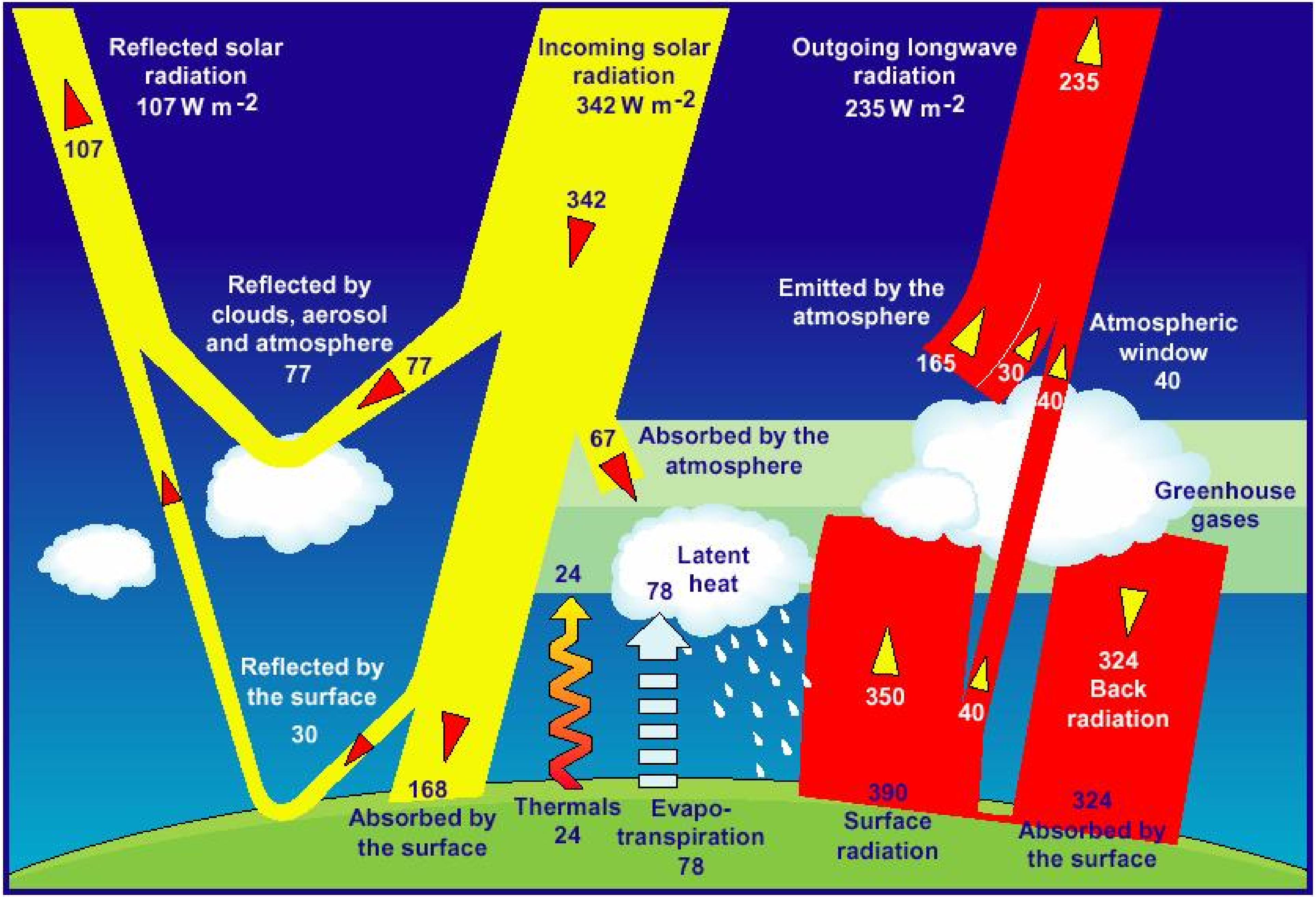
Achieving Climate Quality Data Sets – Using Satellite Observations of Clouds as an Example

W. Paul Menzel
NOAA/NESDIS
Cooperative Institute for Meteorological Satellite Studies
University of Wisconsin-Madison
Madison, Wisconsin,USA

Why study clouds
22 year HIRS stats
Effects of orbit drift, CO2 increase, and sensor changes
Comparison with ISCCP and GLAS
Extending with MODIS
Challenges & GCOS Climate Monitoring Principles

March 2005

Climate System Energy Balance



Rationale for Cloud Investigations

clouds are a strong modulator of shortwave and longwave; their effect on global radiative processes is large

(1% change in global cloud cover equivalent to about 4% change in CO_2 concentration)

accurate determination of global cloud cover has been elusive

(semi transparent clouds often underestimated by 10%)

global climate change models need accurate estimation of cloud cover, height, emissivity, thermodynamic state, particle size

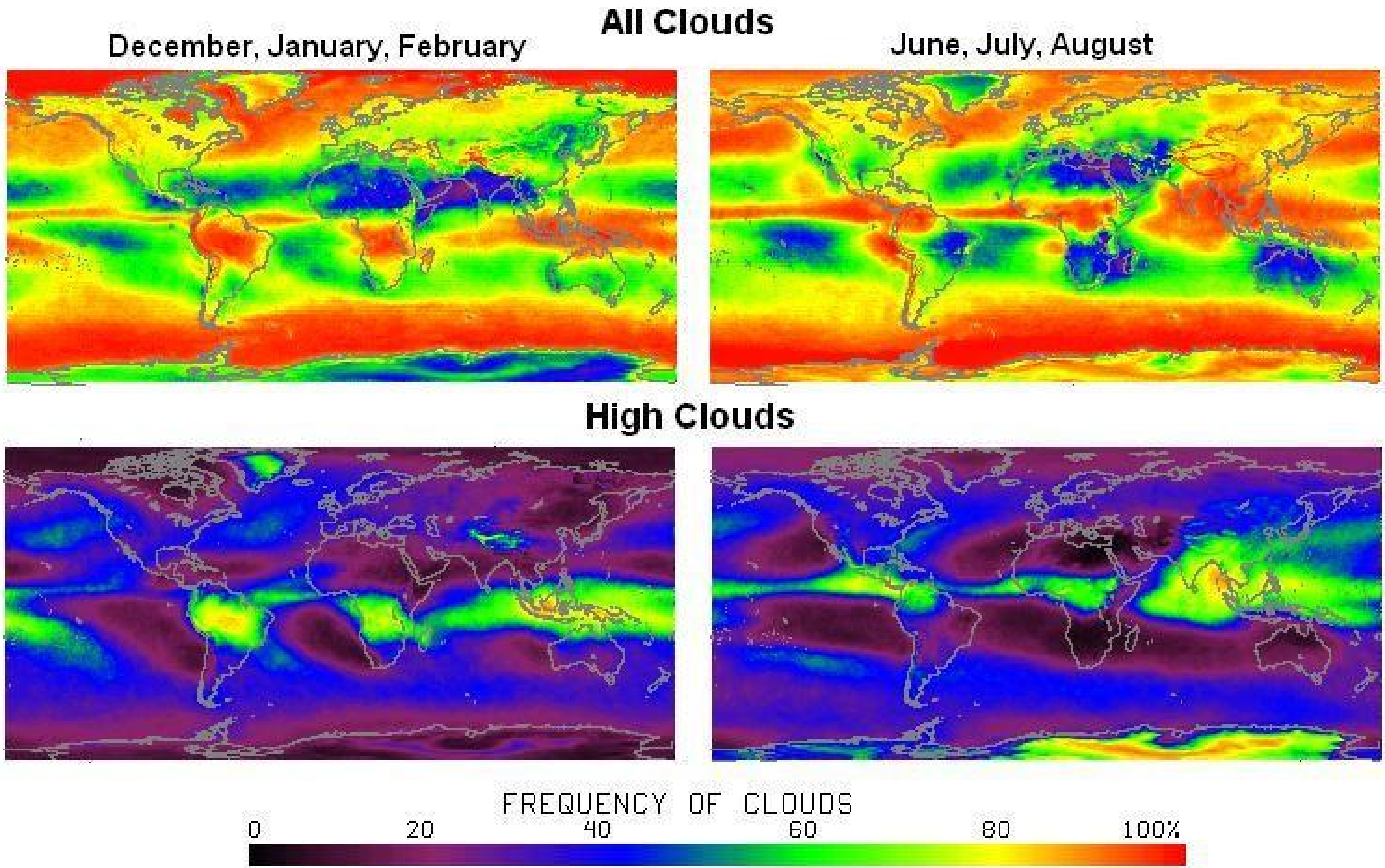
(high/low clouds give positive/negative feedback to greenhouse effect, and higher albedo from anthropogenic aerosols may be negative feedback)

there is a need for consistent long term observation records to enable better characterization of weather and climate variability

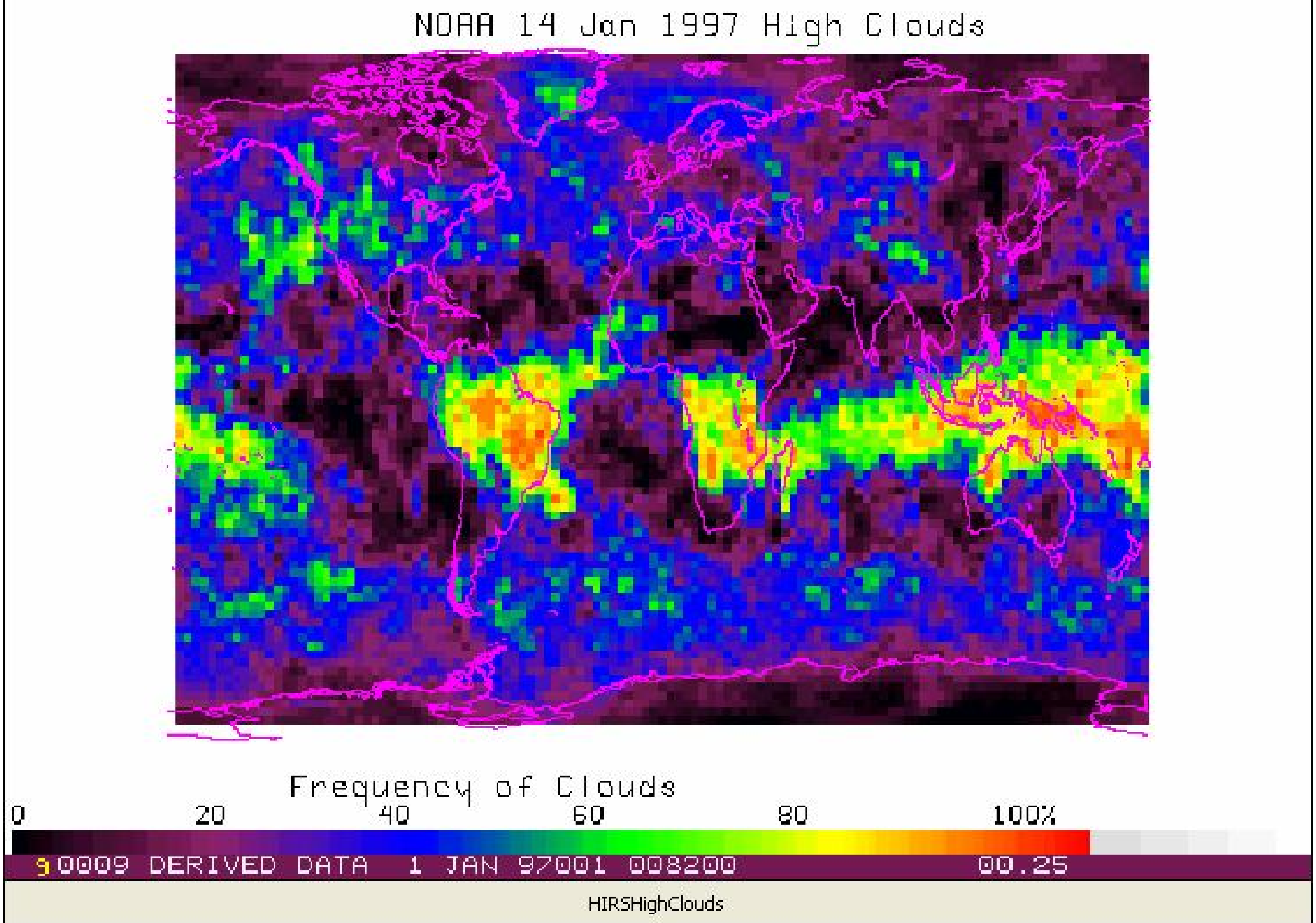
(ISSCP is a good start)

Why are clouds so tough?

- Aerosols <0.1 micron, cloud systems >1000 km
- Cloud particles grow in seconds: climate is centuries
- Cloud growth can be explosive:
  1 thunderstorm packs the energy of an H-bomb.
- Cloud properties can vary a factor of 1000 in hours.
- Few percent cloud changes drive climate sensitivity
- Best current climate models are 250 km scale
- Cloud updrafts are a 100 m to a few km.


All Clouds
December, January, February
June, July, August
High Clouds
FREQUENCY OF CLOUDS
0
20
40
60
80
100%

Looking at animation of monthly means for 1997



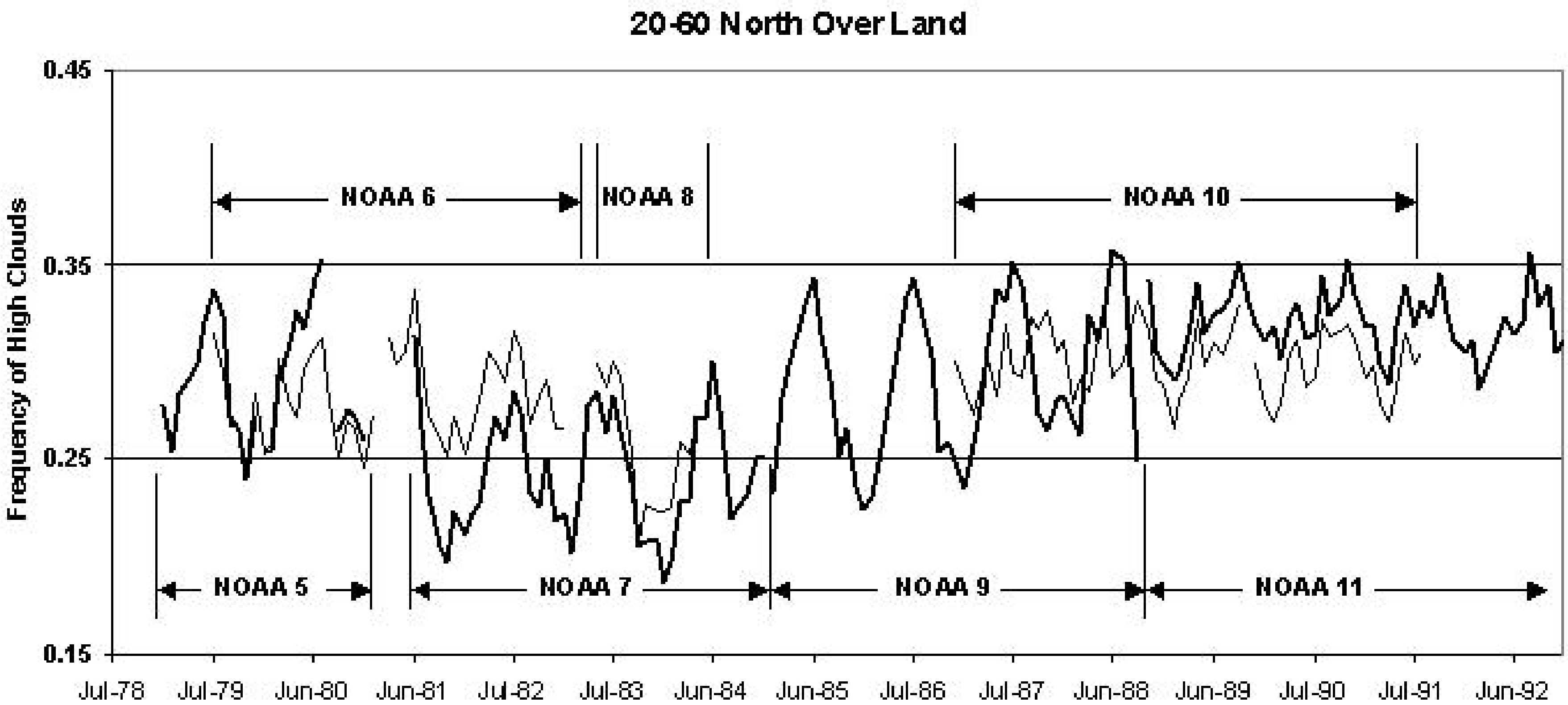
Inferring Decadal HIRS Cloud Trends requires corrections for

(1) anomalous satellite data or gaps
(2) orbit drift
(3) CO_2 increase

constant CO_2 concentration was assumed in analysis

Satellite by satellite analysis

Gap in 8am/pm orbit coverage between NOAA-8 and -10
HIRS cloud trends show unexplained dip with NOAA-7 in 2 am/pm orbit.

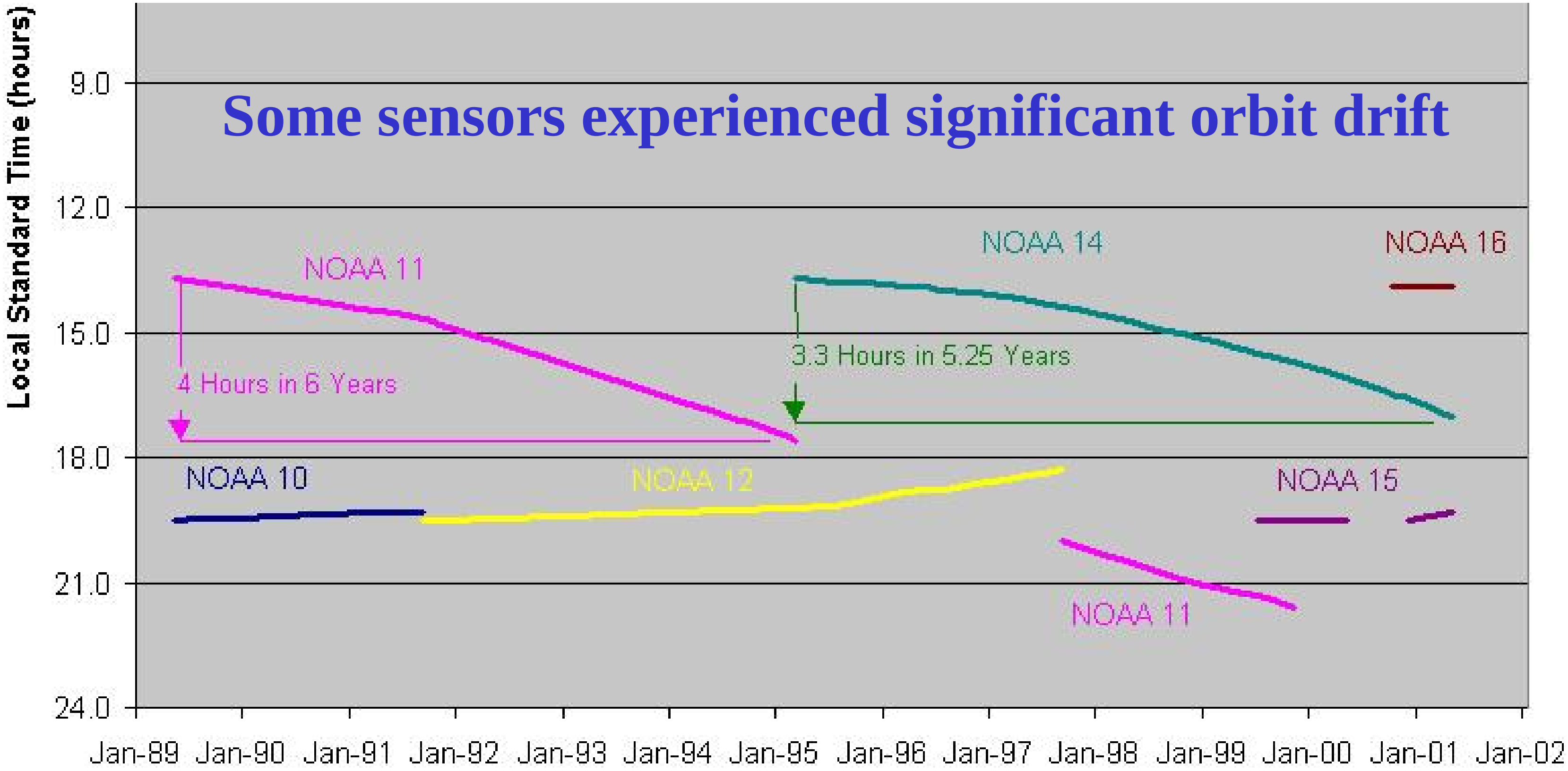


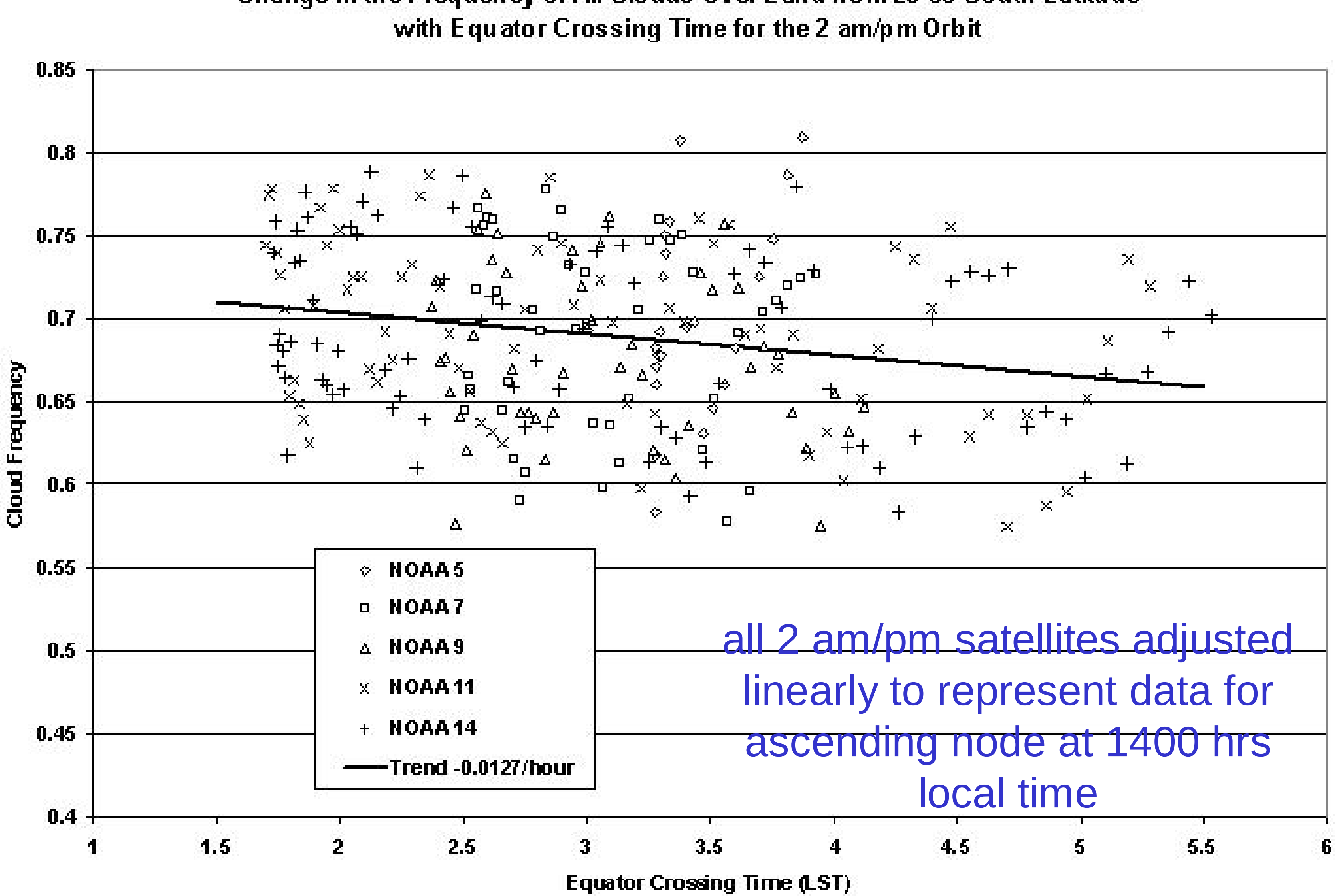
Used only 2 am/pm orbit data after 1985 in cloud trend analysis
for continuity of data and satellite to satellite consistency

Measurements from 9 sensors used in 22 year study of clouds

morning (8 am LST)	afternoon (2 pm LST)
NOAA 6 HIRS/2	NOAA 5 HIRS
NOAA 8 HIRS/2	NOAA 7 HIRS/2
NOAA 10 HIRS/2	NOAA 9 HIRS/2
NOAA 12 HIRS/2	NOAA 11 HIRS/2I *
	NOAA 14 HIRS/2I *

HIRS/2I ch 10 at 12.5 um instead of prior HIRS/2 8.6 um. Asterisk indicates orbit drift





Change in cloud frequency per hour of orbit drift (cloud fraction per hour)

	Orbit drift corrections.			
	All Clouds		High Clouds	
	Land	Ocean	Land	Ocean
20-60 North	-0.004	0.002	0.007	0.004
Tropics 20 S - 20 N	-0.010	0.006	0.010	0.004
20-60 South	-0.013	0.003	0.006	0.000

Atmospheric CO2 has not been constant

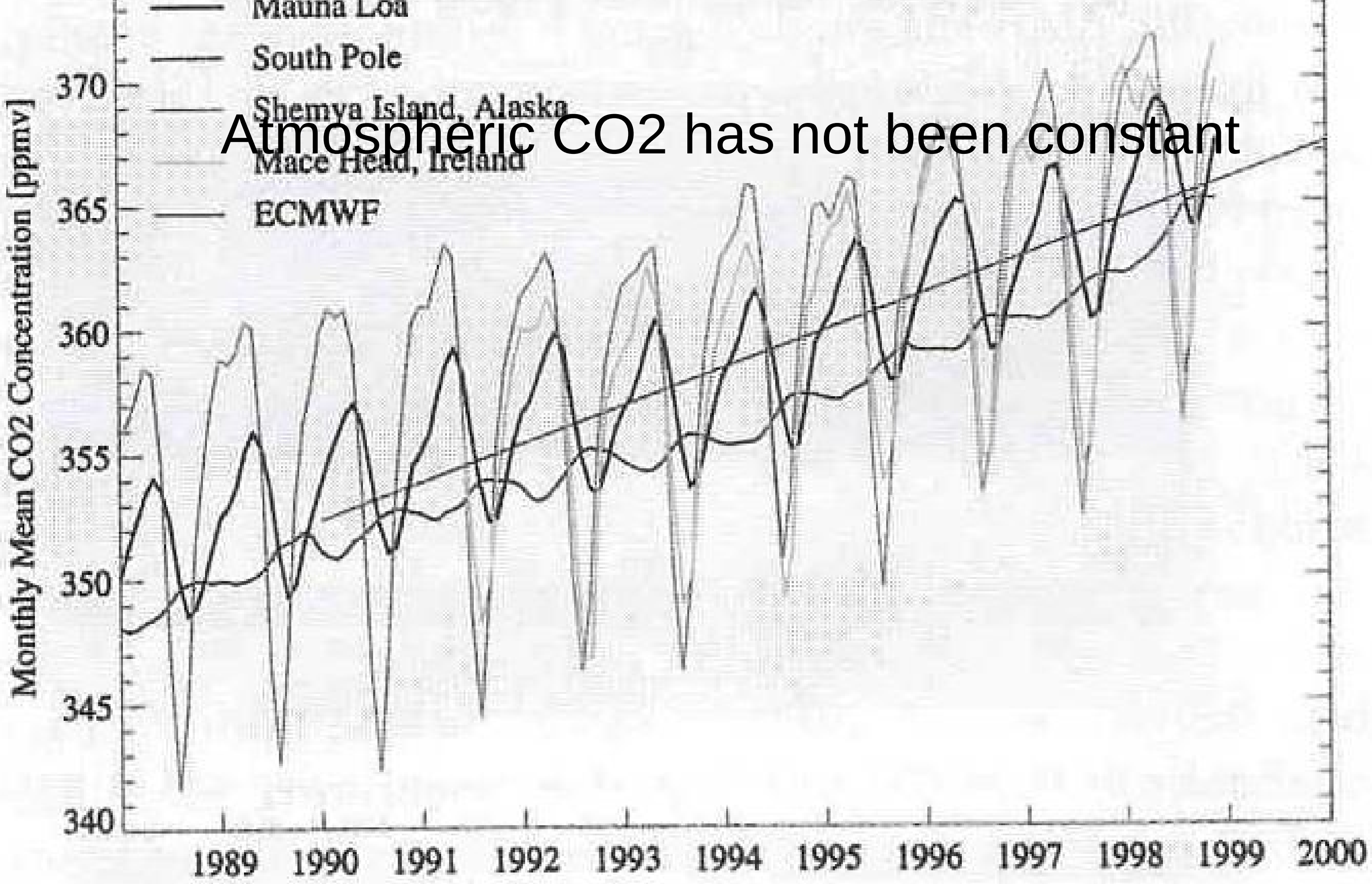
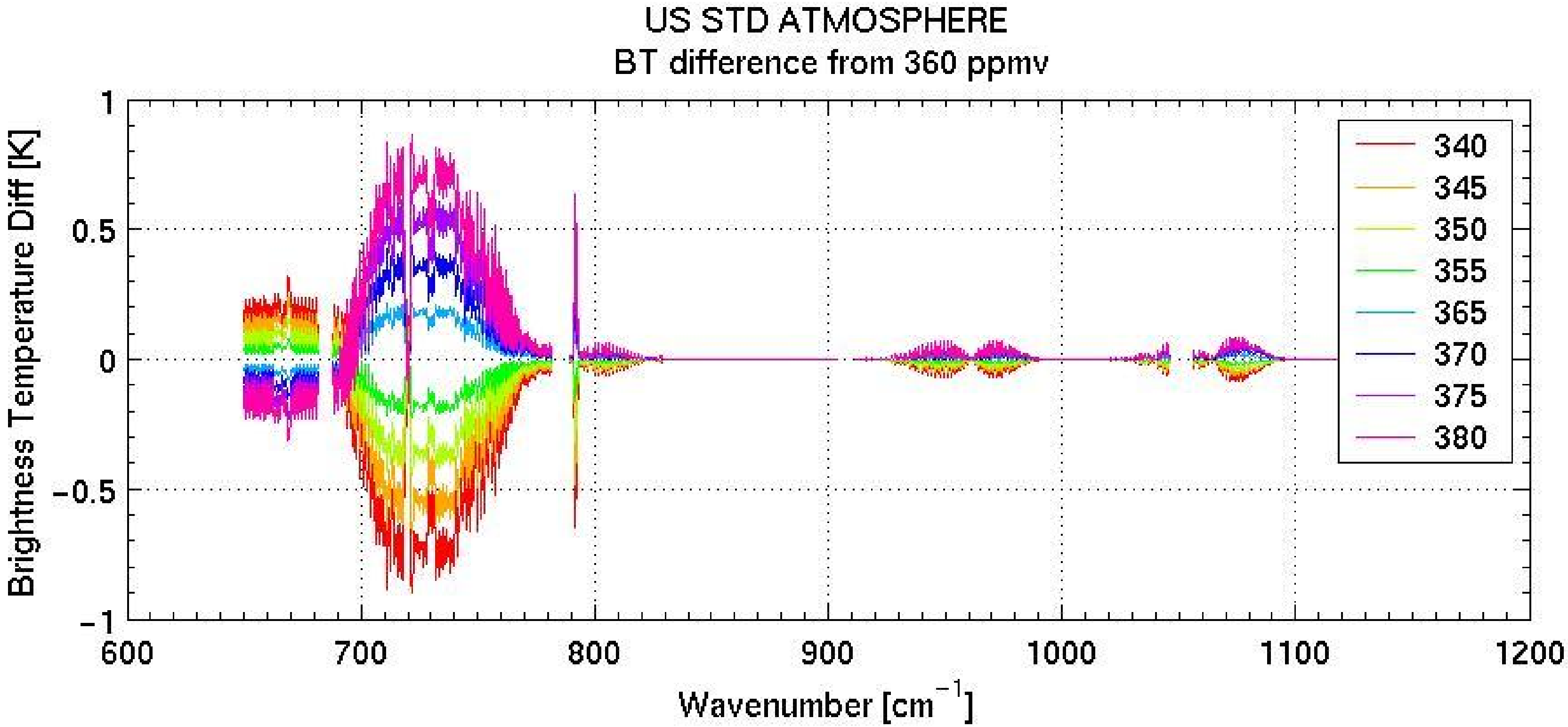


Figure 1. Time series of monthly mean surface CO_2 volume mixing ratios for 4 flask stations. The red line represents the values used by ECMWF.

(From Engelen et al., Geophys Res Lett, 2001)

SARTA calculations: BT with 360 ppmv minus BT with 340,345,…380 ppmv



HIRS cloud trends have been calculated with CO_2 concentration assumed constant at 380 ppm.

Lower CO_2 concentrations increase the atmospheric transmission, so radiation is detected from lower altitudes in the atmosphere.

$$\text{dry}(335,p,ch) = \text{dry}(380,p,ch)^{**}\{335/380)$$

$$(p,ch) = \text{dry}(p,ch)^{*}\ \text{H2O}(p,ch)^{*}\ \text{O3}(p,ch).$$

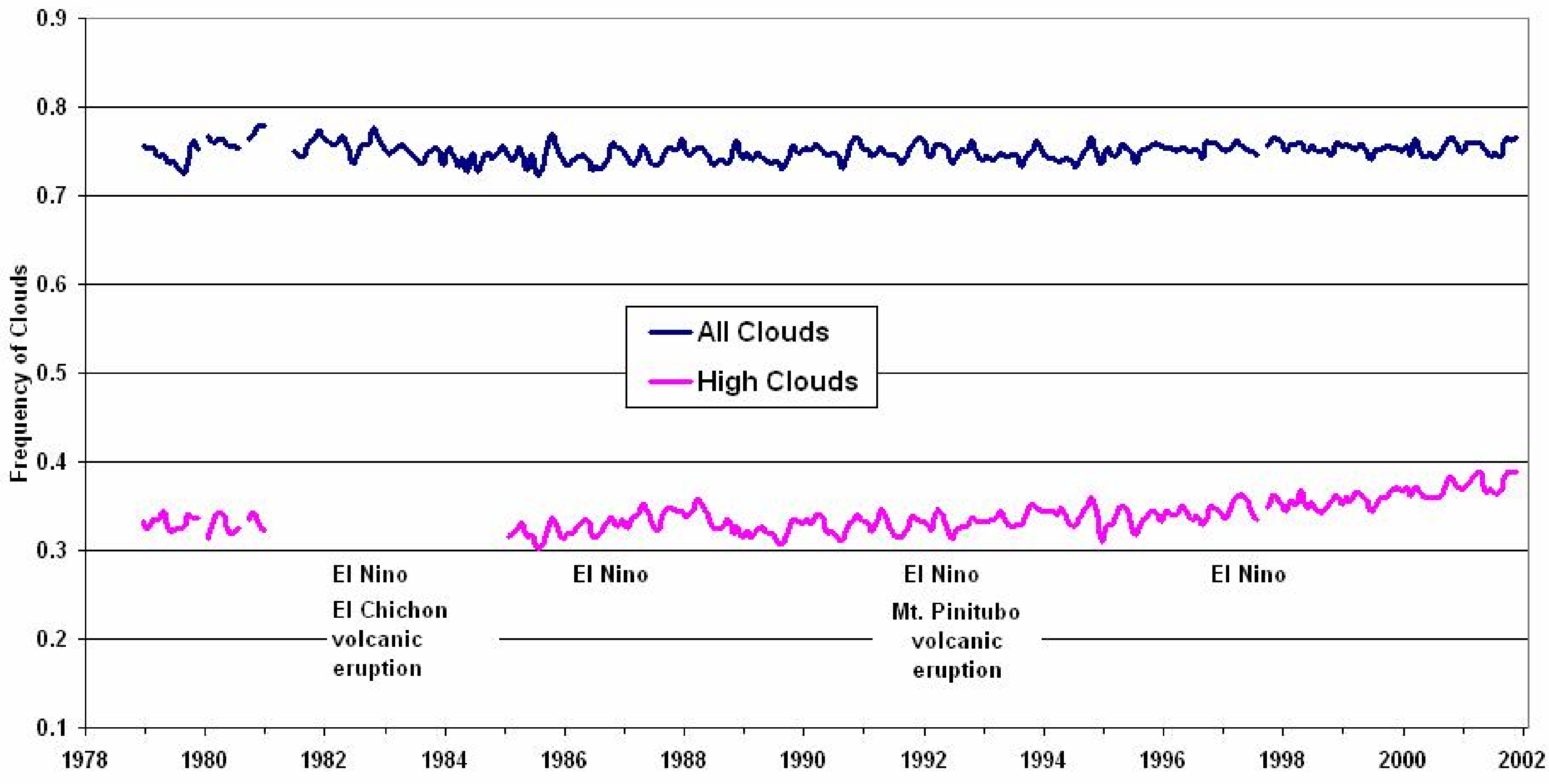
For January and June 2001 the clouds detected by NOAA 14 in the more transparent atmosphere (CO2 at 335 ppm) are found to be lower by 15-50 hPa

More transparent atmosphere (CO2 at 335 ppm) results in HIRS reporting 2% less high clouds than in the more opaque atmosphere (CO2 at 380 ppm); this implies that the frequency of high cloud detection in the early 1980s should be adjusted down.

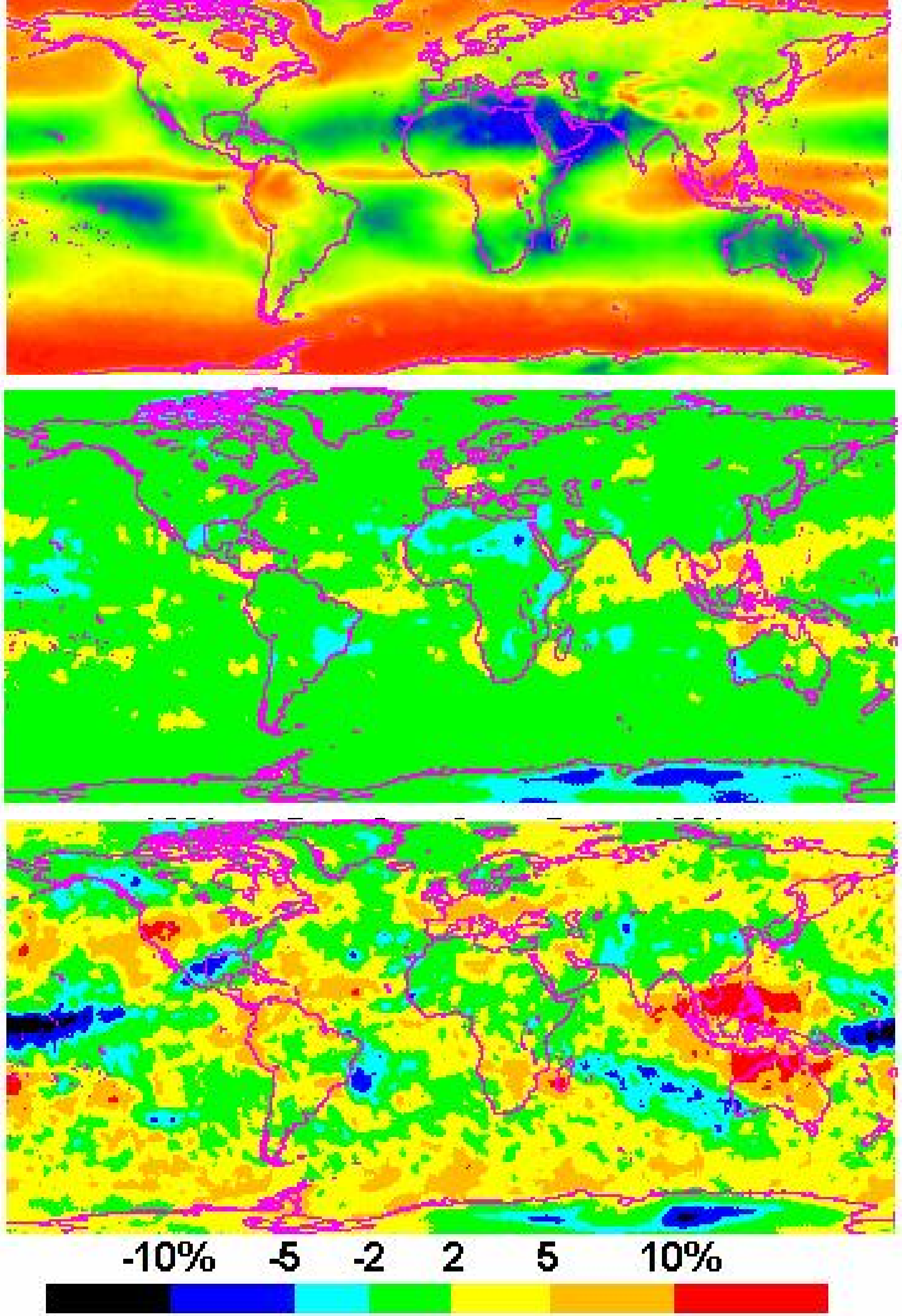
Cloud time series was adjusted to represent a linear increase of CO2 from 335 ppm in 1979 to 375 ppm in 2001

The statistically significant trends in cloud frequency change per decade from 1985-2001

	20-60 N		20 S - 20 N		20-60 S	
	Ocean	Land	Ocean	Land	Ocean	Land
	HIRS uncorrected					
High Clouds	0.013	0.014	none	0.017	0.014	0.021
All Clouds	none	none	0.018	None	none	none
	HIRS corrected					
High Clouds	0.023	0.021	none	0.017	0.027	0.029
All Clouds	none	none	0.014	None	none	none
	ISCCP					
High Clouds	none	-0.015	none	None	none	-0.020
All Clouds	-0.042	-0.031	-0.037	-0.021	-0.017	-0.010



The monthly average frequency of clouds and high clouds (above 6 km) from 70 south to 70 north latitude from 1979 to 2002; Wylie et al 2005.

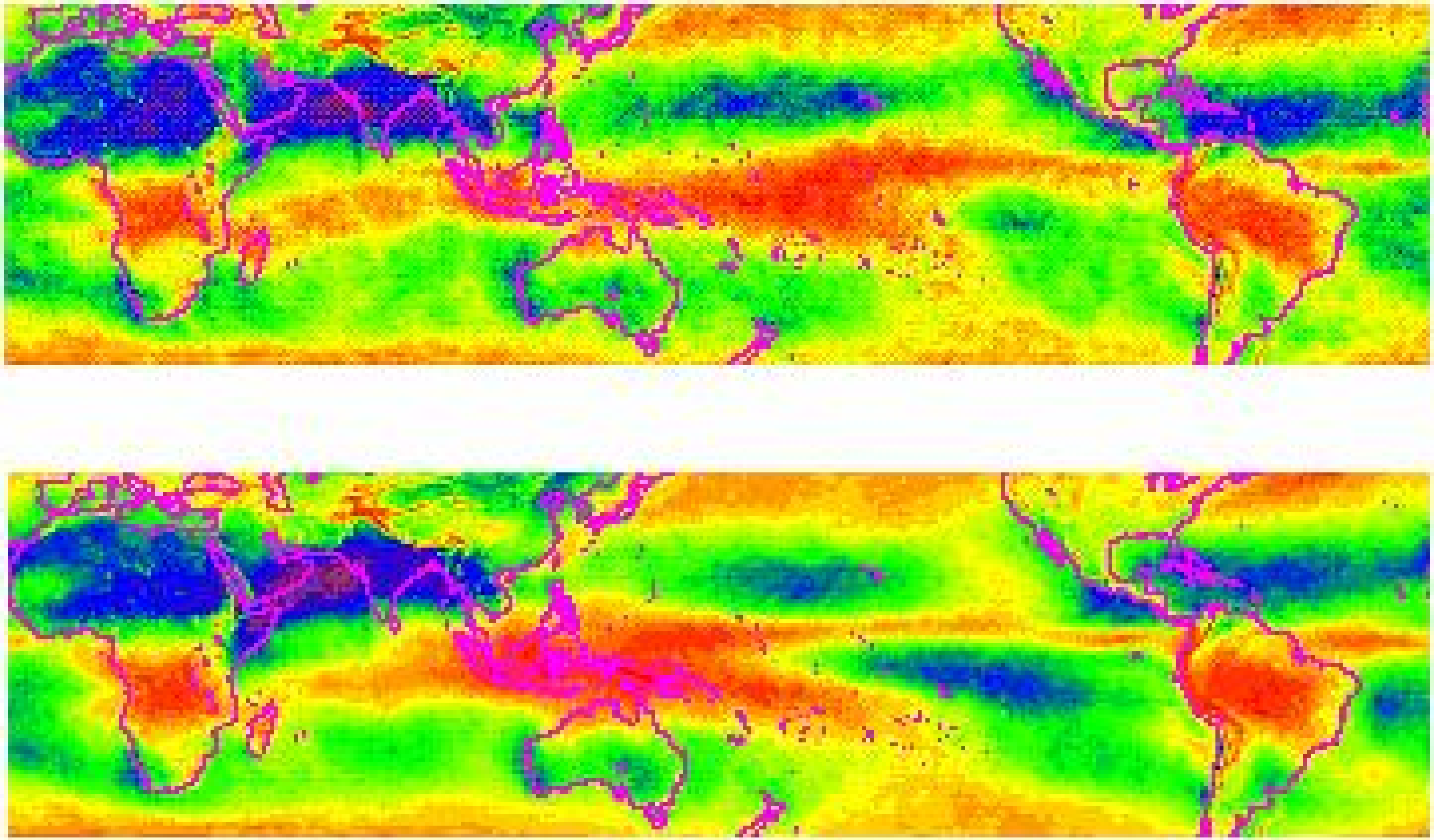


Frequency of all clouds found in HIRS data since 1979

Change in cloud frequency from the 1980s to the 1990s

Change in high cloud (above 6 km) frequency during northern hemisphere winters

Wylie et al 2005



High cloud (above 6 km) frequency during El Nino years (top) compared with all other years (bottom) during northern hemisphere winters (December, January, and February) from 1980s to 1990s.

Comparing with ISCCP and GLAS

(1) using GLAS as a sanity check
(2) understanding ISCCP
and algorithm differences

How Cloudy is the Earth?

	All Clouds			High Clouds		
Source	Land	Sea	Both	Land	Sea	Both
ISCCP	56 %	70 %		25 %	20 %	
HIRS Pathfinder	71	77		34	32	
Surface Reports	52	65		54	43	
SAGE			73			53
CLAVR			60			
GLAS	66	80		34 *	31 *	

**GLAS High Cloud Frequencies adjusted because HIRS reported more high clouds during the GLAS period than its 21 year average.*

GLAS 22 Feb – 28 Mar 2003, HIRS 1979 – 2001, ISCCP 1983 – 2001, SAGE 1985-89, Surface Reports 1980-89, CLAVR 1982 - 2004

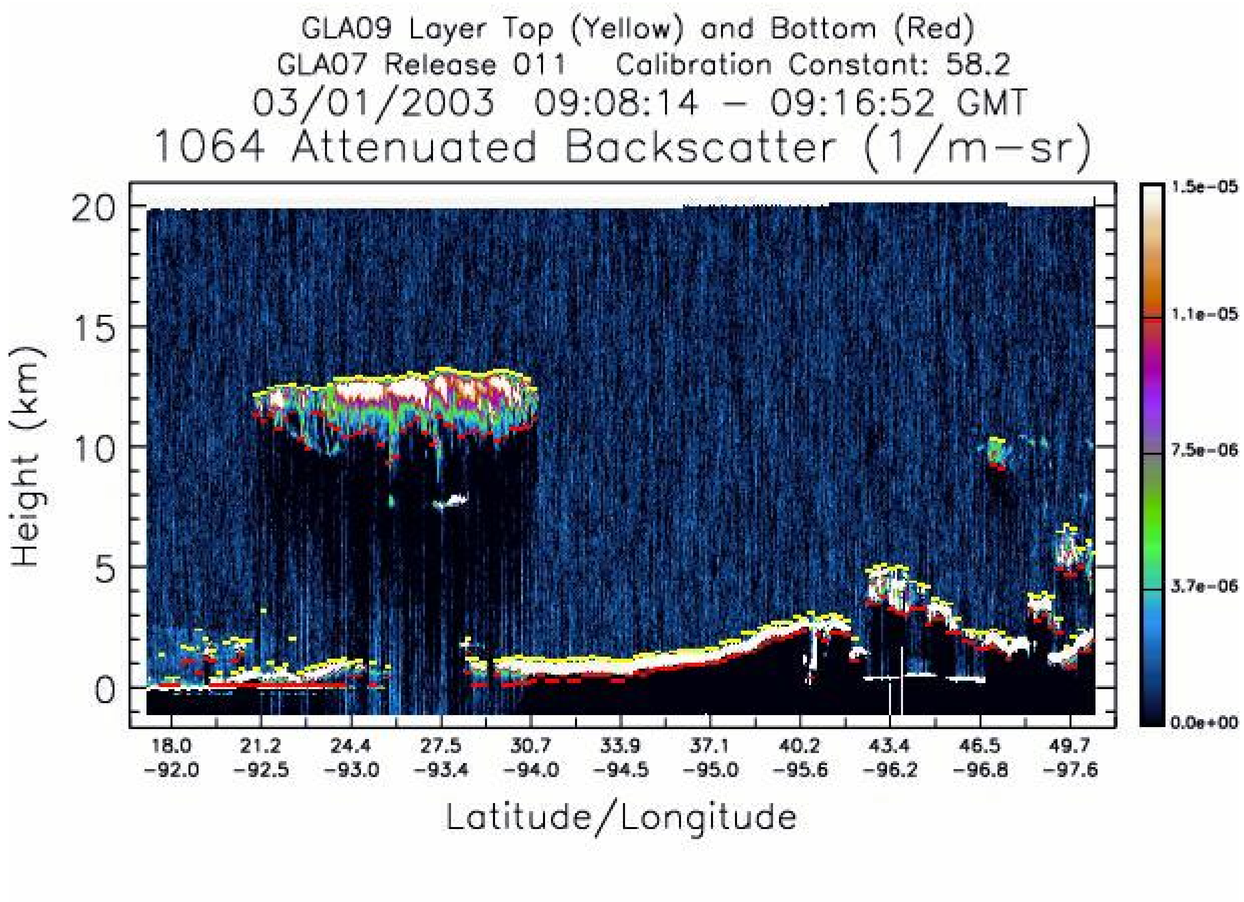
ISCCP reports 7-15% less cloud than HIRS because it misses thin cirrus.

HIRS and GLAS report nearly the same high cloud frequencies.

HIRS reports more clouds over land than GLAS probably because GLAS sees holes in low cumulus below the resolution of HIRS.

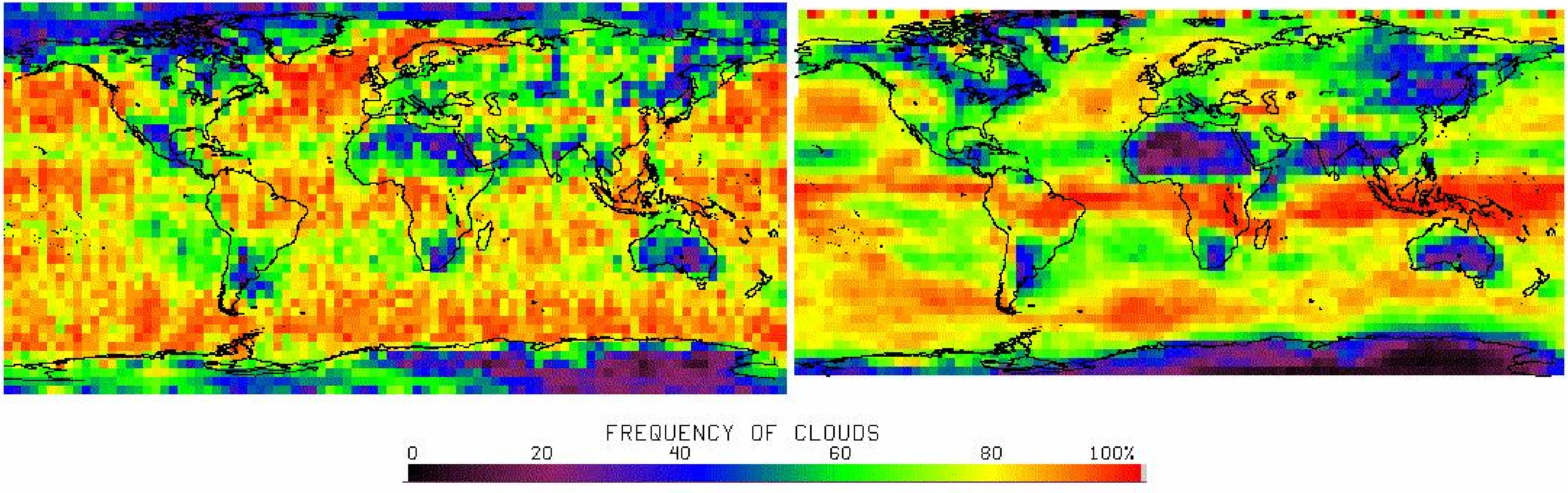
GLAS

Geoscience Laser Altimeter System

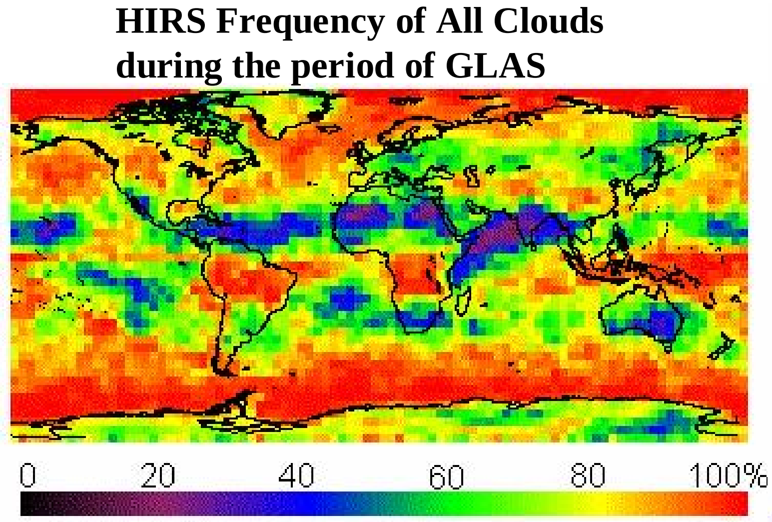


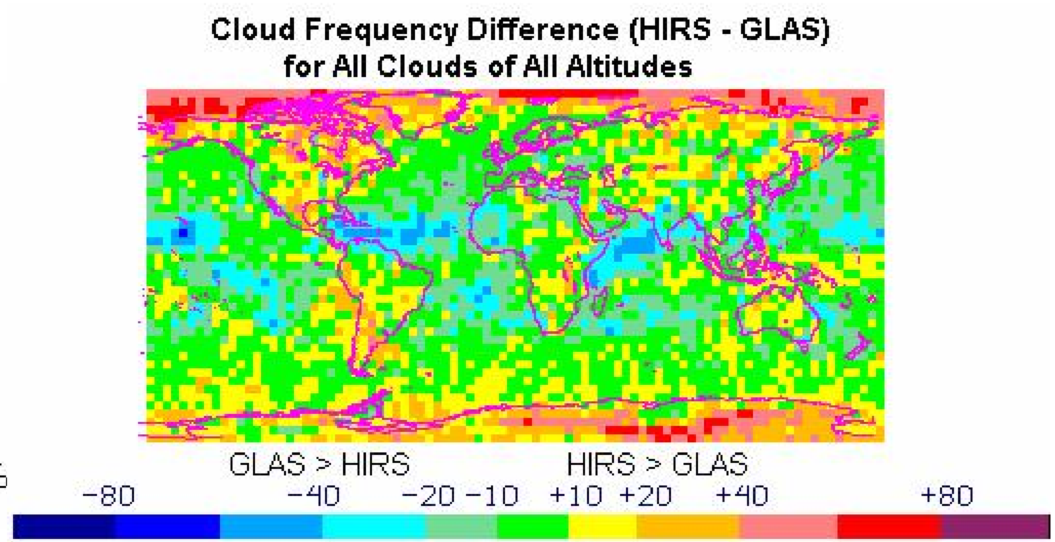
All Cloud Observations from GLAS vs HIRS

GLAS **HIRS**



HIRS minus GLAS All Cloud Difference

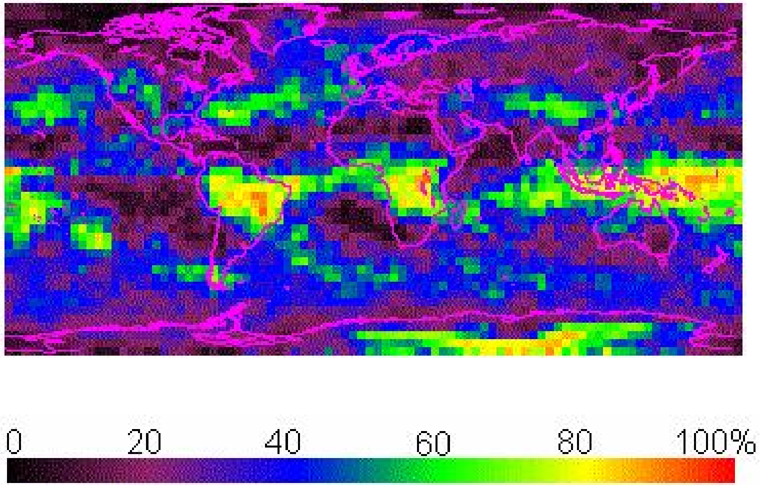




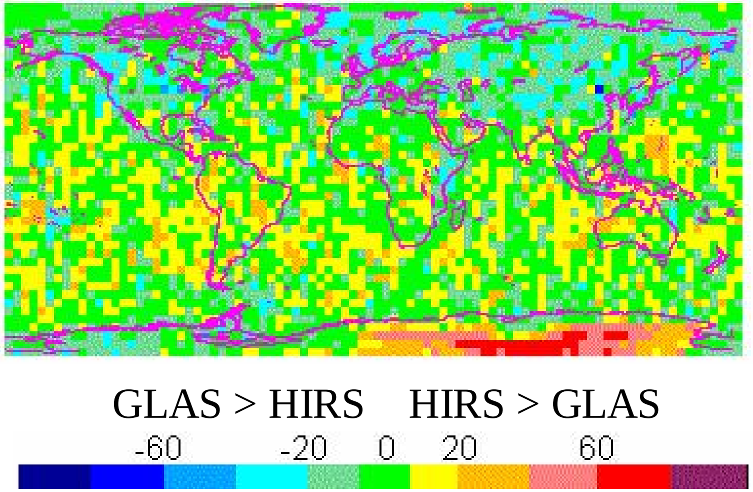
GLAS finds more tropical clouds over oceans where HIRS reports <40%.
GLAS finds less clouds in polar regions and western tropical Pacific.

HIRS minus GLAS High Cloud Difference

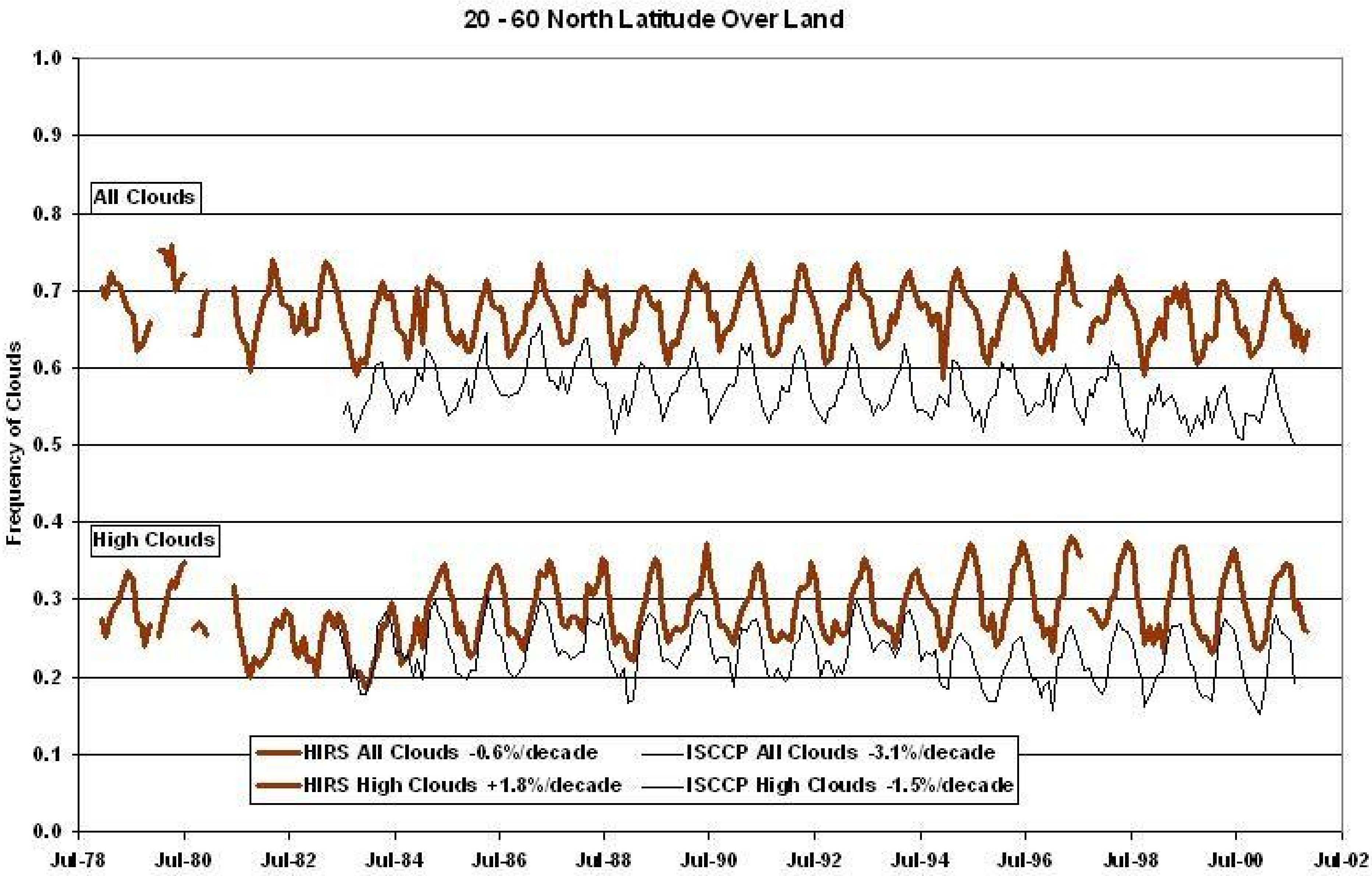
HIRS Frequency of High Cloud

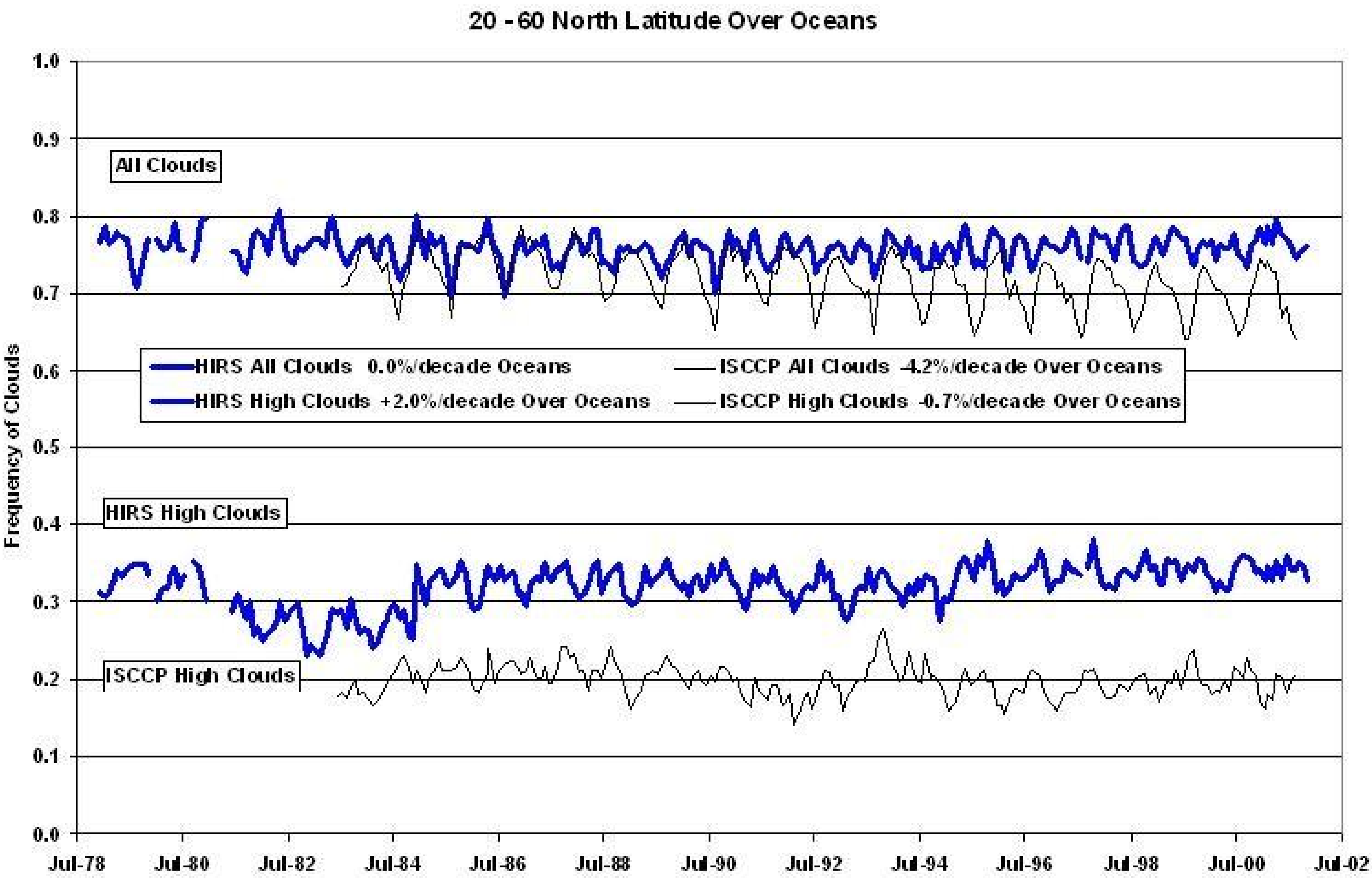


HIRS – GLAS Difference



HIRS reports more high clouds in parts of tropics and southern hemisphere, but areas of differences are scattered and not meteorologically organized.


20 - 60 North Latitude Over Land
All Clouds
High Clouds
Frequency of Clouds
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Jul-78
Jul-80
Jul-82
Jul-84
Jul-86
Jul-88
Jul-90
Jul-92
Jul-94
Jul-96
Jul-98
Jul-00
Jul-02
HIRS All Clouds -0.6%/decade
ISCCP All Clouds -3.1%/decade
HIRS High Clouds +1.8%/decade
ISCCP High Clouds -1.5%/decade



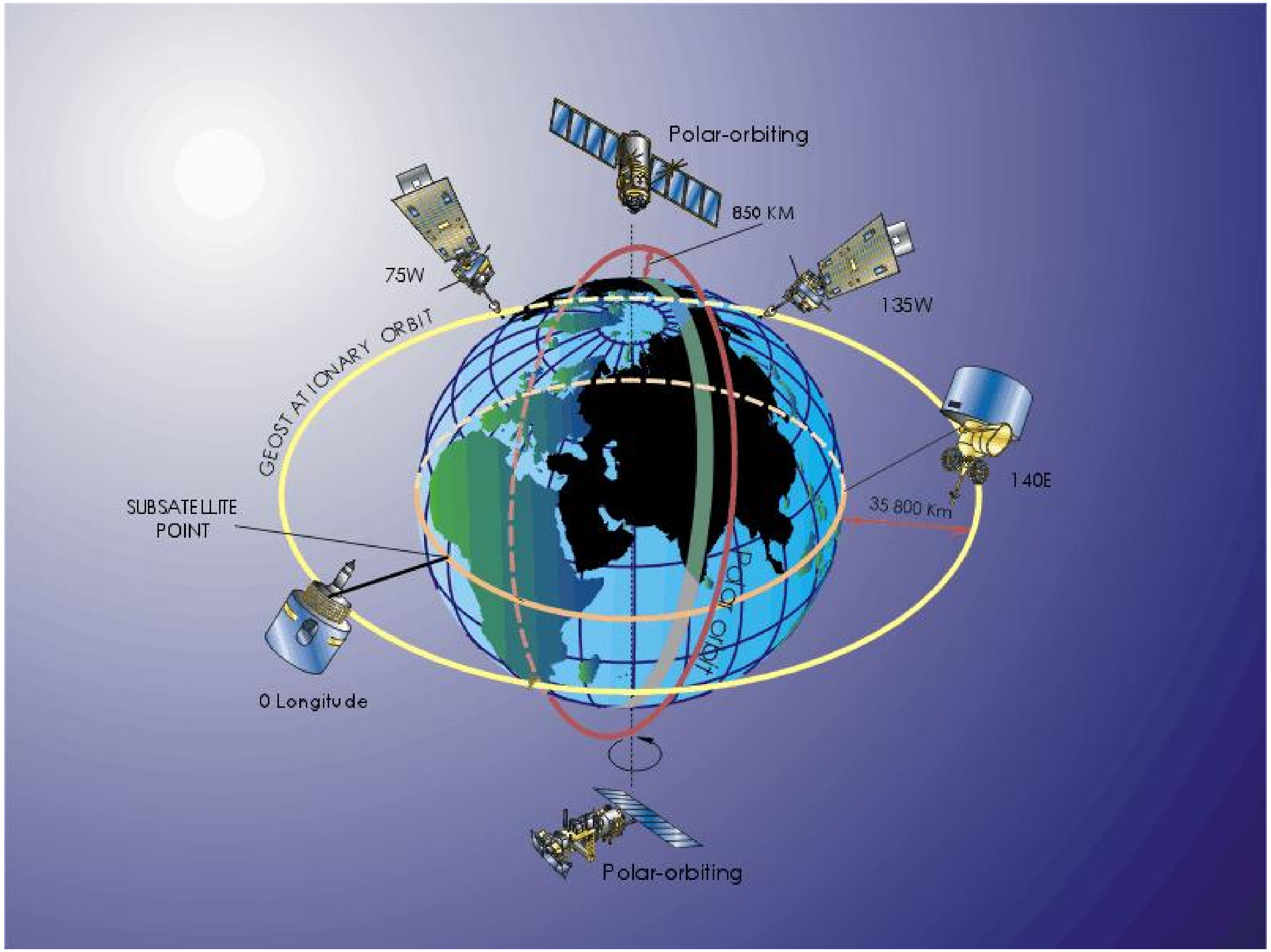
20 - 60 North Latitude Over Oceans
All Clouds
HIRS High Clouds
ISCCP High Clouds
HIRS All Clouds 0.0%/decade Oceans
HIRS High Clouds +2.0%/decade Over Oceans
ISCCP All Clouds -4.2%/decade Over Oceans
ISCCP High Clouds -0.7%/decade Over Oceans
Frequency of Clouds
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Jul-78
Jul-80
Jul-82
Jul-84
Jul-86
Jul-88
Jul-90
Jul-92
Jul-94
Jul-96
Jul-98
Jul-00
Jul-02

Wylie et al

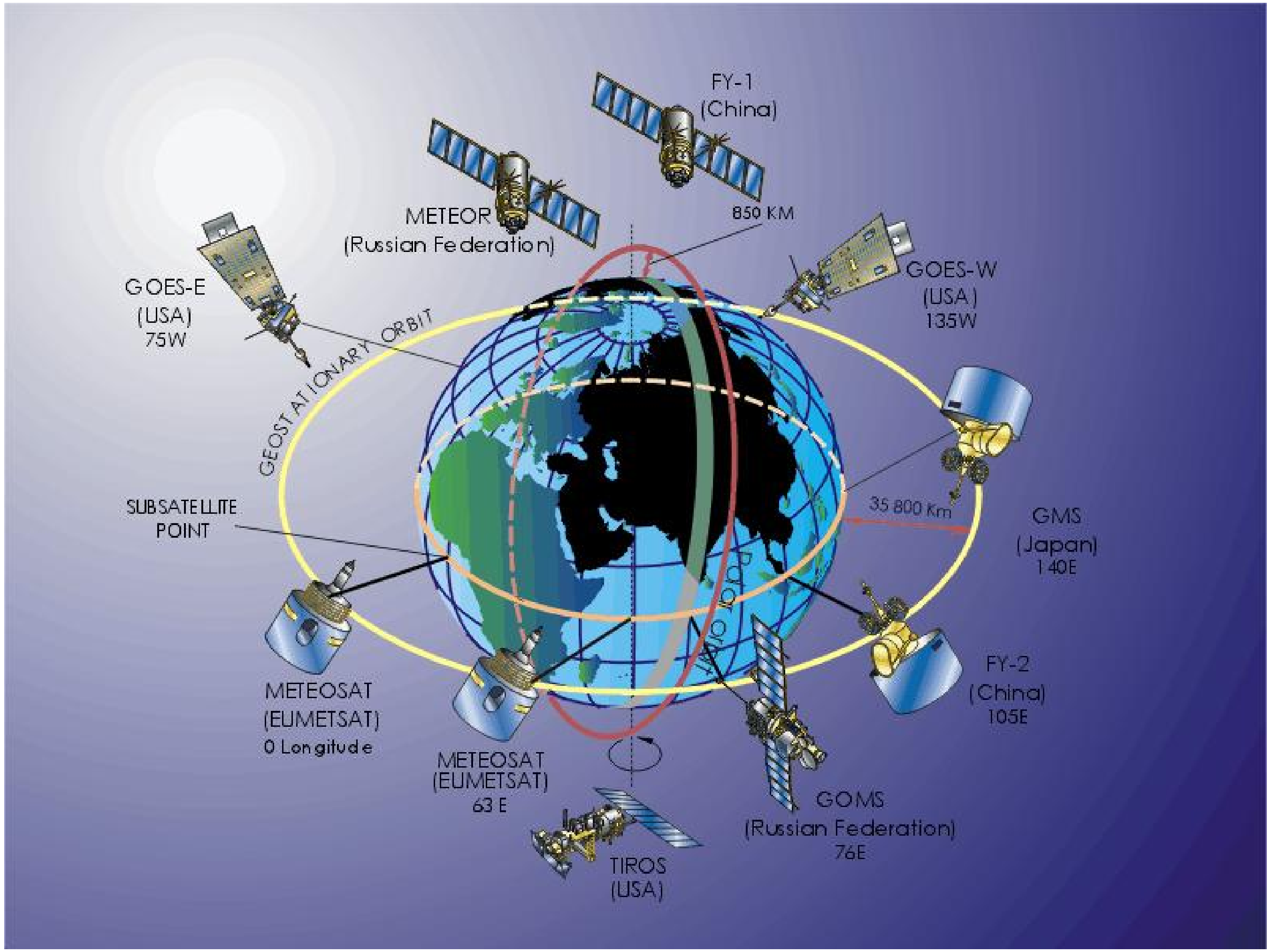
Differences between UW HIRS analysis and the ISCCP are primarily (a) ISCCP uses visible reflectance measurements with the infrared window thermal radiance measurements, which limits transmissive cirrus detection to only day light data; (b) UW HIRS analysis uses only longwave infrared data from 11 to 15 µm which is more sensitive to transmissive cirrus clouds, but is relatively insensitive to low level marine stratus clouds

Campbell and VonderHaar

ISCCP may be showing fewer clouds as satellite coverage (and hence more nadir viewing coverage) increases in later years.



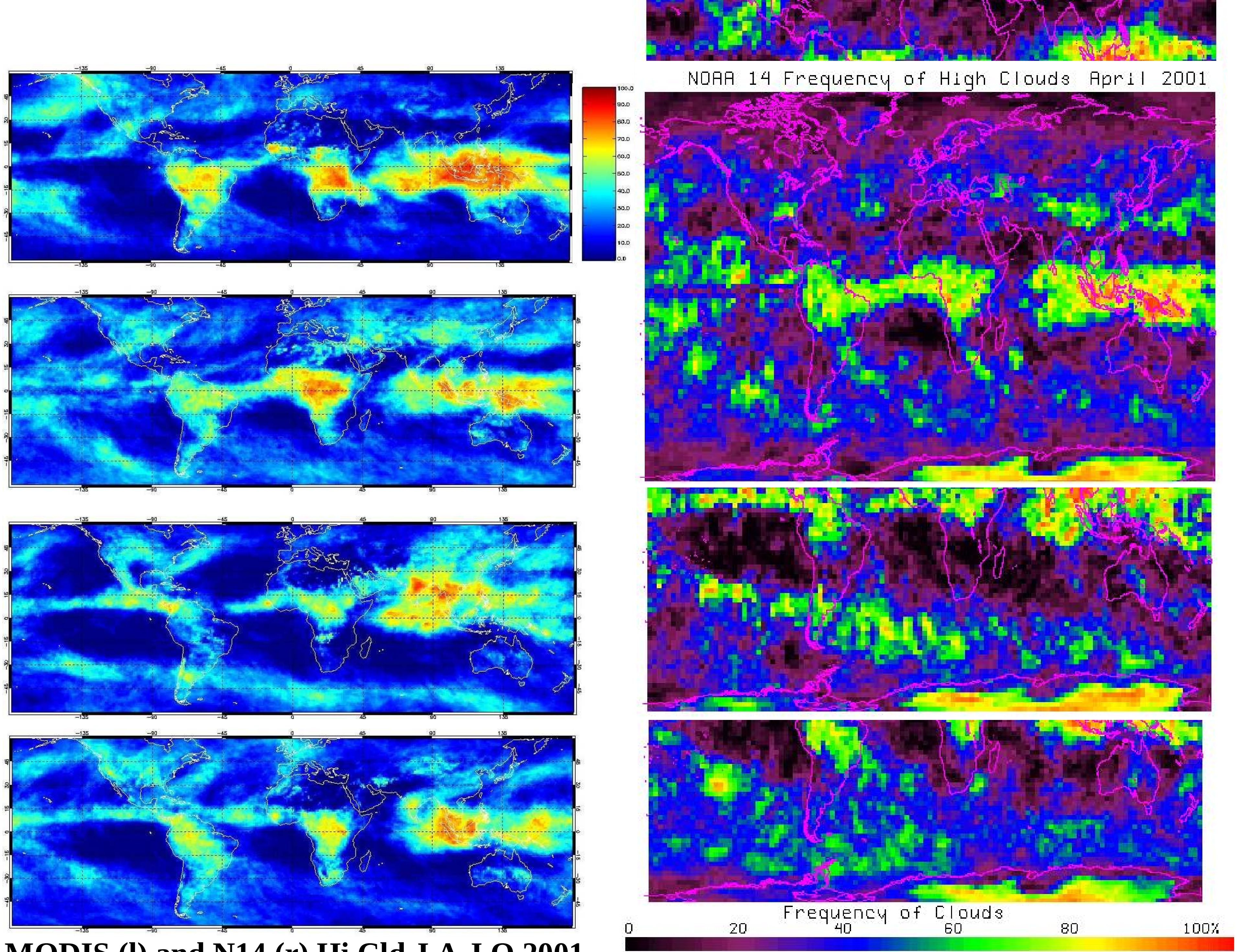
Satellite Observing System in 1978



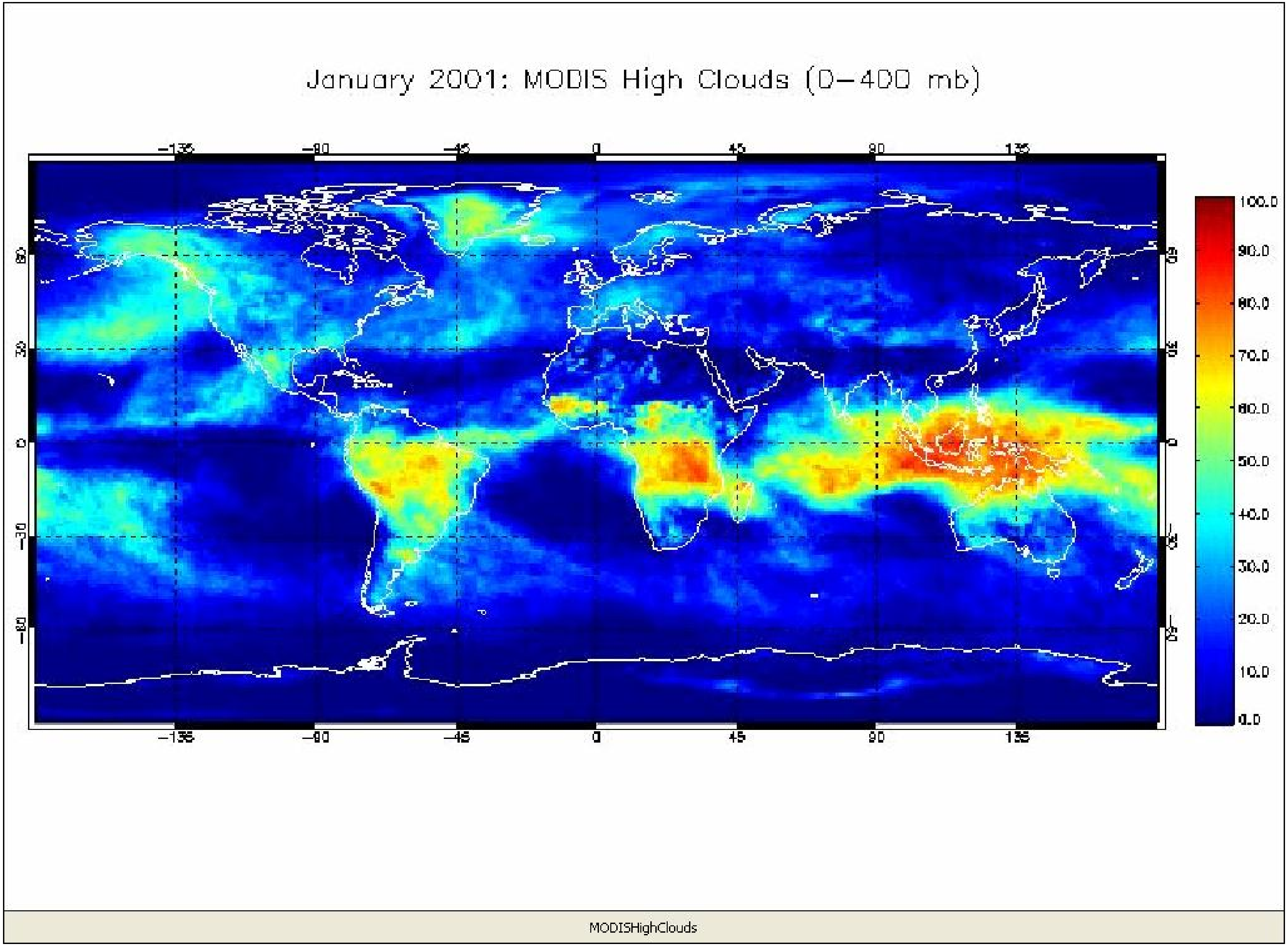
Satellite Observing System in 2000

Extending HIRS Cloud Trends with MODIS requires corrections for

(1) improved spatial resolution
(2) spectral changes



MODIS (l) and N14 (r) Hi Cld J,A,J,O 2001

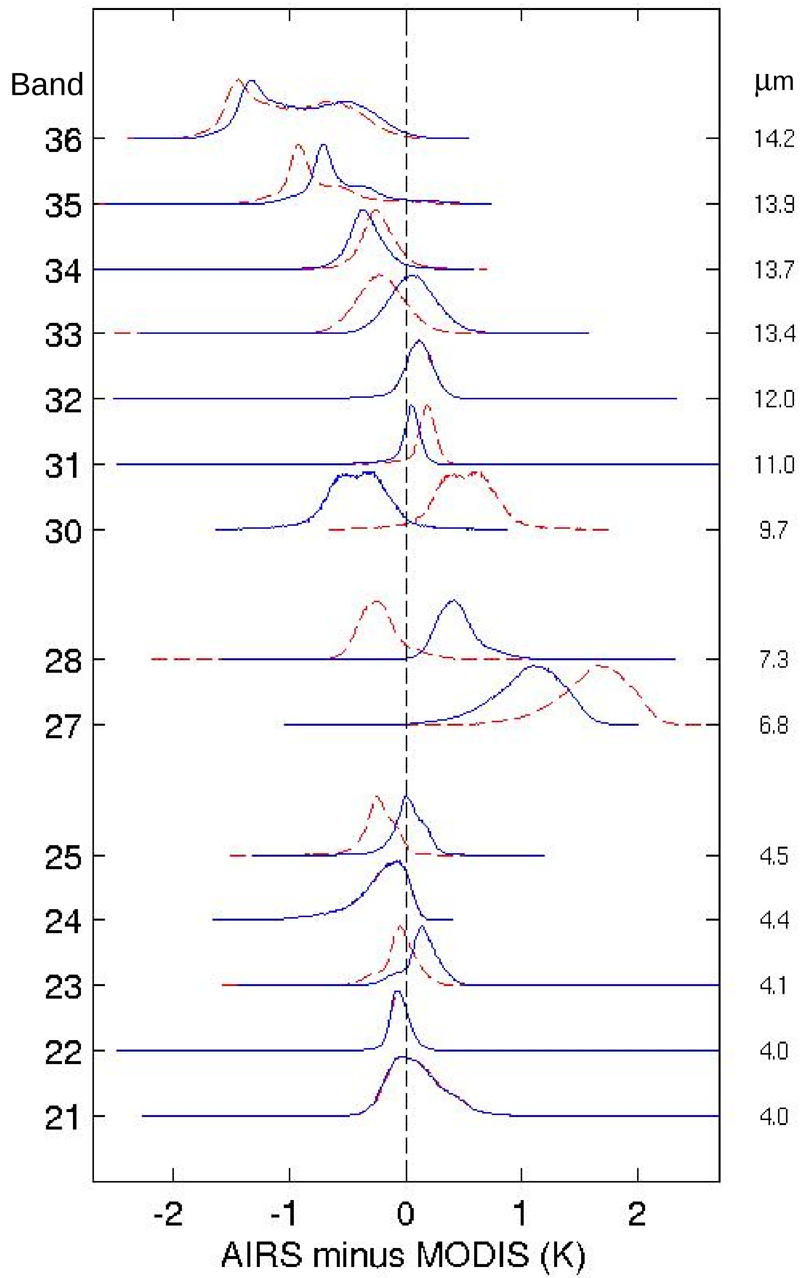

January 2001: MODIS High Clouds (0–400 mb)
−135
−90
−45
0
45
90
135
60
30
0
−30
−60
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
MODISHighClouds

Summary of AIRS minus MODIS mean Tb differences, 6 Sept 2002

Red=without accounting for ce

Blue=accounting for ce with mean correction from standard atmospheres

Band	Diff	CE	Diff	Std	N
21	0.10	-0.01	0.09	0.23	187487
22	-0.05	-0.00	-0.05	0.10	210762
23	-0.05	0.19	0.14	0.16	244064
24	-0.23	0.00	-0.22	0.24	559547
25	-0.22	0.25	0.03	0.13	453068
27	1.62	-0.57	1.05	0.30	1044122
28	-0.19	0.67	0.48	0.25	1149593
30	0.51	-0.93	-0.41	0.26	172064
31	0.16	-0.13	0.03	0.12	322522
32	0.10	0.00	0.10	0.16	330994
33	-0.21	0.28	0.07	0.21	716940
34	-0.23	-0.11	-0.34	0.15	1089663
35	-0.78	0.21	-0.57	0.28	1318406
36	-0.99	0.12	-0.88	0.43	1980369

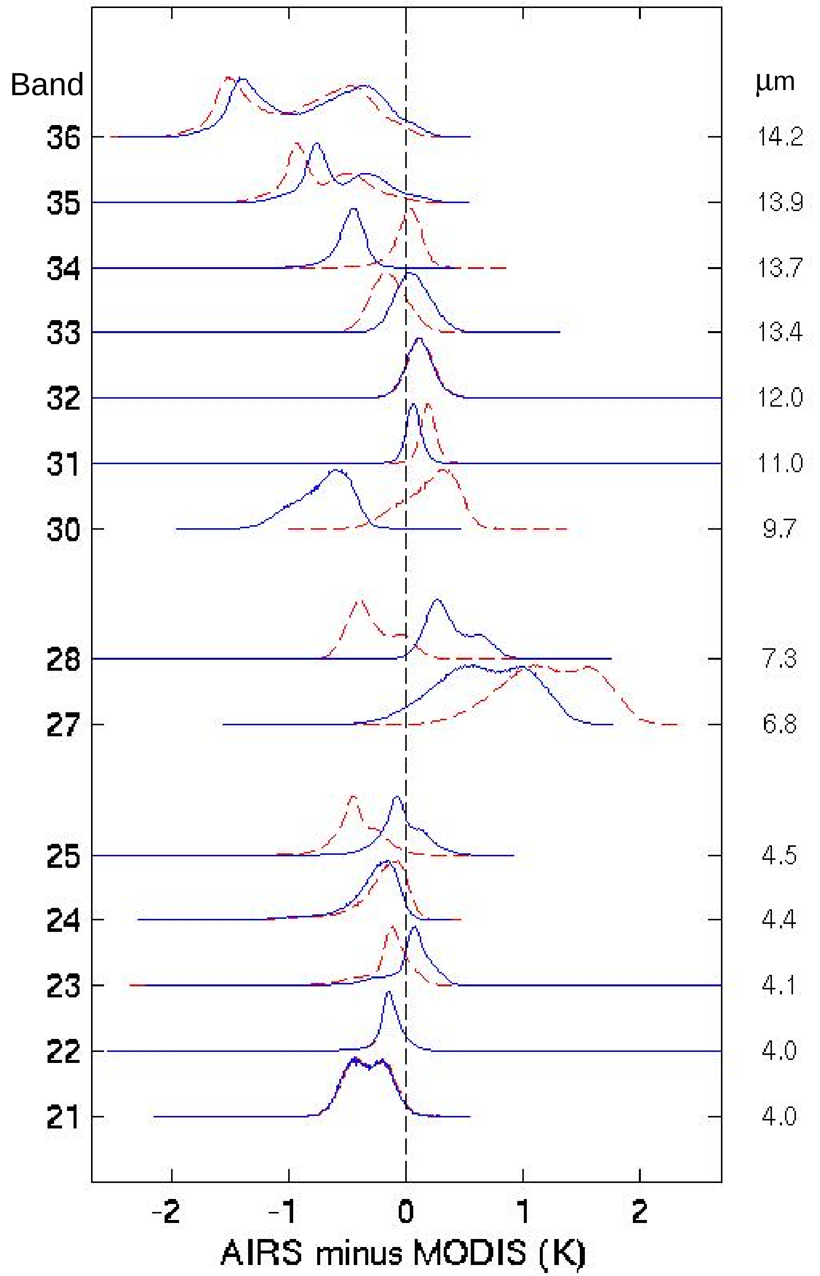


Summary of AIRS minus MODIS mean Tb differences, 18 Feb 2004

Red=without accounting for ce

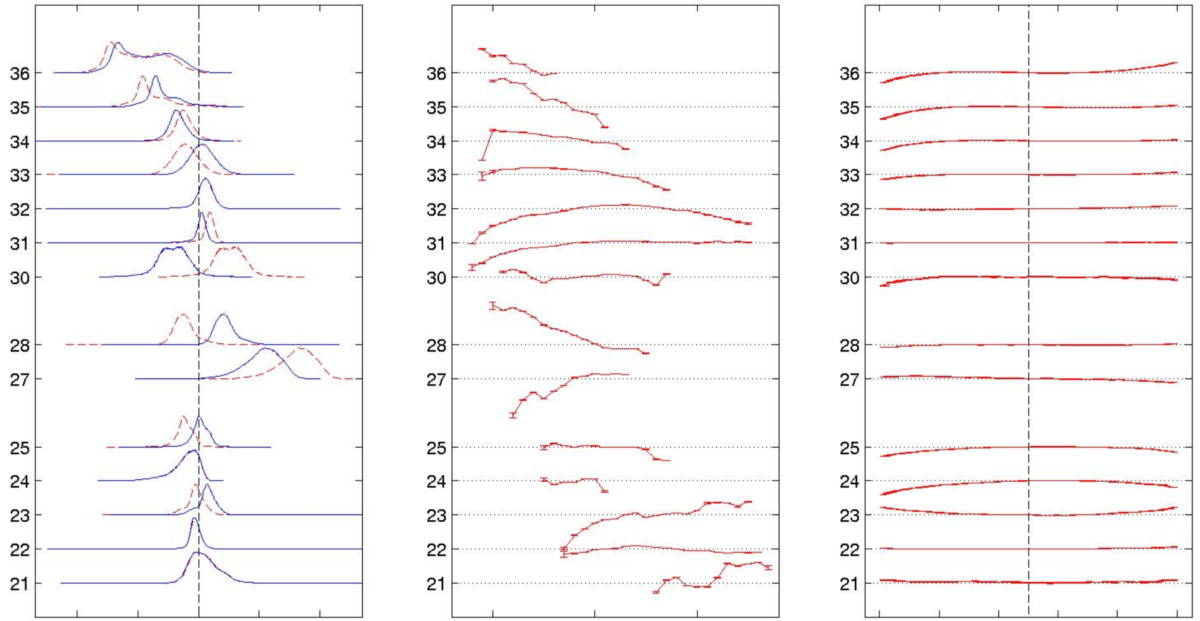
Blue=accounting for ce with mean correction from standard atmospheres

Band	Diff	CE	Diff	Std	N
21	-0.32	-0.01	-0.33	0.18	80388
22	-0.14	-0.00	-0.14	0.25	246112
23	-0.15	0.19	0.04	0.20	277755
24	-0.22	-0.08	-0.30	0.25	511821
25	-0.41	0.38	-0.03	0.18	573261
27	1.24	-0.57	0.67	0.39	1098476
28	-0.29	0.67	0.38	0.21	1250087
30	0.21	-0.91	-0.70	0.23	358698
31	0.19	-0.13	0.06	0.09	393559
32	0.13	-0.01	0.12	0.13	401780
33	-0.15	0.21	0.06	0.16	817442
34	0.01	-0.49	-0.48	0.12	1228199
35	-0.72	0.17	-0.55	0.31	1480551
36	-0.92	0.12	-0.81	0.51	2151789

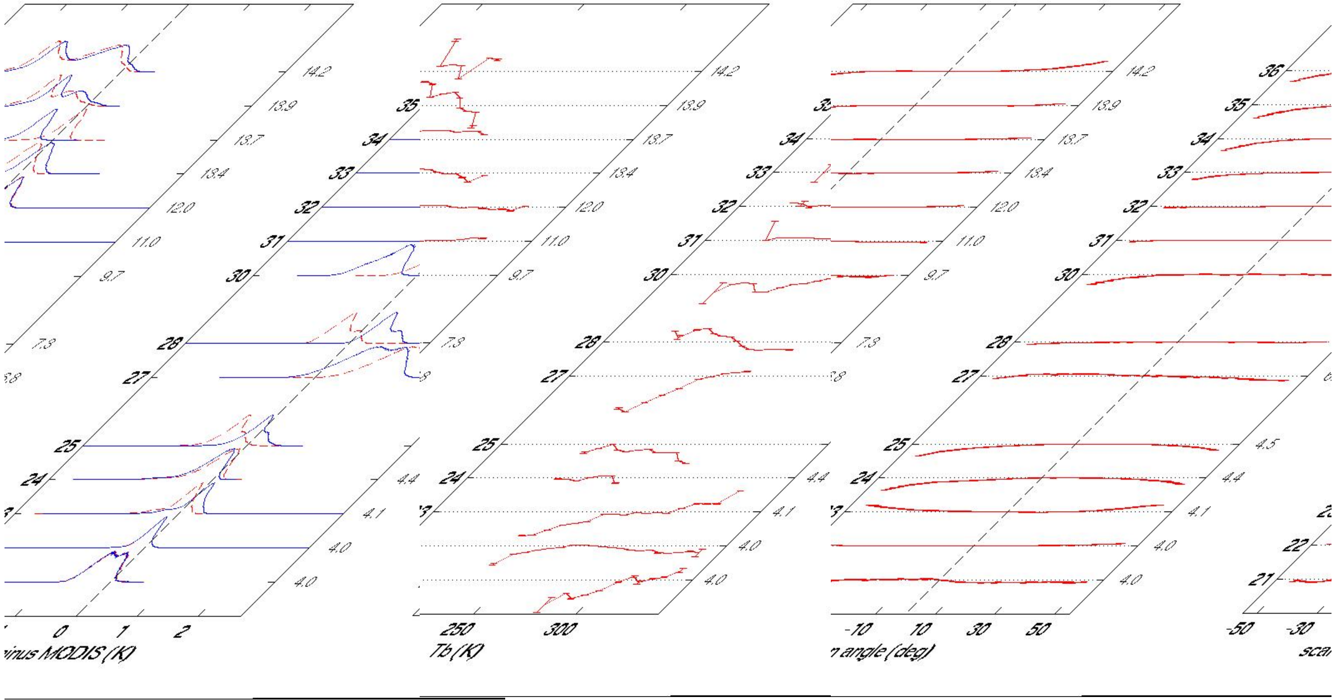


band 36: +1.0 cm-1
band 35: +0.8 cm-1
band 34: +0.8 cm-1
band 33: -0.15 cm-1

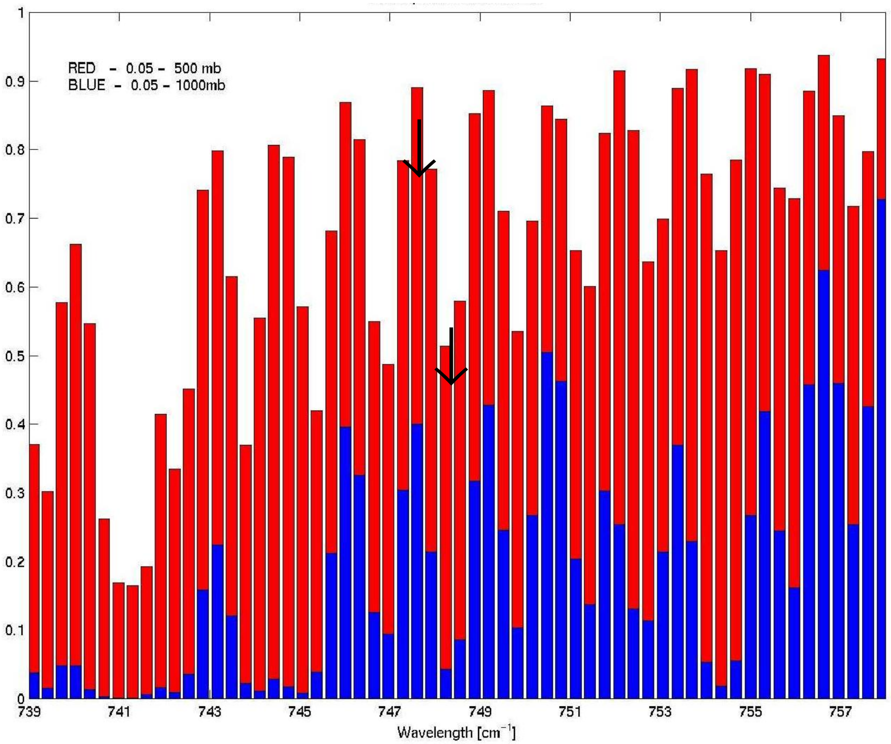
06 Sep 2002:



18 Feb 2004:

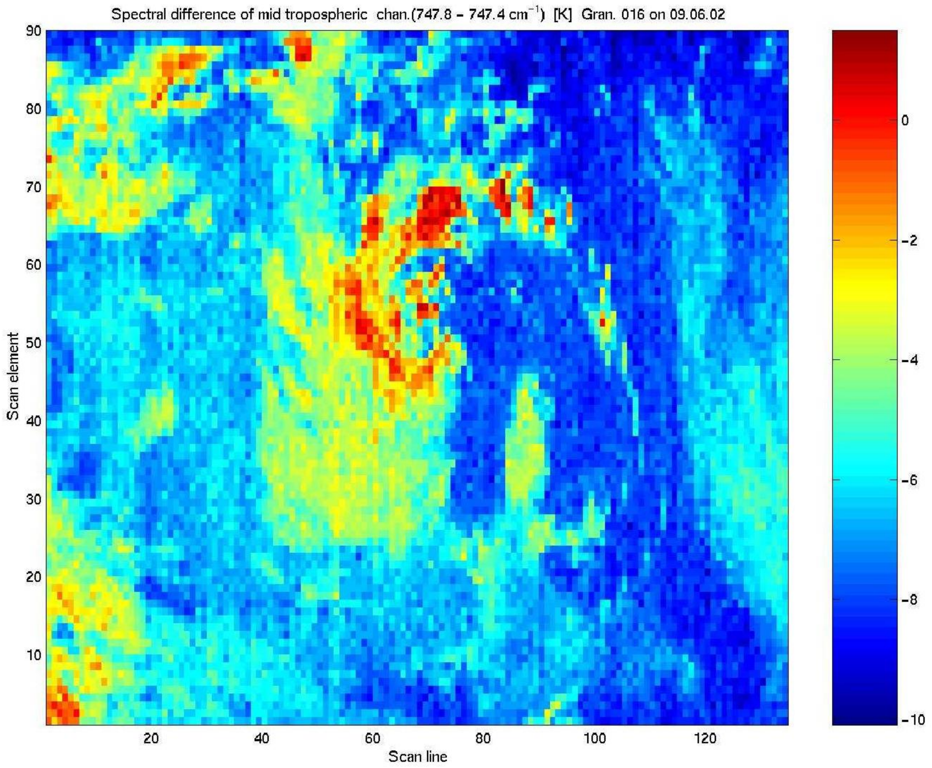


Atmospheric transmittance in



Studying spectral sensitivity with AIRS Data

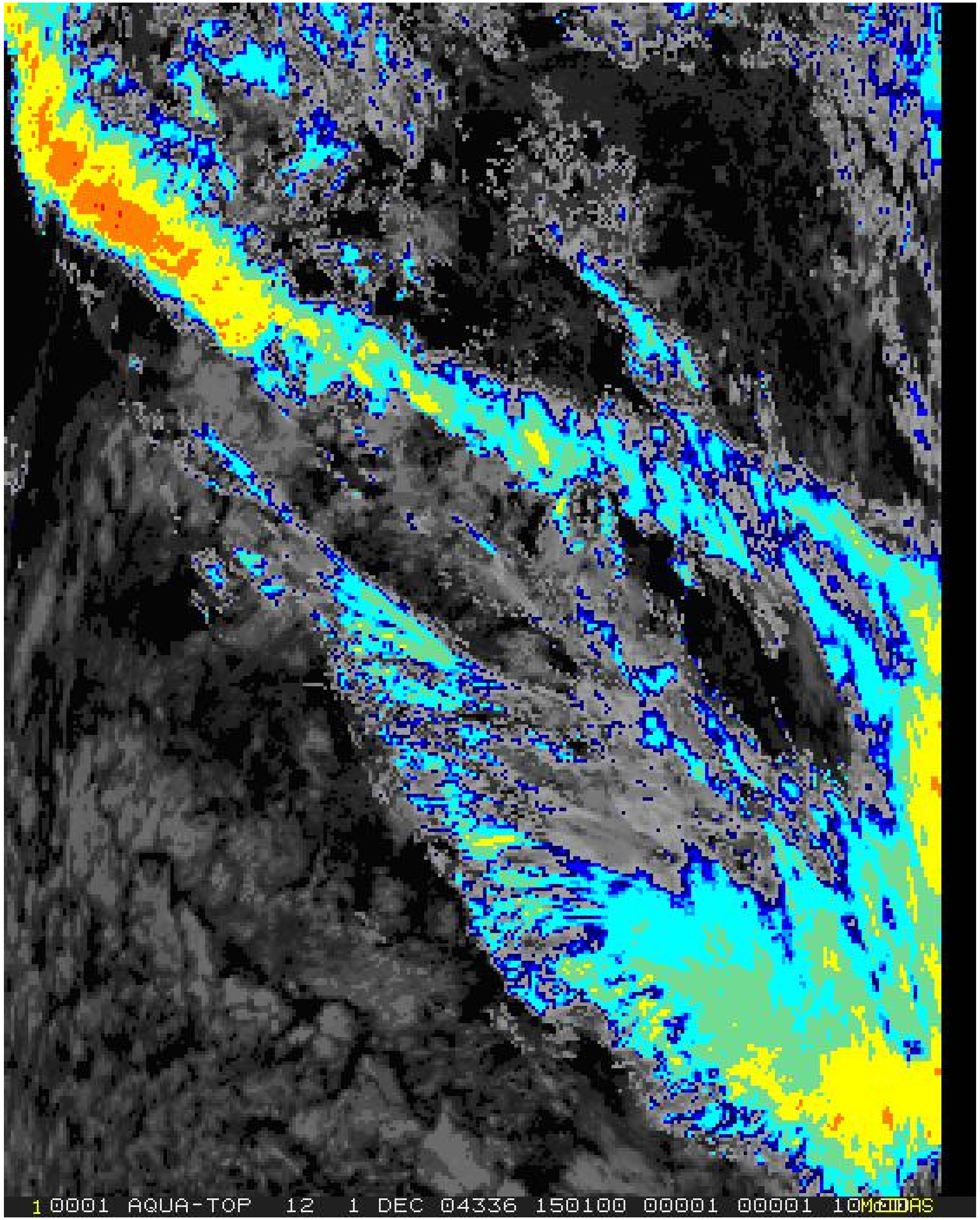
AIRS BT[747.8] – BT[747.4]



Spectral change of 0.4 cm-1 causes BT changes > 8 C

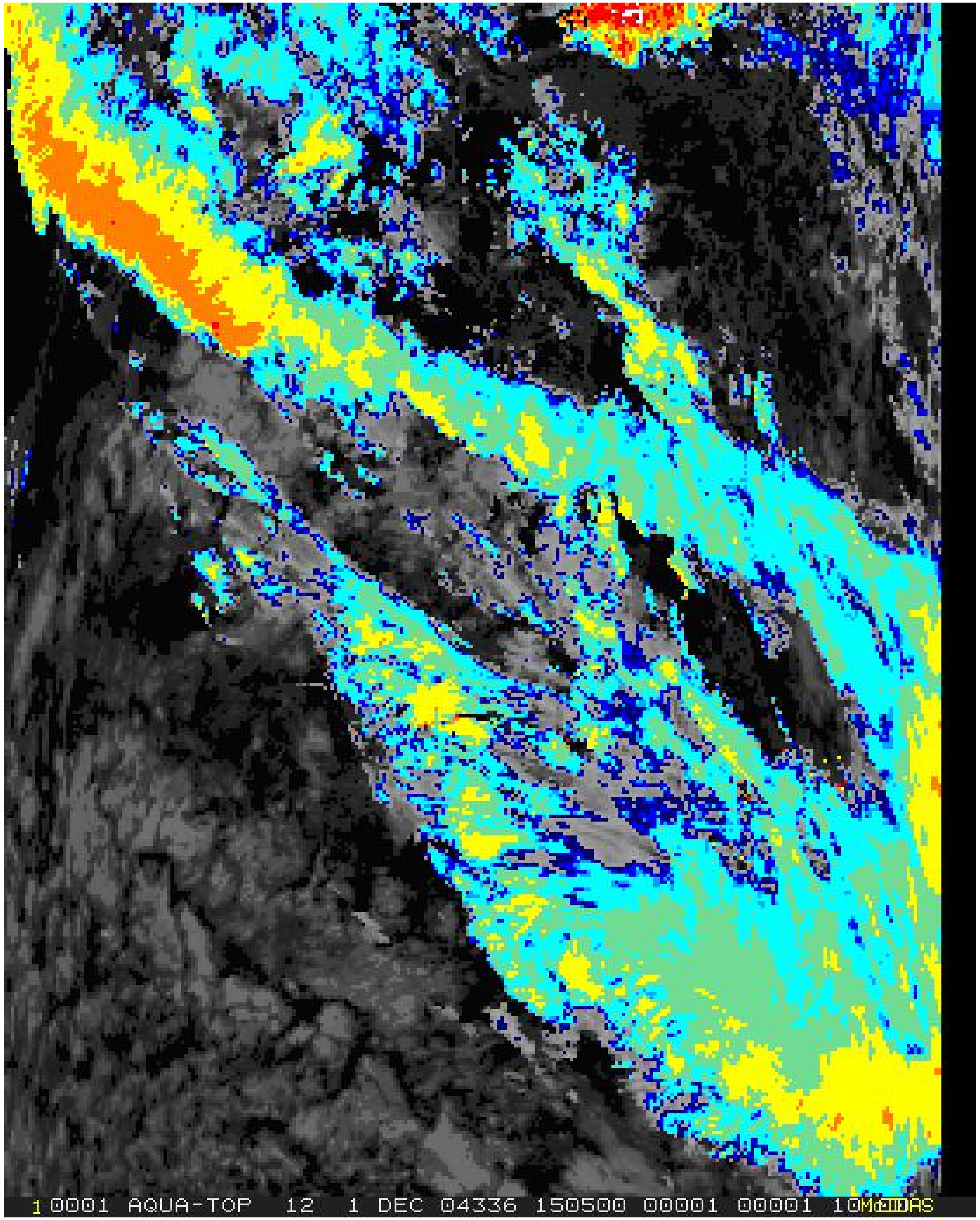
Current CTP (HI clouds)

White: 95 ~ 125
Red: 125 ~ 160
Orange:160~190
Yellow: 190~225
Aqua: 225 ~ 260
Cyan: 260~300
Sky: 300~ 330
Blue: 330~360
Navy: 360~ 390



CTP with SRF Adjustment
(band 34,35,36)
(HI clouds)

White: 95 ~ 125
Red: 125 ~ 160
Orange:160~190
Yellow: 190~225
Aqua: 225 ~ 260
Cyan: 260~300
Sky: 300~ 330
Blue: 330~360
Navy: 360~ 390



Challenges for Climate data sets

Spectral consistency
(if not possible at least spectral knowledge)

Accurate radiative transfer
(accommodating seasonal and interannual CO2 changes)

Orbit constancy
(maintain equator crossing times for leos)

Consistency with the Global Observing System
(using NWP data assimilation)

Reprocessing opportunities
(adjusting algorithms with experience)

GCOS Climate Monitoring Principles

Satellite systems for monitoring climate need to:

(a) Take steps to make radiance calibration, calibration-monitoring and satellite-to-satellite cross-calibration of the full operational constellation a part of the operational satellite system; and

(b) Take steps to sample the earth system in such a way that climate-relevant (diurnal, seasonal, and long-term interannual) changes can be resolved.

Thus satellite systems for climate monitoring should adhere to the following specific principles:

11. Constant sampling within the diurnal cycle (minimizing the effects of orbital decay and orbit drift) should be maintained.

12. A suitable period of overlap for new and old satellite systems should be ensured for a period adequate to determine inter-satellite biases and maintain the homogeneity and consistency of time-series observations.

13. Continuity of satellite measurements (i.e. elimination of gaps in the long-term record) through appropriate launch and orbital strategies should be ensured.

14. Rigorous pre-launch instrument characterization and calibration, including radiance confirmation against an international radiance scale provided by a national metrology institute, should be ensured.

15. On-board calibration adequate for climate system observations should be ensured and associated instrument characteristics monitored.

16. Operational production of priority climate products should be sustained and peer-reviewed new products should be introduced as appropriate.

17. Data systems needed to facilitate user access to climate products, metadata and raw data, including key data for delayed-mode analysis, should be established and maintained.

18. Use of functioning baseline instruments that meet the calibration and stability requirements stated above should be maintained for as long as possible, even when these exist on de-commissioned satellites.

19. Complementary in-situ baseline observations for satellite measurements should be maintained through appropriate activities and cooperation.

20. Random errors and time-dependent biases in satellite observations and derived products should be identified.