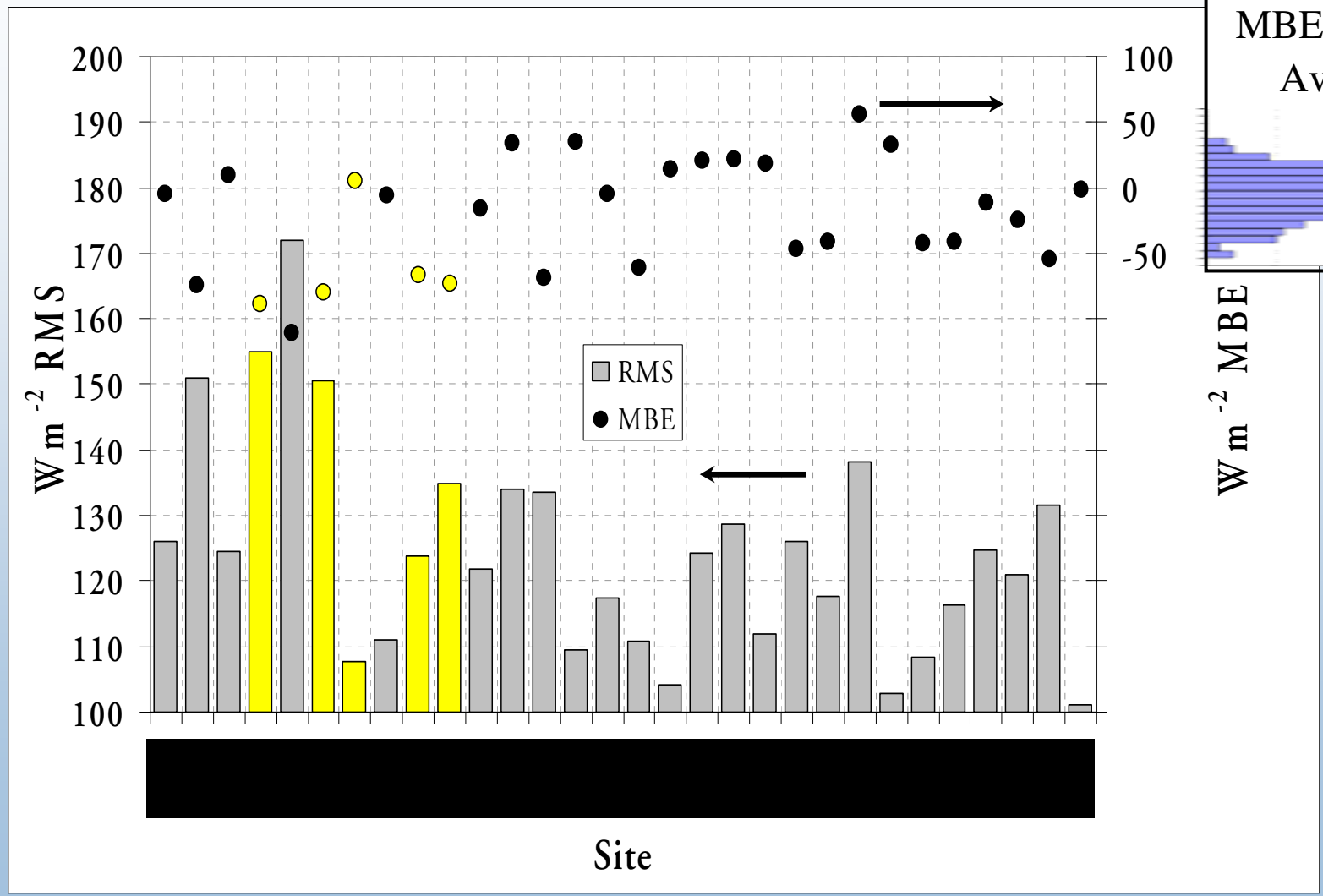
**RMS ~ 133 $Wm^{-2}$**

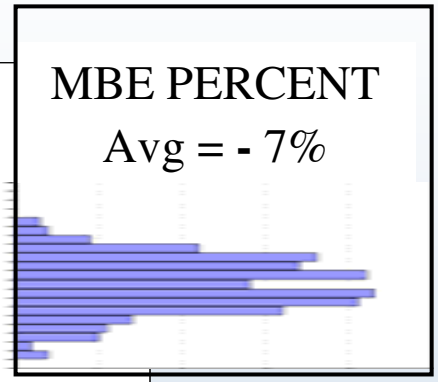
**MBE ~ - 7%,**

**-32%<MBE<+17%**

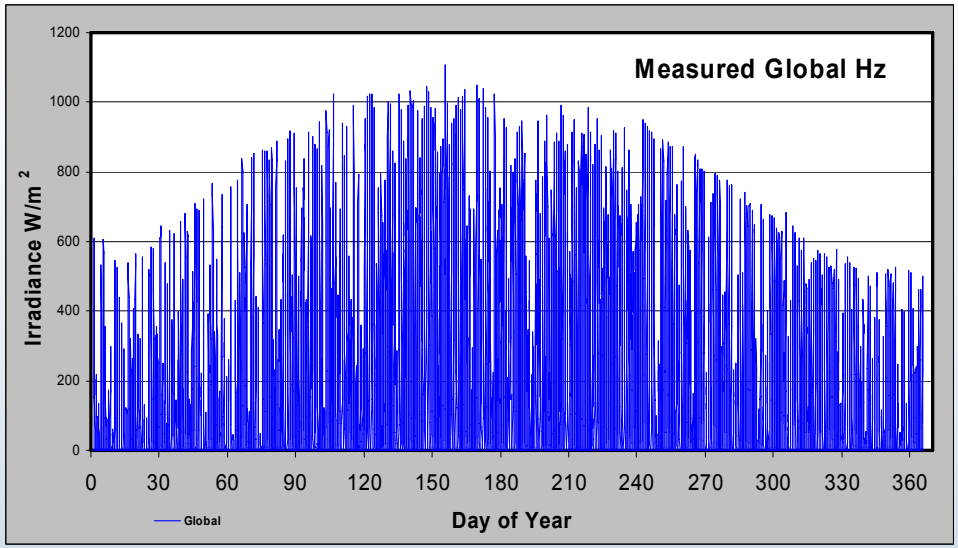
**RMS ~ 40%**

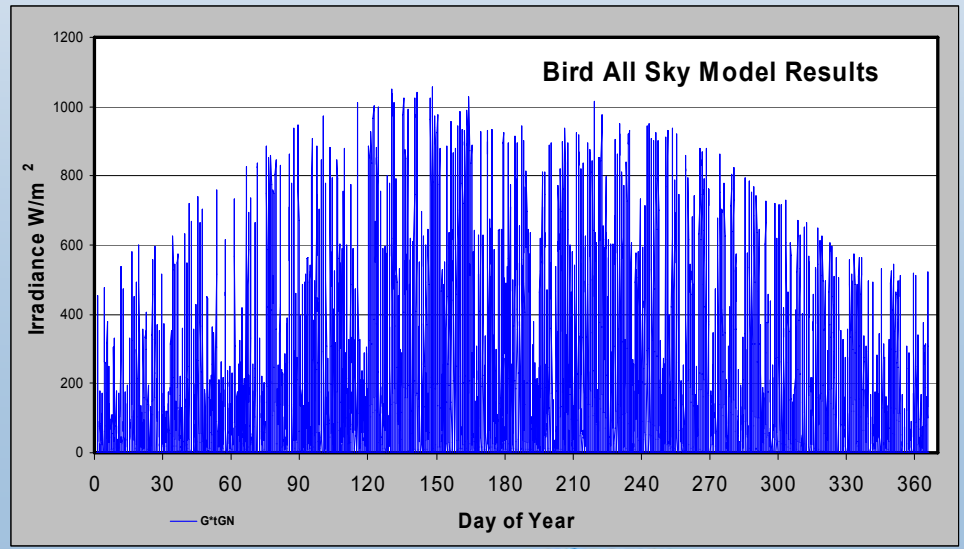
# Mean Bias and RMS Monthly Hourly Averages 30 Sites



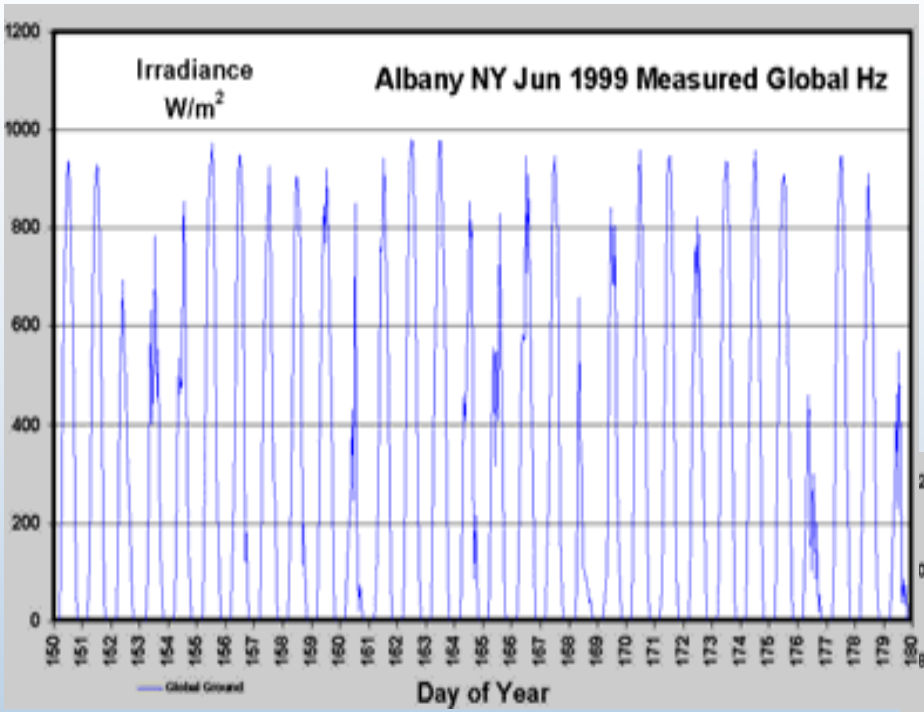



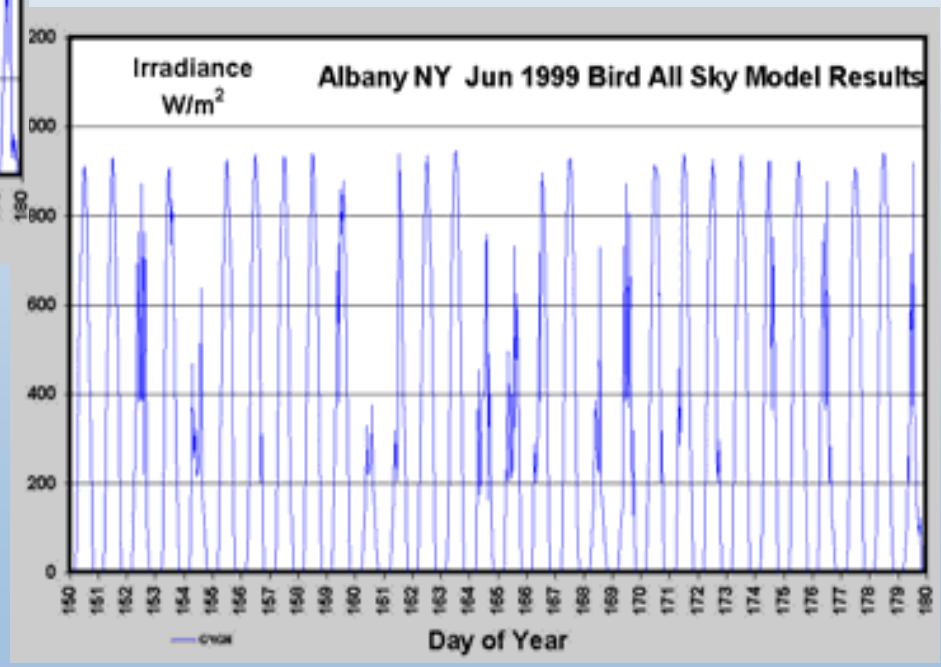
# 1999 Albany NY



# June 1999 Albany NY

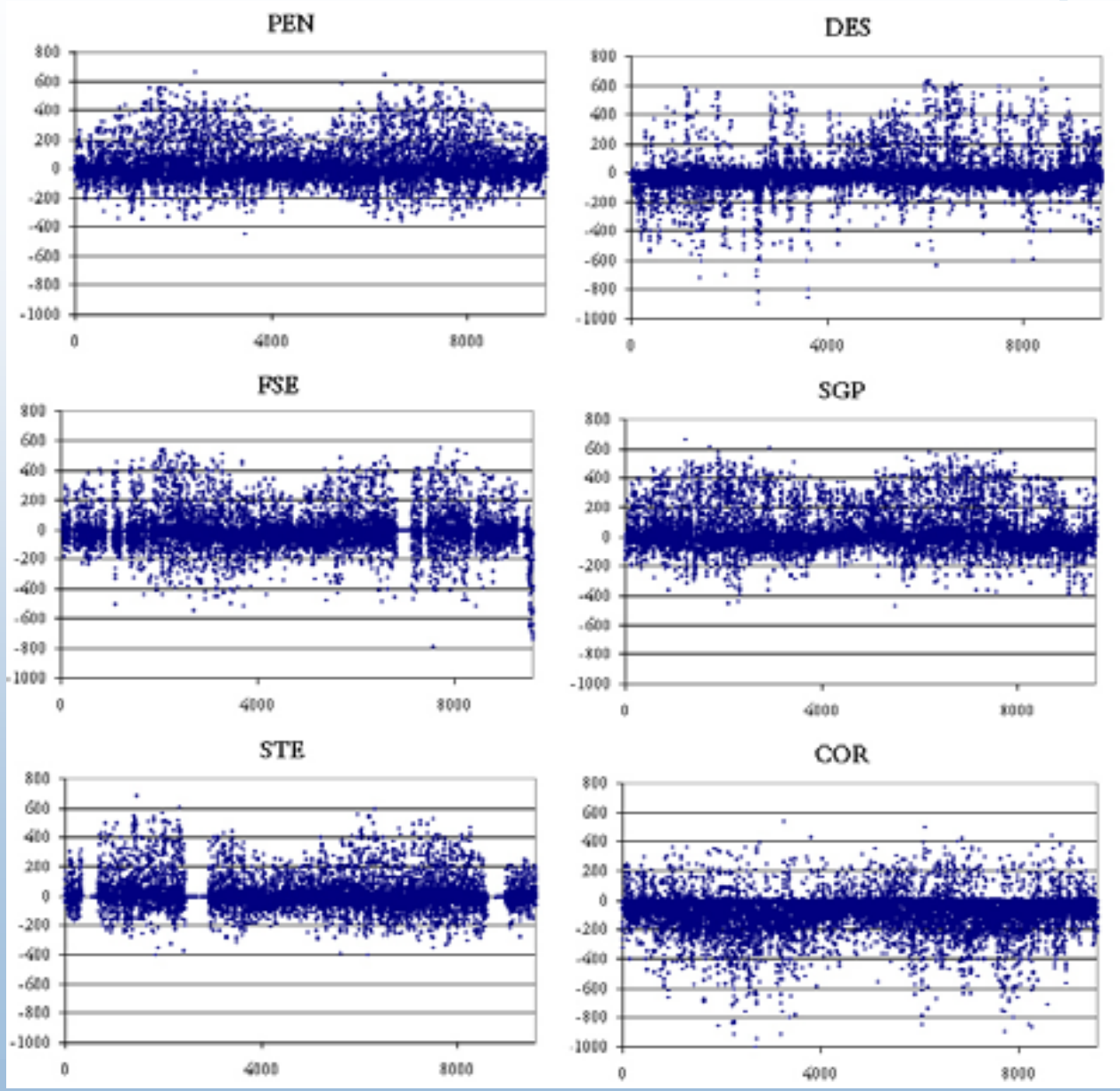


# Albany 1999 Monthly Mean Hourly Bias Errors

| | Measured Monthly Hr Mean | Modeled Monthly Hr mean | MBE % of MEAS |
|---|---|---|---|
| **Jan** | 45.4 | 40.4 | -12.3 |
| **Feb** | 99.0 | 91.1 | -8.6 |
| **Mar** | 133.0 | 157.0 | 15.3 |
| **Apr** | 204.5 | 187.5 | -9.1 |
| **May** | 230.5 | 242.0 | 4.7 |
| **Jun** | 271.2 | 266.9 | -1.6 |
| **Jul** | 269.2 | 260.0 | -3.5 |
| **Aug** | 214.7 | 210.3 | -2.1 |
| **Sep** | 173.8 | 164.5 | -5.7 |
| **Oct** | 99.6 | 91.6 | -8.7 |
| **Nov** | 75.7 | 77.9 | 2.7 |
| **Dec** | 55.7 | 31.6 | -76.3 |
| **TOTAL** | **1872.3** | **1820.9** | **-2.8** |

# Seasonal Bias Errors (1999-2000)



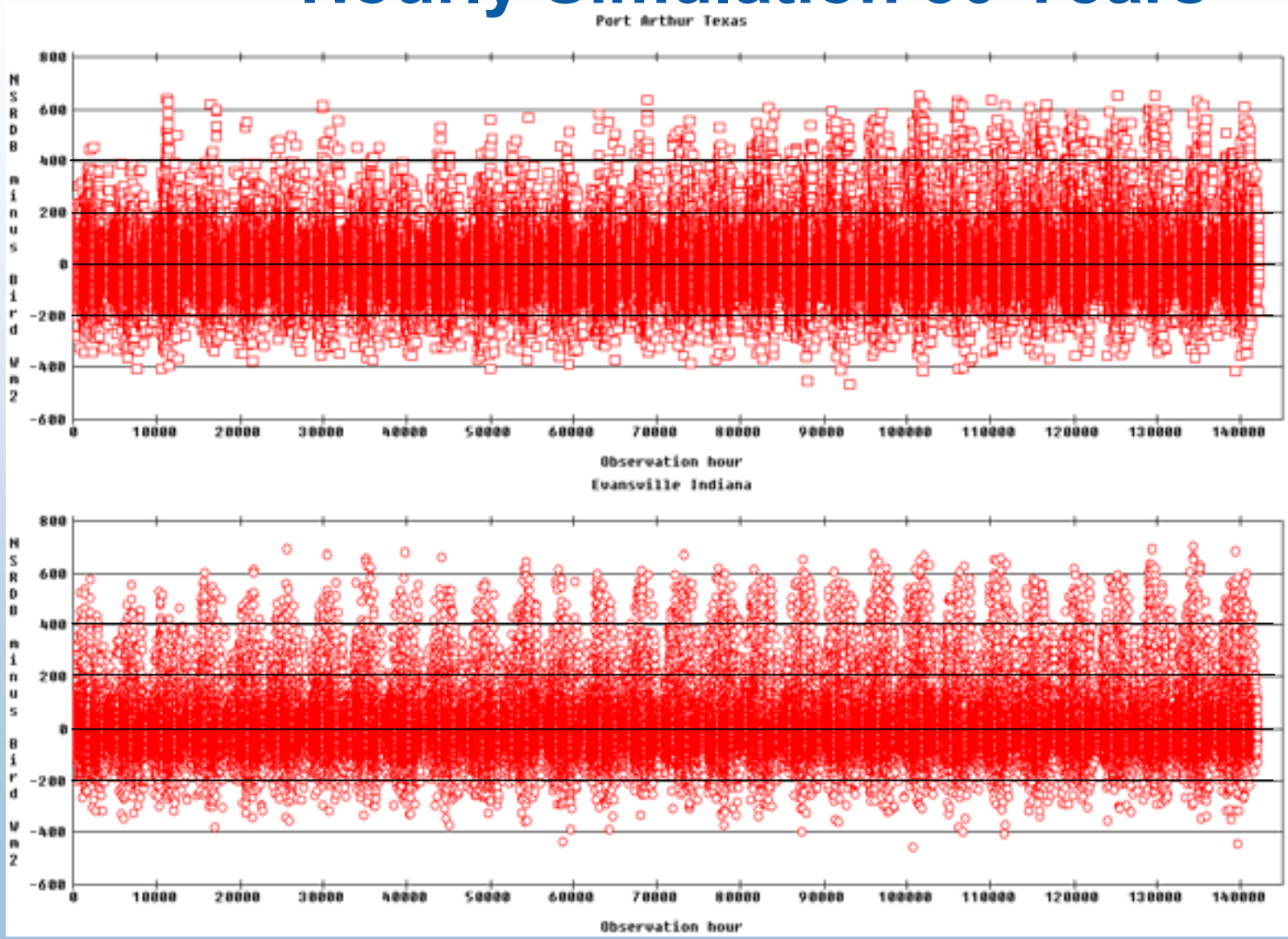

**? From ?**
**NSRDB Daily Aerosol Optical Depth "Annual Sine Curve"**

**Climatological (Long Term) Water Vapor & Imprecision in Model**

# Compare NSRDB/METSTAT Data and Cloudy Sky Model Results

- Selected 30 Years of Hourly Global Hz Irradiance, Total CC (10ths)
- Convert CC 10ths  to Octas
- Compute Bird Clear Sky Irradiance
  - USE NSRDB (daily) aerosol, (hourly) water vapor
- Modify with Cloud Transmittance
- Compare with NSRDB Results
  - Remember: NSRDB hourly data are STATISTICAL for 95% of NSRDB—hour by hour matching is unlikely; but MONTHLY MEANS agree well with measured data

# Port Arthur Texas & Evansville Indiana Hourly Simulation 30 Years



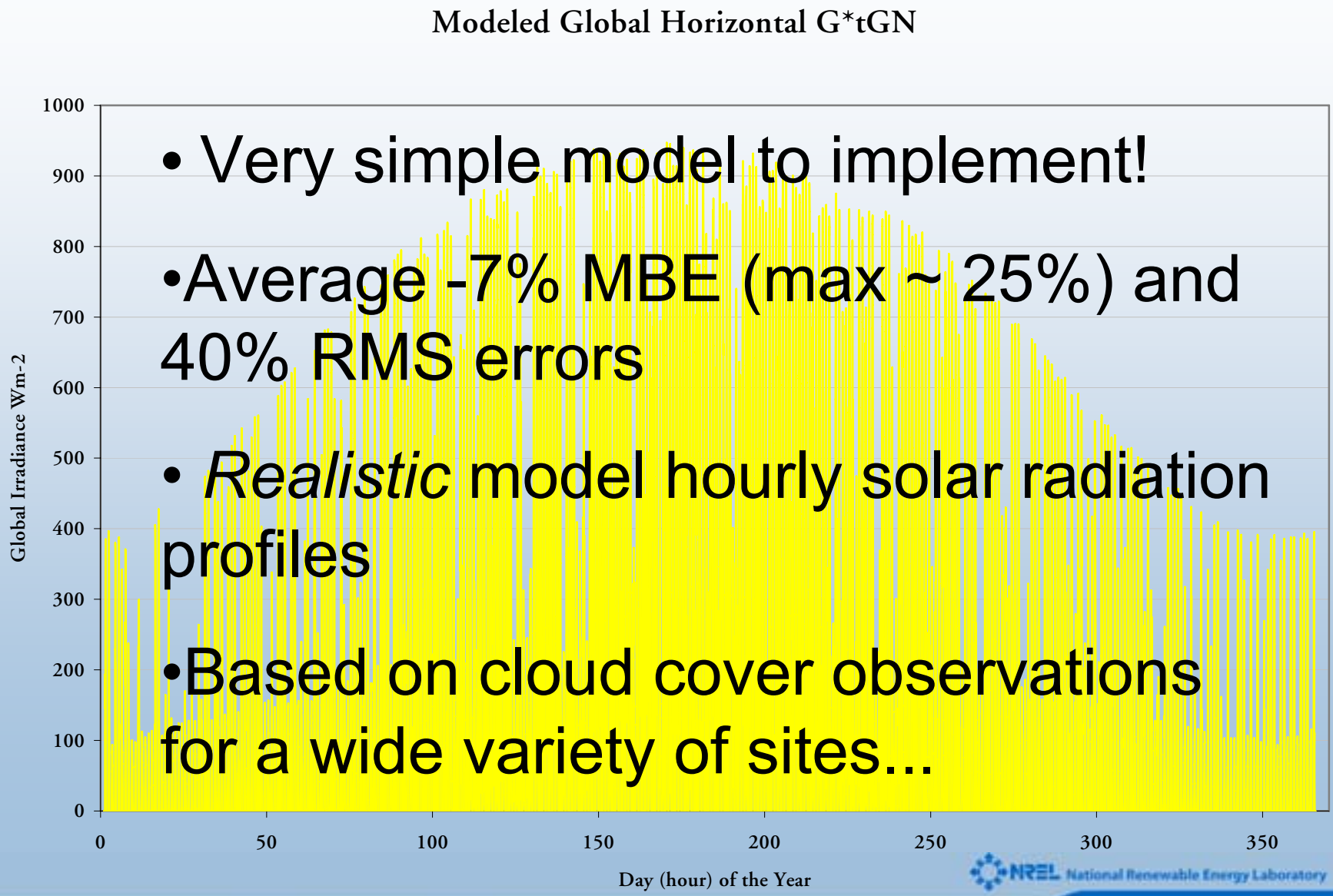

Mean Difference
**-8 $Wm^{-2}$**

Std Dev
**±88 $Wm^{-2}$**

Mean Difference
**1.6 $Wm^{-2}$**

Std Dev
**±93 $Wm^{-2}$**

# Summary




- Very simple model to implement!
- Average -7% MBE (max ~ 25%) and 40% RMS errors
- *Realistic* model hourly solar radiation profiles
- Based on cloud cover observations for a wide variety of sites...