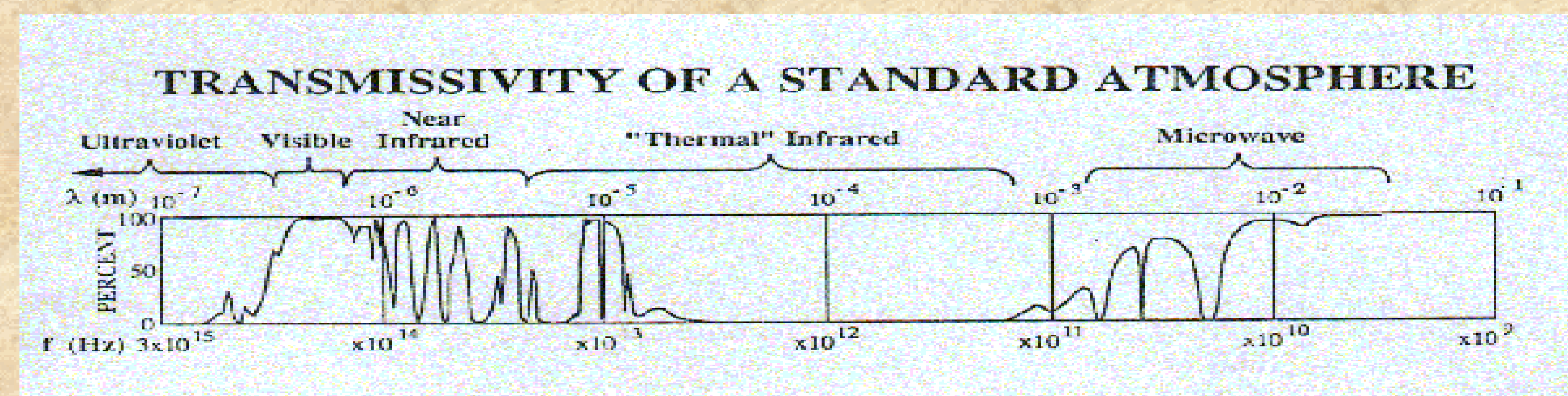
Operational SSM/I and AMSU Derived Rainfall Retrievals for Synoptic and Climatic Applications

Ralph Ferraro
NOAA/NESDIS/Office of Research & Applications
Camp Springs, MD
rferraro@nesdis.noaa.gov
301-763-8251

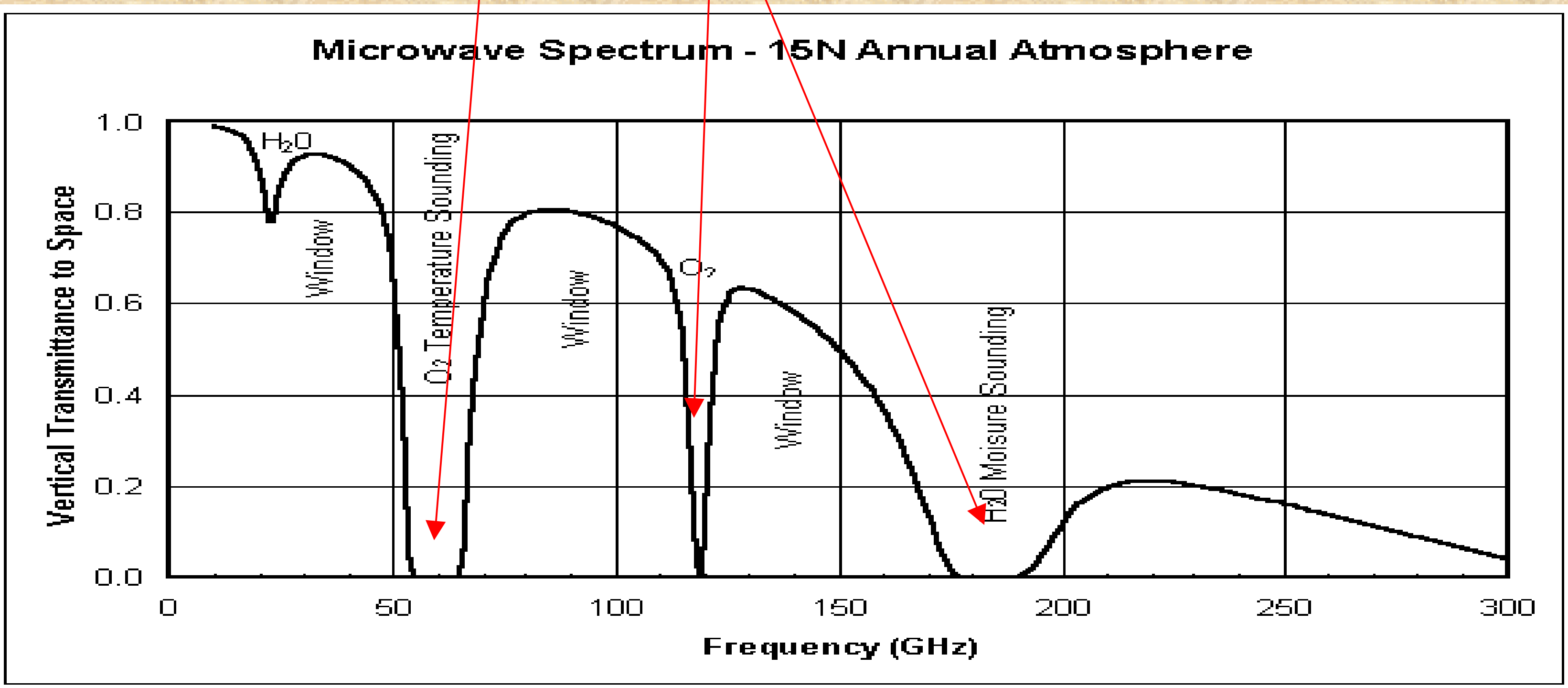
Outline/Objectives

- Physical Principles & Concepts
- Overview of operational "imagers"
  - DMSP & NOAA Series
- SSM/I & AMSU Algorithm Development
  - Rain Detection and Rate
  - Total Precipitable Water
- Synoptic Applications
  - Stratiform, Convective & Tropical
- Climatic Applications
  - Annual, Interannual and Regional

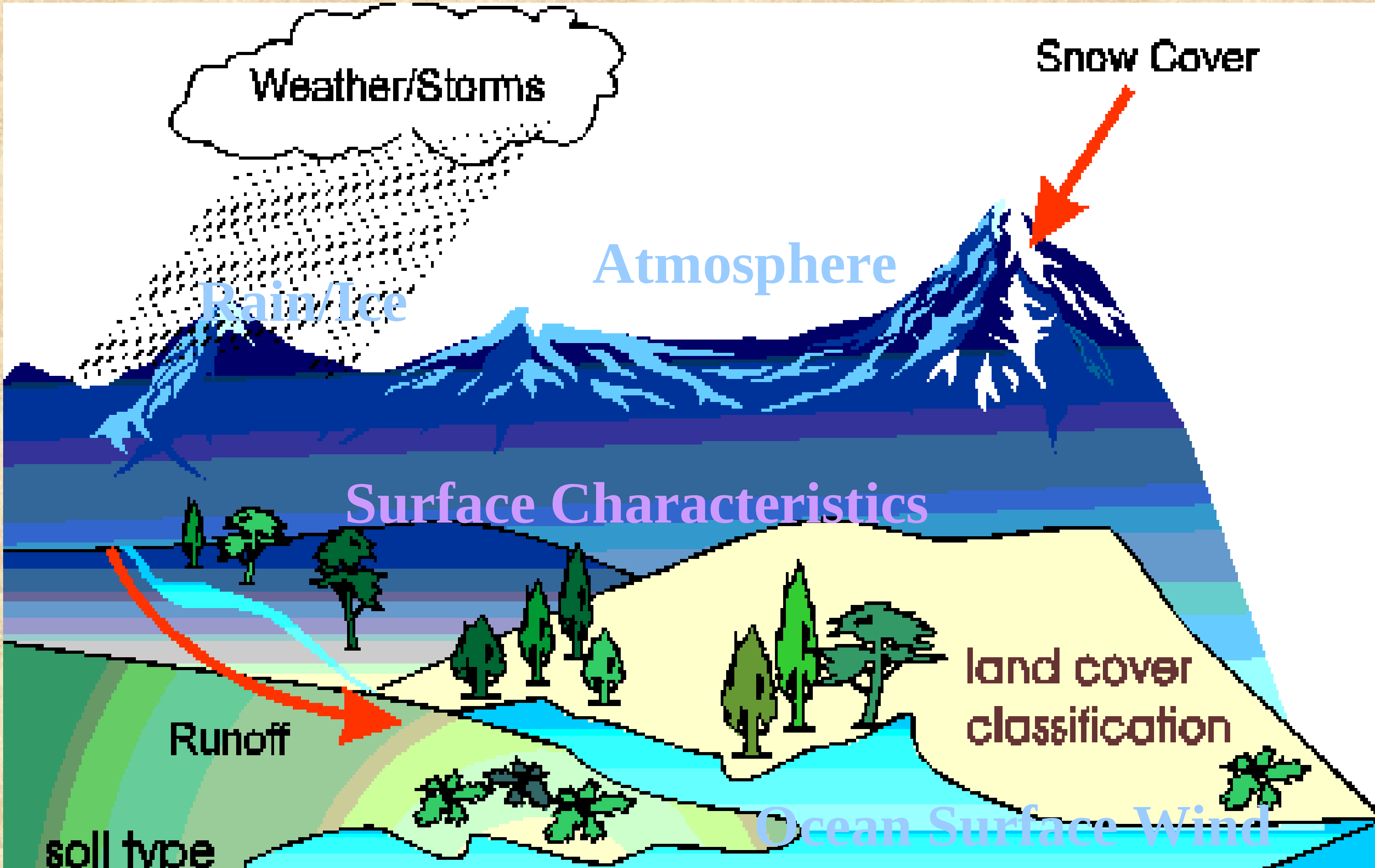
Passive Microwave-Basic Concepts



"Sounder Channels"

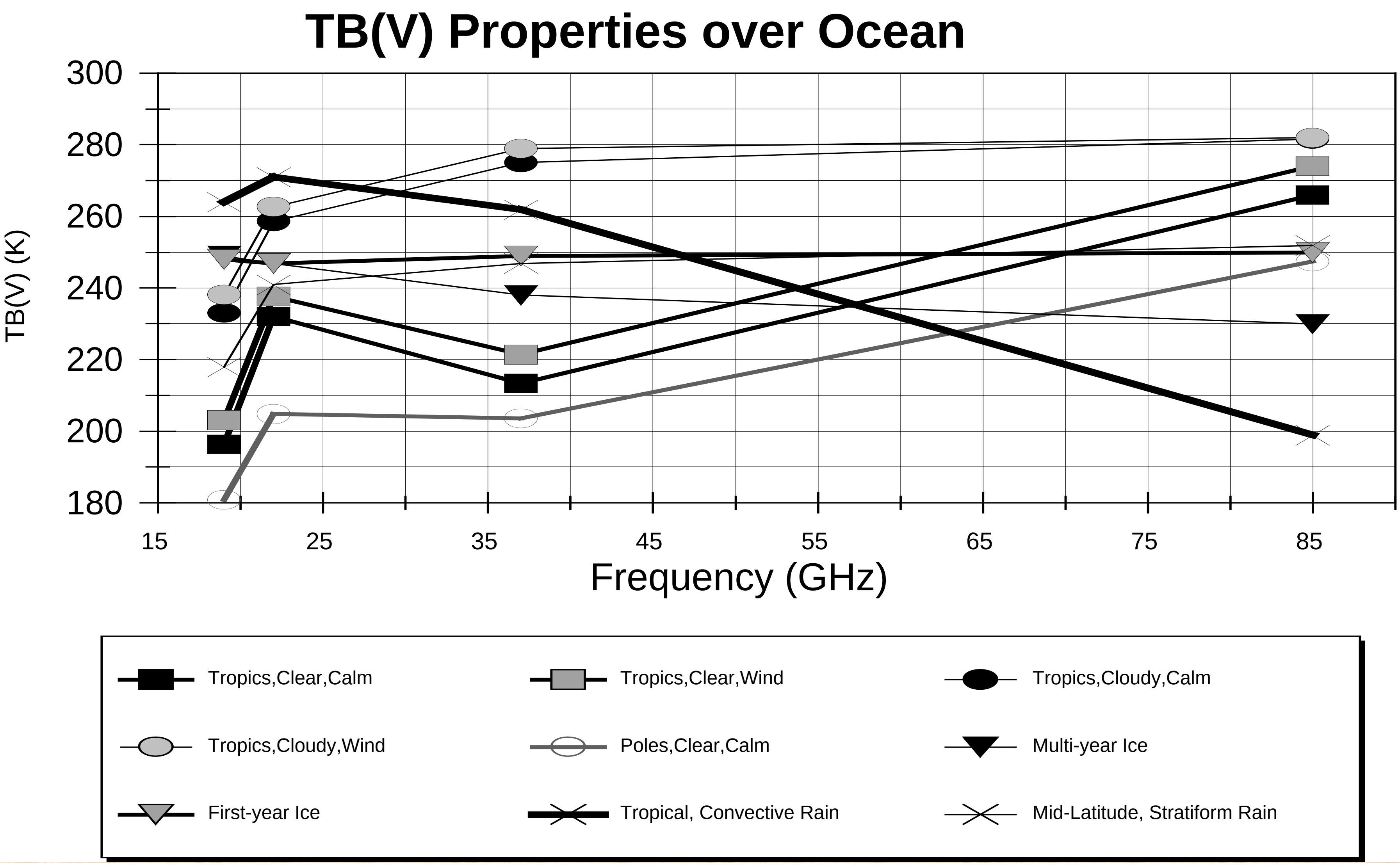


Passive Microwave Signatures Affected By:



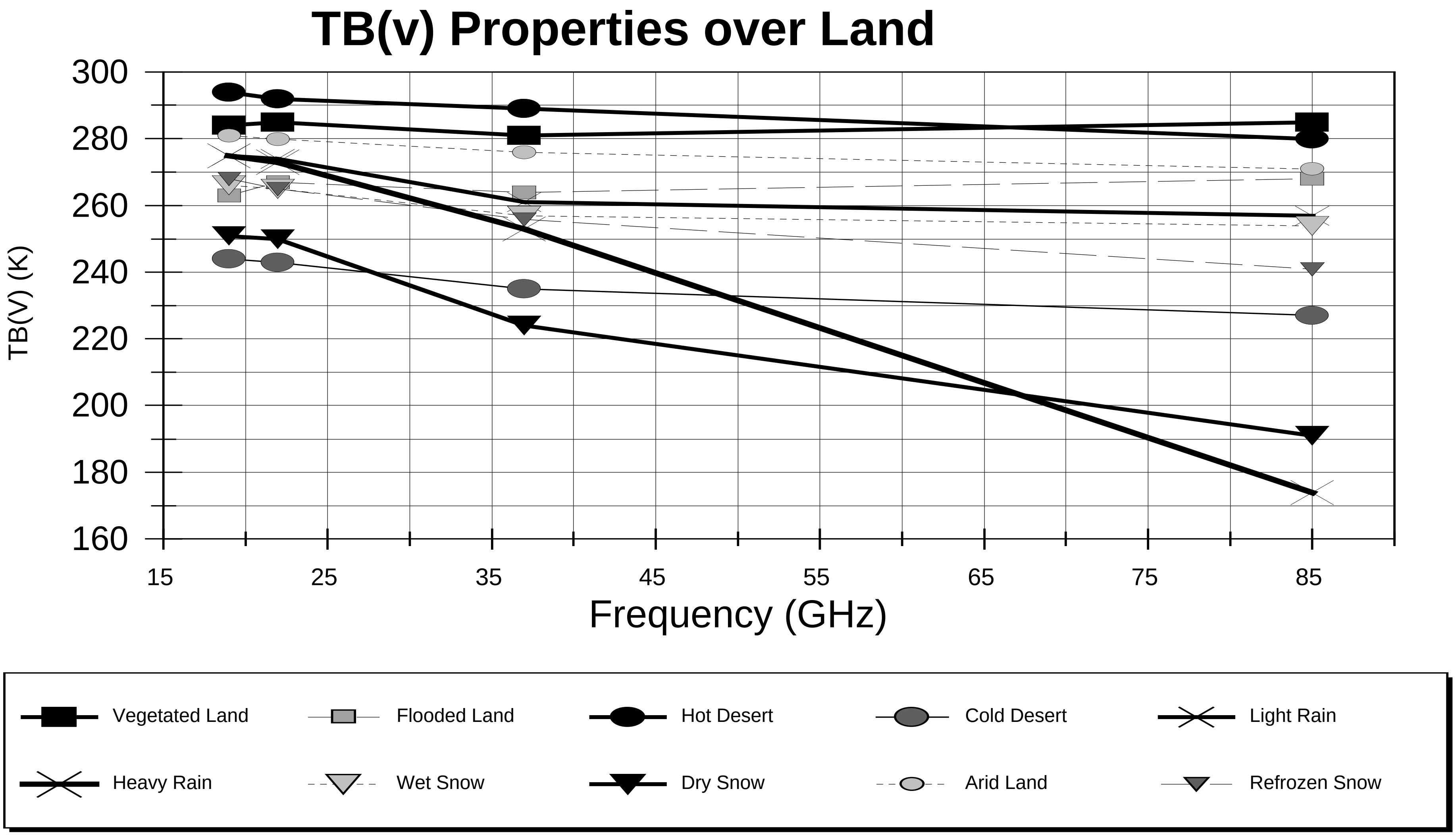
Ocean Surface Characteristics

$$TB = T_u + \tau[\varepsilon T_S + (1-\varepsilon)T_d]$$



Land Surface Characteristics

$$TB = T_u + \tau[\varepsilon T_S + (1-\varepsilon)T_d]$$



GOES Vis/IR vs. Polar Microwave

	GOES vis/IR	*POES MW*
Temporal Sampling	CONUS/NH – 0.5 hr Full disk – 3 hr	Every 12 hr
Spatial Resolution	Imager: 1 km vis 4-8 km IR Sounder: 10 km	SSMI: 15 km @85 GHz 60 km @19 GHz AMSU: Nadir: 45/15 km Limb: 150/45 km
Spatial Coverage	40 S – 40 N best	Global, but with orbital gaps, esp. SSM/I
Cirrus Penetraion	None	Almost always
Rain Physics	Cloud tops	Liquid water – ocean Ice particles – land/ocean
TPW Physics	Water vapor @6.7um Imager & Sounder	Water Vapor line @22 GHz

Rainfall Signatures (Model Based)

From Ferriday and Avery (JAM, 1994)

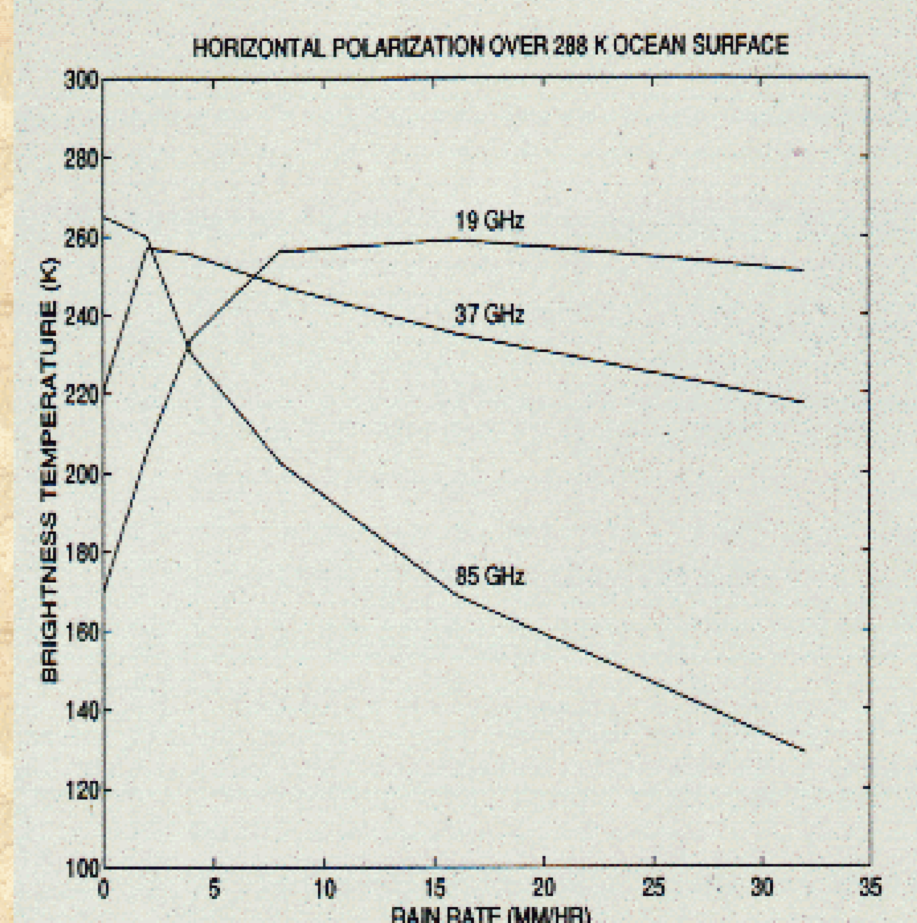


FIG. 3. Theoretical horizontally polarized brightness temperatures as a function of cloud model rain rate over the ocean.

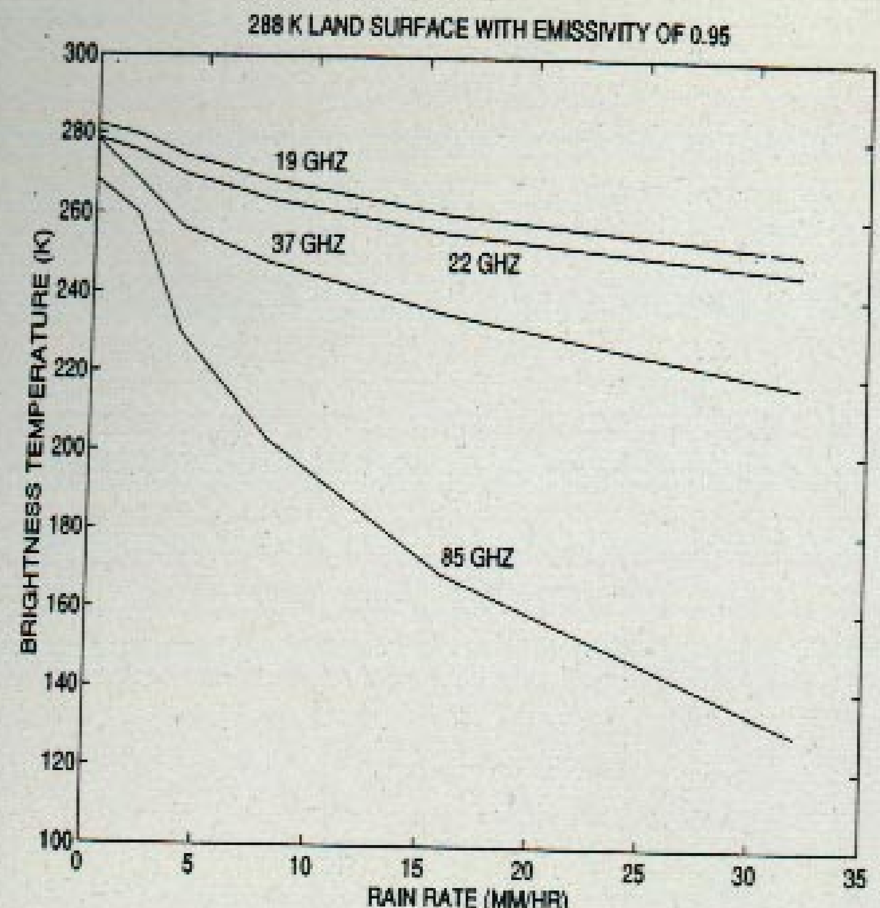
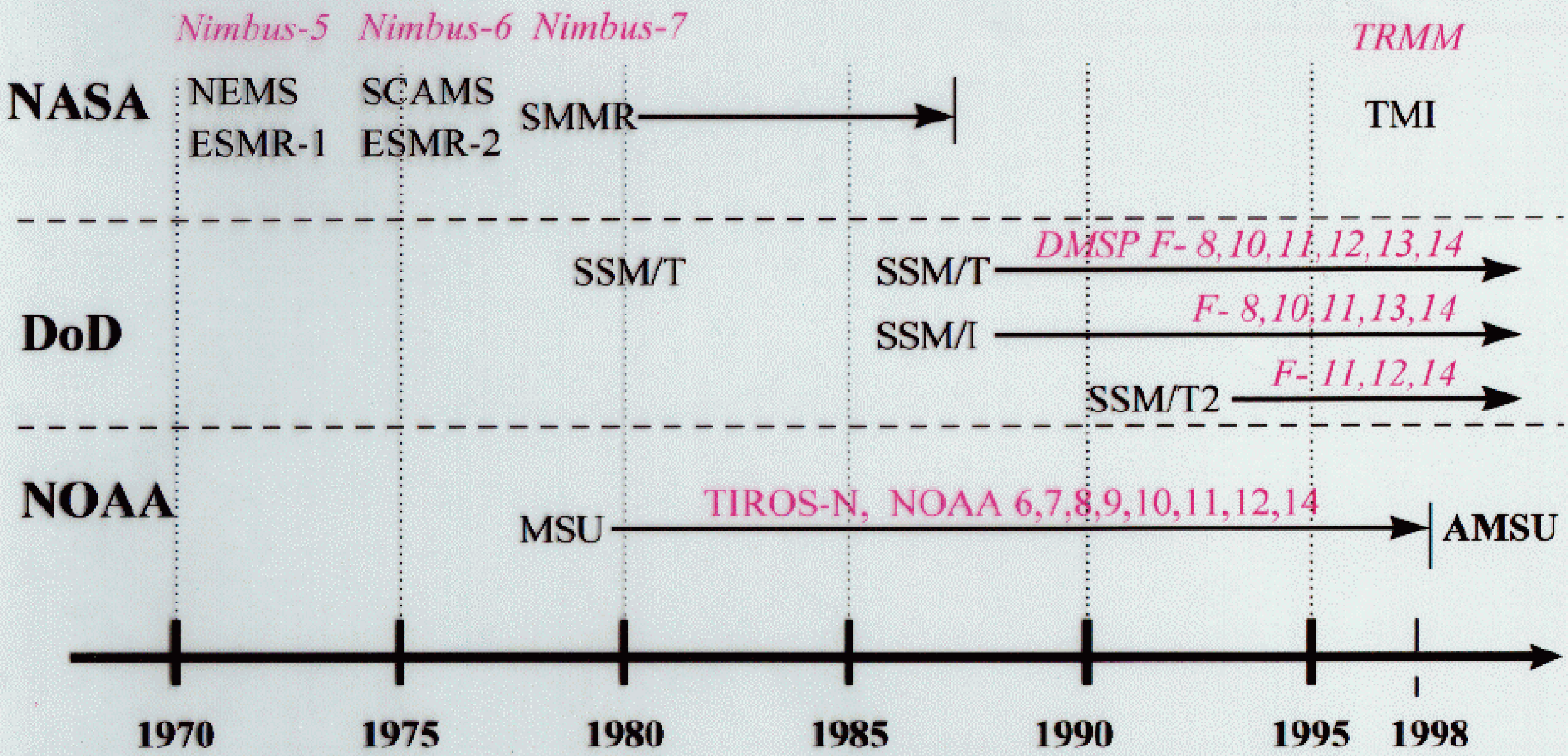


FIG. 4. Theoretical brightness temperatures as a function of rain rate over land.

Evolution of Passive Microwave Sensors



Satellite History

- DMSP - SSM/I, SSM/T, SSM/T2
  - First SSM/I on F-8 satellite (June 1987)
  - Subsequent SSM/I's on F-10 (Nov 90), F-11 (Dec 91), F-12 (failed), F-13 (Apr 95), F-14 (Apr 97)
  - 2-3 SSM/I's in operation at a time (~6 am/pm & 10 am/pm orbits)
- NOAA - MSU, AMSU
  - MSU "sounder" since 1970's
  - AMSU "sounder" & "imager" (May 98)
  - NOAA-15   730am/pm orbit

DMSP SSM/I

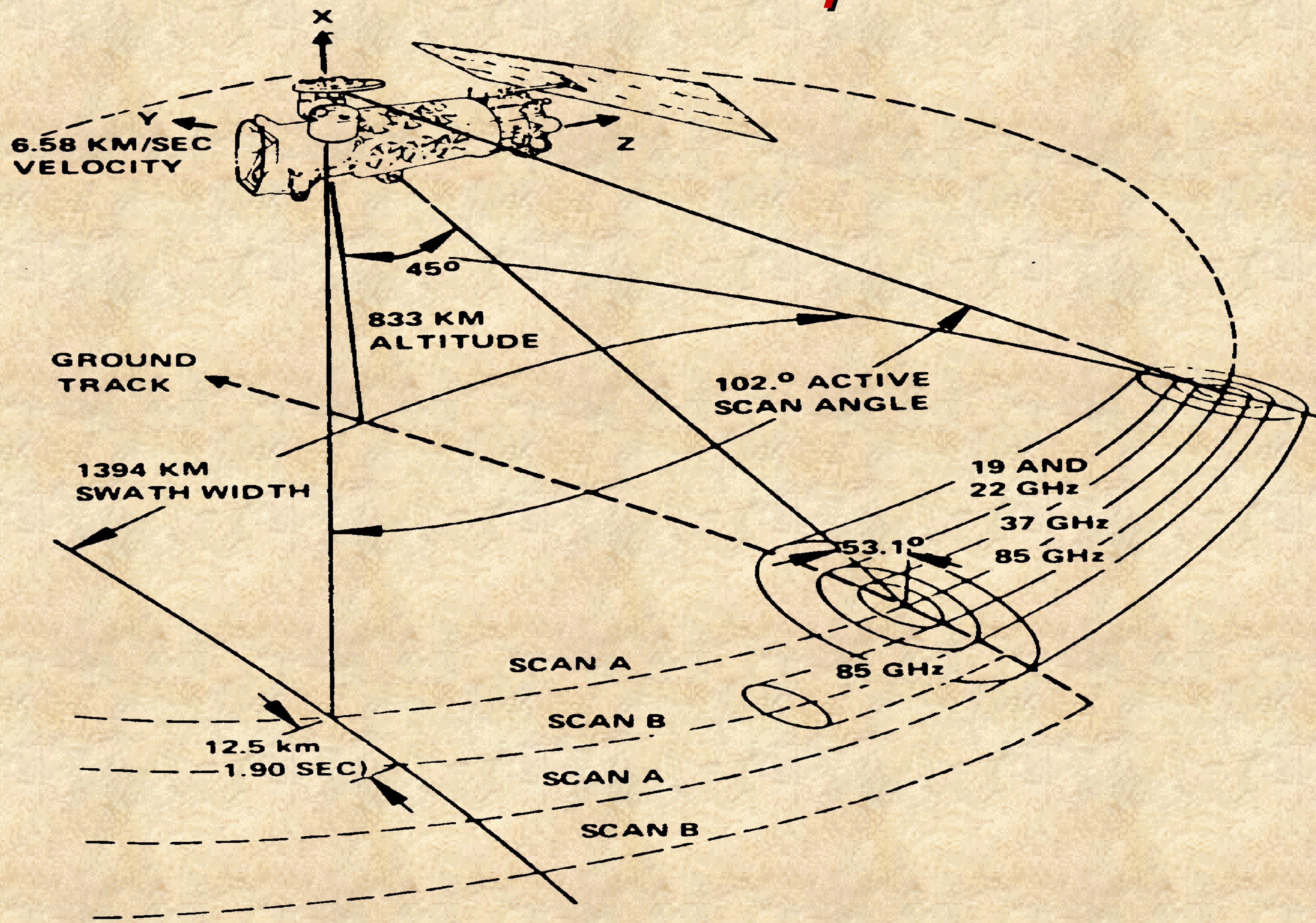


Figure II.9 SSM/I scan geometry

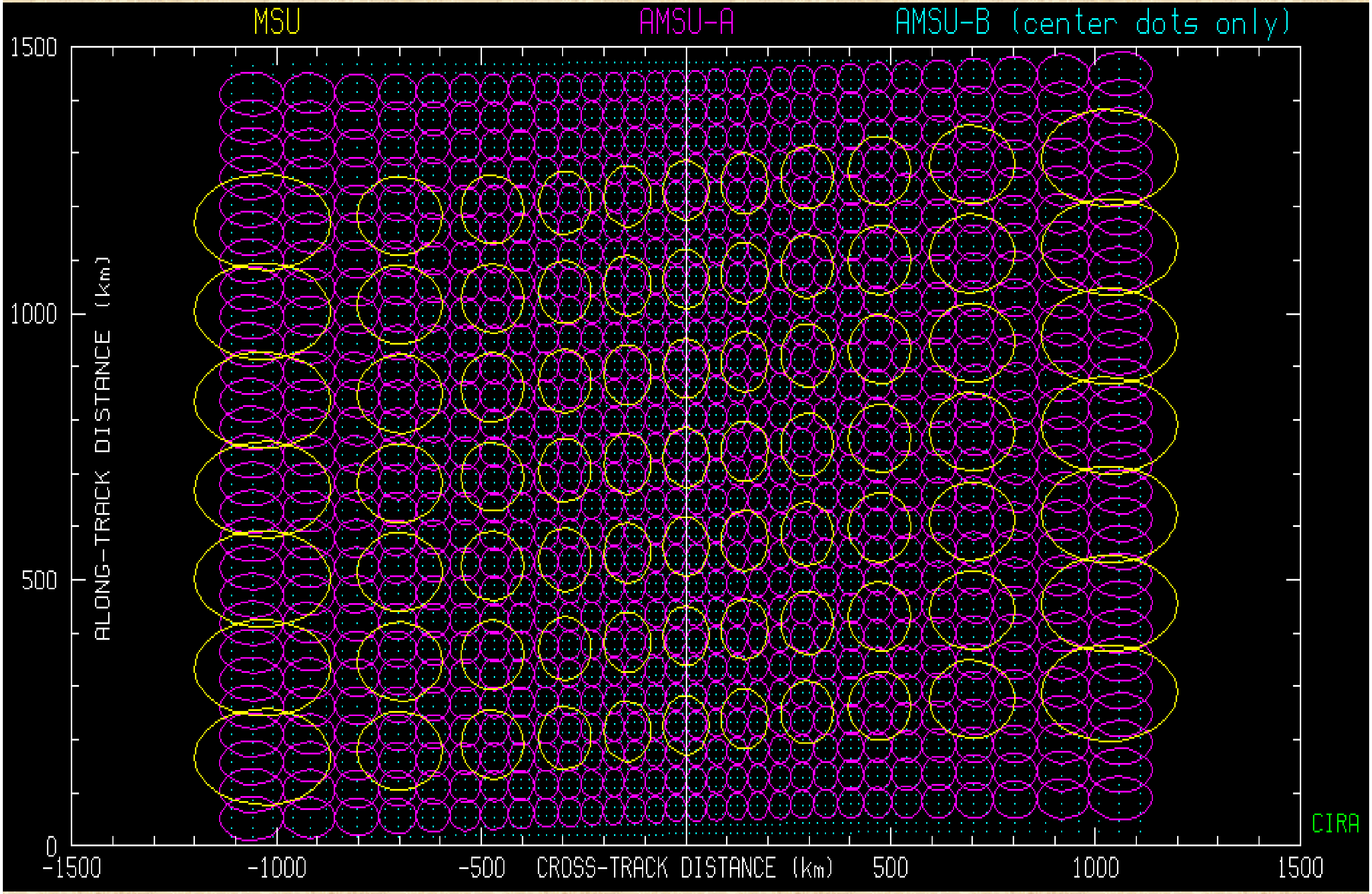
DMSP SSM/I

Channel	Frequency(GHz)	Polarization	FOV size(km)
1	19.35	Vertical	69 by 43
2	19.35	Horizontal	69 by 43
3	22.35	Vertical	50 by 40
4	37.0	Vertical	37 by 28
5	37.0	Horizontal	37 by 28
6	85.5	Vertical	15 by 13
7	85.5	Horizontal	15 by 13

NOAA AMSU

Channel	Frequency	Channel	Frequency
A1	23.8 GHz	A8	55.5 GHz
A2	31.4	A9-A14	57.290**
A3	50.3	A15	89.0
A4	52.8	B1	89.0
A5	53.6	B2	150.0
A6	54.4	B3-5	183.31**
A7	54.9		

NOAA AMSU



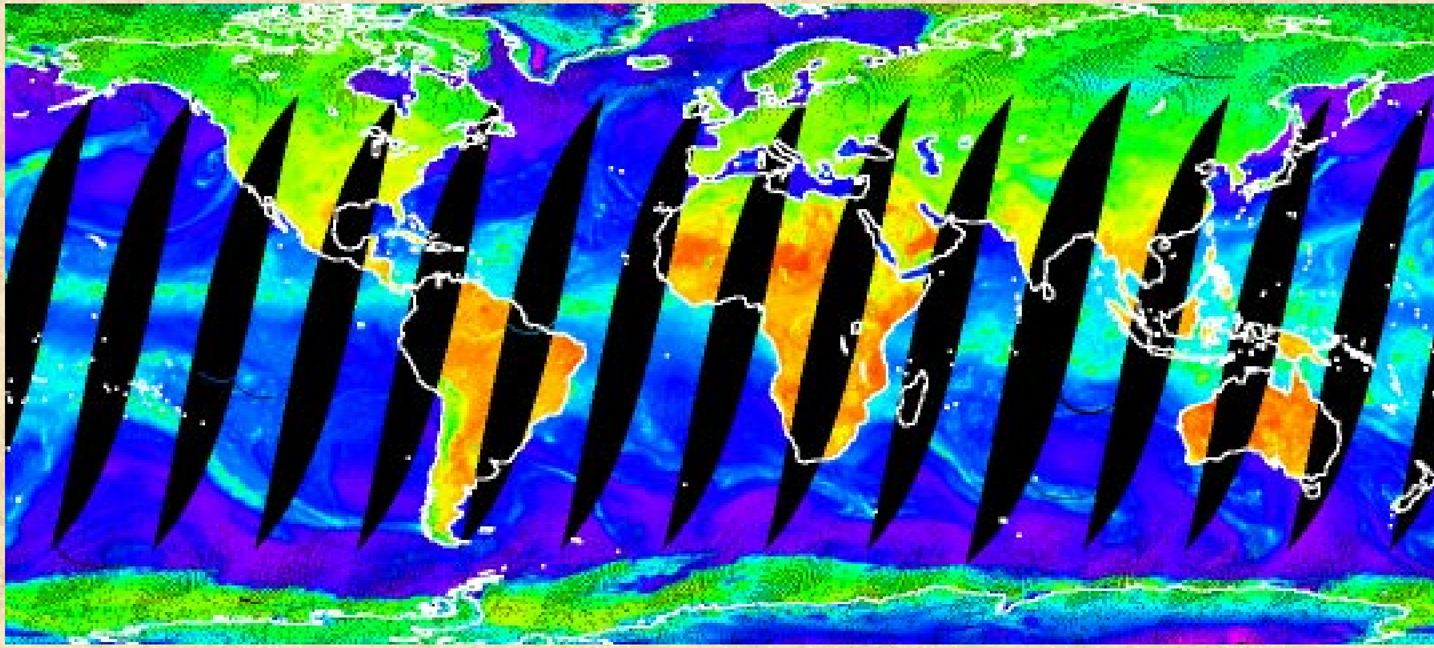
MSU
AMSU-A
AMSU-B (center dots only)
1500
1000
500
0
ALONG-TRACK DISTANCE (km)
-1500
-1000
-500
CROSS-TRACK DISTANCE (km)
500
1000
1500
CIRA

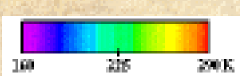
AMSU vs. SSM/I

Parameter	AMSU	SSM/I
Window Channels	23.8,31.4,89.0	19.4,22.2,37.0,85.5
Polarization	Mixed	V & H
Scan Geometry	0 - 48 deg	Fixed 45 deg
FOV's	Vary with view angle: 45 (15) km/nadir 150 (50) km/limb	Vary with frequency: 15 km @ 85 GHz 60 km @ 19 GHz
Swath Width	~2200 km	~1400 km

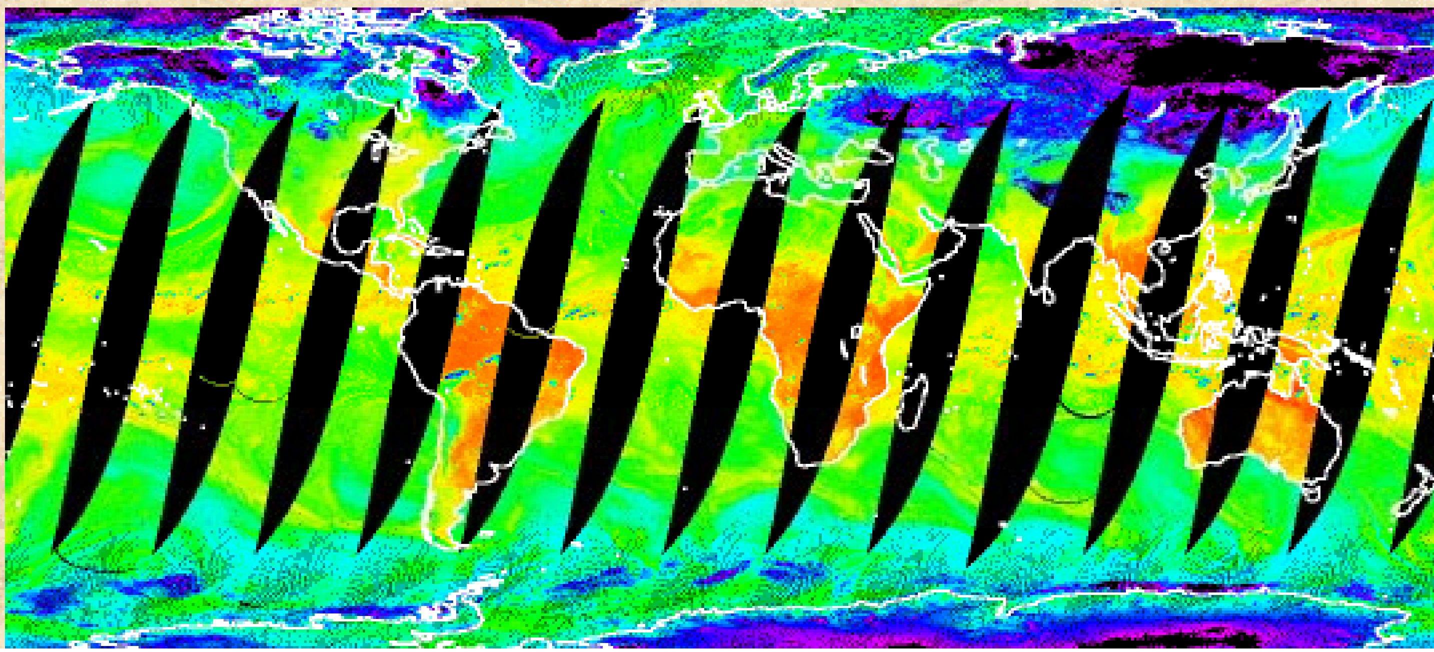
SSM/I Sample Imagery - 11/30/98

19V

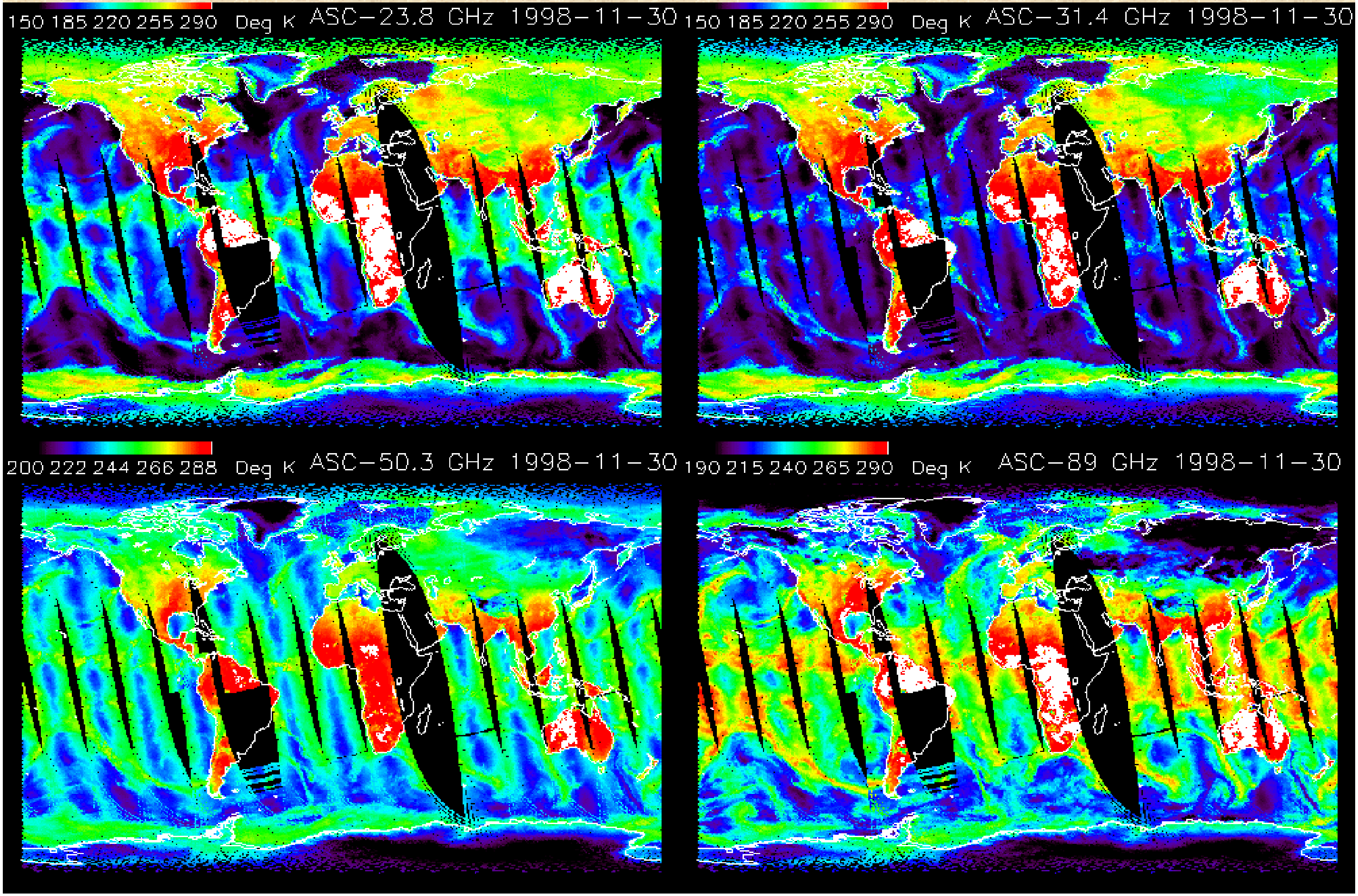




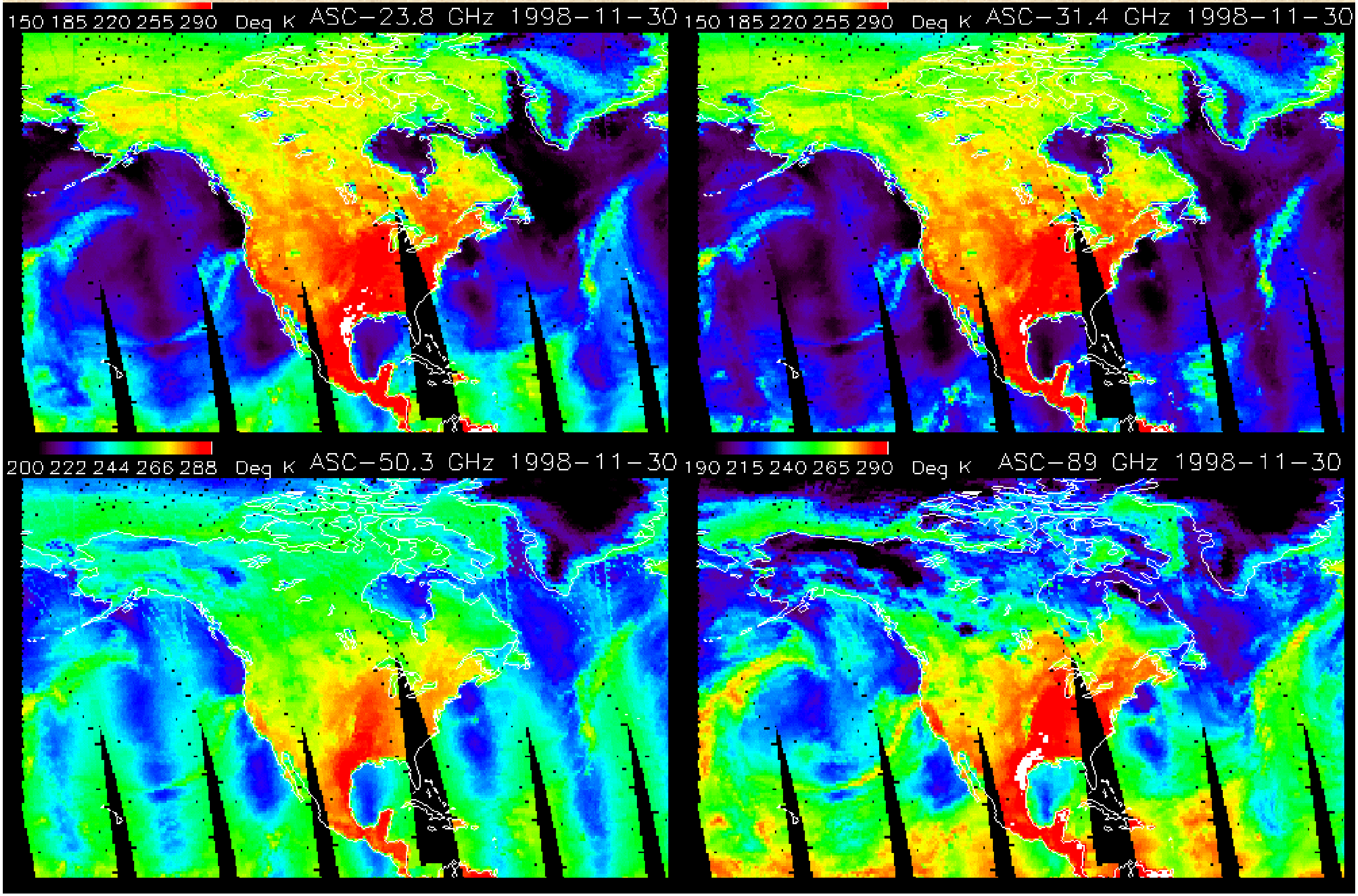
85V



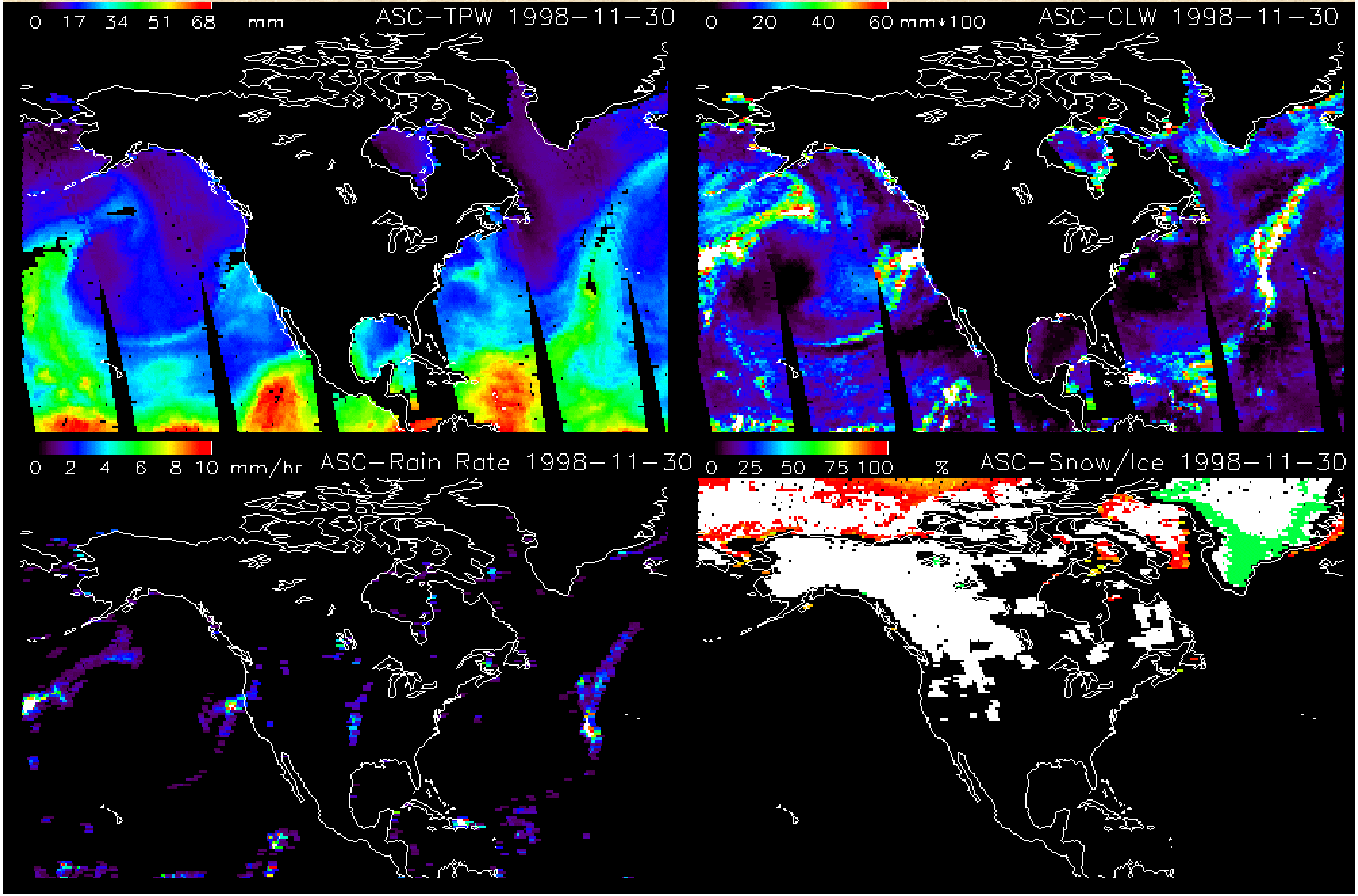
AMSU Sample Imagery - 11/30/98



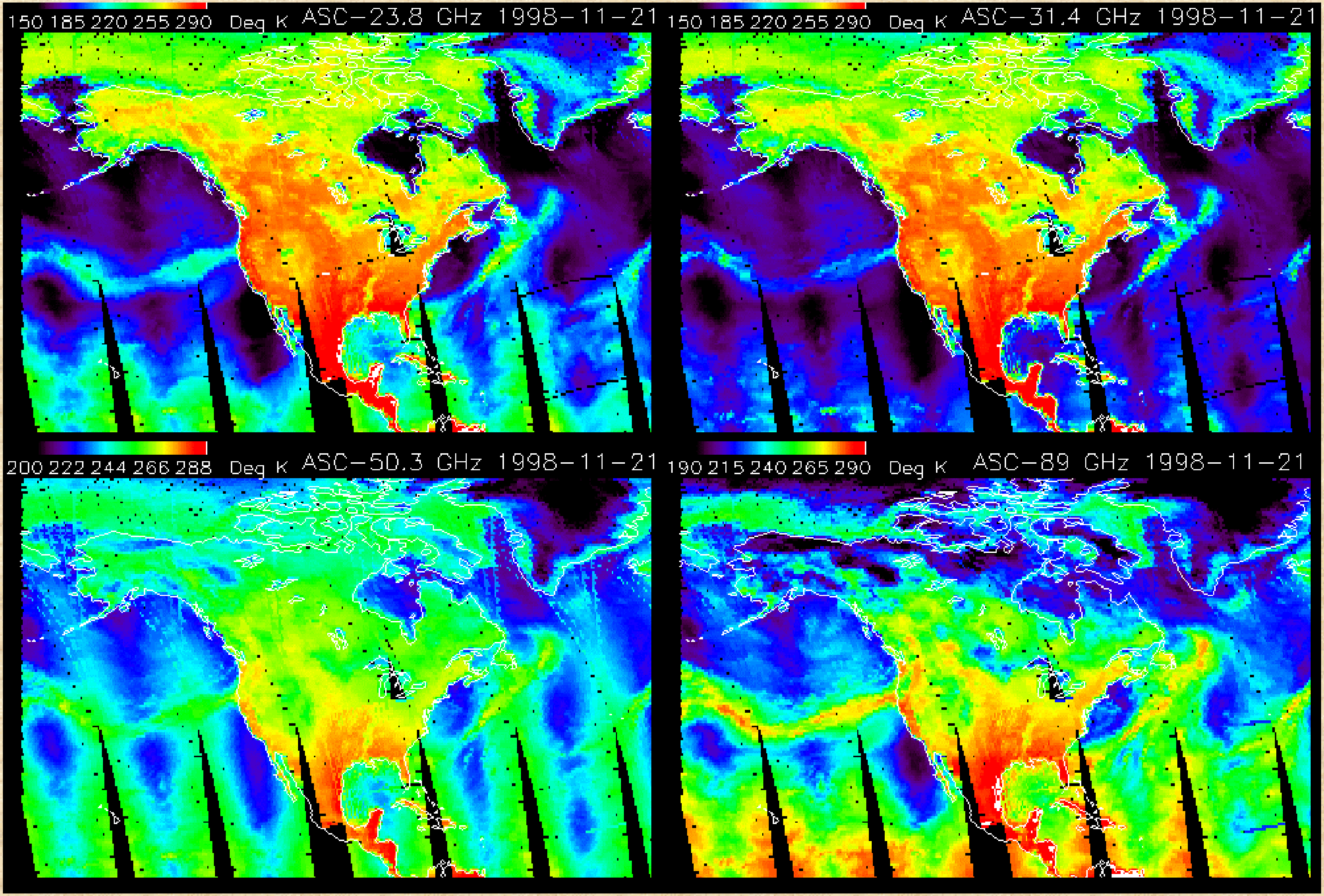
AMSU Sample Imagery - 11/30/98



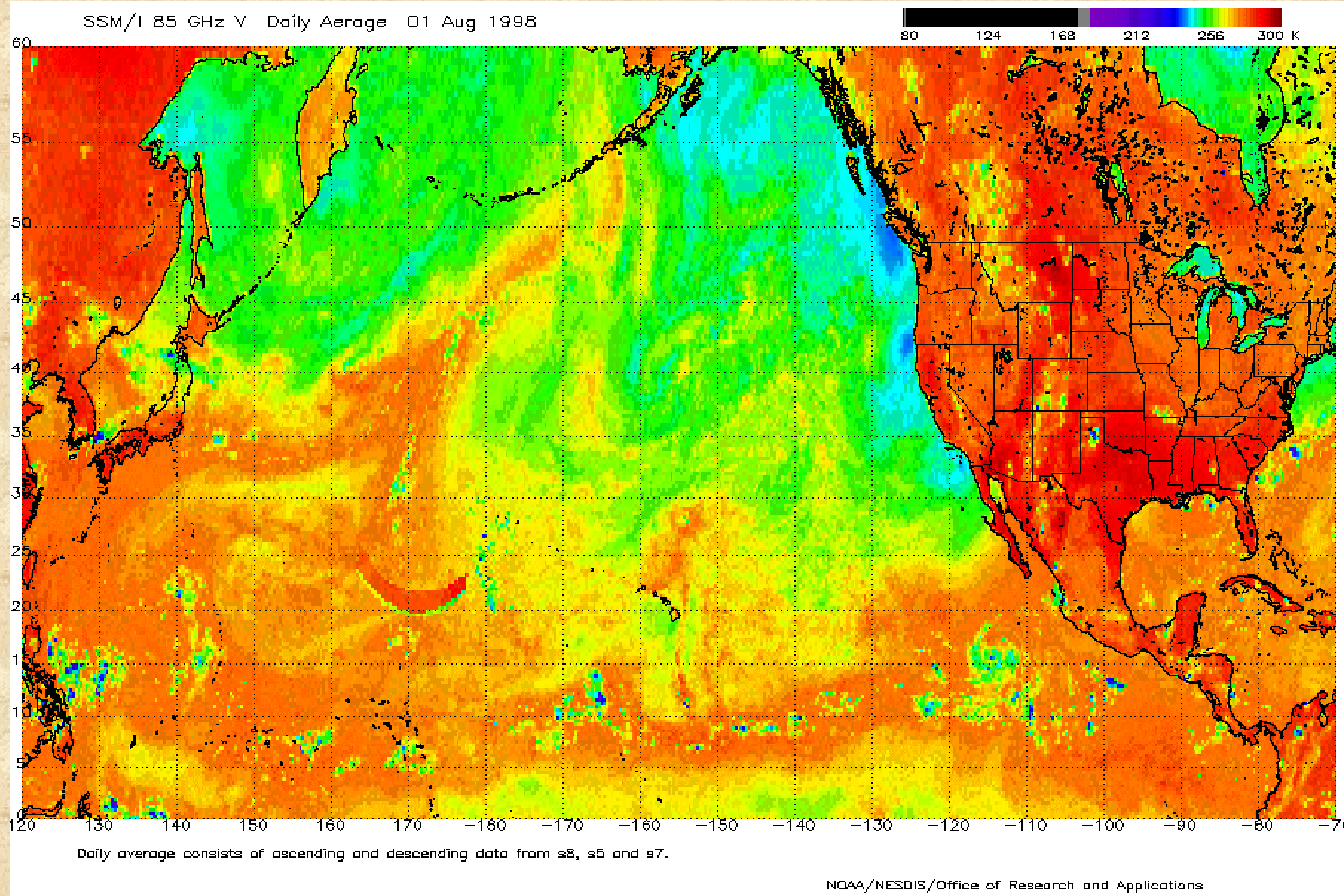
AMSU Derived Products - 11/30/98



Time Series of AMSU BT's



SSM/I 85 GHz TB's - 8/01 to 9/30/98



Operational Algorithm Development

- Considerations:
  - Complexity, processing, delivery "balance"
  - Impact on other processing systems
  - User requirements
- Things are changing
  - Stand alone workstations
  - Faster computers
  - TRMM setting the stage….

Rainfall Over Ocean

- Utilize both emission and scattering signatures of rainfall
  - Emission: 19-37 GHz/Scattering: 85+ GHz
- Rain identification:
  - Emission:
    - CLW (Q) cloud/rain threshold (0.2-0.3 mm)
    - Function of freezing level, cloud base, etc.
    - Operational algorithm for SSM/I and AMSU use static threshold (for now)
    - AMSU-Limb Affects
  - Scattering:
    - Scattering “Index” (ice phase/falling snow)
  - Remove sea-ice signature

Rainfall Over Ocean (con't)

- Rain rate determination
  - Empirical tuning to co-incident radar
  - $RR = a\ Q^{b}$ $\qquad RR = a\ SI^{b}$
- Accuracy and limitations
  - Instantaneous rain rate +/- 25%?
    - Questions on low and high end rates
    - Beam filling errors
  - Rain area fairly reliable
  - Some concerns on "west coast" rainfall; too low?
    - Freezing level/Q depth incorrect?
  - Tropical systems; too low?
  - Coastline rainfall limited due to land effects:
    - Minimize noise reduces sensitivity to stratiform rain

TPW over ocean

- "Grandfather" of MW products
  - Most accurate MW product: RMS ~10%
  - Generated since 1970's (research)
- TPW "signal" comes from 22 GHz region
  - SSM/I near center (22.235 GHz)
    - saturation at high TPW's
  - AMSU off center (23.8)
    - no saturation, but **limb affects**
- Utilize other channels to remove Q effects
  - SSM/I: 19 and/or 37 GHz
  - AMSU: 31.4 and/or 50.3 GHz

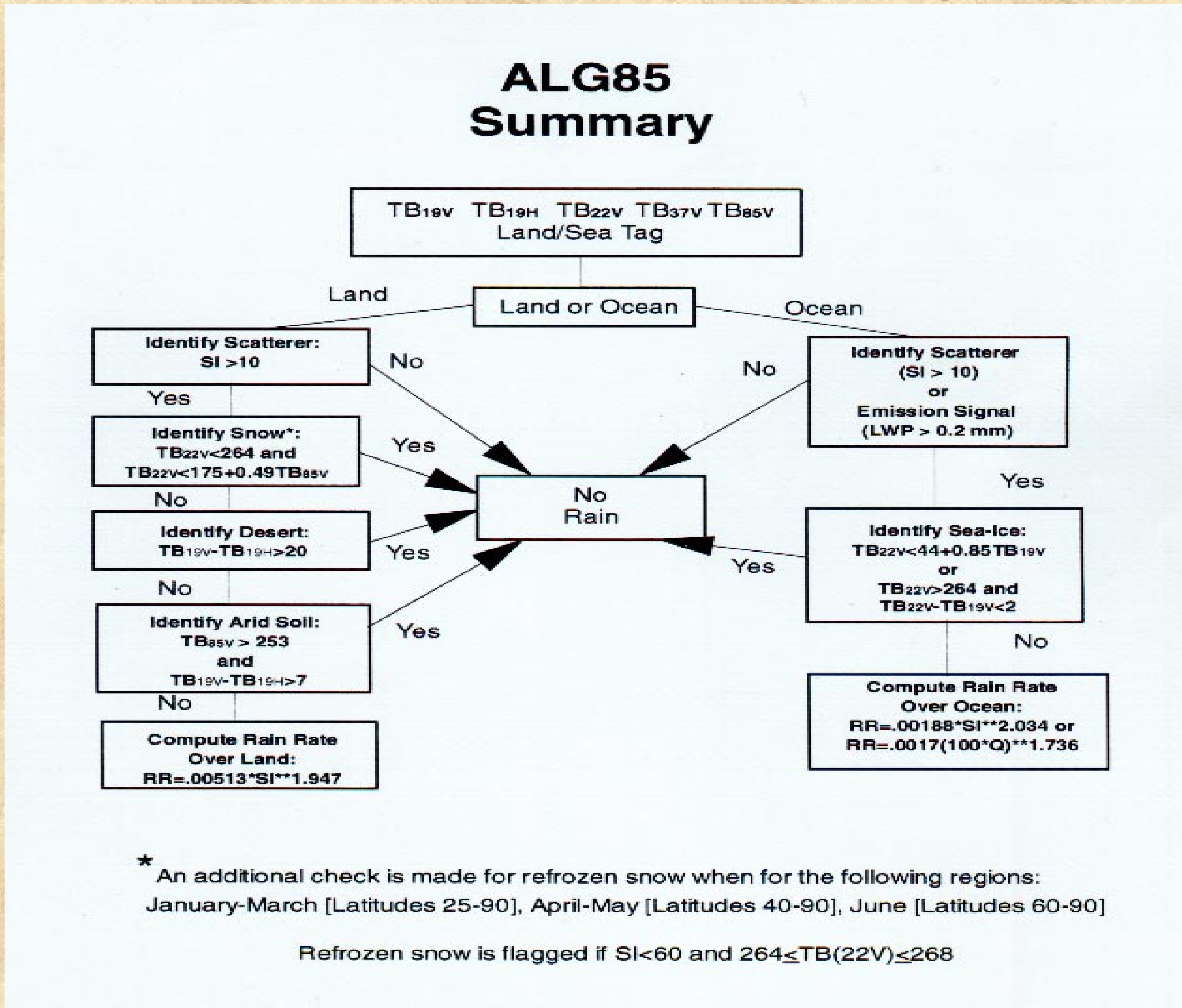
Rainfall Over Land

- Can only utilize scattering signature:
  - Emission not really feasible; it's there but signal is smaller (high emissivity) AND emissivity highly variable
  - Less direct measure of rain
  - Mainly convective & widespread stratiform
- Special care to remove "false" signatures:
  - Snow cover (melting snowpack), deserts
  - Empirical "sceens"; decision tree approach
  - Non-uniqueness of signatures
  - conservative vs. aggressive screening

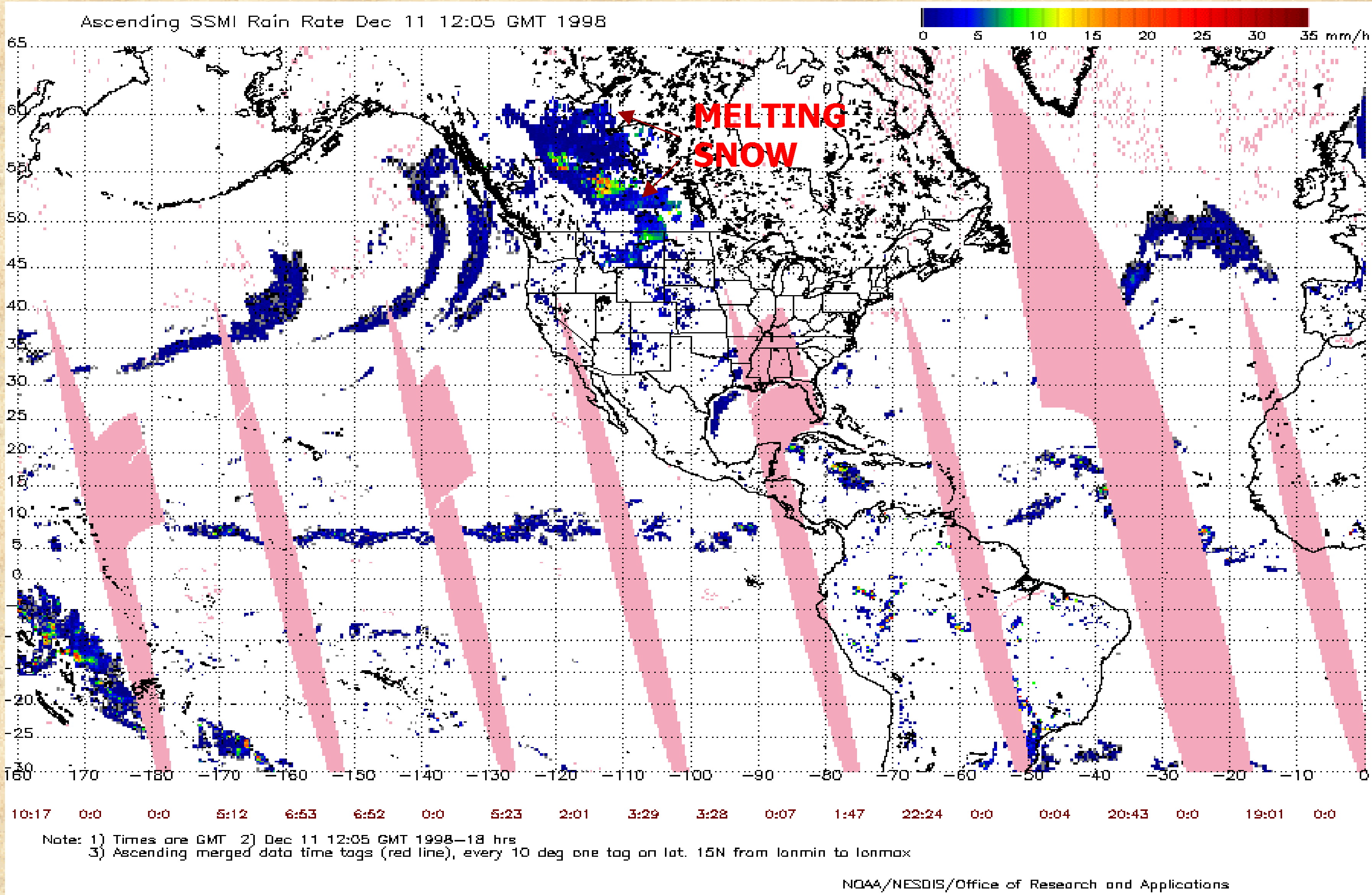
Rainfall Over Land (con't)

- Rainfall detection via scattering 85/89 GHz:
  - TB depressions indicate possible rain
    - Larger the depression, heavier rain
  - Proper rain/no-rain threshold to minimize noise
  - Scattering Index=f(TB19,TB22)-TB85
- Rain Rate - radar tuned; RR = a SI ^{b}
- Accuracy and limitations:
  - Instantaneous rate +/- 50%
  - Summer season rain/no-rain most reliable
  - "W. Coast" land systems problematic:
    - maritime air mass/less ice/smaller precipitation particles?
  - Single SI-RR used (ie, global "Z-R" relationship)
  - Melting snow in winter and spring seasons
    - False moderate rain rates
    - "Stationary"

SSM/I Rain Retrieval Algorithm



Melting Snow Signature



Preliminary AMSU Rain Retreival Algorithm

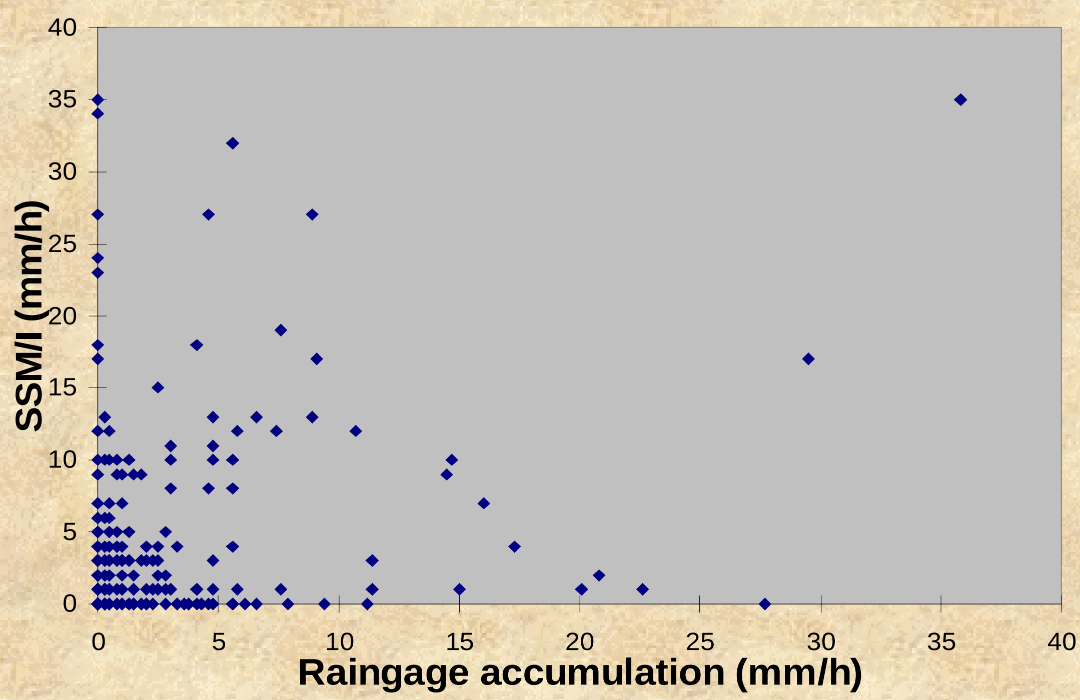
Few Thoughts on Validation

- Open ocean - virtually impossible
  - Use of Pacific Atoll gauges (Morrissey)
  - TOGA-COARE, etc.
  - Acoustic/Optical devices
- Validation Data “questionable”
  - Radar best suited for passive microwave, but….
    - Calibration issues
    - Z-R relationships; factor of 2-3
  - Gauges vs. satellite: point vs. average
- Which parameters are most important?
  - **How do you assess “usefulness”?**
  - Bias, correlation, skill score…image interpretation
- A LOT of “inconclusive” rainfall intercomparisons
  - GPCP - AIP’s & NASA WetNet - PIP’s

Land Validation - Stage IV Gauge Product

SE U.S. - Sep - Nov 1998

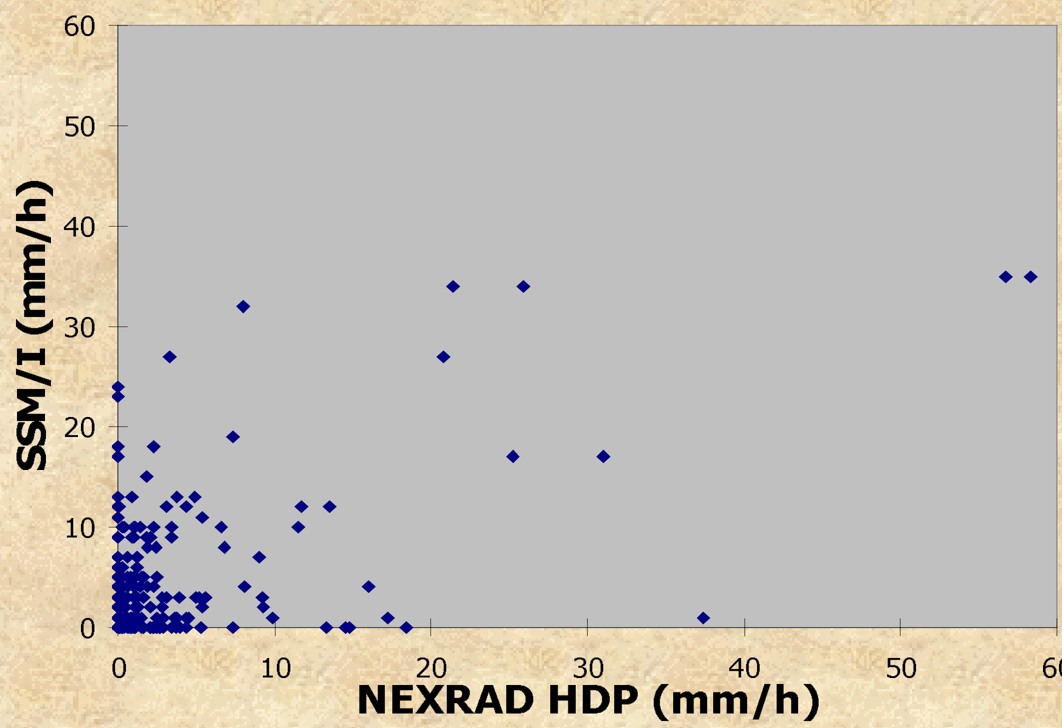
Estimate	Bias Ratio	RMSE (%)	R	POD	FAR
NEXRAD HDP	1.07	298.3	0.49	82	32
SSMI	1.66	328.0	0.40	71	34



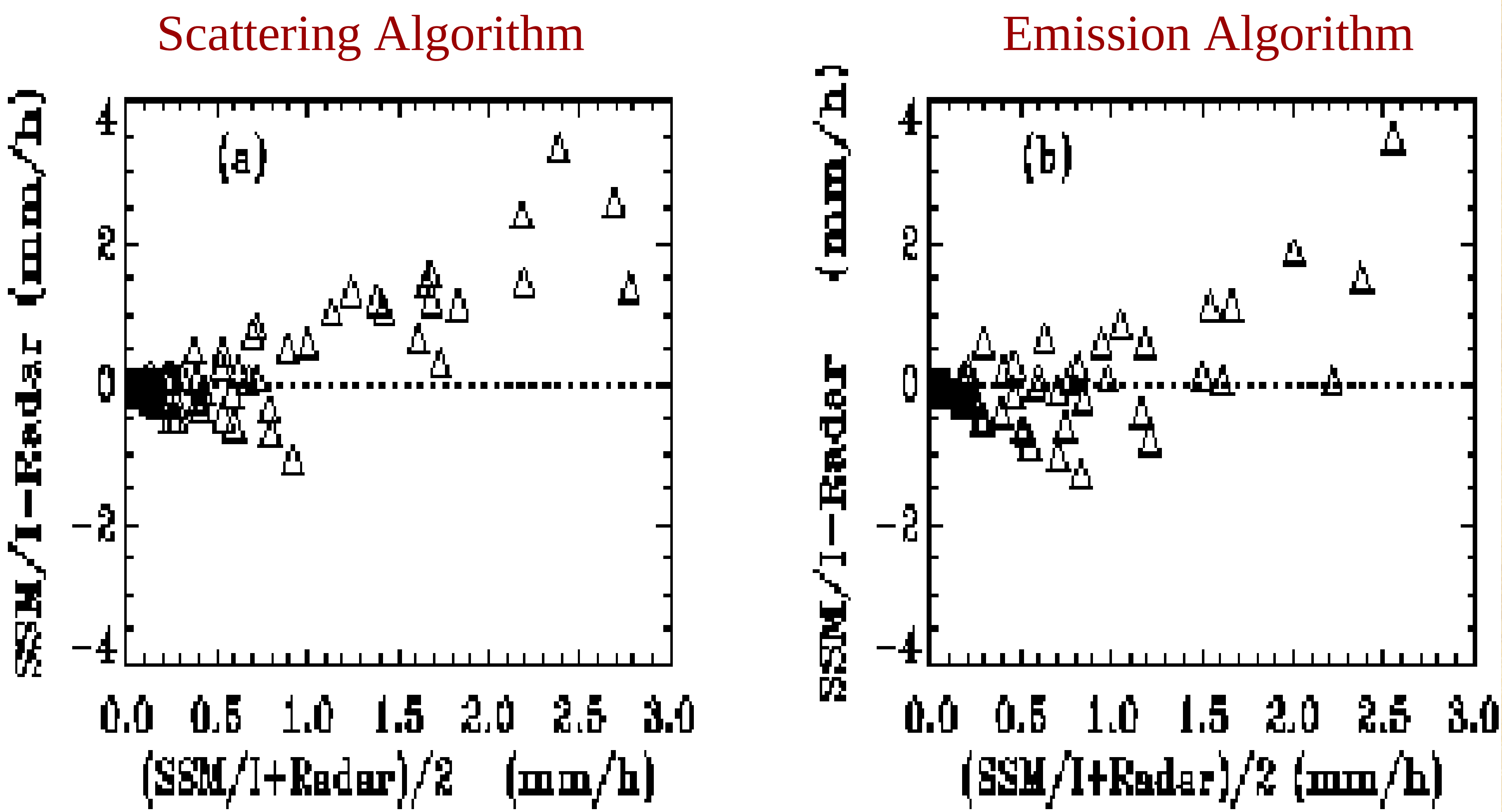
Land Validation - NEXRAD

SE U.S. - Sep - Nov 1998

Estimate	Bias Ratio	RMSE (%)	R	POD	FAR
Gauge Only	0.9	257.6	0.51	77	22
SSMI	1.55	285.2	0.55	69	26



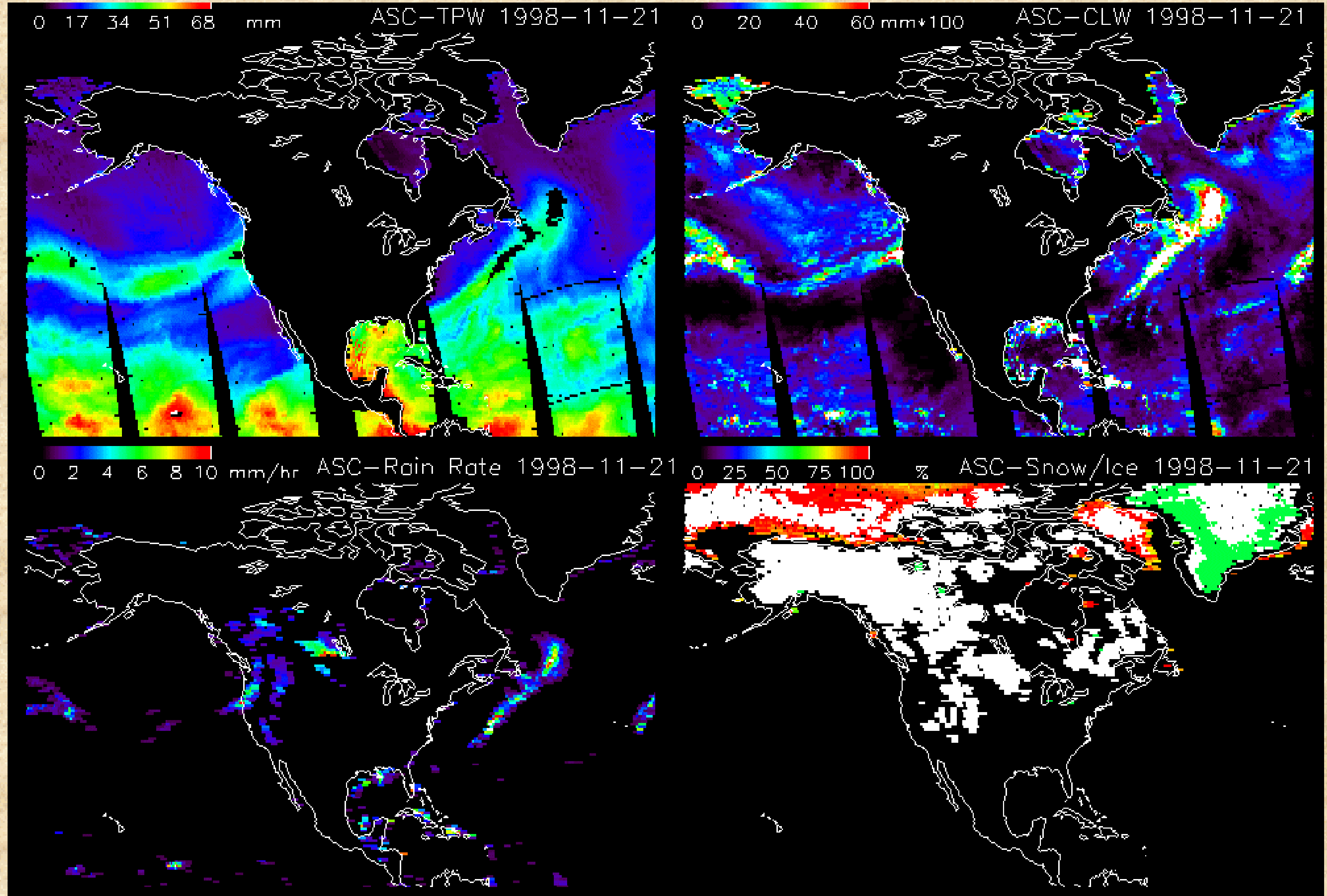
Ocean Validation - TOGA COARE



Uses of Products

Weather Forecasting and Analysis

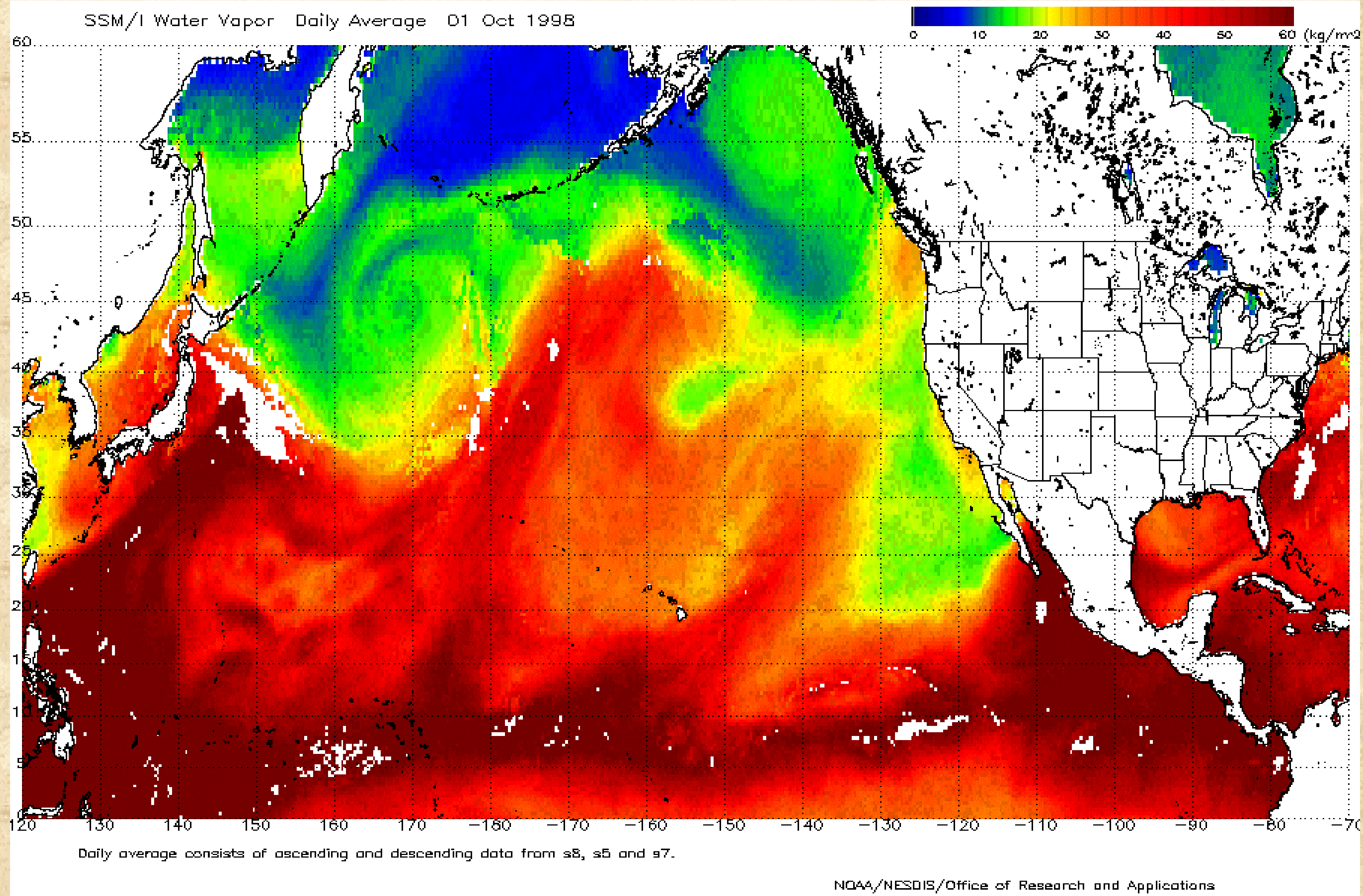
Time Series of AMSU Products



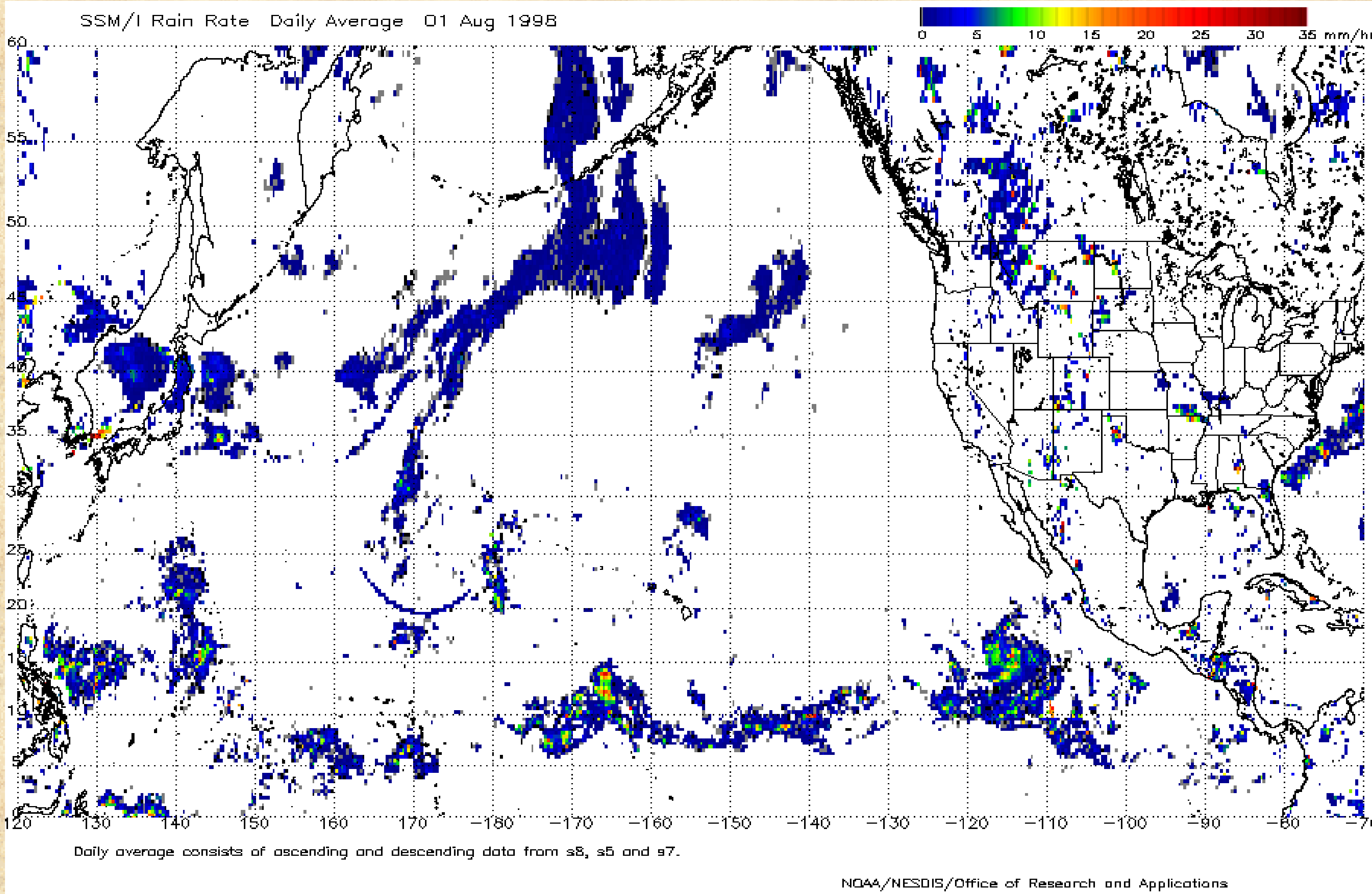
Synoptic Applications

- Polar satellite products have found their “niche”, despite their obvious temporal and spatial limitations
- For some regions, only satellite date that can be used:
  - Hawaii and Alaska
- The SSM/I and AMSU products offer complements to GOES, NEXRAD, etc:
  - Cirrus penetration
  - Off shore synoptic-scale and tropical systems
  - Objective, easy to use (little interpretation)
- Used daily by NESDIS/SAB, NWS WSFO and NWP model assimilation (at least TPW; Rain soon)

SSM/I Daily Mean TPW - 10/1 to 11/30/98
Dual Satellite/Daily Means



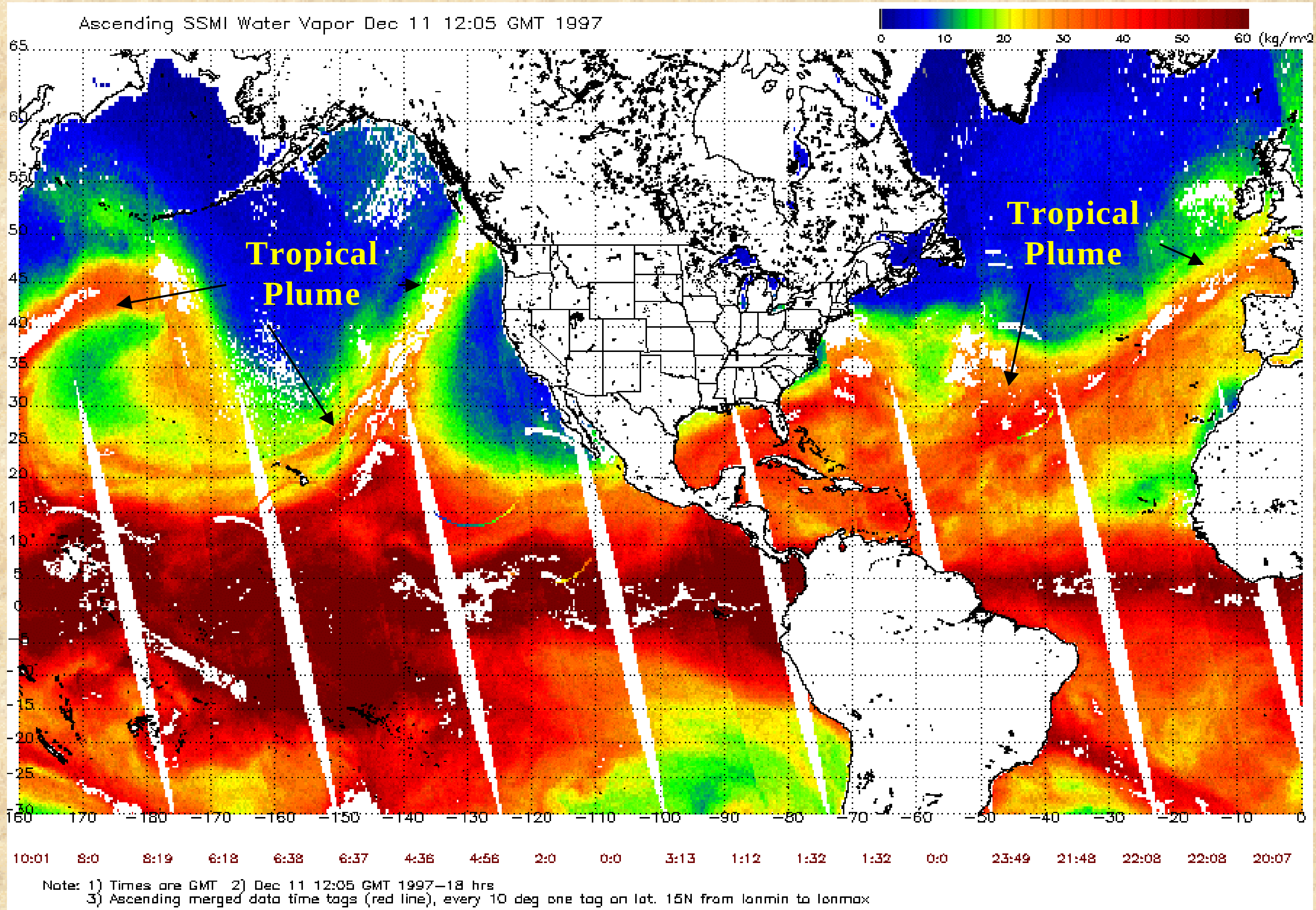
SSM/I Daily Mean Rain Rates - 8/1 to 9/30/98
Dual Satellite/Daily Means

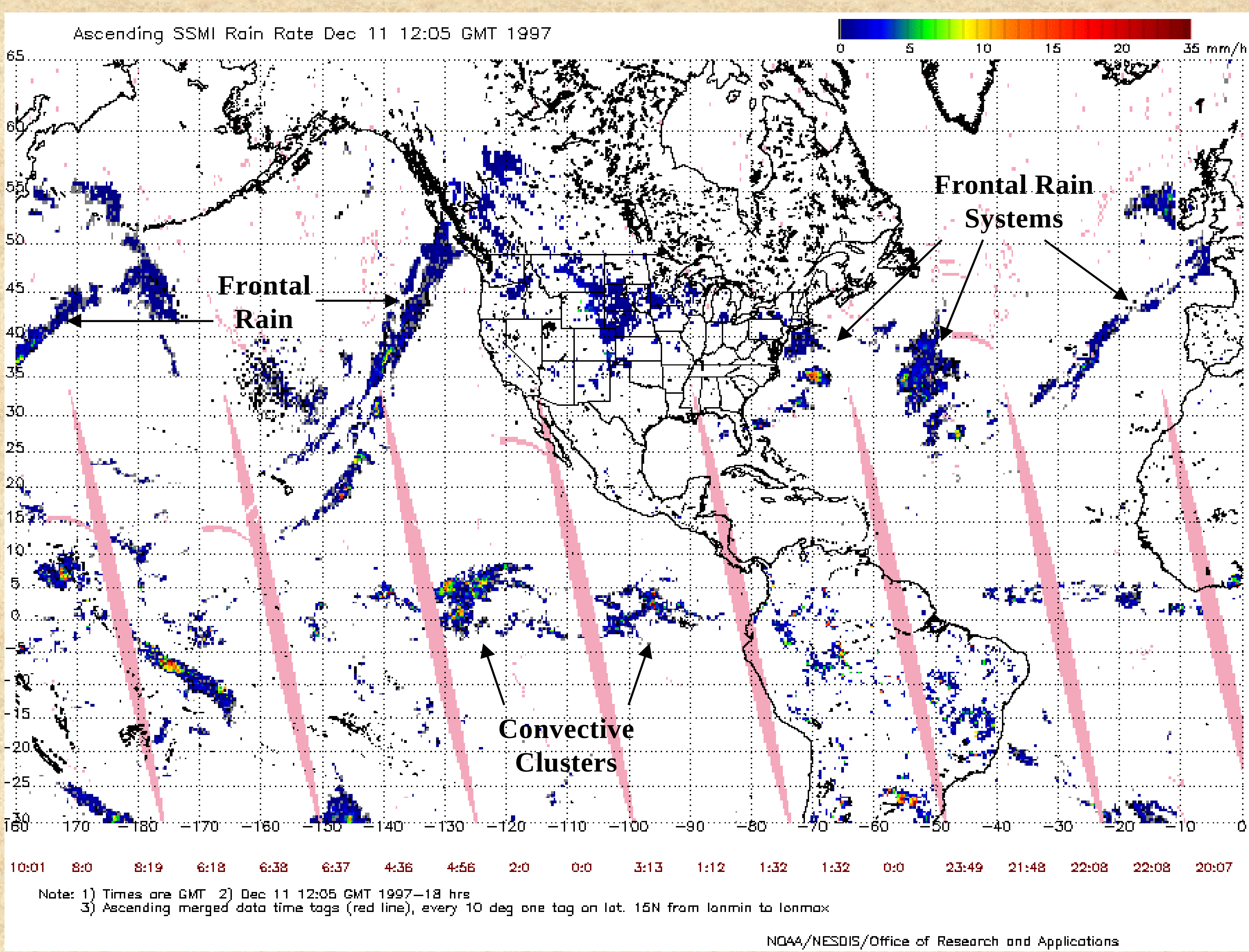


West Coast United States

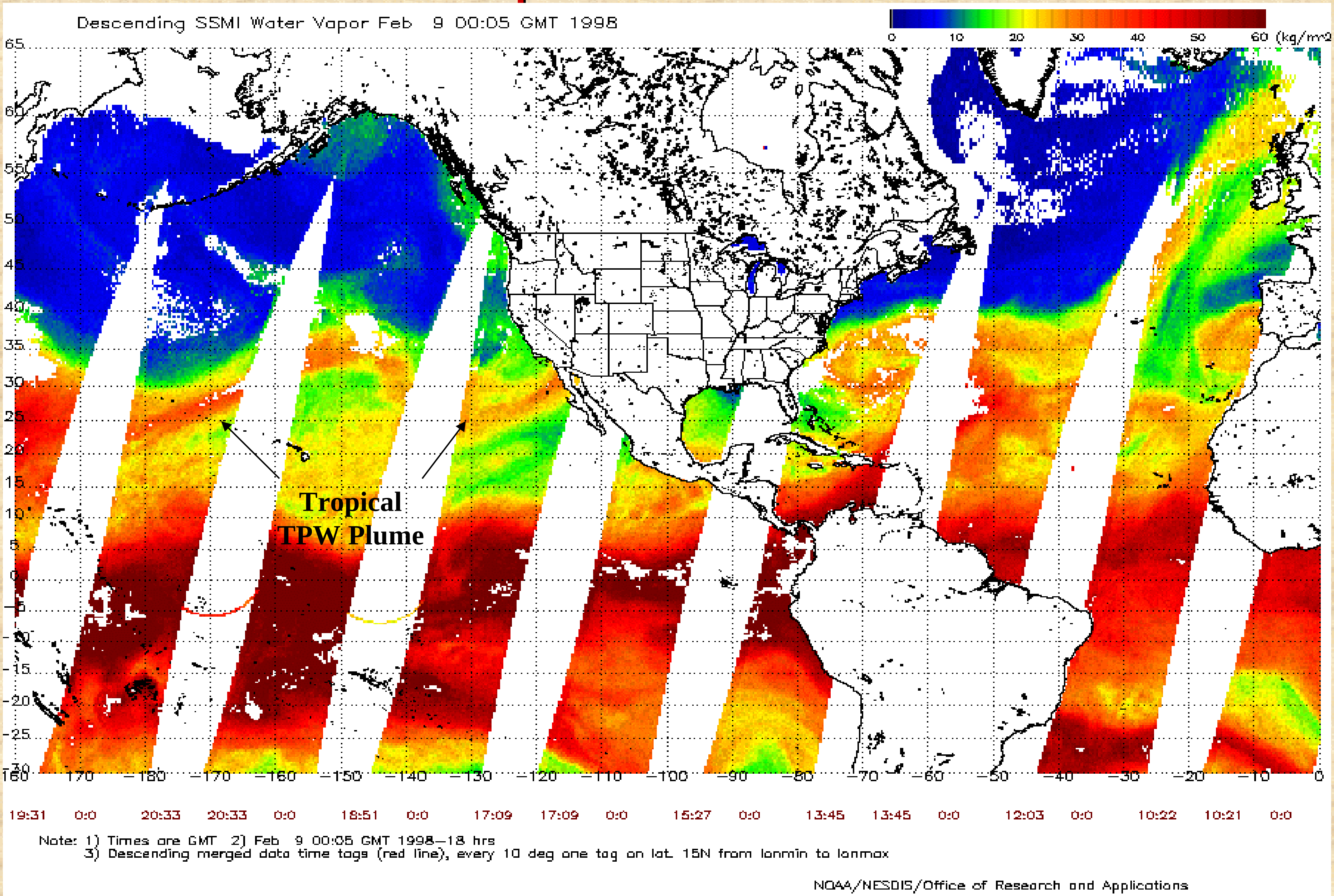
- TPW plumes ("Pineapple Connection")
  - 24-48 advance warning of heavy precipitation
  - Duration of heavy precipitation
- Rain rates of offshore systems
- Model inadequacies:
  - Poor timing of rain systems
  - Poor moisture initialization
  - Poor QPF/oragraphy

"Typical" Example

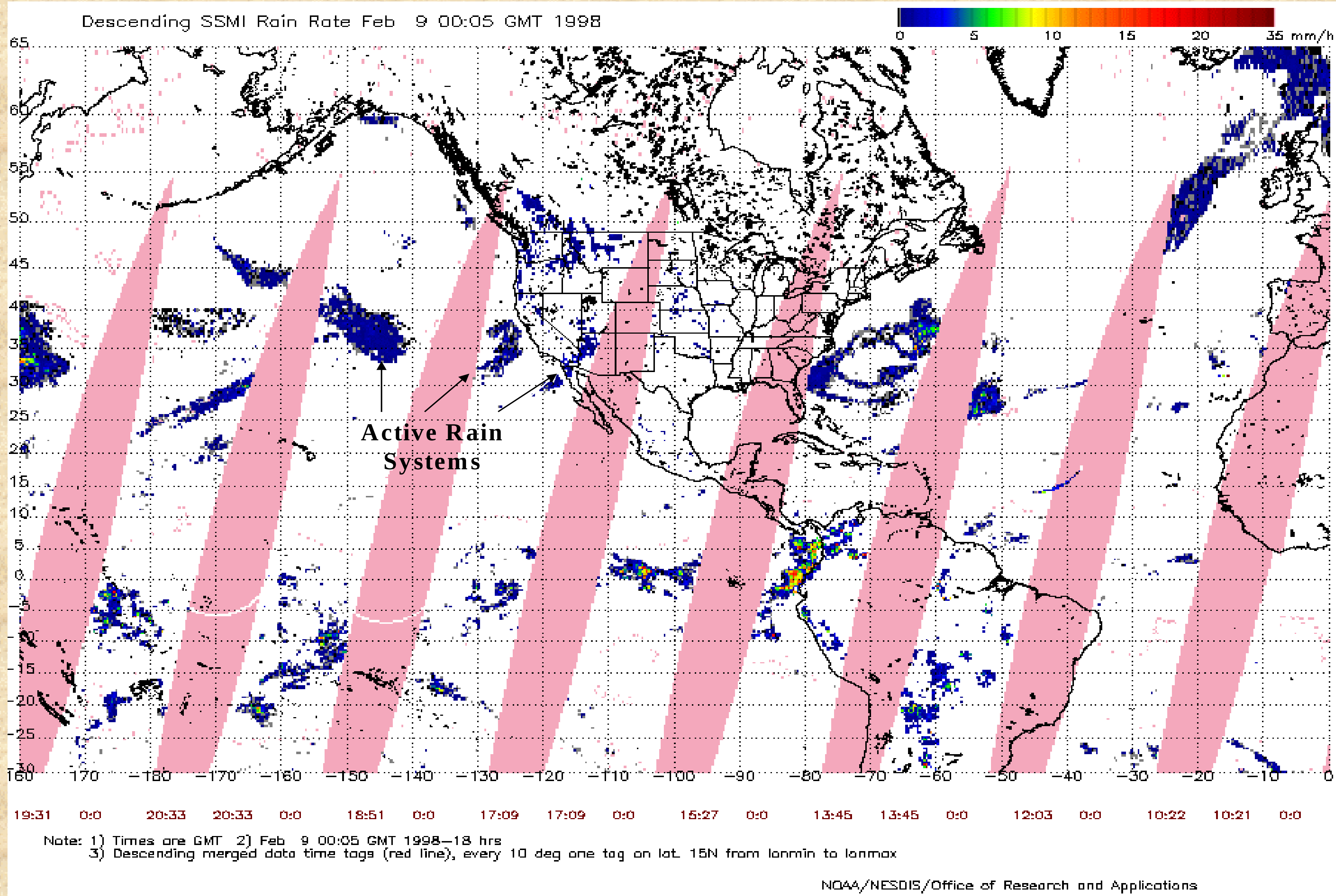



Ascending SSMI Rain Rate Dec 11 12:05 GMT 1997
0 5 10 15 20 35 mm/hr
Frontal Rain
Frontal Rain Systems
Convective Clusters
65
60
55
50
45
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
160 170 -180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0
10:01 8:0 8:19 6:18 6:38 6:37 4:36 4:56 2:0 0:0 3:13 1:12 1:32 1:32 0:0 23:49 21:48 22:08 22:08 20:07
Note: 1) Times are GMT 2) Dec 11 12:05 GMT 1997–18 hrs
3) Ascending merged data time tags (red line), every 10 deg one tag on lat. 15N from lonmin to lonmax
NOAA/NESDIS/Office of Research and Applications

An SAB Example - 1998 ENSO Storm



An SAB Example - 1998 ENSO Storm



ZCZC NFDSPENES ALL DDHHMM;390,1220 340,1190 340,1210 390,1240;
TTAA00 KNFD DDHHMM

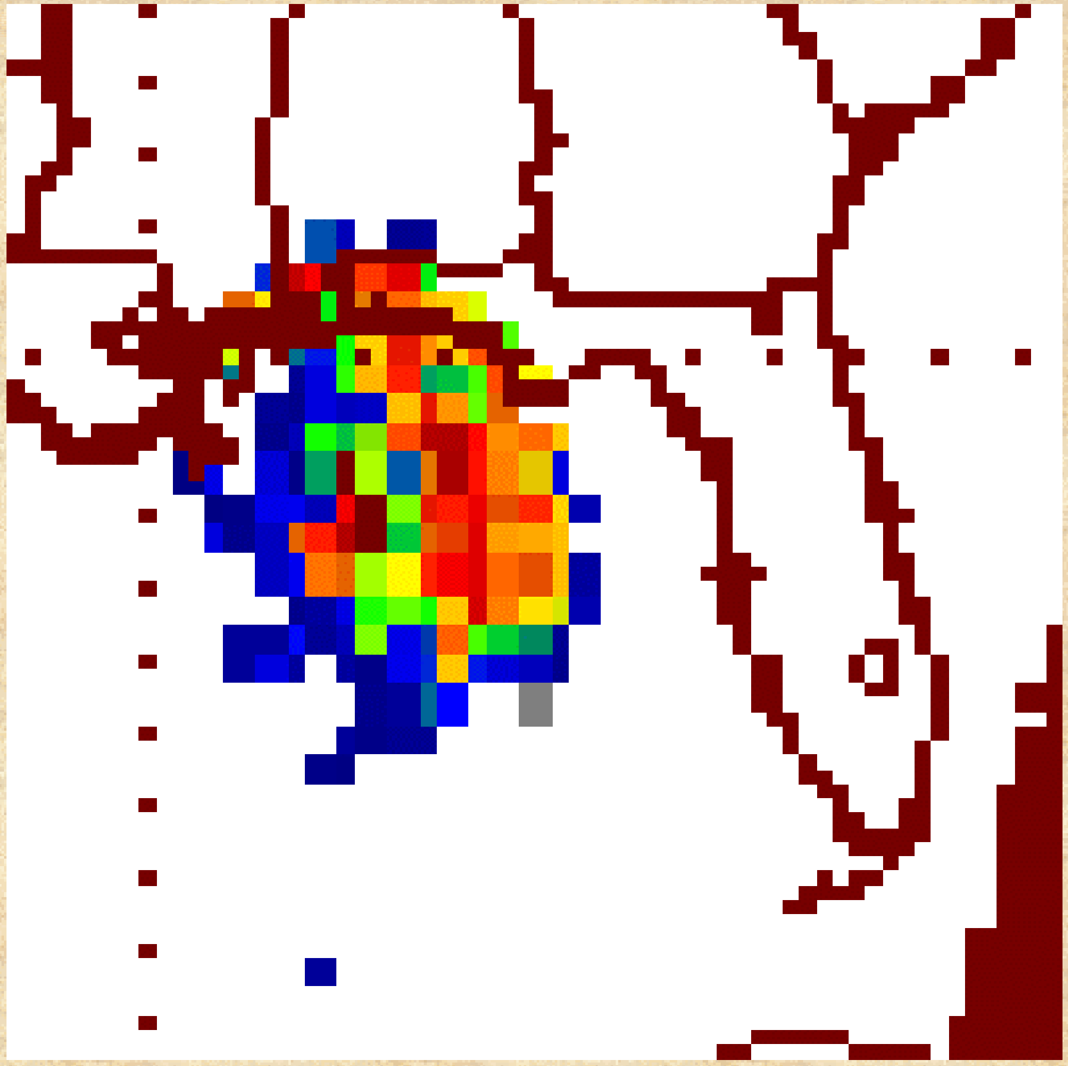
SATELLITE PRECIPITATION ESTIMATES..DATE/TIME 2/8/98 1930Z
THE SATELLITE ANALYSIS BRANCH/NESDIS---NPPU--- TEL.301-763-8678
VALUES ARE MAX OR SGFNT EST. NO OROGRAPHIC CORRECTION UNLESS NOTED.
...EST'S FM: /GOES8-CNTRL AND E. U.S. / GOES9 - W. U.S...
REFER TO TPB#375 FOR DETAILS. *LATEST DATA USED: GOES-9 1900Z SJK*
SSM/I 1710Z
LOCATION... CNTRL CA/S CA...SEE GRAPHIC FOR AMTS...
.
REMARKS FOR CA...LATER SSMI PASS AT 1710Z WIDTH OF RAIN BAND AVGING ABOUT 1 DEG AND CNTRD FROM 32N/127W TO 35N/124W TO 37N/124W... CURLING NWWD TO 38N/125W. GENERAL RAIN RATES CONTINUE BELOW 0.1"/HR ...HOWEVER THERE WERE SOME ISOLATED POCKETS OF NR 0.15"/HR AT 33.5N/125W (HEADING FOR SOUTHERN CA) AND 36N/124W AND 38N/125W HEADING FOR CENTRAL AND N CA...THESE RATES ARE ABOUT THE SAME AS 14Z SSMI PASS AND MUCH WEAKER/LOWER THAN YDYS STORM. NOT TOO MENTION ALSO THAT 700MB TRANSPORT WINDS ONLY BLOWING A SHT DISTANCE PARALLEL TO THE BEST MOISTURE WITH FRONT...SO EVEN MORE REASON TO EXPECT QUICKER AND MUCH LESS PRECIP BOTH NORTHERN TO CENTRAL CA NXT SEVERAL HRS AND SOUTHERN CA LATER TODAY AND EVE...*IN-HOUSE RAINFALL POTENTIAL USING SSMI RAIN RATES GIVING UP TO 0.5" PER 6HRS OF NON OROGRAPHIC PRECIP.*
LATEST GOES VIS SHOWING GOOD BURST IN S SAN MATEO COUNTY INTO N SANTA CRUZ AND WILL BE AFFECTING SANTA CLARA NXT HR OR SO...THIS GOOD BURST COULD GIVE UP TO 0.5"/HR AS IT MOVES BY...ADDTIONAL BURSTS JUST OFFSHORE KMRY AND KSFO COULD GIVE LOCALLY HVY BUT RELATIVELY BRIEF HVY RAIN BY 22-23Z. LEADING EDGE OF LT TO MODERATE RAIN HEADING INTO SANTA BARBARA BY 22Z AND CONTINUING THRU AT LEAST 00Z THERE. WILL CONTINUE TO MONITOR...
.
G9 MOTOR WINDING OPERATIONS HAVE STARTED FM NOW TIL MARCH 1. MOST OF DATA FM 0430 TO 1200Z WILL BE MISSING. G8 DATA IS STILL AVLBL DURING THAT PERIOD....ALONG WITH THE EVENING PASSES OF SSMI MICROWAVE DATA.
.
SATELLITE ESTIMATE GRAPHIC FOR THE PERIOD 16-19Z ON INTERNET AT THE ADDRESS BELOW...OROGRAPHICS INCLUDED
.
PLEASE SEE HPC QPF DISCUSSIONS AND GRAPHICS FOR DETAILS OF FORECAST PRECIP AMOUNTS.
.
http://www.ssd.noaa.gov/SSD/ML/pcpn-ndx.html
[ONLINE SSD PRECIPITATION PRODUCT INDEX

Tropical Cyclones

- NESDIS/Satellite Analysis Branch:
  - Tropical Cyclone Team has global responsibility
  - Rainfall Potential via **objective** technique
  - Rapid intensification @85 GHz prior to visible eye
- Simple Method:
  - Assume storm intensity not changing much
  - Determine direction & speed of motion from GOES
  - Use SSM/I to calculate “maximum” rainfall:
    - Slice through storm center and parallel to direction of motion
    - Determine rainfall mean from SSM/I rainfall EDR

Rainfall Estimation - Steps 1 & 2

Hurricane Georges 27 Sep 98 1500 Z

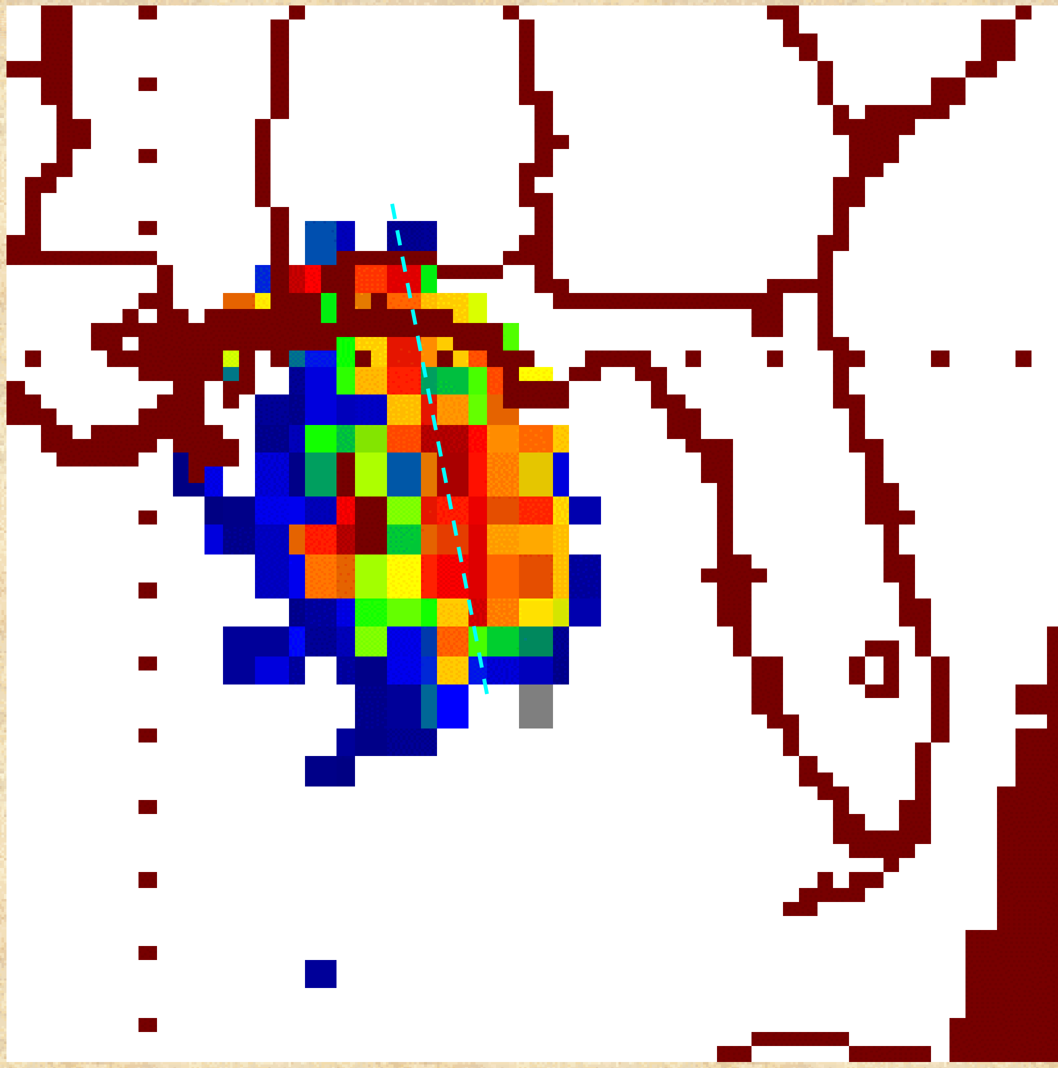


1. Obtain most recent SSM/I rainfall composite

2. Determine storm speed, V, and direction of movement from GOES loops

Rainfall Estimation - Steps 3 - 5

Hurricane Georges 27 Sep 98 1500 Z

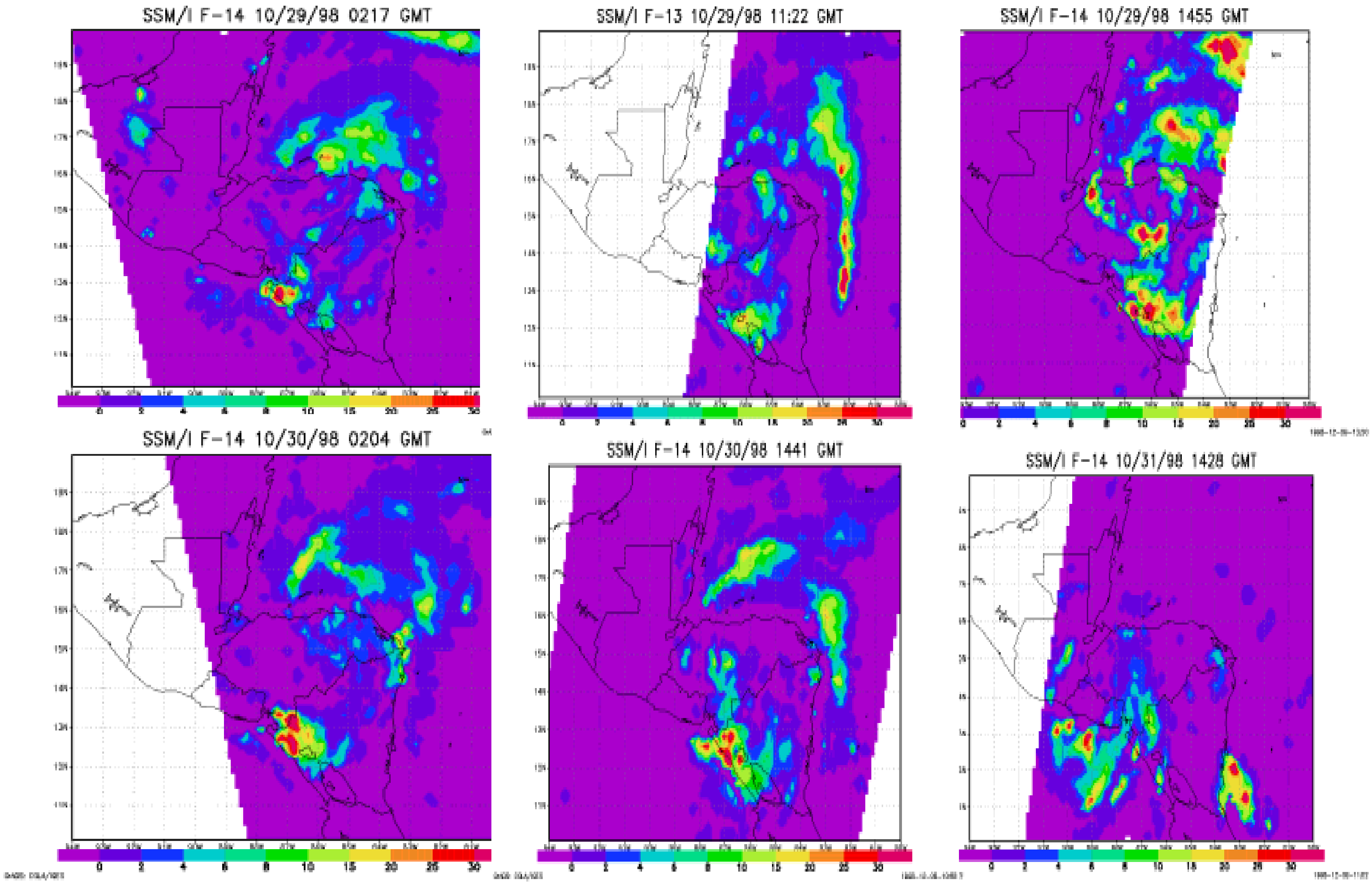


3. Determine x-section through storm center (or maximum rain bands).

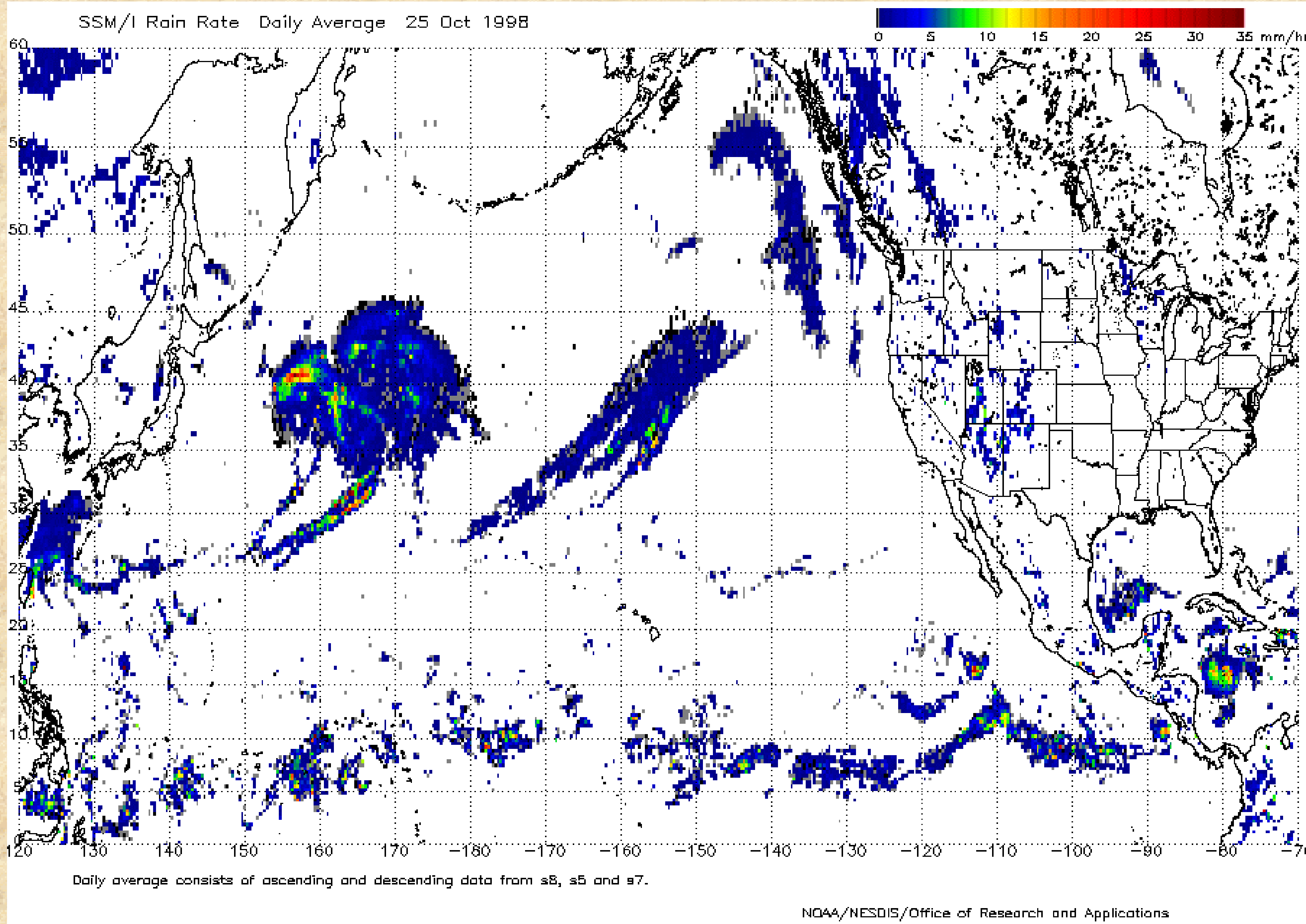
4. Compute mean rain through x-section, R_{avg}, and width, D, via automated, objective routine.

5. Rainfall potential= $(R_{avg})(D)/V$

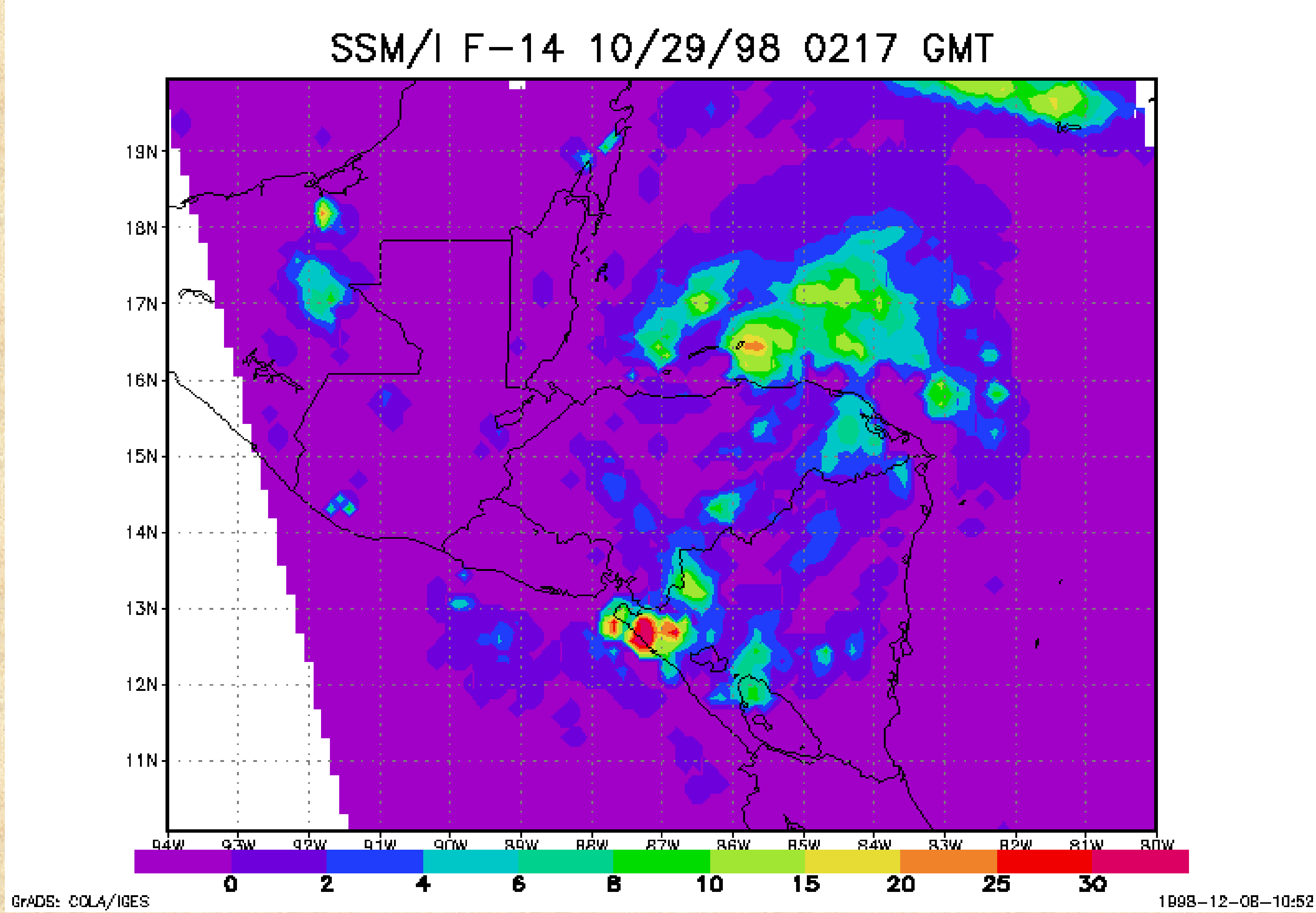
Hurricane Mitch from SSM/I



Hurricane Mitch (con't)



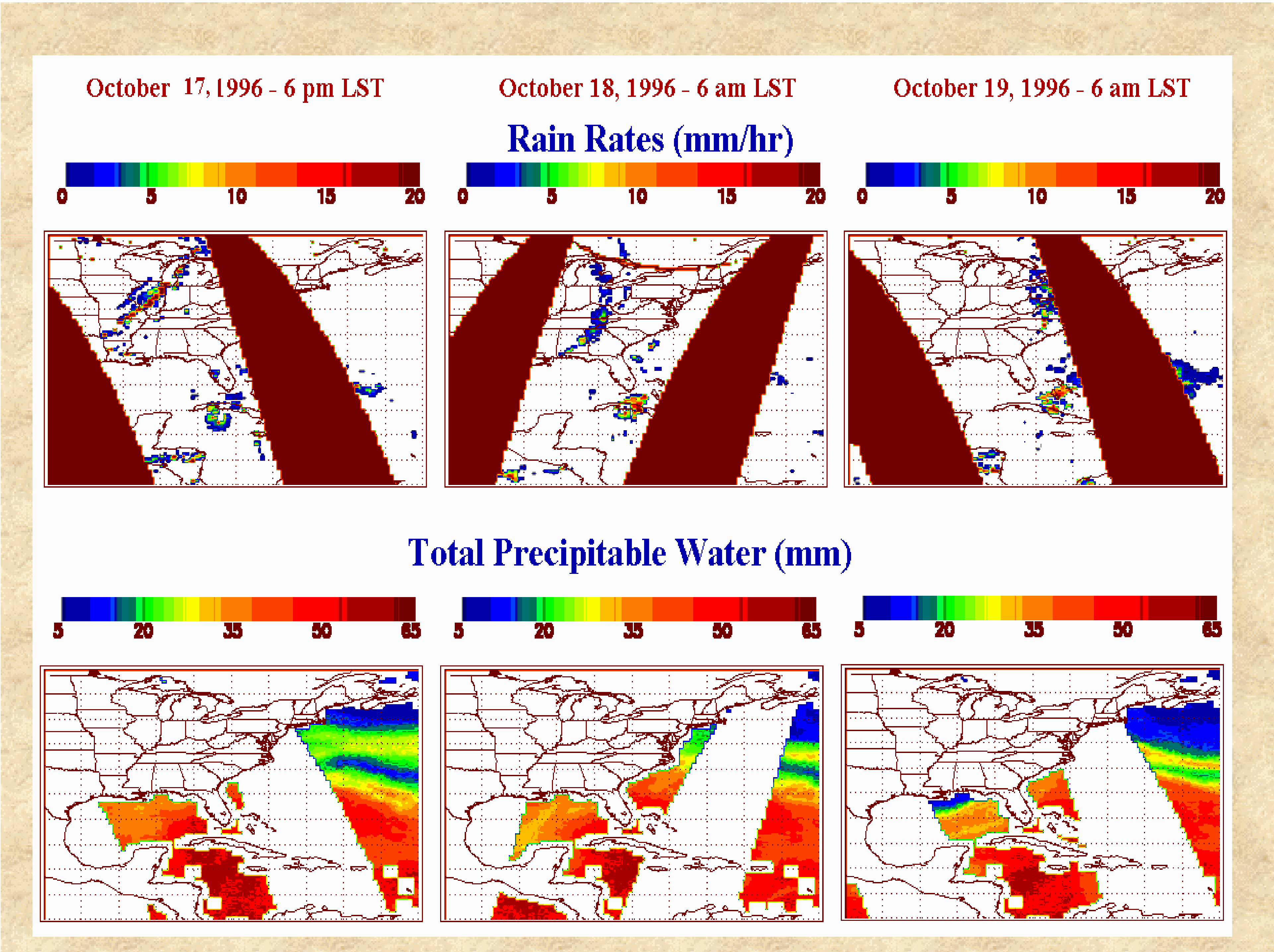
Hurricane Mitch (con't)



Hybrid Systems - Hurricane Lili

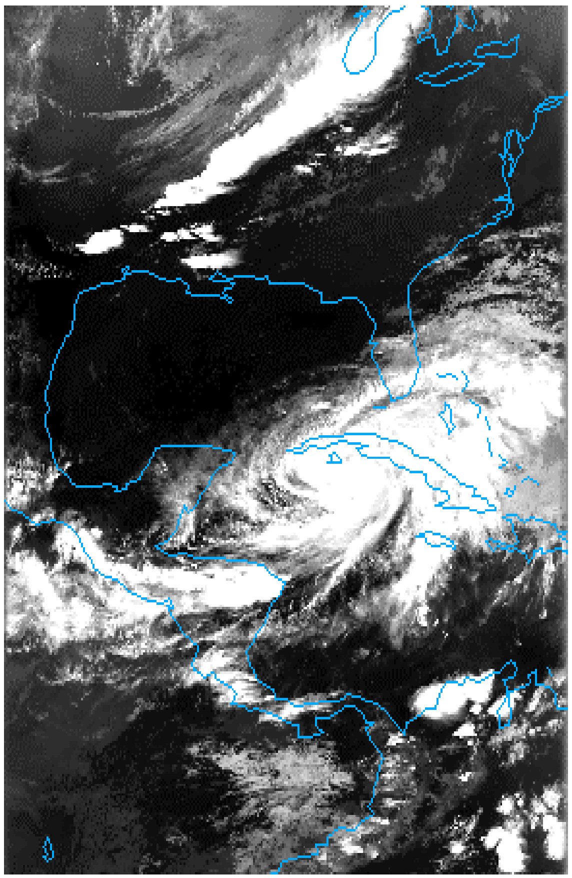
In October 1996, and interesting meteorological situation evolved over the eastern United States, which eventually caused widespread flooding rains from the Mid-Atlantic states through New England. The SSM/I fields of rain rate and Total Precipitable Water (TPW), in conjunction with co-incident visible and IR observations from the DMSP OLS instrument, depict this evolution quite nicely.

On October 17, 1996, Hurricane Lili was gaining strength south of Cuba, while a strong band of thunderstorms formed along a strong cold front in the Central United States. Two days later, a strong surface low formed along the mid-Atlantic coast, and the entire system slowed as the upper level low feature began to "cut off" at 500 mb. Lili emerged north of Cuba, and the moisture from this storm began feeding into the storm system over the United States, as depicted by the increasing values of TPW converging along the east coast. The "connection" between the two systems is quite apparent from the SSM/I rain rate and TPW fields, as well as the OLS visible image. The storm system moved slowly up the eastern over the next 2 days, causing copious amounts of rainfall over eastern New England, with a maximum of 19.2" at Camp Ellis, ME. Although Lili moved eastward away from the United States, the tropical connection between the two systems maintained itself through the episode.

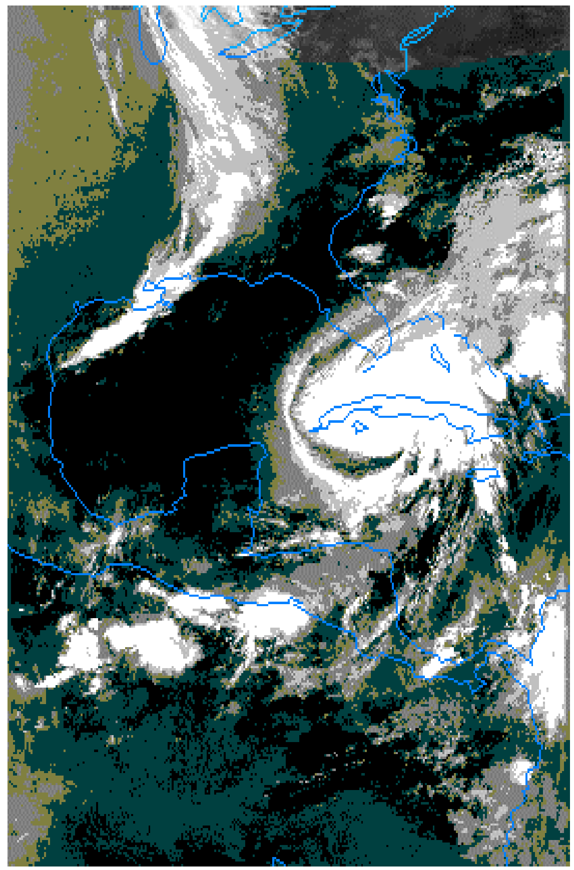

October 17, 1996 - 6 pm LST
October 18, 1996 - 6 am LST
October 19, 1996 - 6 am LST
Rain Rates (mm/hr)
0 5 10 15 20
Total Precipitable Water (mm)
5 20 35 50 65

DMSP OLR Imagery
(Courtesy of NOAA/NGDC)

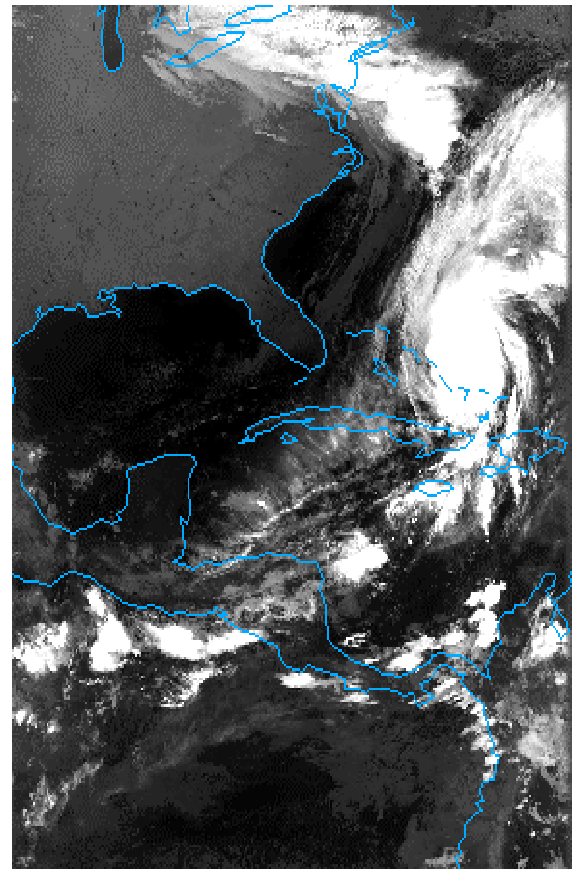
IR - 10/17/96 - 2303 Z

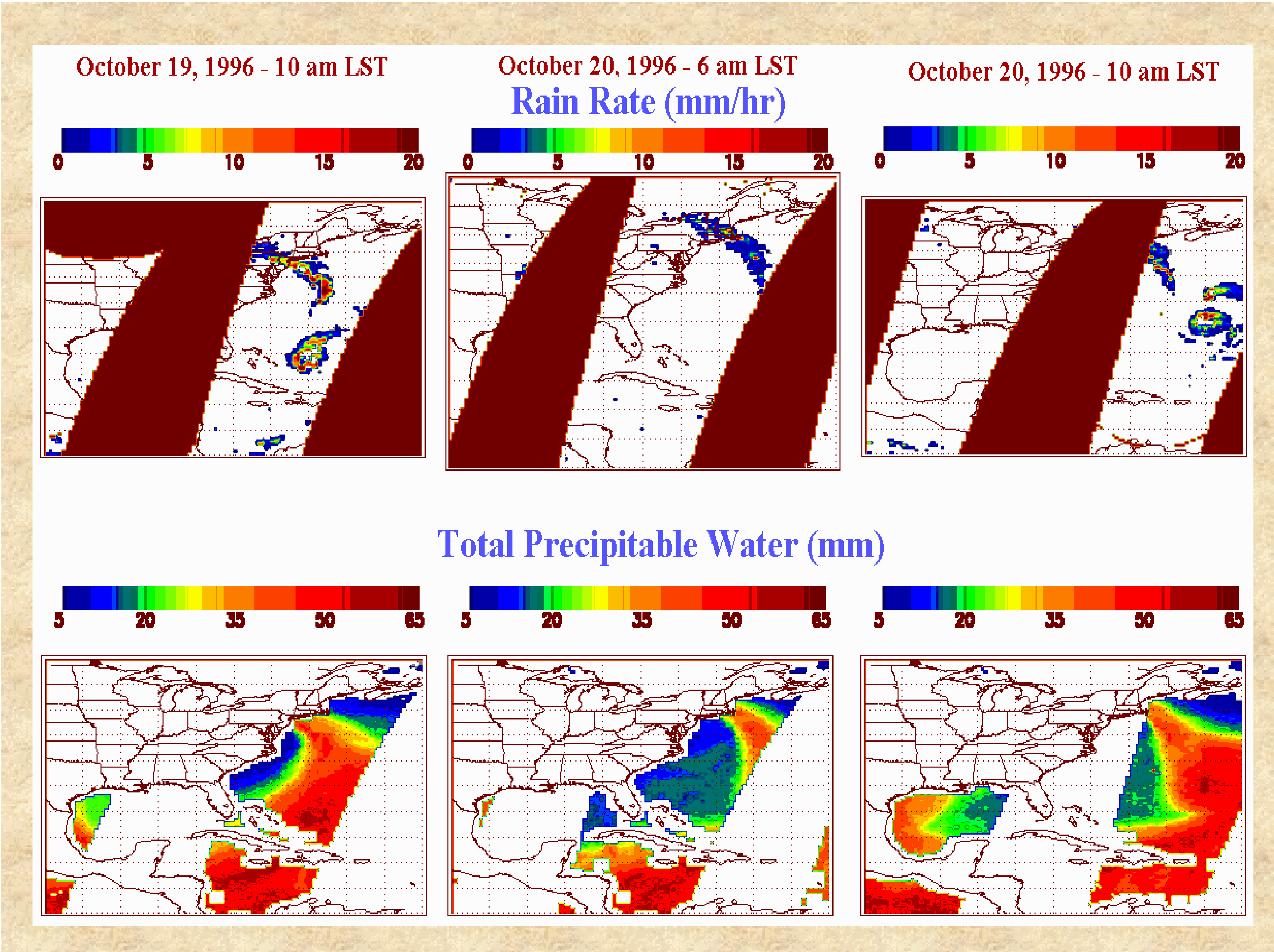


IR - 10/18/96 - 1957 Z



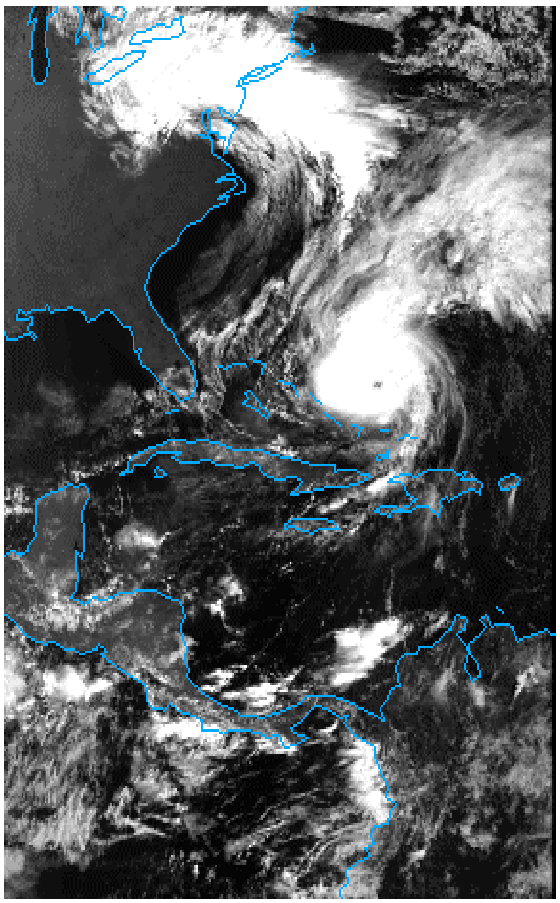
IR - 10/19/96 - 1045 Z



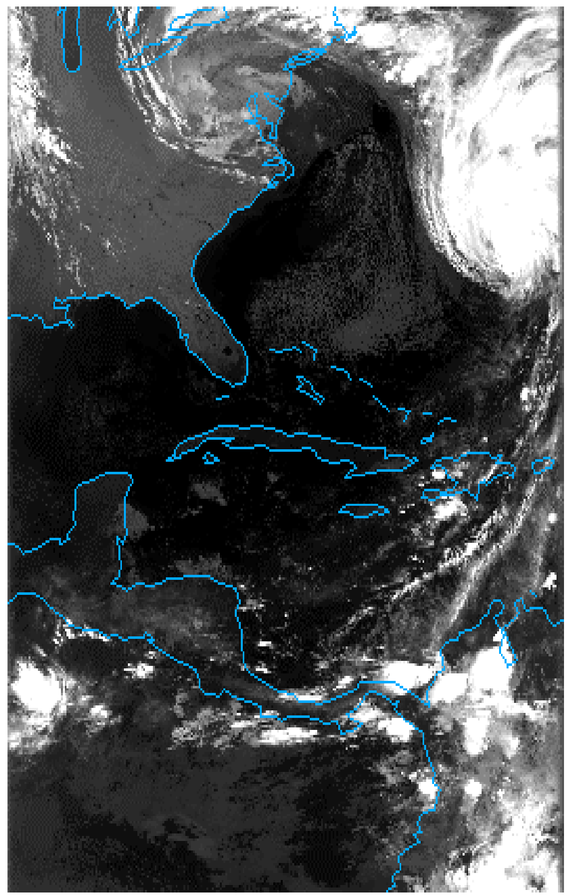

October 19, 1996 - 10 am LST
October 20, 1996 - 6 am LST
October 20, 1996 - 10 am LST
Rain Rate (mm/hr)
0 5 10 15 20
Total Precipitable Water (mm)
5 20 35 50 65

DMSP OLS Imagery
(Courtesy of NOAA/NGDC)

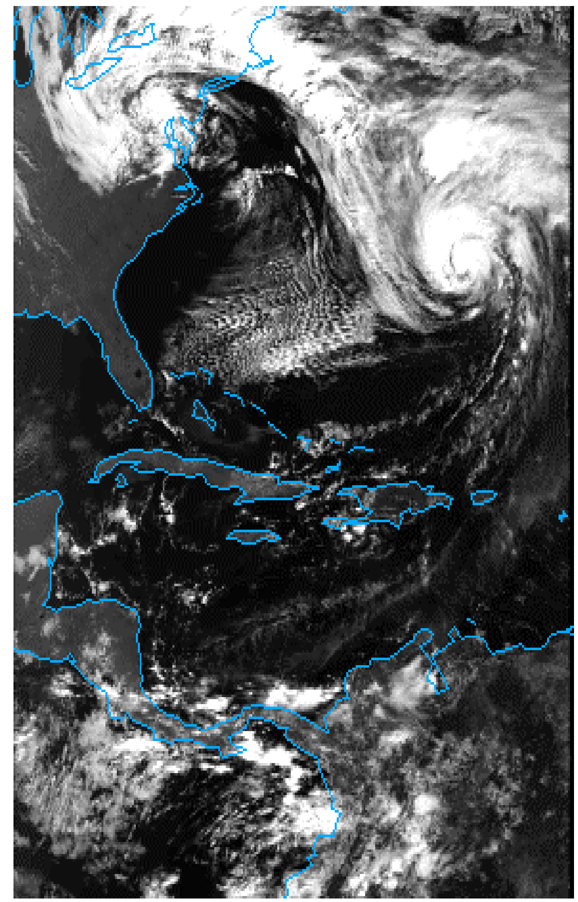
VIS - 10/19/96 - 1409 Z

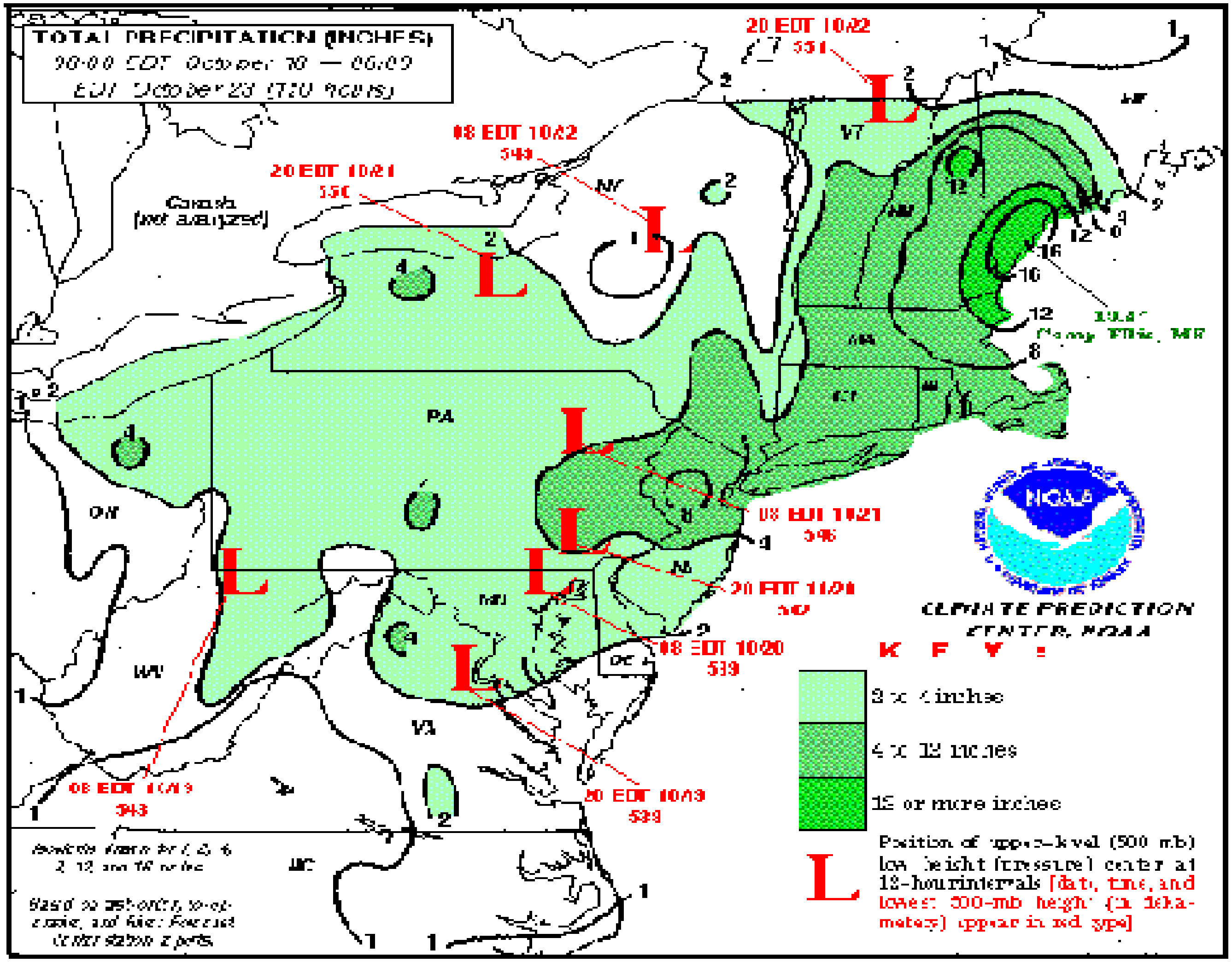


IR - 10/20/96 - 1033 Z



VIS - 10/20/96 - 1357 Z





A deep, slow–moving storm pulled abundant tropical moisture (enhanced by outflow from Hurricane Lili) into the Northeast in late October, resulting in widespread heavy rainfall. The largest totals were measured in eastern New England, where locations from northeastern Massachusetts, northeastward through southern Maine received 12.0 to 19.2 inches during October 18–22, establishing a few new records

Uses of Products

Climate Applications

Climate Applications

- SSM/I time series:
  - Over 11 years in length
- Good for “climate”
  - Orbital overpass times +/- 1 hour
  - Sensor calibration stable
  - Intersatellite calibrations
  - Global coverage
- Limitations:
  - 2 overpasses/day +/- 50 deg. Latitude
  - Tropics ~ 1/day

Climate Applications

- Various types of applications:
  - Long term monitoring/annual cycle
  - Interannual variability
    - ENSO signatures
    - Monthly/seasonal variations
  - Episodic events
    - Floods/droughts
    - Daily mean loops; synoptic variations

How is it done?

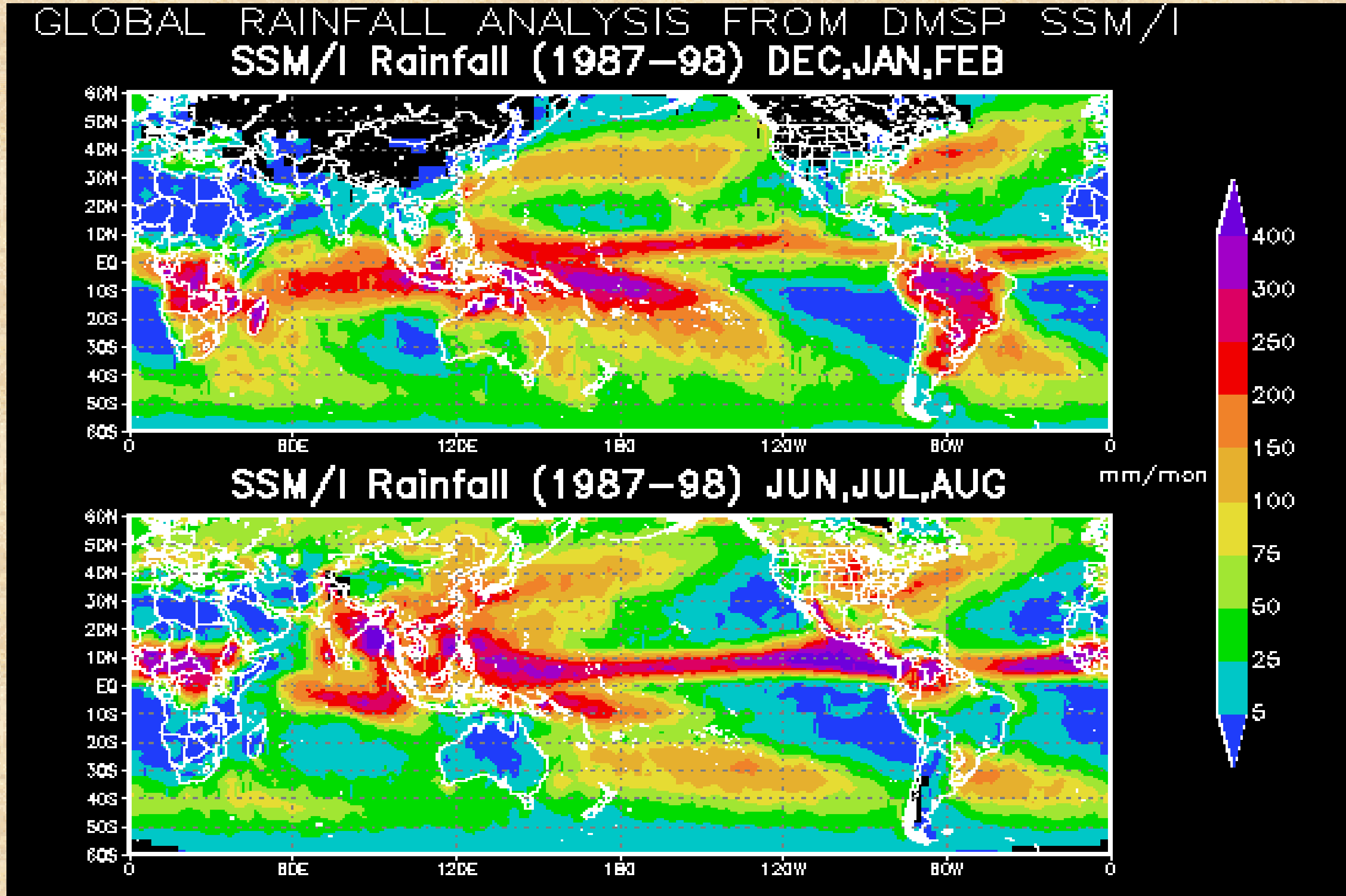
- Generate “time/space average” products:
  - Monthly, 1 degree and 2.5 degree grids
    - compensate time with space
    - correlation length:
      - rainfall 10’s of km
      - TPW 100’s of km
  - Averaging:
    - Simple linear methods
    - PDF’s; might be more realistic
- Define base period to compute “anomaly”

SSM/I Time Series

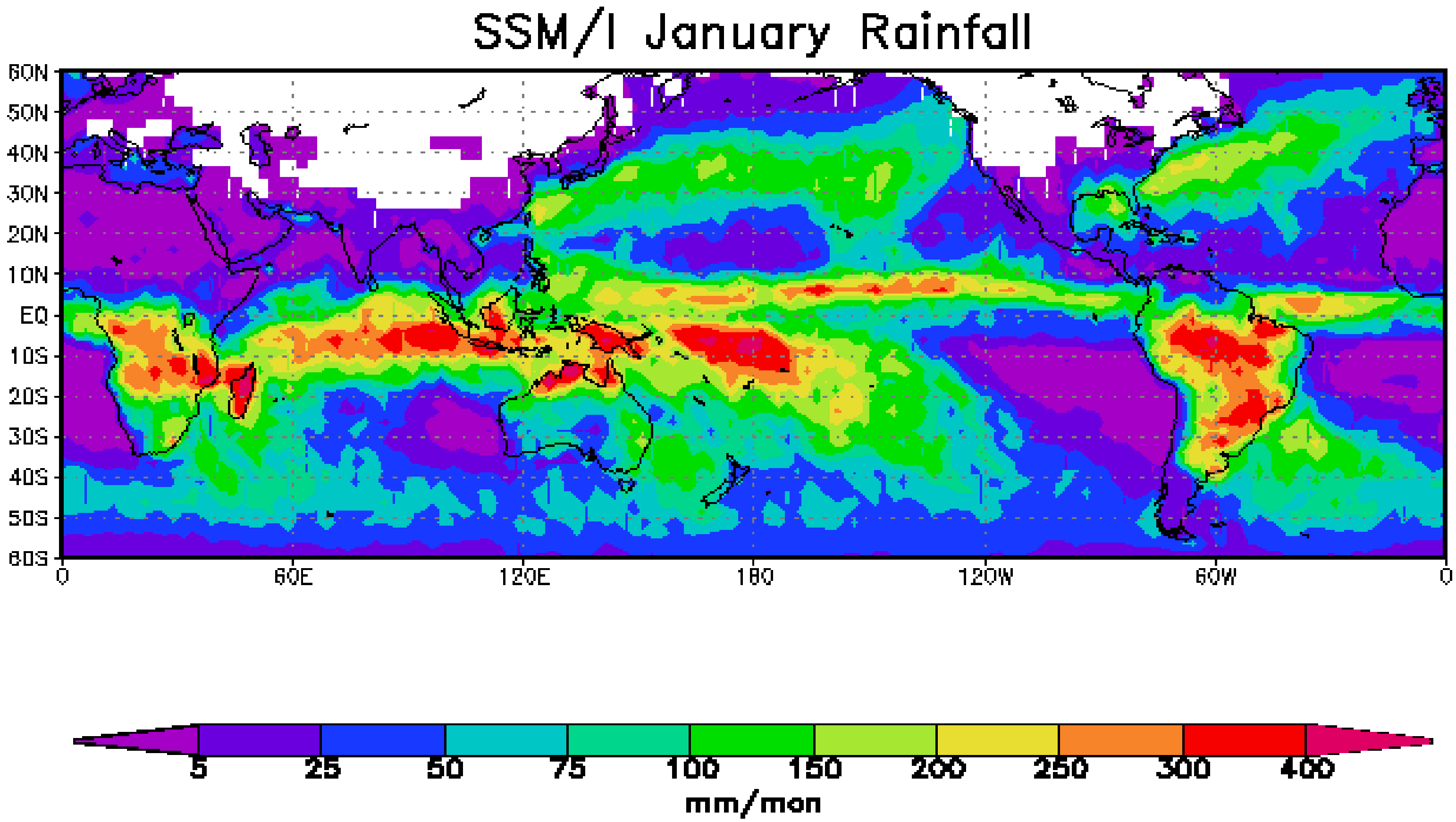
Satellite	***A/D Overpass Time (LST)***	***Period of Record***
F-8	0615/1815	7/87 - 12/91*
F-10	2200/1000	1/92 - present
F-11	1815/0615	1/92 - 4/95
F-12	2130/0930	failed
F-13	1730/0530	5/95 - present
F-14	2130/0930	6/97 - present

*85 GHz failure 6/90

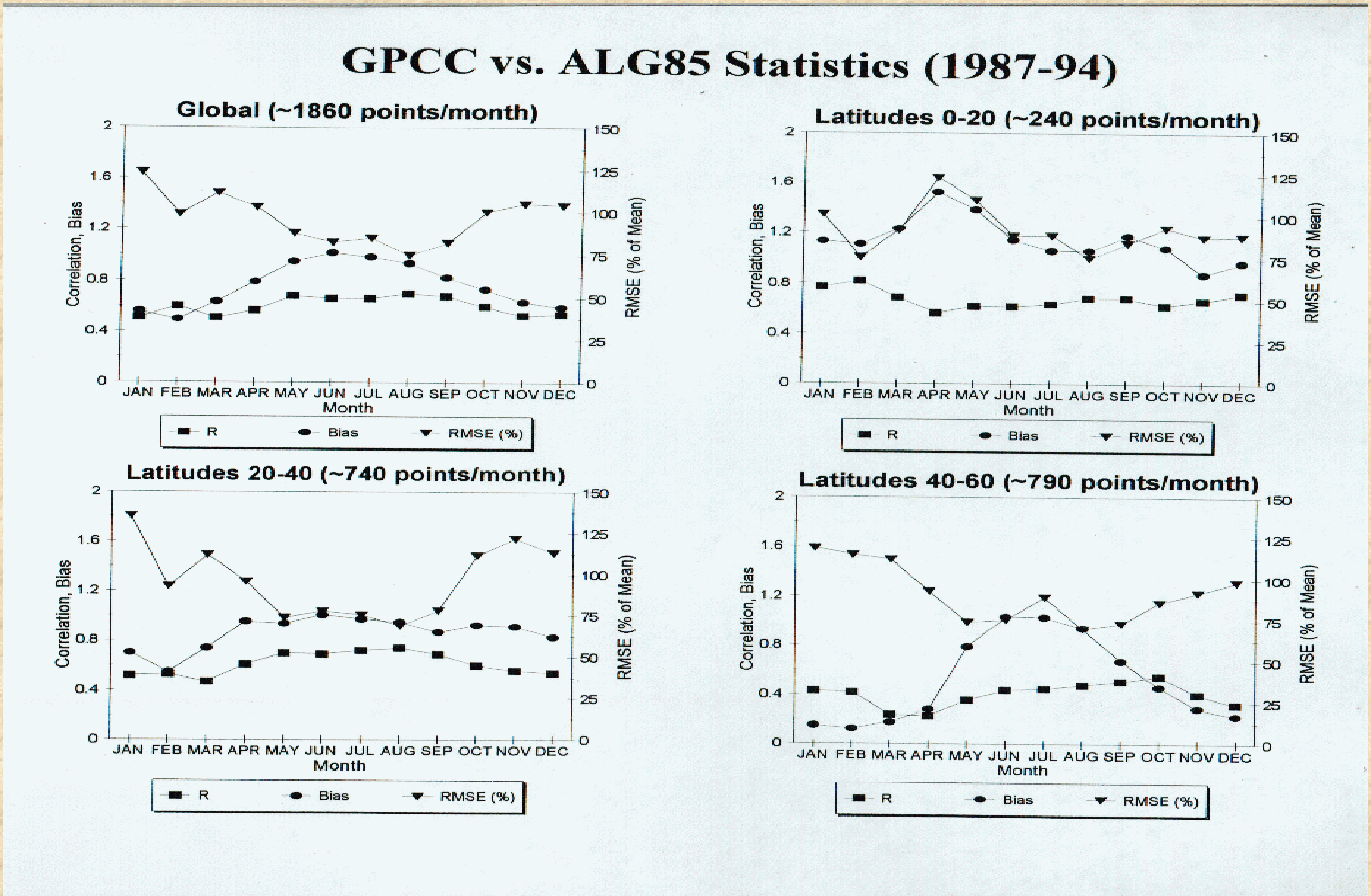
Global Rainfall Patterns



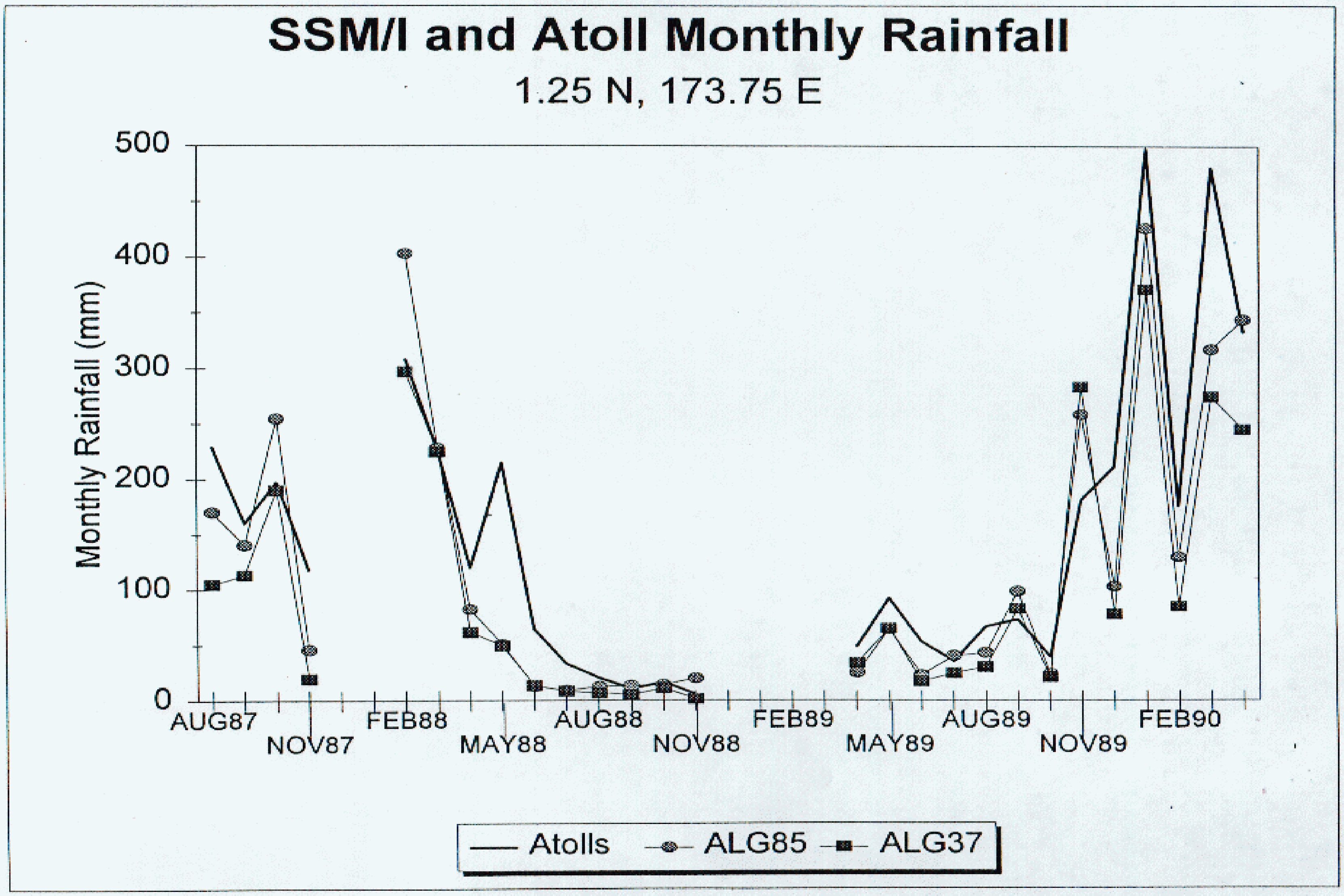
Global Rainfall Patterns



Global Rainfall Validation



Global Rainfall Validation



Error sources

$$R_A(t) = 1/A \int_A r(x,t)\, dx$$

$$R_{AT} = (1/AT) \int_A \int_T r(x,t)\, dx\, dt$$

$$= 1/T \int_T R_A(t)\, dt$$

$$R_{SAT}(t) = R_A(t) + \sigma(t)$$

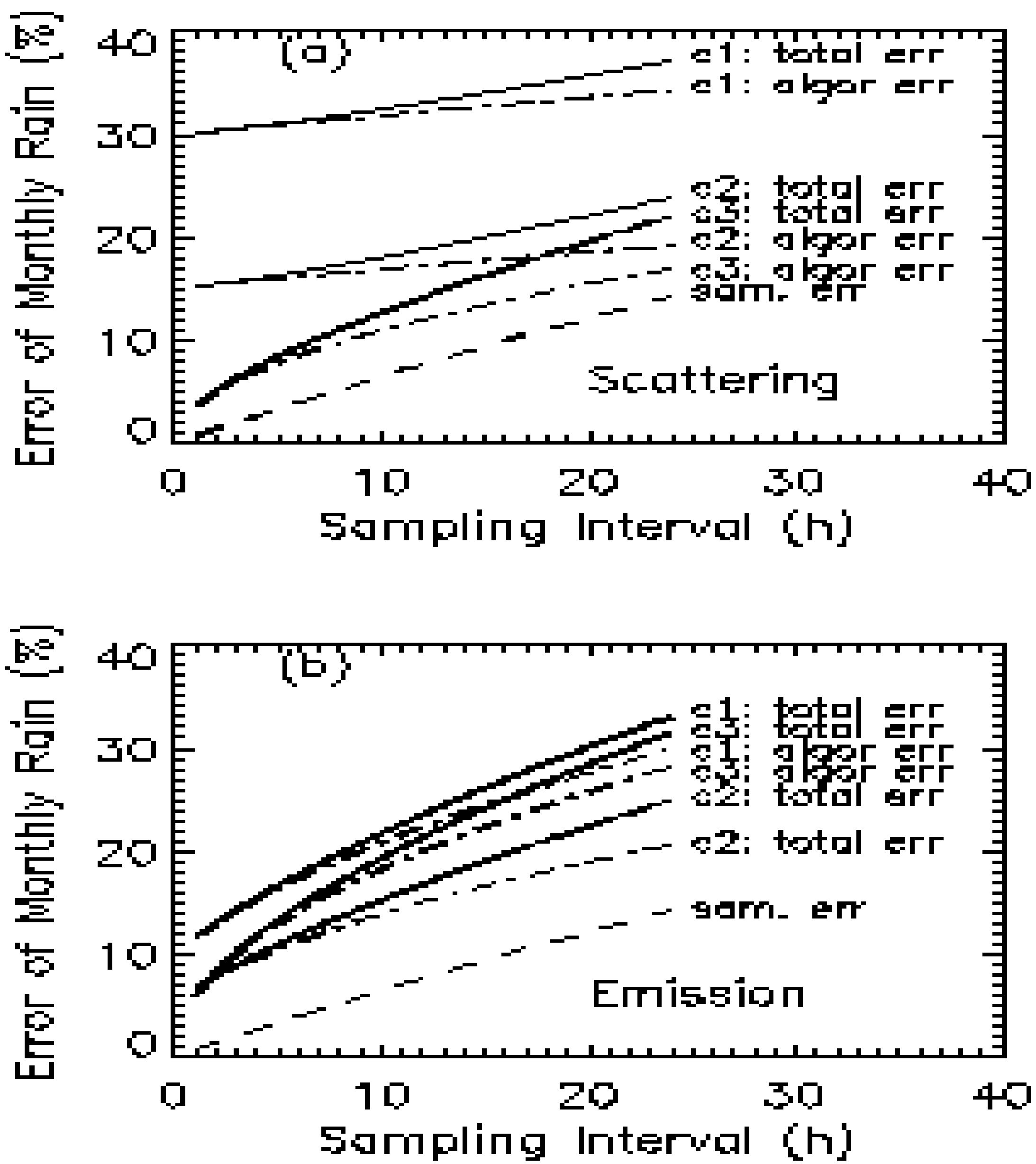
$$\sigma^2_{AT} = \sigma^2_{ALG} + \sigma^2_{SAM}$$

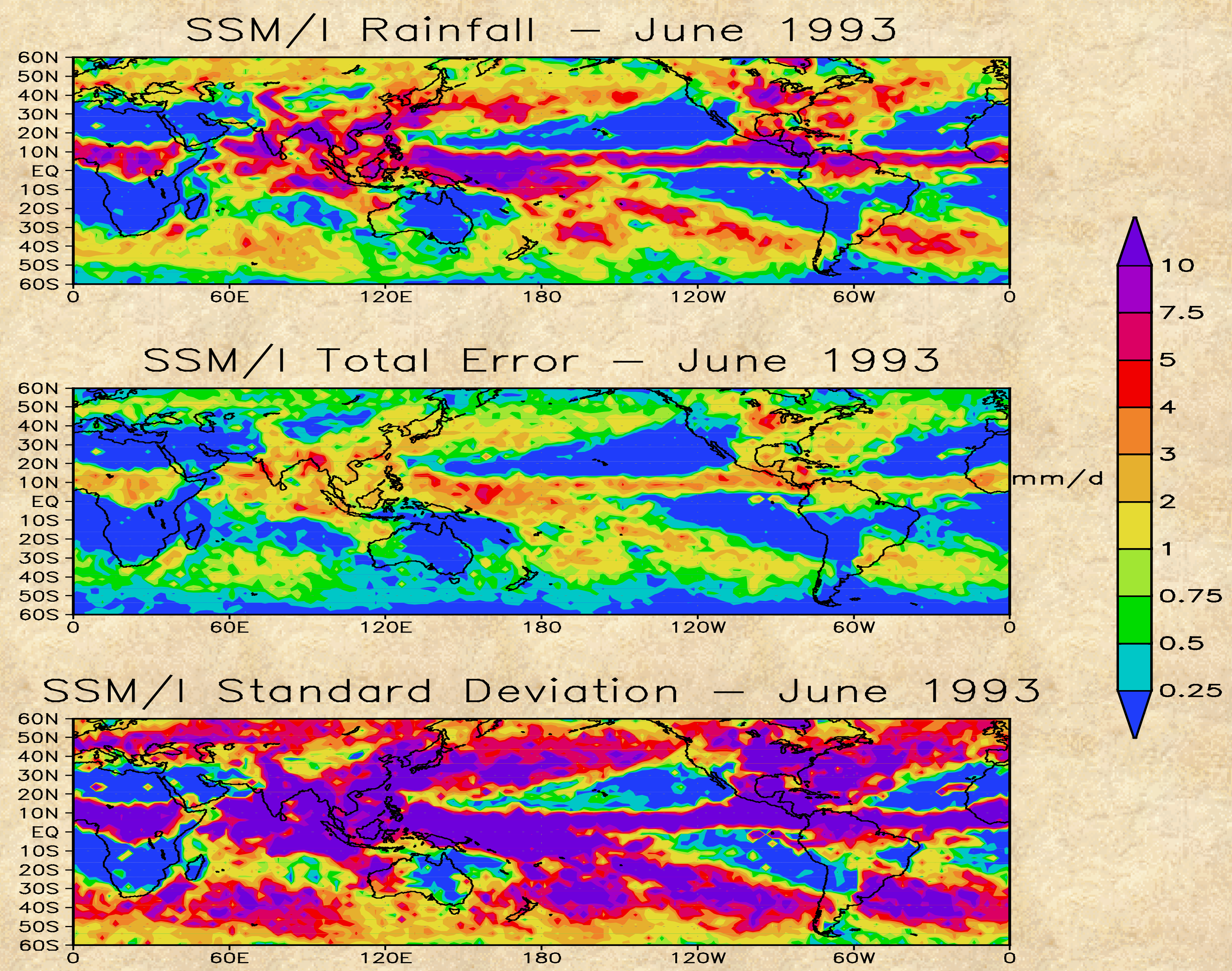
Ocean Rain Retrieval Errors

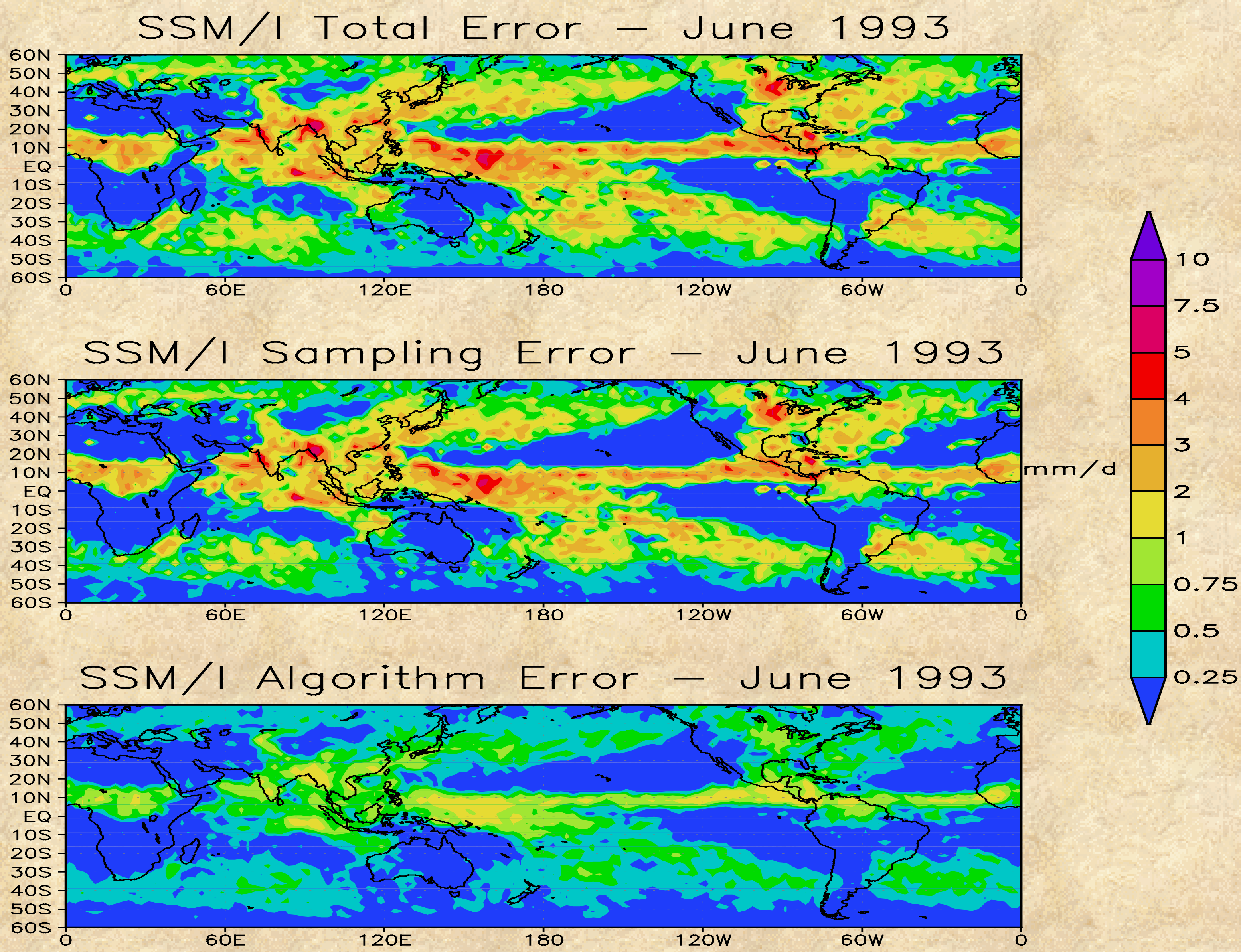
C1:radar is perfect

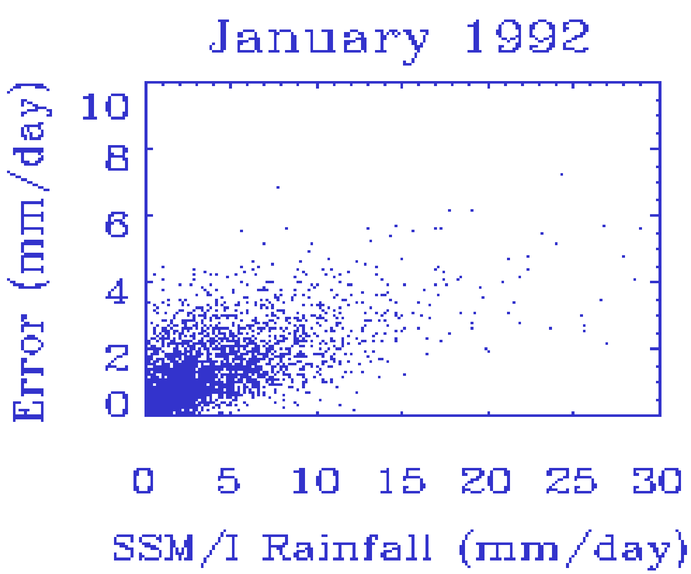
C2: radar=ssmi
in bias and variance

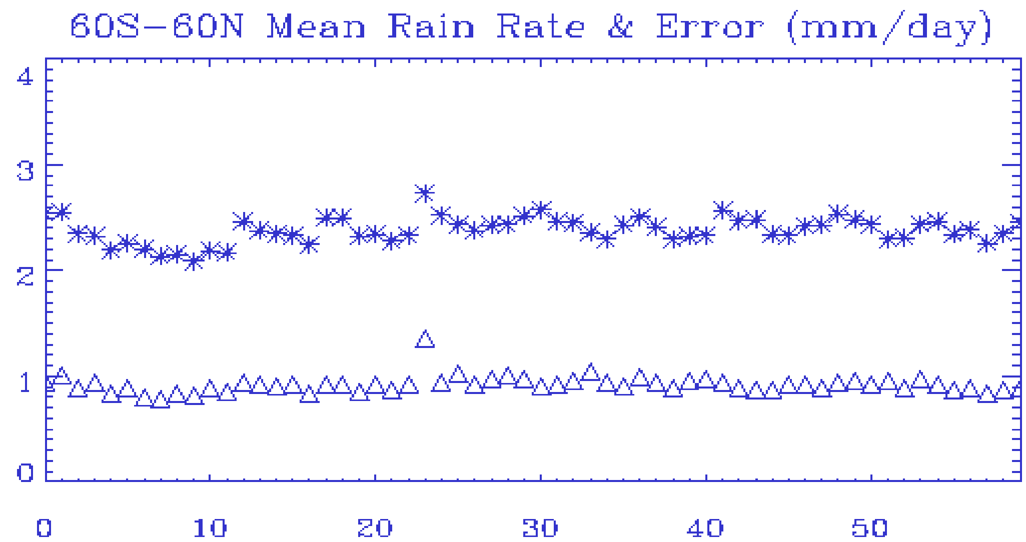
C3: bias -->radar
random-->ssmi

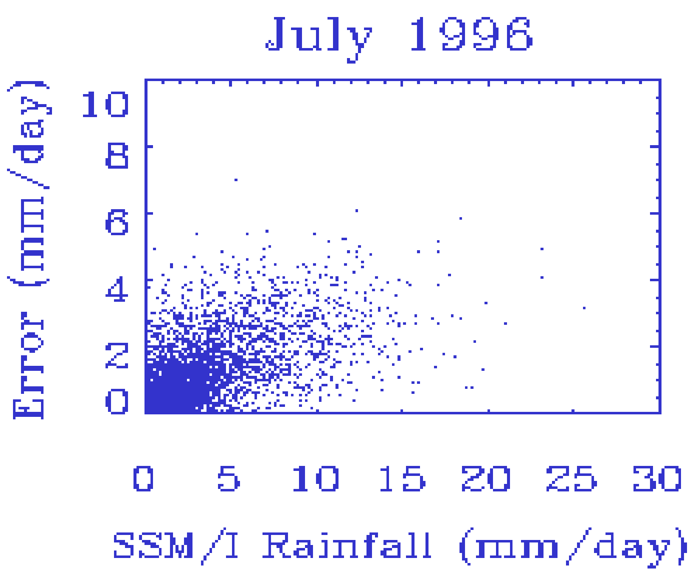


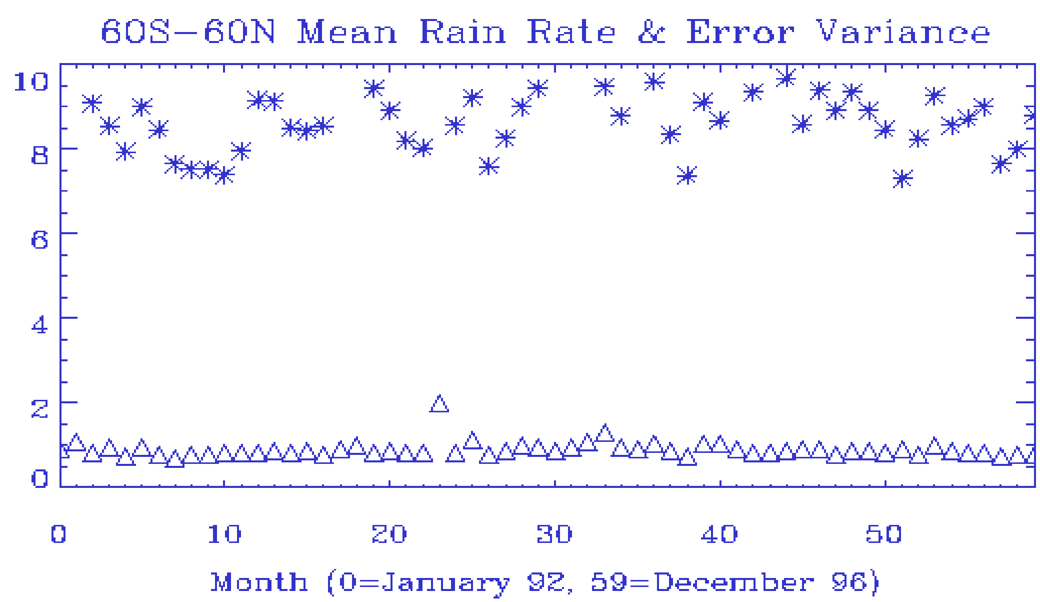

SSM/I Rainfall – June 1993
SSM/I Total Error – June 1993
SSM/I Standard Deviation – June 1993
60N
50N
40N
30N
20N
10N
EQ
10S
20S
30S
40S
50S
60S
0
60E
120E
180
120W
60W
0
mm/d
10
7.5
5
4
3
2
1
0.75
0.5
0.25


SSM/I Total Error — June 1993
SSM/I Sampling Error — June 1993
SSM/I Algorithm Error — June 1993
60N
50N
40N
30N
20N
10N
EQ
10S
20S
30S
40S
50S
60S
0
60E
120E
180
120W
60W
0
mm/d
10
7.5
5
4
3
2
1
0.75
0.5
0.25


January 1992
Error (mm/day)
0 2 4 6 8 10
0 5 10 15 20 25 30
SSM/I Rainfall (mm/day)

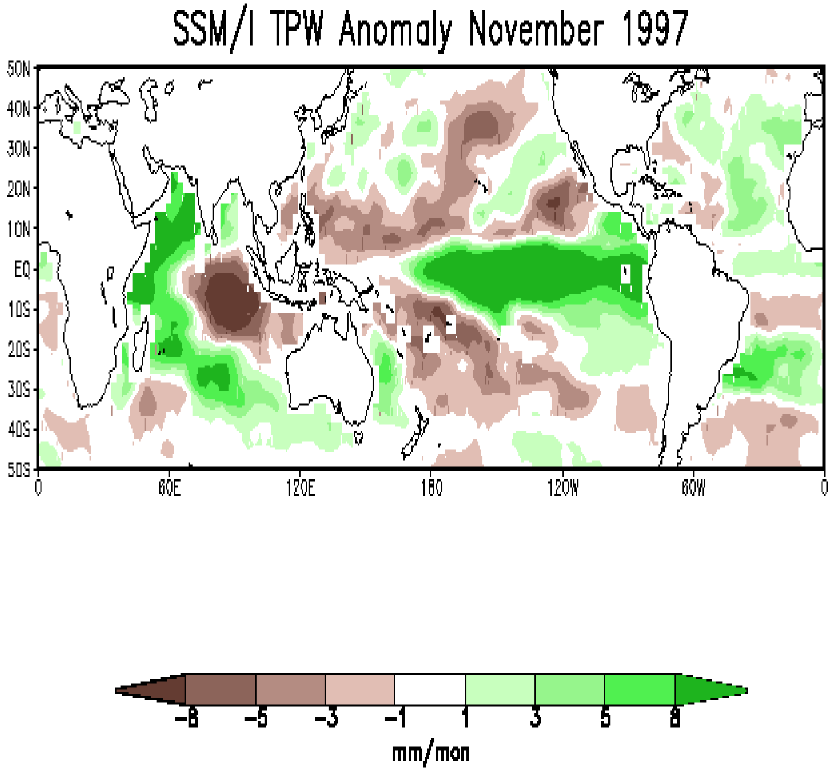

60S–60N Mean Rain Rate & Error (mm/day)
0 1 2 3 4
0 10 20 30 40 50

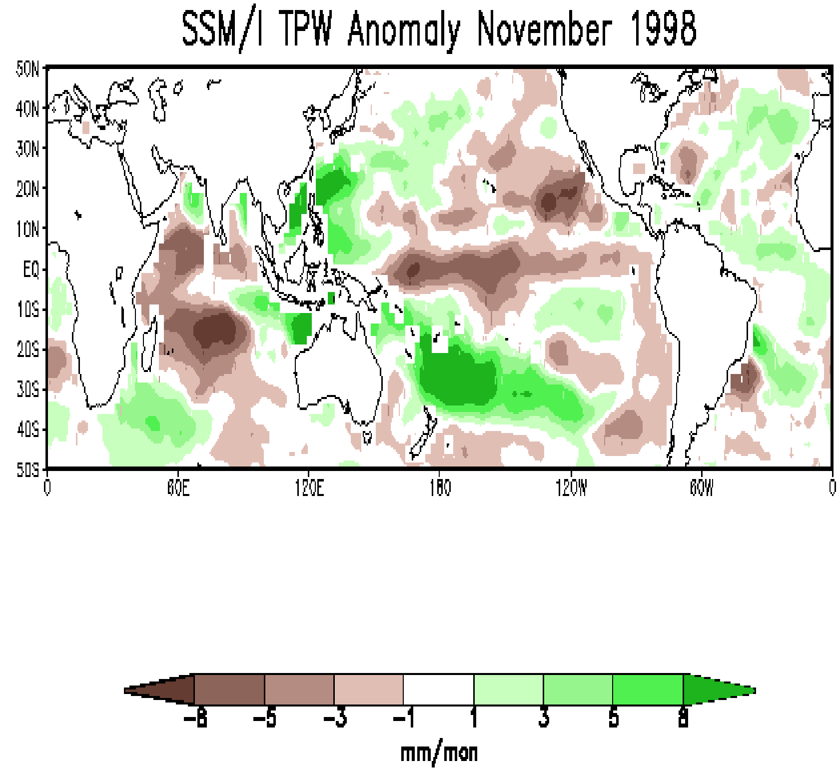

July 1996
Error (mm/day)
0 2 4 6 8 10
0 5 10 15 20 25 30
SSM/I Rainfall (mm/day)


60S–60N Mean Rain Rate & Error Variance
0 2 4 6 8 10
0 10 20 30 40 50
Month (0=January 92, 59=December 96)

Interannual Variations

Monthly Total Precipitable Water Anomaly based on departure from 1987-97 base period





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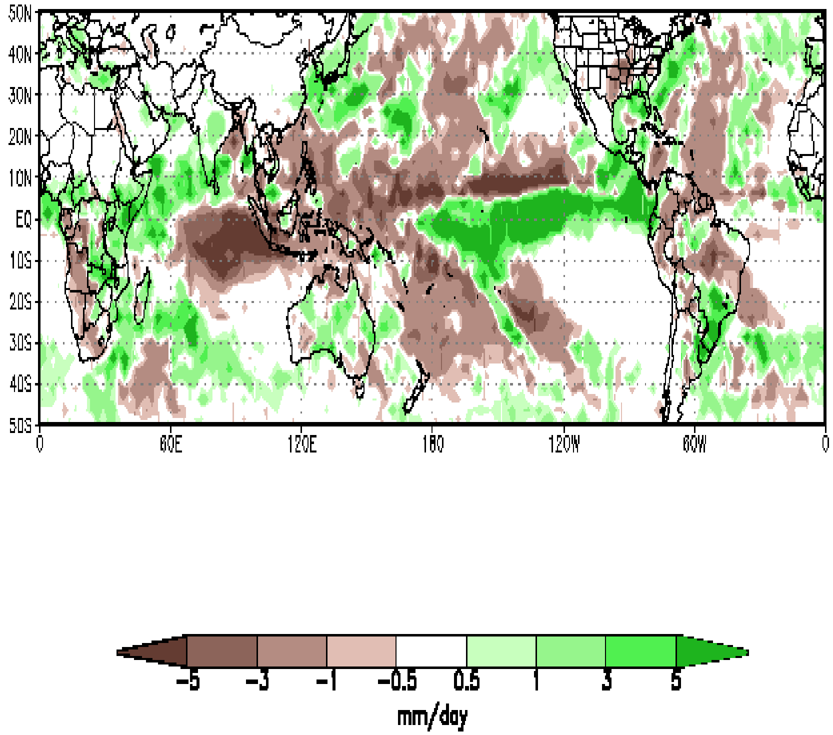
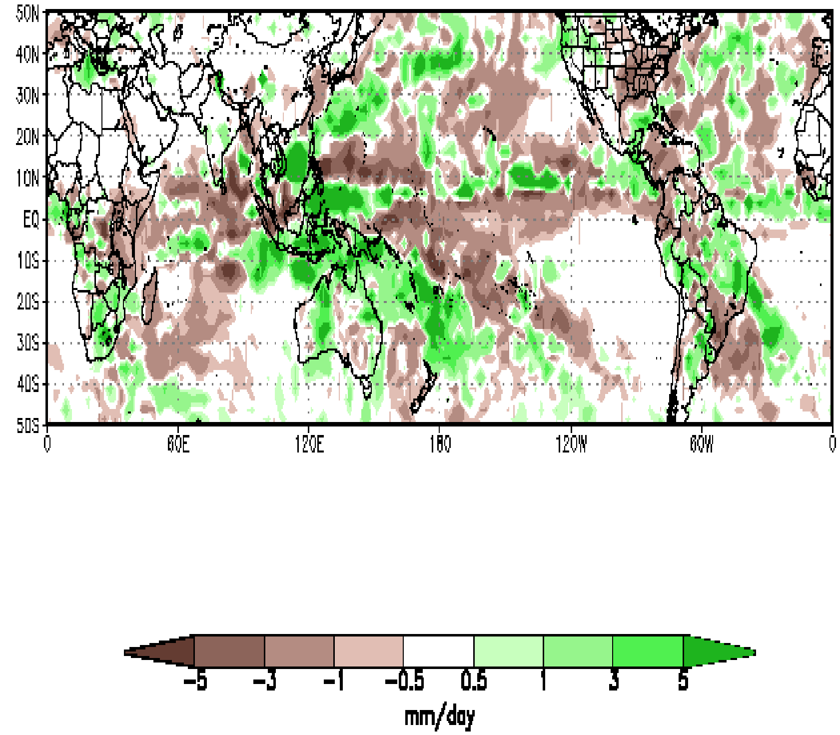
Interannual Variations

Monthly Rainfall Anomaly based on departure from 1987-97 base period

SSM/I Rainfall Anomaly November 1997



SSM/I Rainfall Anomaly November 1998



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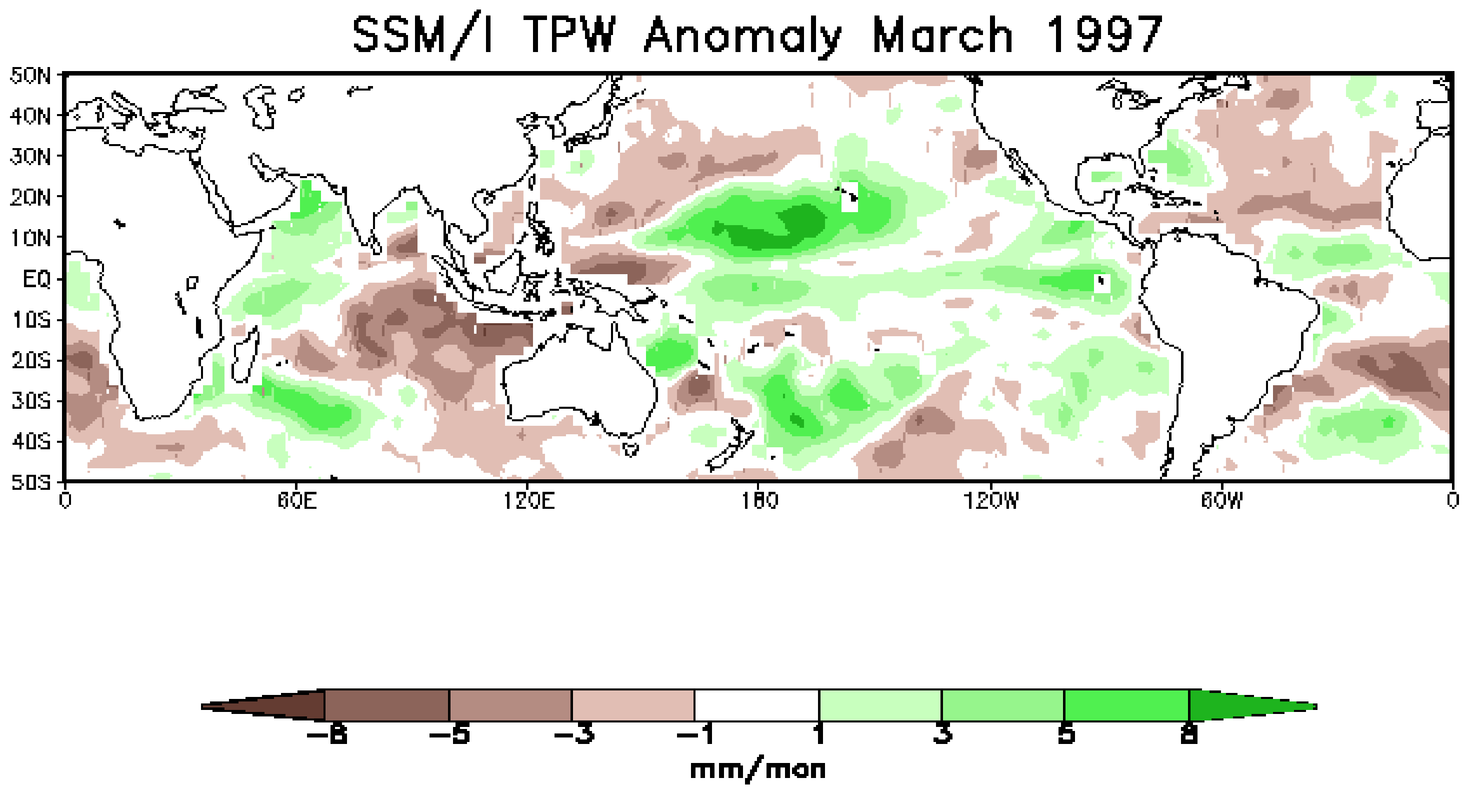
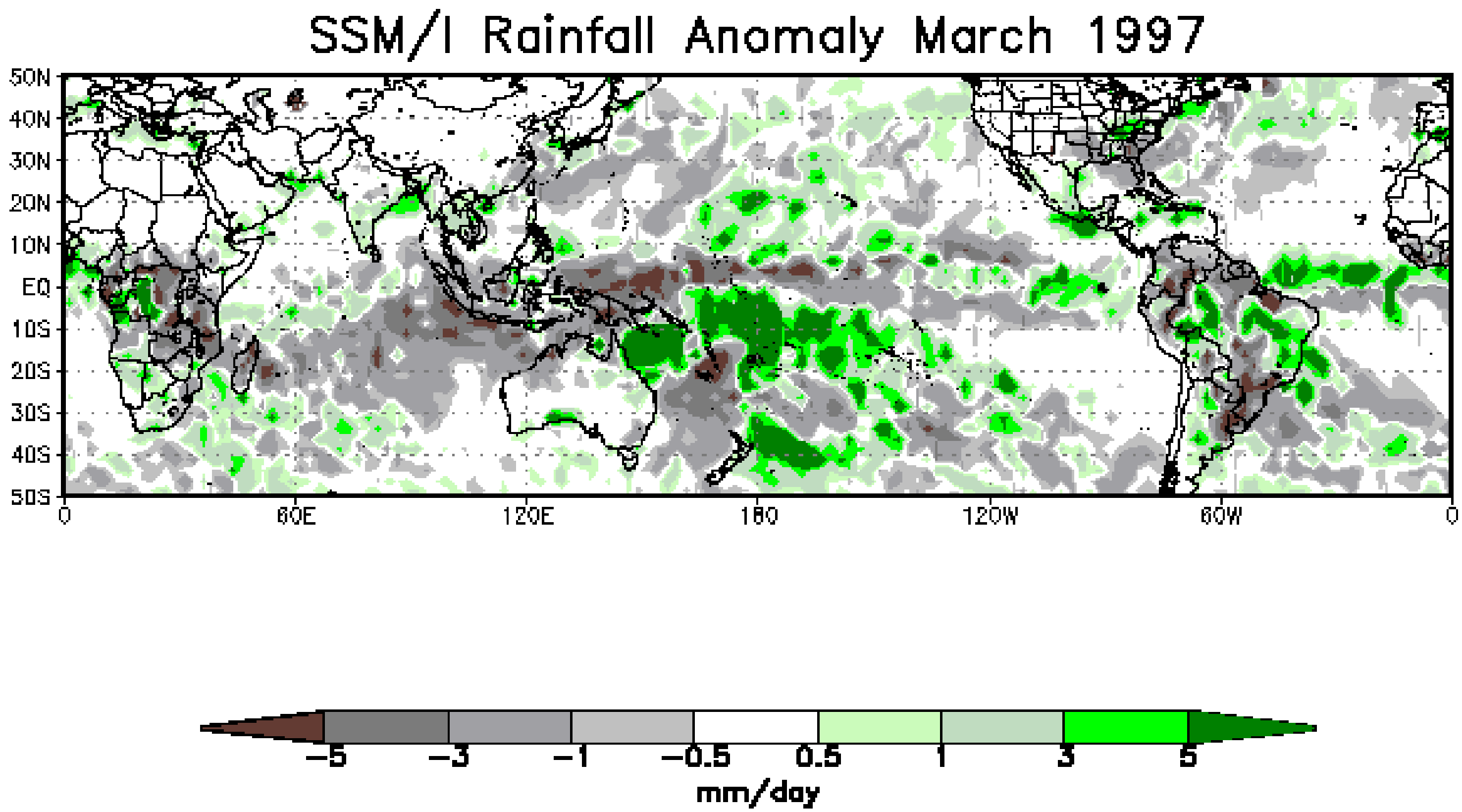
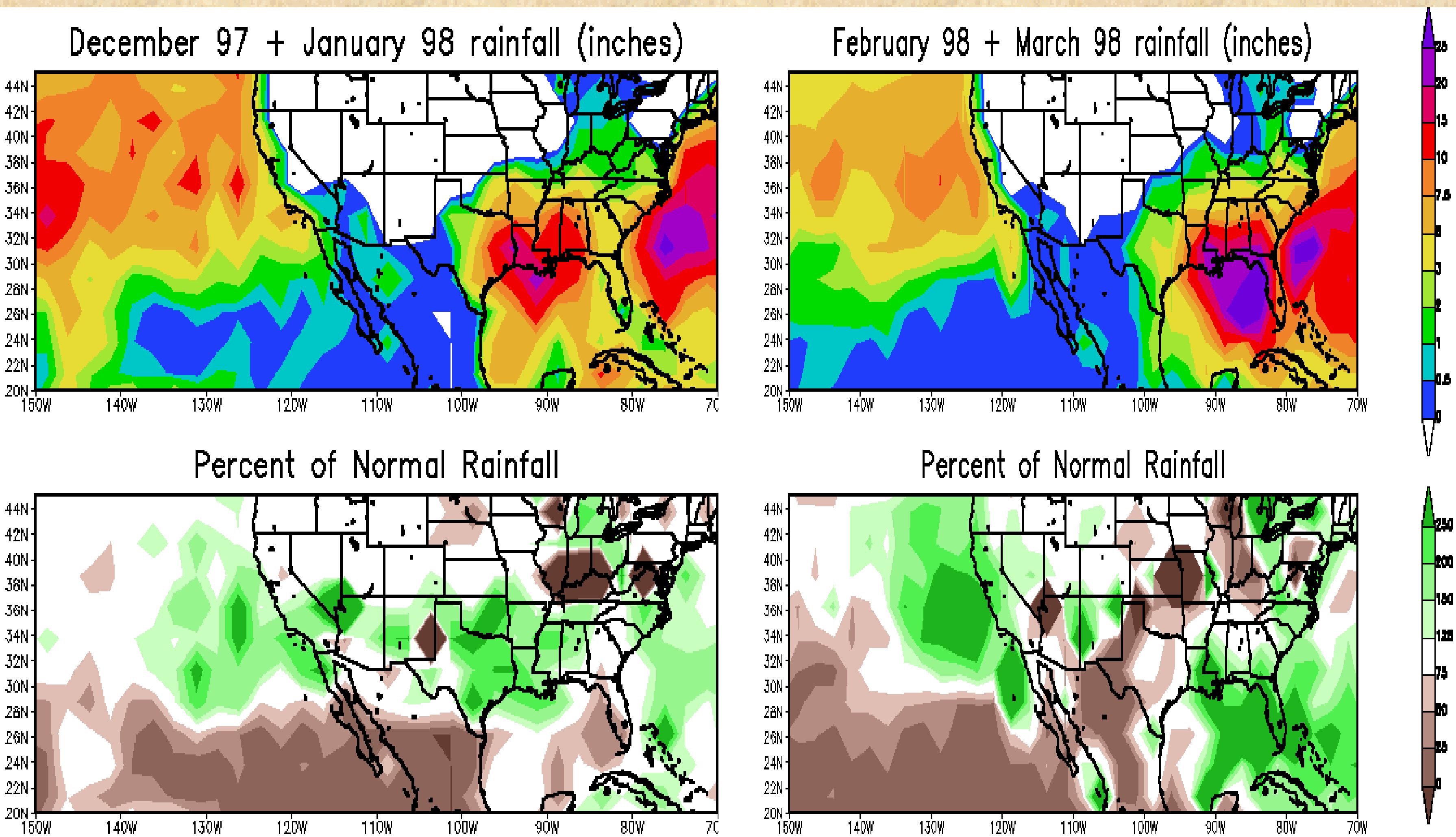
Interannual Variations



Interannual Variations



Regional Monitoring



Useful Web Sites

WEB SITE	URL ADDRESS	WHAT'S THERE
NOAA/NESDIS/ORA Hydrology Team, Microwave Sensing Group	http://orbit35i.nesdis.noaa.gov/arad2/index.html	Access to imagery of daily SSM/I and AMSU channel measurements, monthly climate products, and case studies
NOAA/NESDIS/ORA Ocean Sciences Team	http://manati.wwb.noaa.gov/doc/ssmiprecip.html	Ocean wind speeds, TPW, and rain rates, updated every 6 hours. Loops of daily mean SSM/I products.
NOAA/NESDIS/ORA Hydrology Team	ftp://orbit35i.nesdis.noaa.gov/arad/ht/ff/swi.html	Soil wetness and anomalies
NOAA/NESDIS/OSDPD Shared Processing	http://psbsgi1.nesdis.noaa.gov:8080/PSB/SHARED_PROCESSING/SHARED_PROCESSING.html	Access to SSM/I products as received from FNMOC
NCDC	http://www.ncdc.noaa.gov/ol/satellite/ssmi/ssmiproducts.html	Access to archived global monthly products
NGDC	http://www.ngdc.noaa.gov/dmsp/dmsp.html	Access to archived DMSP data, case studies, and good background information
CIRA	http://amsu.cira.colostate.edu/	Access to AMSU products

Useful References

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- Ferraro, R.R. and G.F. Marks, 1995: The development of SSM/I rain rate retrieval algorithms using ground based radar measurements. *J. Atmos. Oceanic Technol.,* ***12,*** 755-770.
- Ferraro, R.R., F. Weng, N.C. Grody, and A. Basist, 1996: An eight year (1987-1994) time series of rainfall, clouds, water vapor, snow-cover, and sea-ice derived from SSM/I measurements. *Bull. Amer. Meteor. Soc.,* **77**, 891-905.
- Ferraro, R.R., E.A. Smith, W. Berg, and G. Huffman, 1998: A review of screening techniques for passive microwave precipitation retrieval algorithms. *J. Atmos. Sci.,* **55**, 1583-1600.
- Ferraro, R.R., 1997: SSM/I derived global rainfall estimates for climatological applications. *J. Geophys. Res*., **102**, 16,715-16,735.
- Grody, N.C., 1991: Classification of snow cover and precipitation using the Special Sensor Microwave/Imager (SSM/I). *J. of Geophys. Res.*, **96**, 7423-7435.
- Weng, F. and N.C. Grody, 1994: Retrieval of cloud liquid water using the special sensor microwave imager (SSM/I). *J. Geophys. Res.*, **99**, 25535-25551.

References on Validation

- GPCP Algorithm Intercomparison Program (AIP's):
  - Ebert and Arkin - BAMS, 199x?
- WetNet Precipitation Intercomparison Projects (PIP's):
  - PIP-1: Remote Sensing Reviews, ***11***, No. 1-4,1994
  - PIP-2: JAS, ***55***, No. 9, May 1998
- Some recent studies:
  - Li, Q, R. Ferraro and N. Grody, 1998: Detailed analysis of the error ….Tropical Ocean Rainfall. JGR, ***103***, 11419-11427.
  - Connor, M. and G. Petty, 1998: Validation and Intercomparison of SSM/I….United States, JAM, ***37***, 679-700.
  - Xie, P. and P. Arkin, 1996: Analysis of global monthly precipitation using gauge observations and satellite estimates…., JCLIM, ***9***, 840-858.

For More Information….

Ralph Ferraro

Office of Researcn & Applications

E/RA2, WWB Room 601

NOAA/NESDIS

5200 Auth Road

Camp Springs, MD 20746-4304

rferraro@nesdis.noaa.gov