Use of COSMIC GPS RO Data for Verification of Moisture Analysis and Prediction of an Atmospheric River Event

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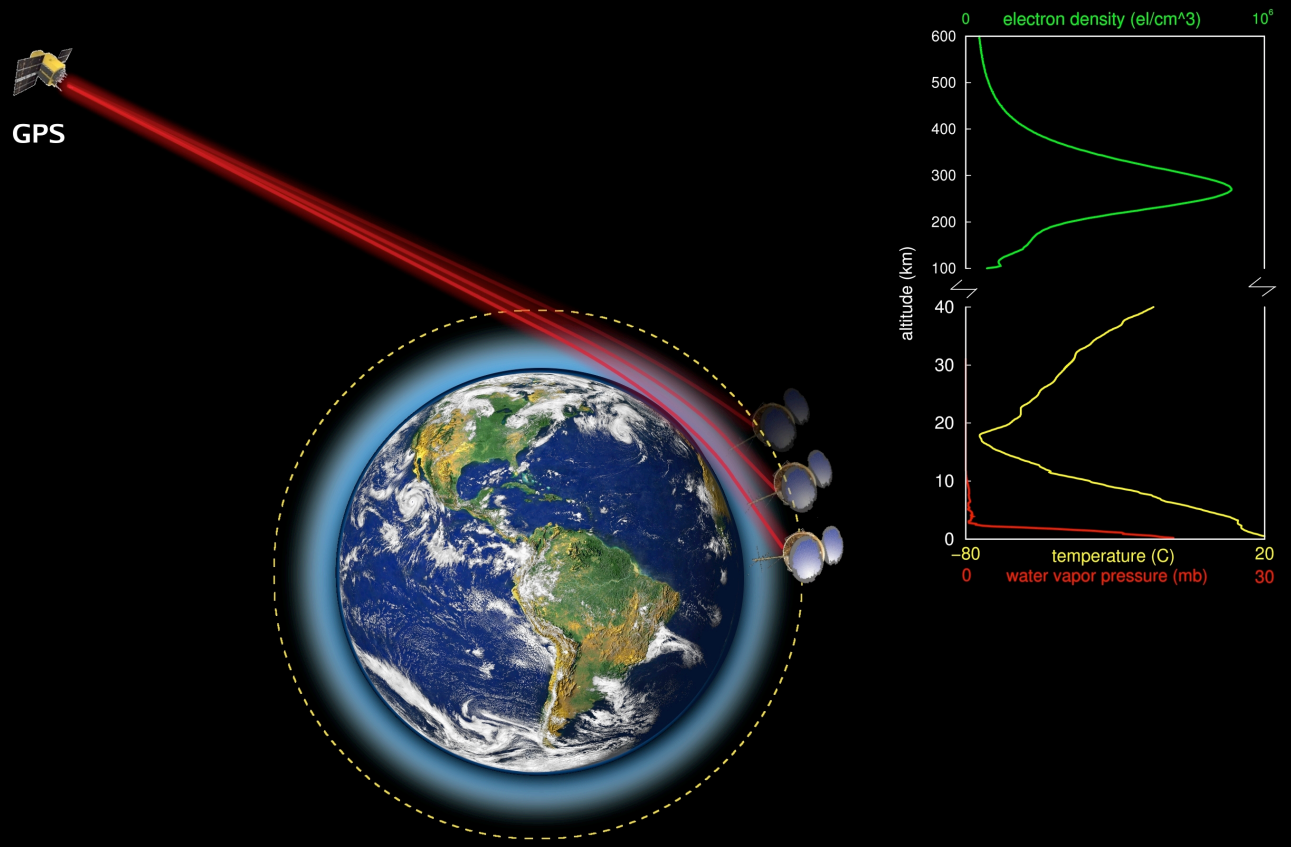
Outline

- Characteristics of GPS RO observations
- The Atmospheric River event of Nov 2006
- Use of GPS RO data for the analysis of Atmospheric River
- Use of GPS RO data to evaluate SSM/I retrieval
- Assimilation of GPS RO data and its impact on the prediction of Atmospheric River

Characteristics of GPS RO Observations



COSMIC / FORMOSAT - 3

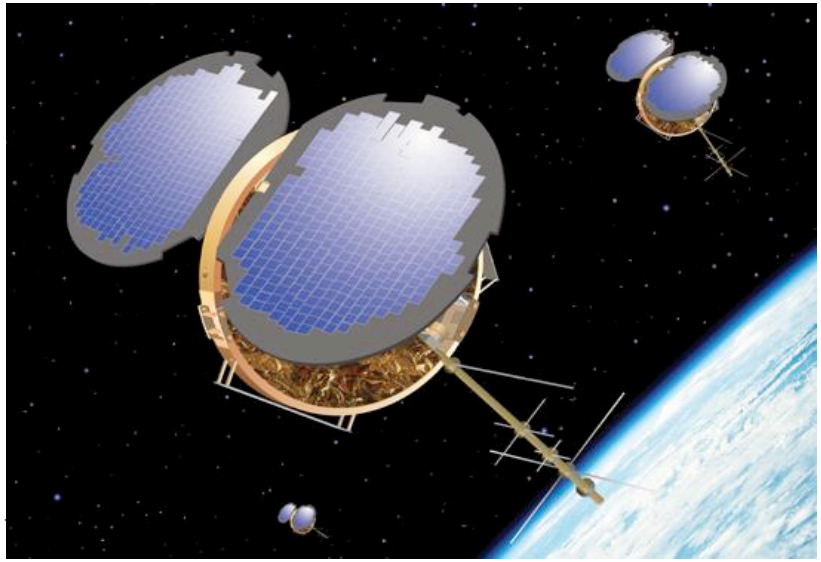
Profiling the Atmosphere by Radio Occultation

Characteristics of GPS RO Data

- **Limb sounding geometry complementary to ground and space nadir viewing instruments**
- **High accuracy**
- **High vertical resolution**
- **All weather-minimally affected by aerosols, clouds or precipitation**
- **Independent height and pressure**
- **Requires no first guess sounding**
- **Independent of radiosonde calibration**
- **No instrument drift**
- **No satellite-to-satellite bias**

COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate)

- 6 Satellites was launched:
  01:40 UTC 15 April 2006
- Three instruments:
  GPS receiver, TIP, Tri-band beacon
- Weather + Space Weather data
- Global observations of:
  Pressure, Temperature, Humidity
  Refractivity
  Ionospheric Electron Density
  Ionospheric Scintillation
- Demonstrate quasi-operational GPS limb sounding coverage in near-real time
- Climate Monitoring

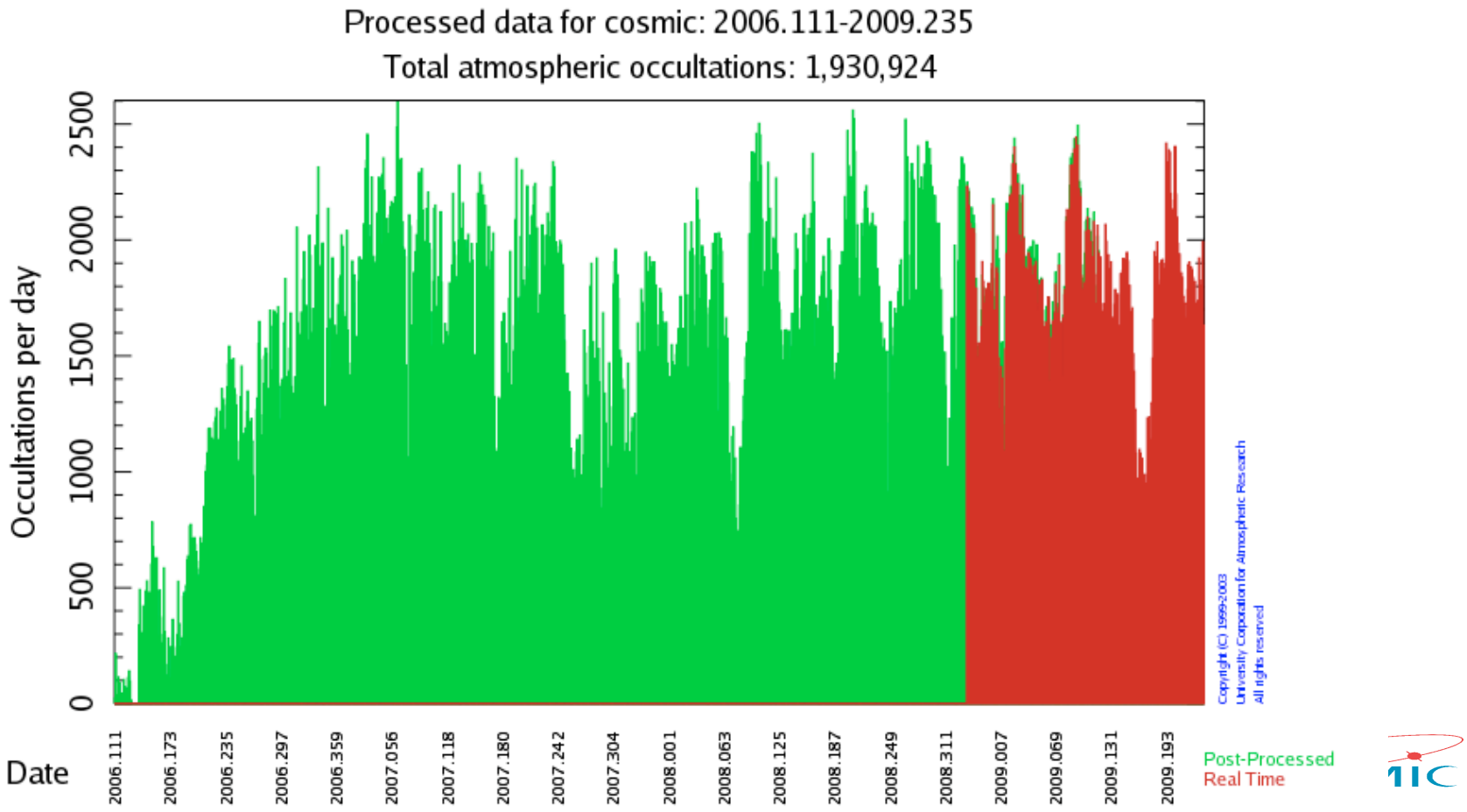


A Joint Taiwan-U.S. Mission

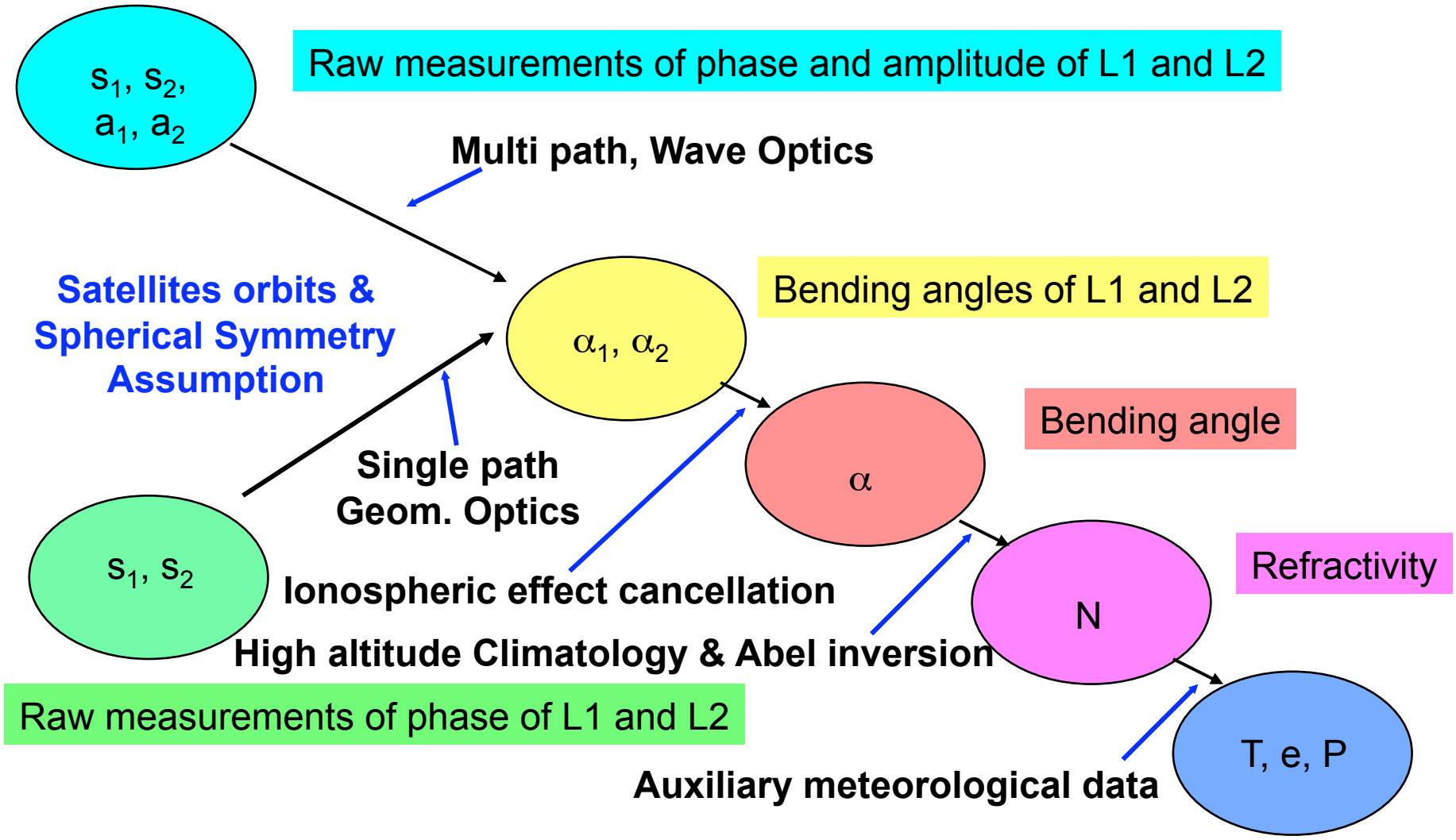
FORMOSAT-3 in Taiwan

COSMIC

1.93 Million Profiles in Real Time
4/21/06 – 8/26/2009
1131 registered users from 52 countries



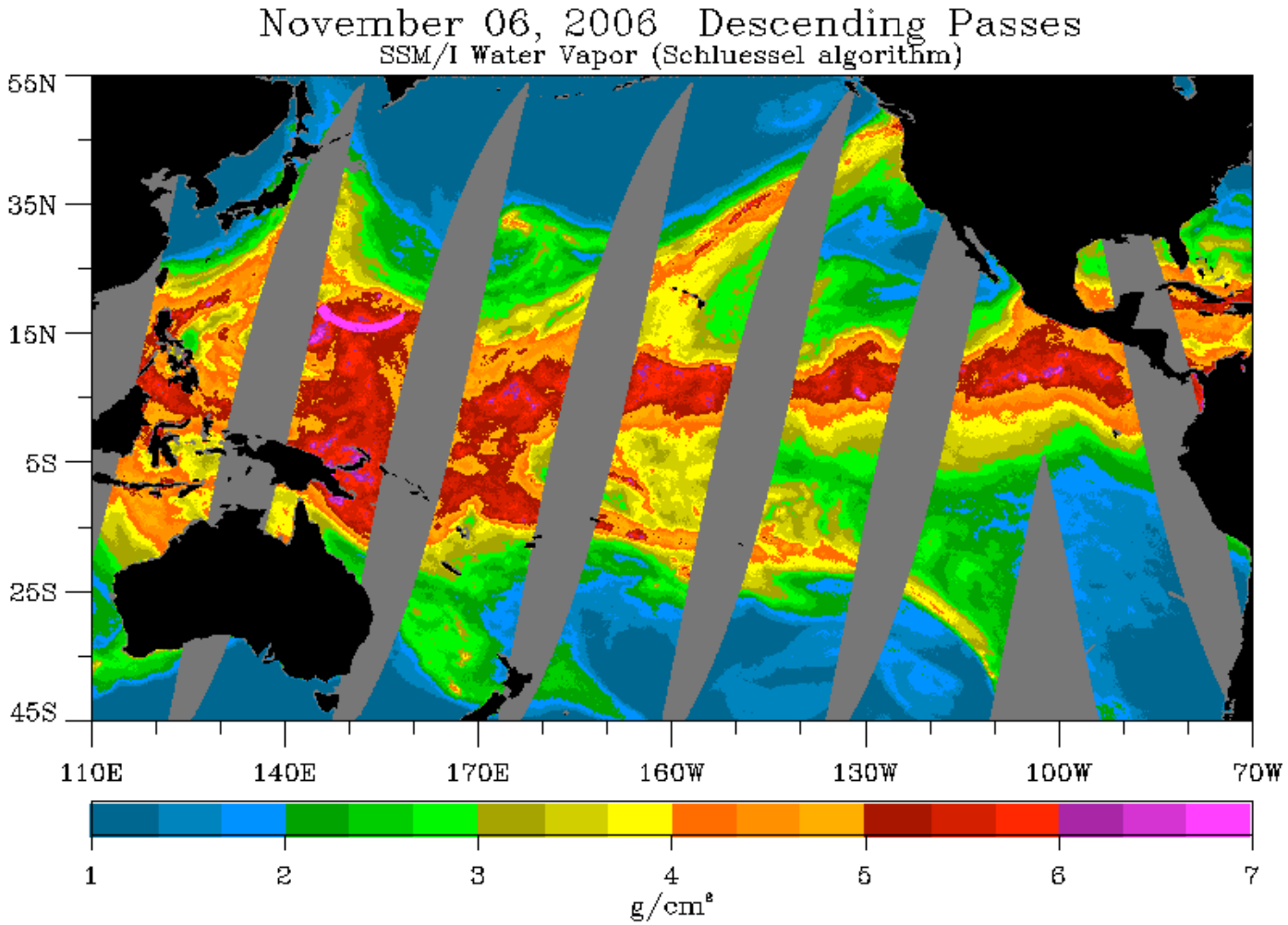
GPS radio occultation measurements & processing

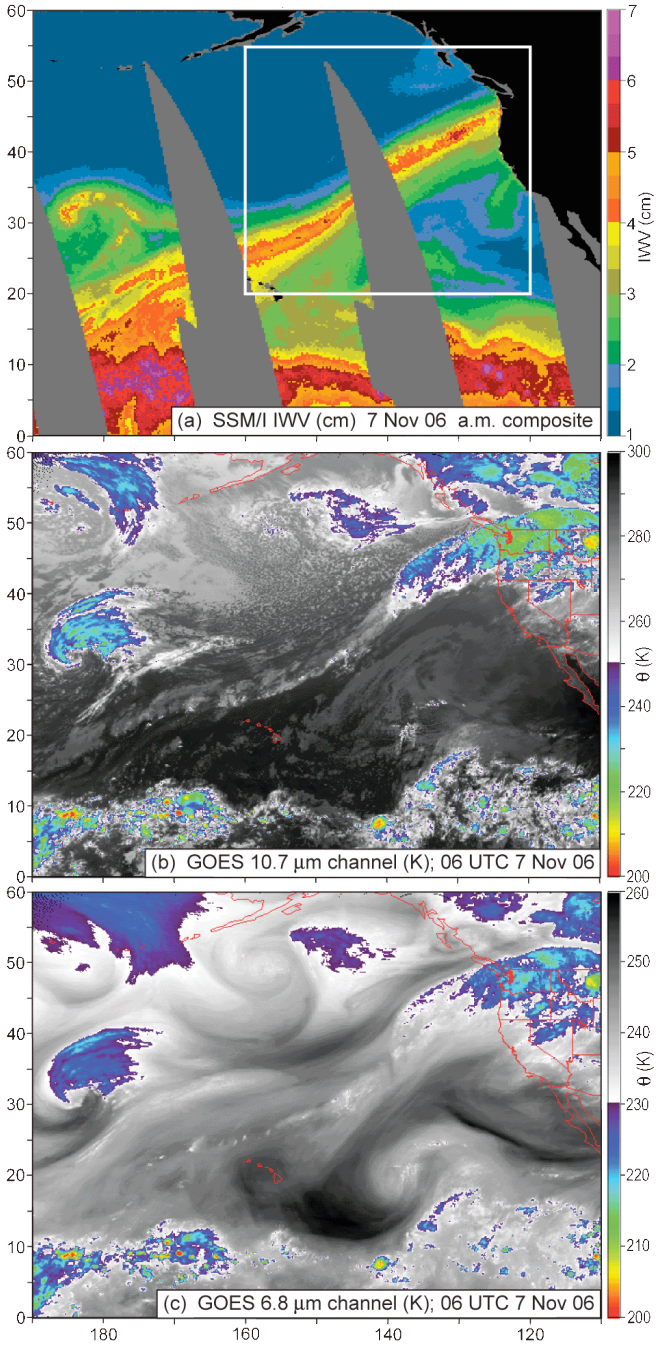


See Kuo et al. (2000, TAO, 11 (1), 157-186) for details

Atmospheric River Event of November 2006

Atmospheric River case: Nov 6-8, 2006



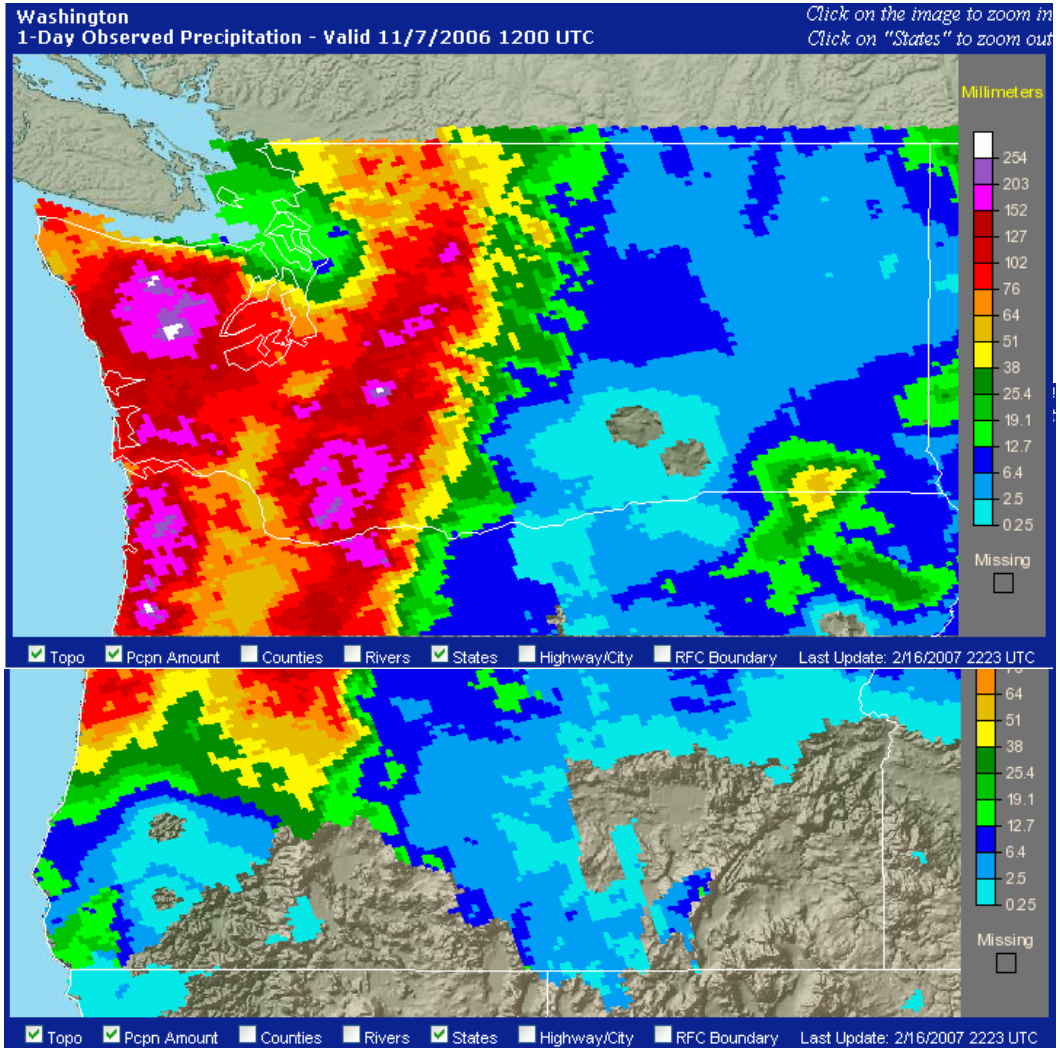


Satellite imagery on the morning of 7 November 2006: (a) composite SSM/I image of integrated water vapor (IWV; cm) constructed from polar-orbiting swaths between ~0200 and 0615 UTC; (b) GOES 10.7-µm channel (i.e., infrared) image of cloud-top brightness temperature (θ, K) at 0600 UTC; and (c) GOES 6.8-µm channel (i.e., water vapor) image of brightness temperature (θ, K)

GOES images do not tell you where the moisture is, and how it is distributed.

From Neiman et al. (2008)

Observed Daily Precipitation



24-h precipitation

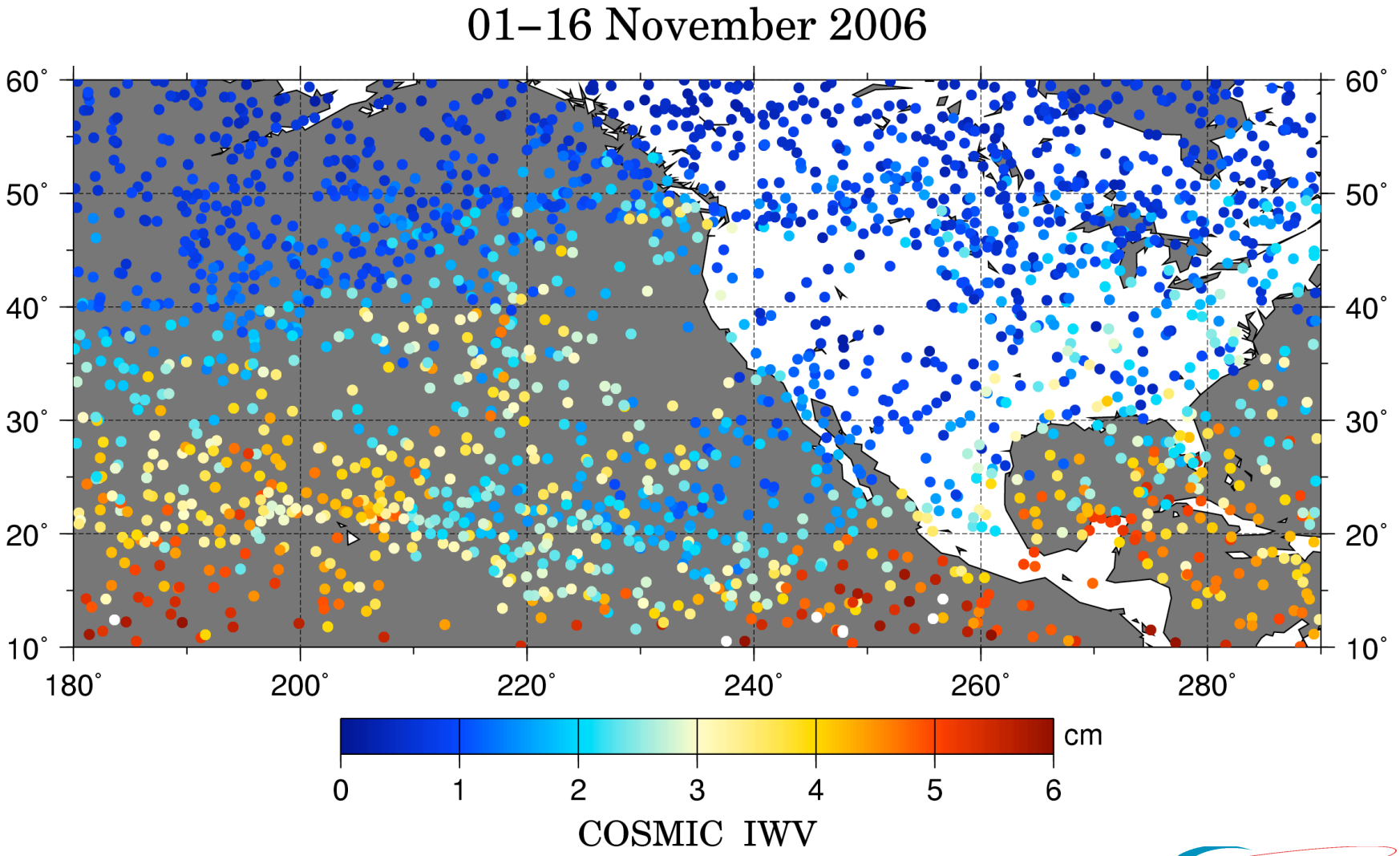
Ending at

1200 UTC 7 November 2006

Atmospheric River Event of 6-7 November 2006

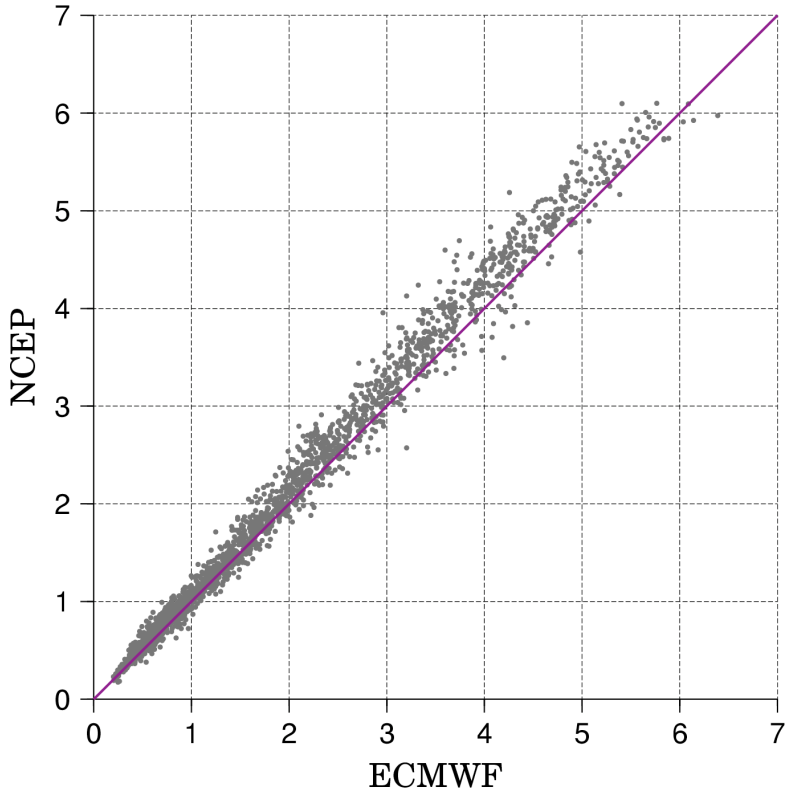
The aftermath of flooding and a debris flow on the White River in Oregon, on 7 November 2006. This view is of the down-river side of the White River Bridge on Highway 35, southeast of Mt. Hood. Photo courtesy of Doug Jones, Mt. Hood National Forest

PW estimated from COSMIC GPS RO data

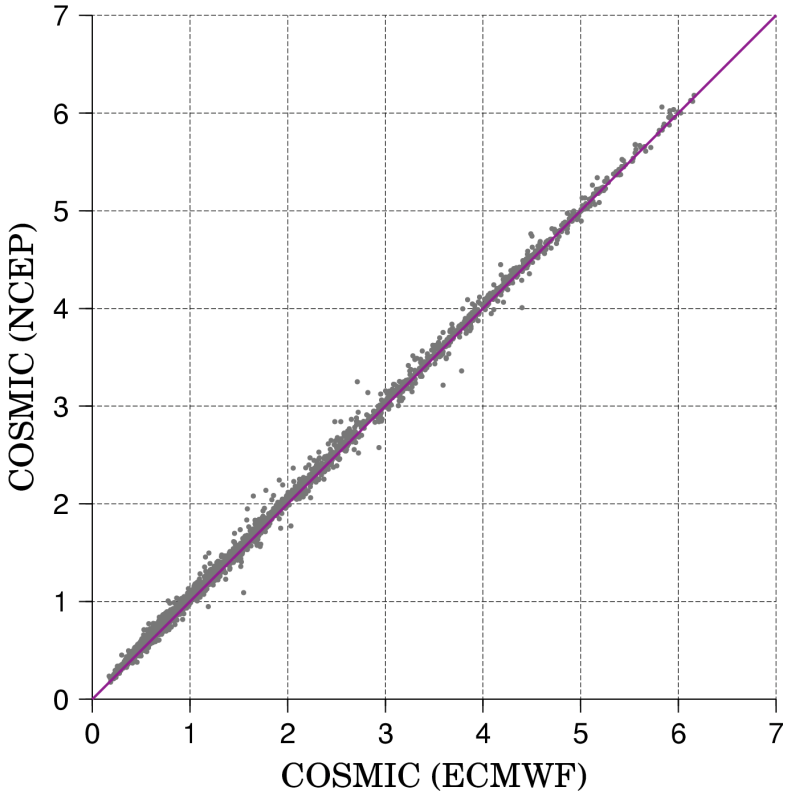


Comparison of PW data from COSMIC and global analyses

PW derived from NCEP or ECMWF analyses

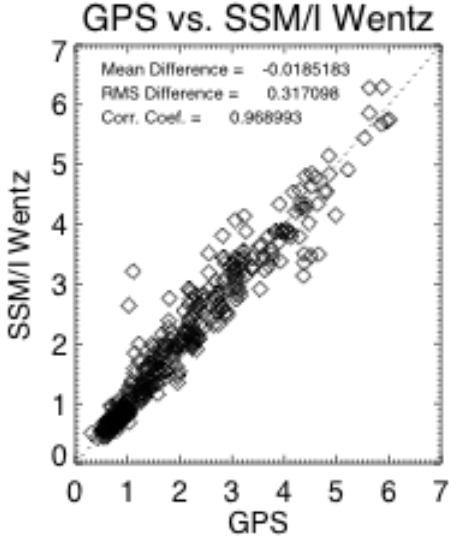


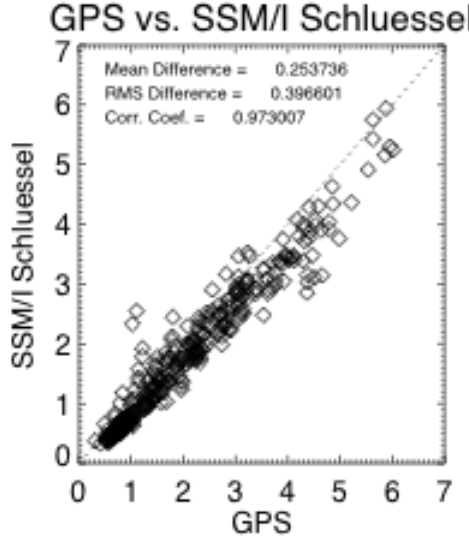
PW retrieved from COSMIC GPS RO data using NCEP or ECMWF analysis as first guess

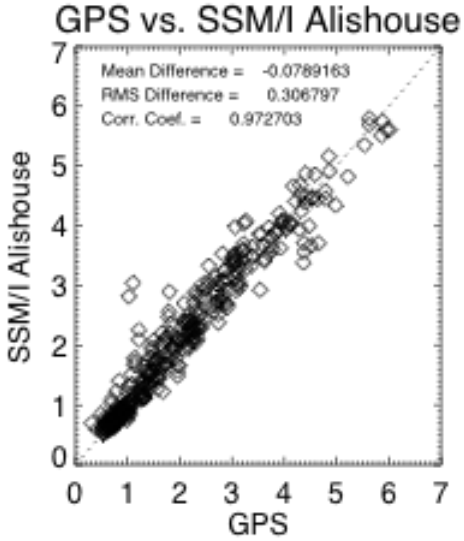


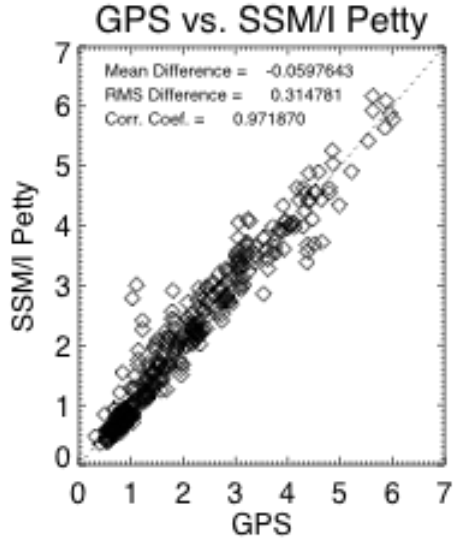
From: Wee and Kuo (2007)

Comparison of SSM/I retrieval with COSMIC

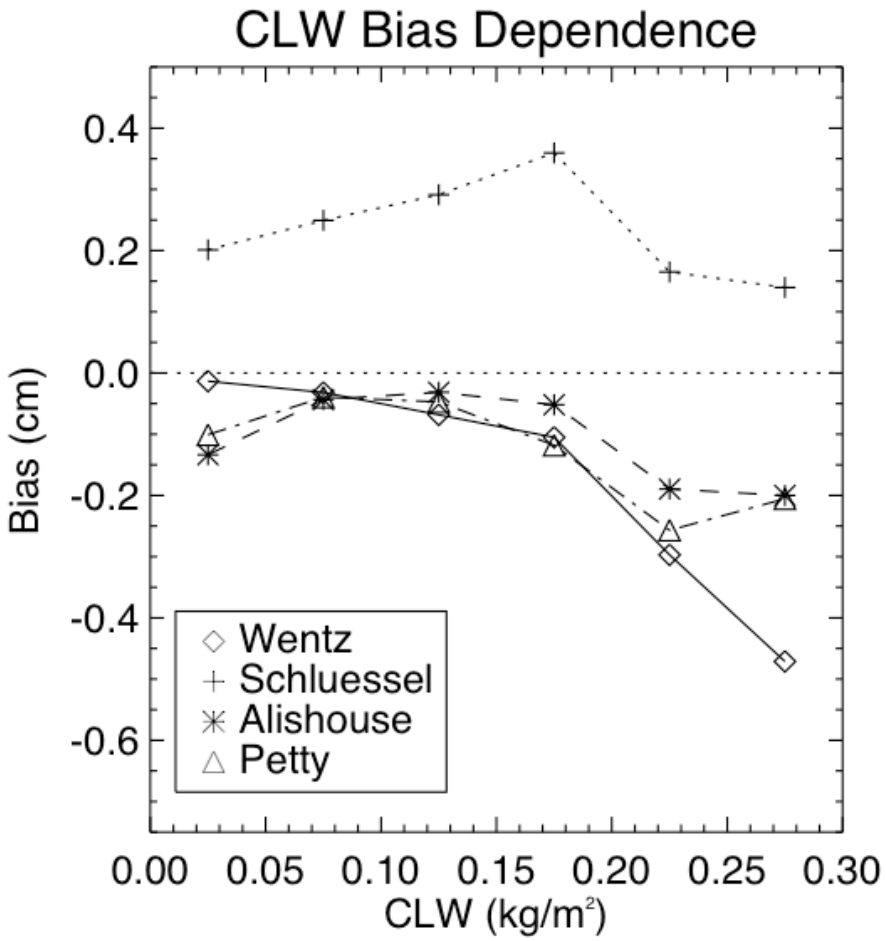








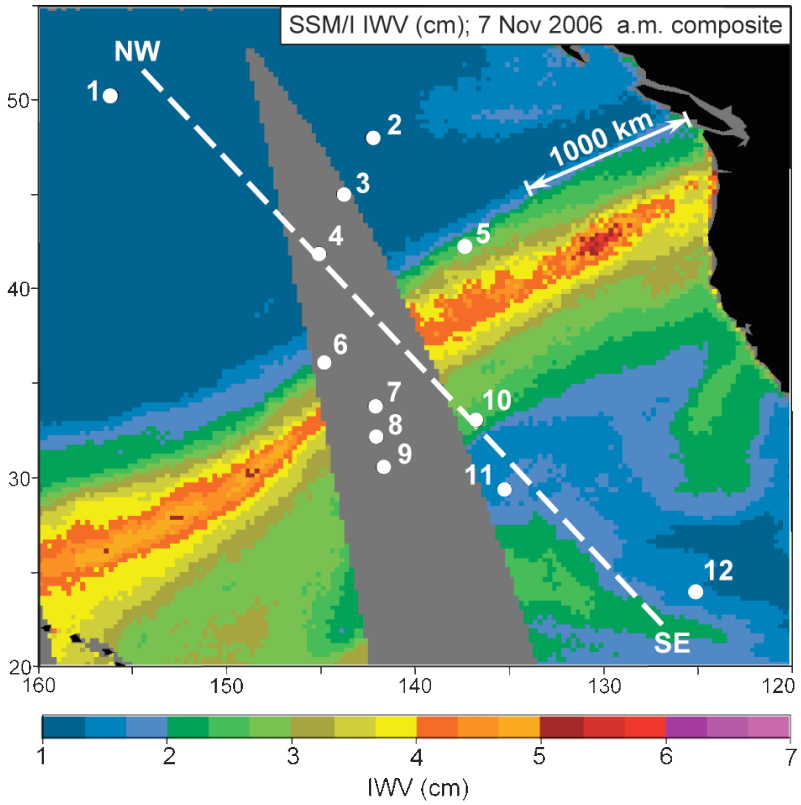
Bias of SSM/I retrieval compared with COSMIC

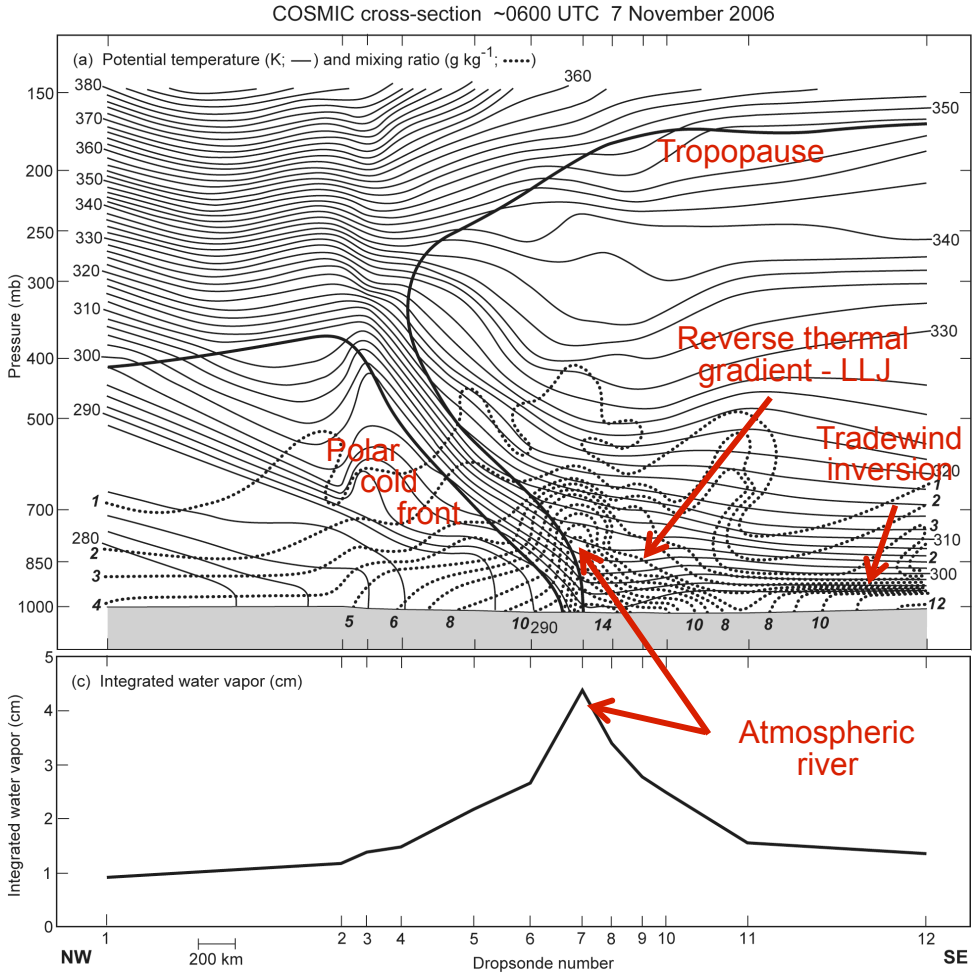


SSM/I retrieval shows visible bias when clouds are present

The Schluessel SSM/I retrieval algorithm clearly shows high bias

COSMIC-Derived Cross Section of an Atmospheric River





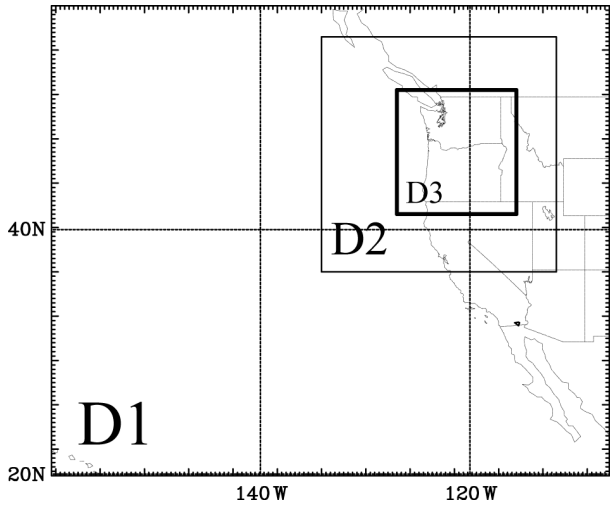
- 12 COSMIC soundings used to construct X-section along NW-SE axis through the AR
- The COSMIC soundings yield cross-sectional thermodynamic structures comparable in character and detail to previous aircraft-based dropsonde surveys.

Neiman et al. (2008), Mon. Wea. Rev.

Assimilation of GPS RO Data

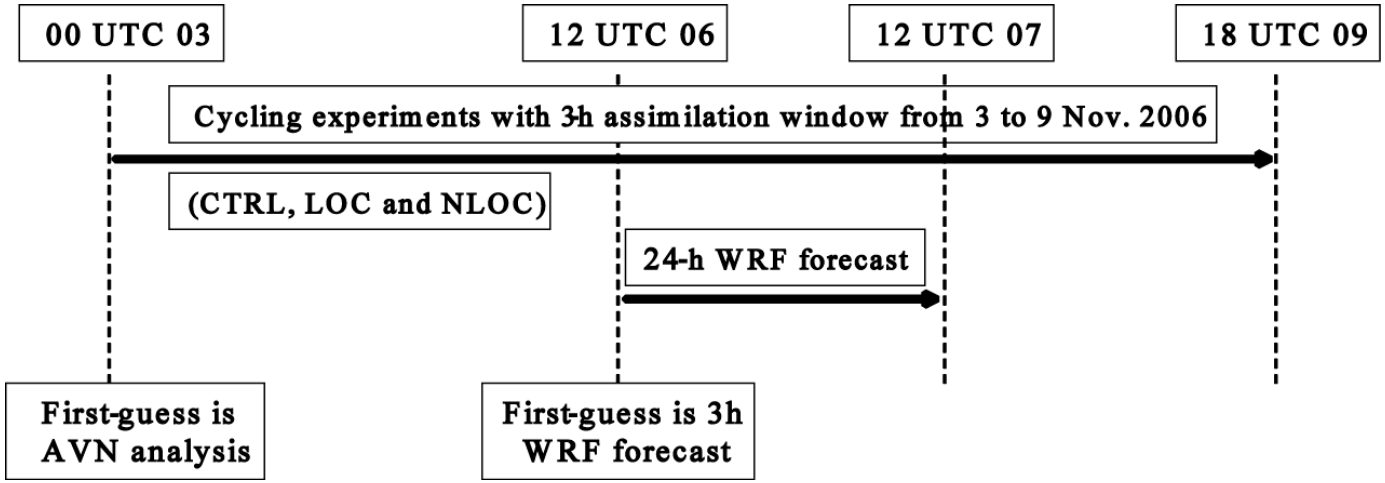
Experiment Setup

- System: NCEP Gridpoint Statistical Interpolation (GSI) + WRF ARW
- Case: AR took place in the early of Nov.2006
- Setup:
  - ❖ Cycling Assimilation: 36km38L; Ptop: 50hPa
  - ❖ 24h Forecast: triple nested domain, 36x12x4km

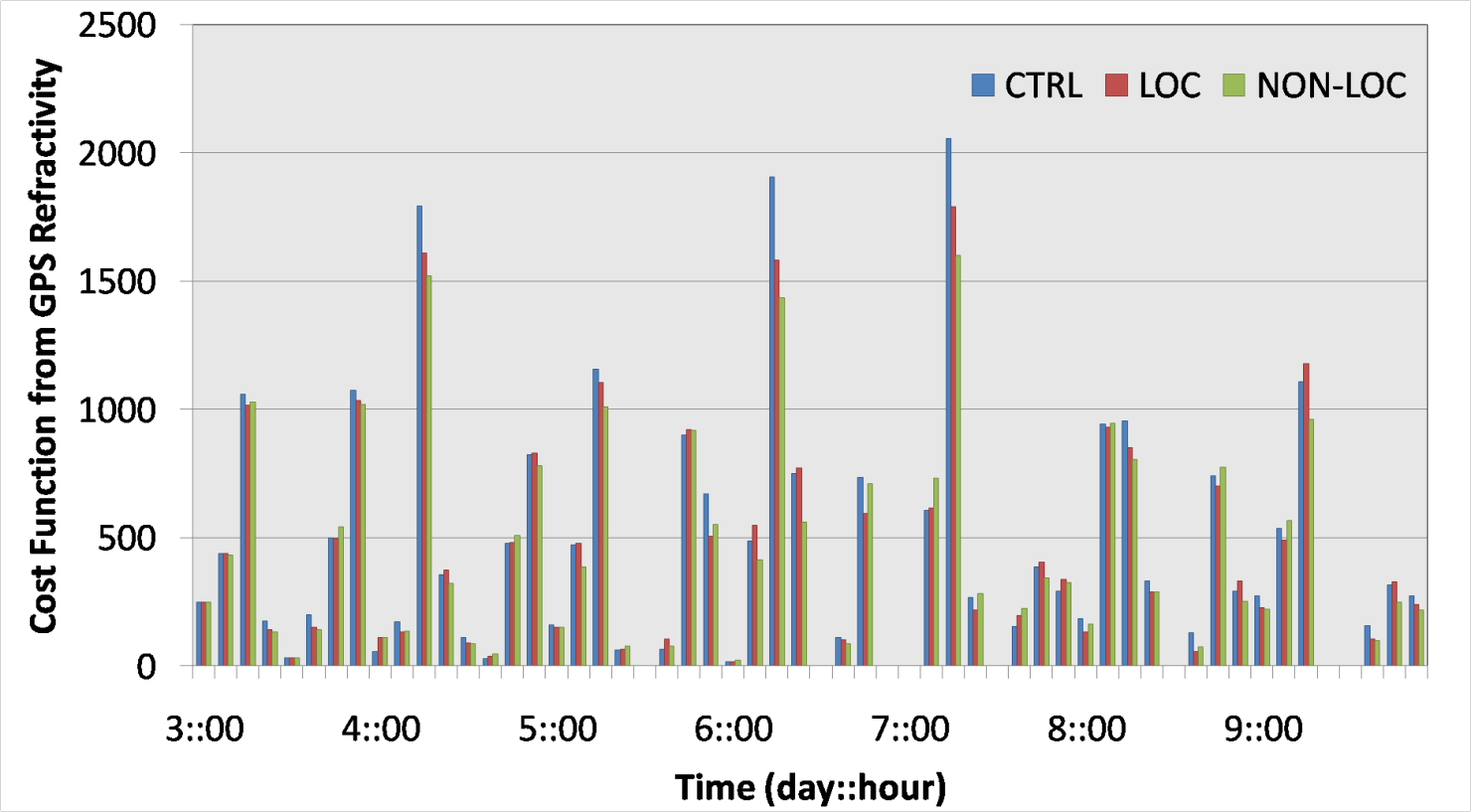


Three runs:

- ➢ CTRL: operational observation data;
- ➢ LOC: CTRL+GPS with Local operator
- ➢ NON: CTRL+GPS with Non-local operator

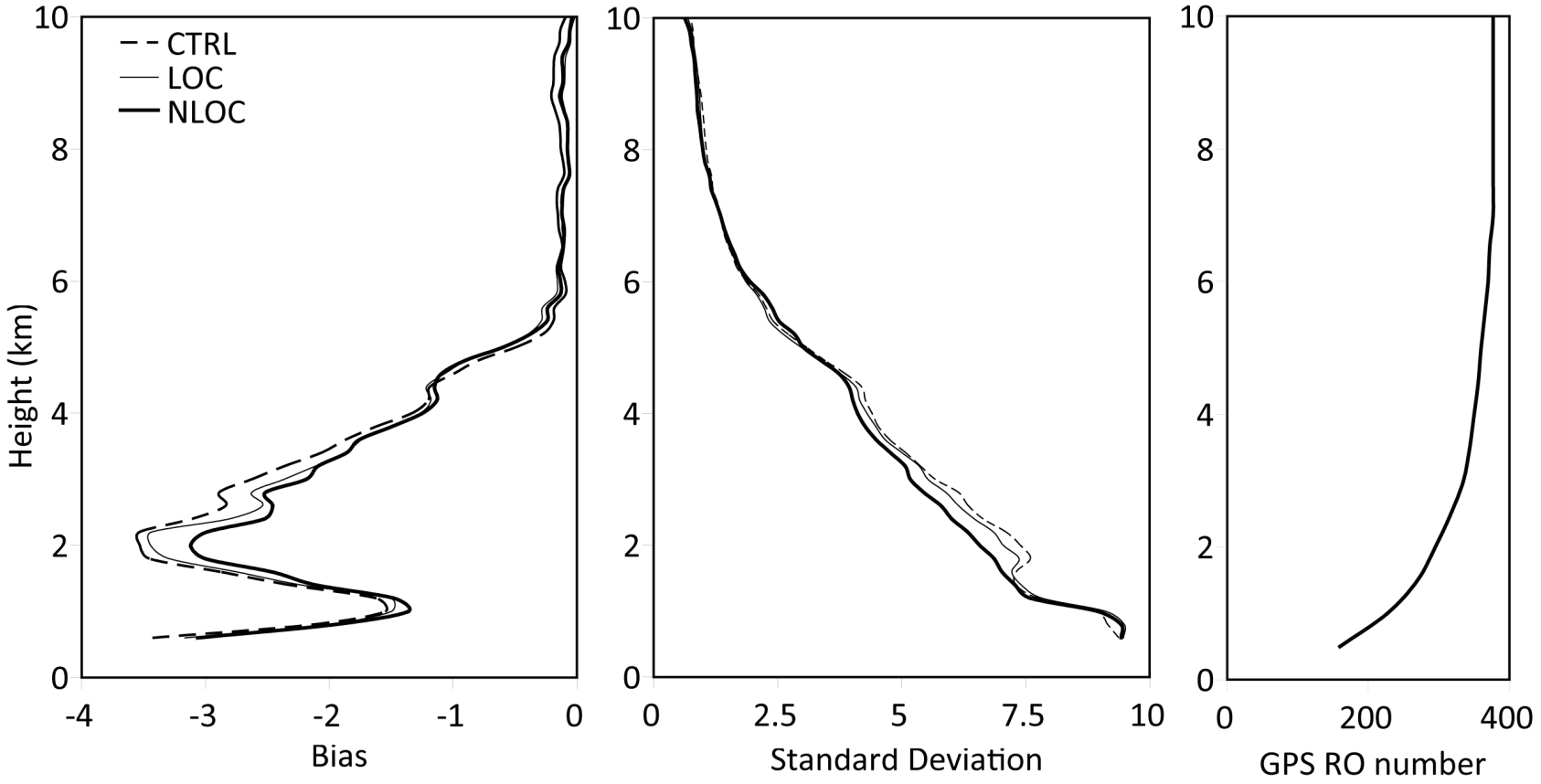


Cycling: 3h Forecast Verification



The 3-h WRF forecasts fit to GPS refractivity with time. The value is cost function for CTRL (blue), LOC (red) and NON-LOC (green) runs, respectively.

Cycling: 3h Forecast Verification …



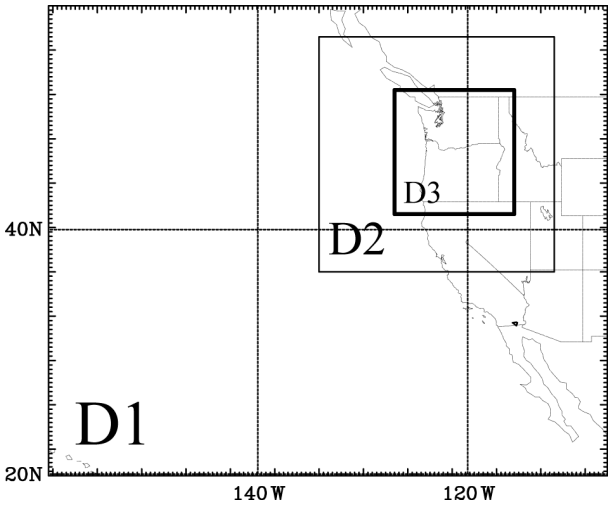
The statistics of difference for the assimilation domain from 0000 UTC 03 to 1800 UTC 09 November 2006. Bias (left panel) and Standard Deviation (middle panel) errors of 3-h WRF forecasts verified against GPS RO refractivity for CTRL (dashed curve), LOC (thin curve) and NON-LOC (thick curve). The right panel shows the total number of verifying GPS soundings at each level during one-week cycling period.

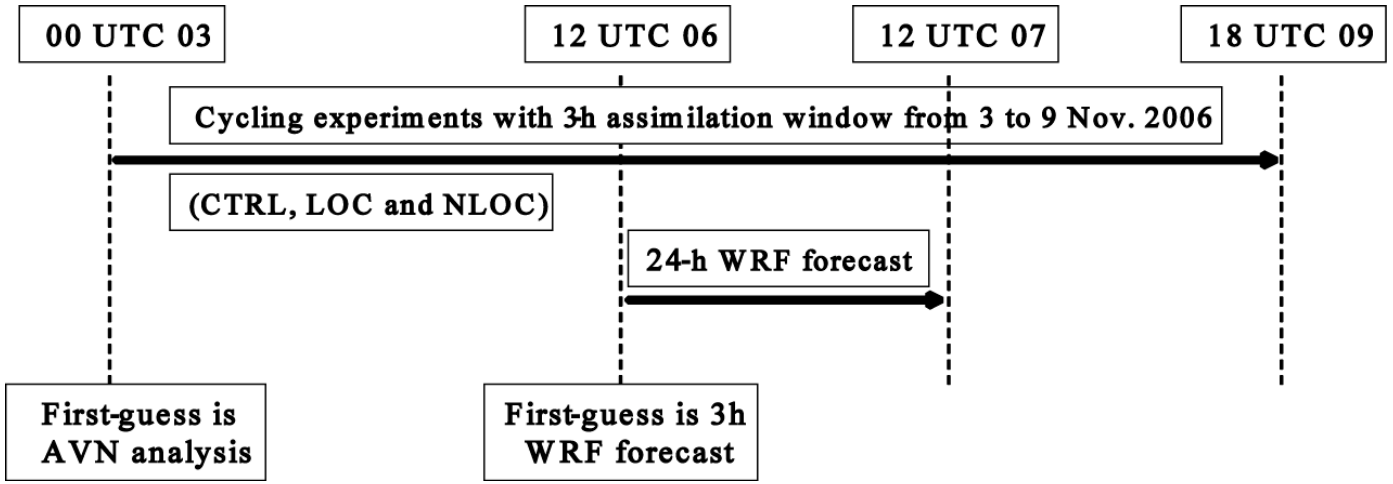
GPS Impact on 24h WRF forecast

24h forecast starting from 1200 UTC 6,

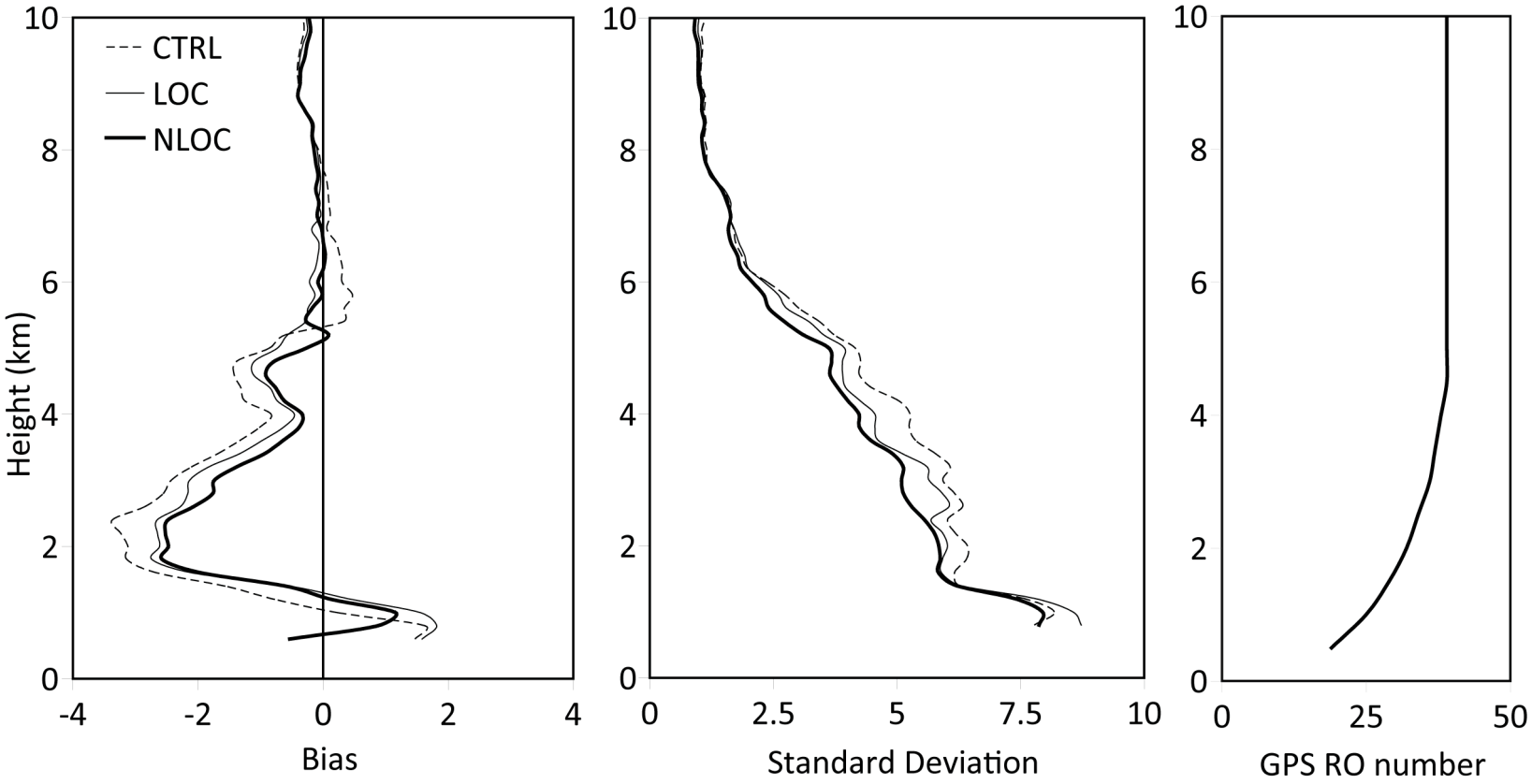
3 domains nested. Assimilation on domain D1.

D3 only covers Washington and Oregon states.



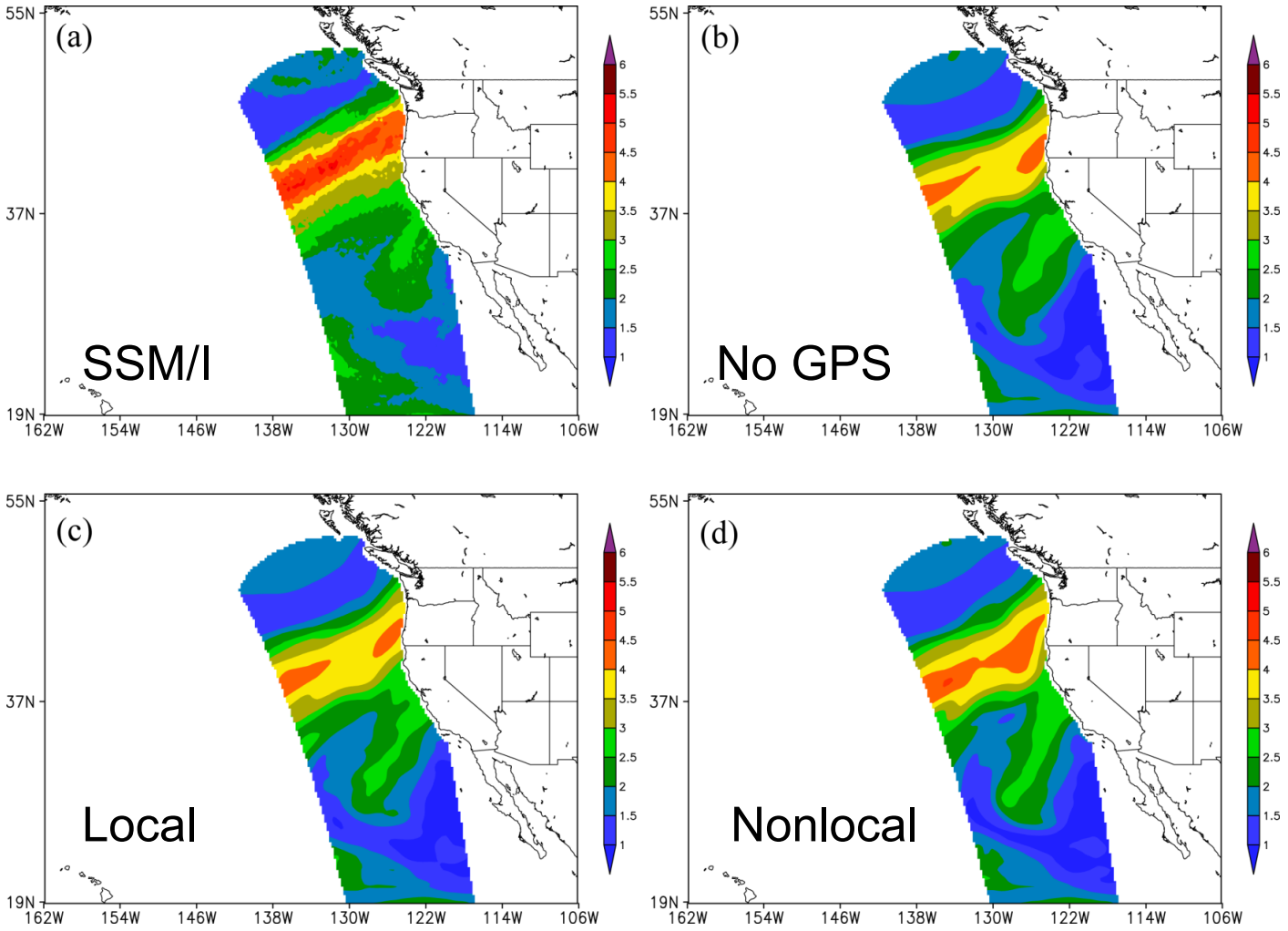


Forecast: Verification with GPS Refractivity



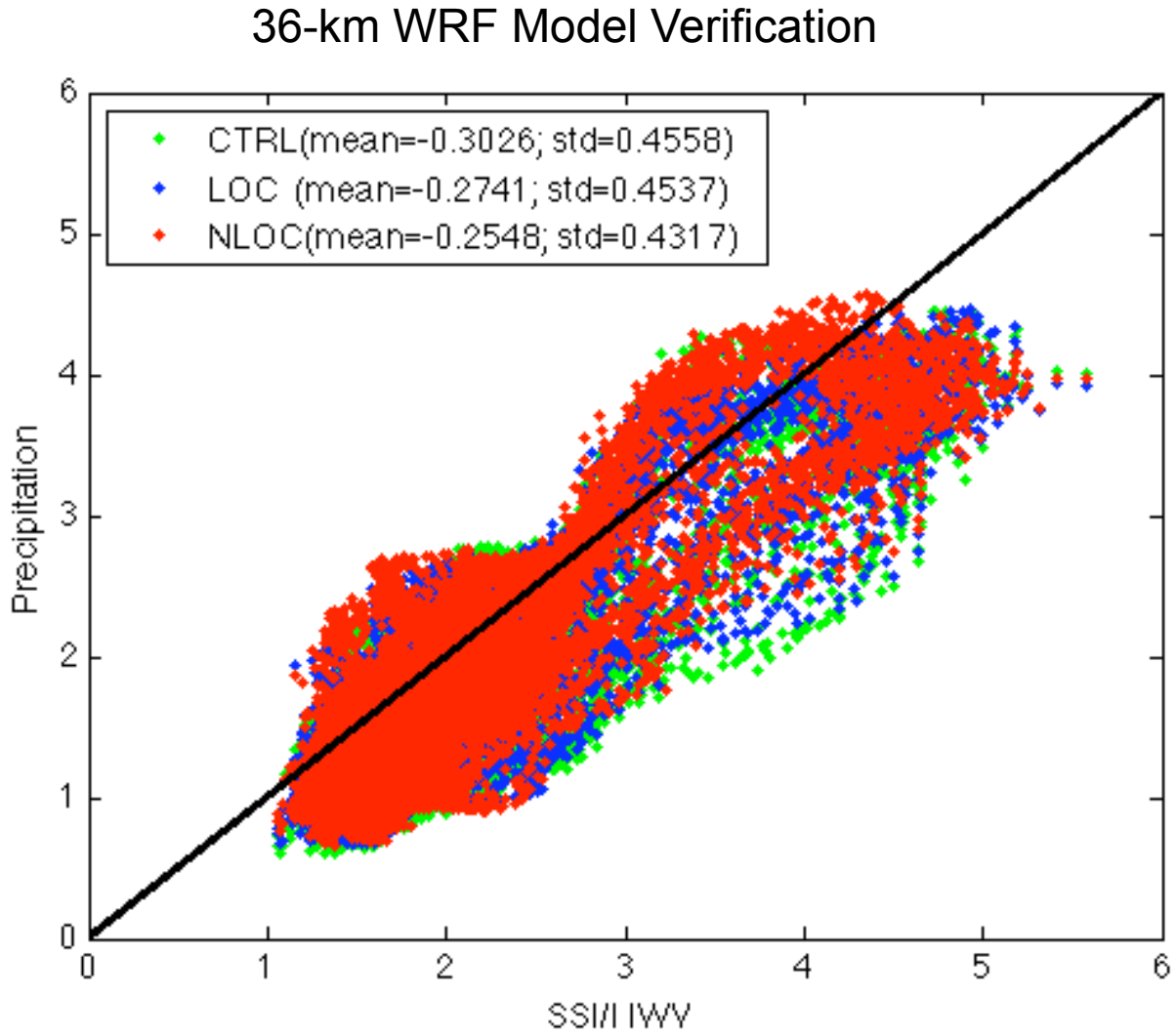
Bias and Standard Deviation of 24h forecast fit to GPS Refractivity on domain D1

Forecast: Verification with SSM/I



Valid at 0200 UTC 7 November 2006 on domain D1

Forecast: Verification with SSM/I …



Forecast: Verification with SSM/I …

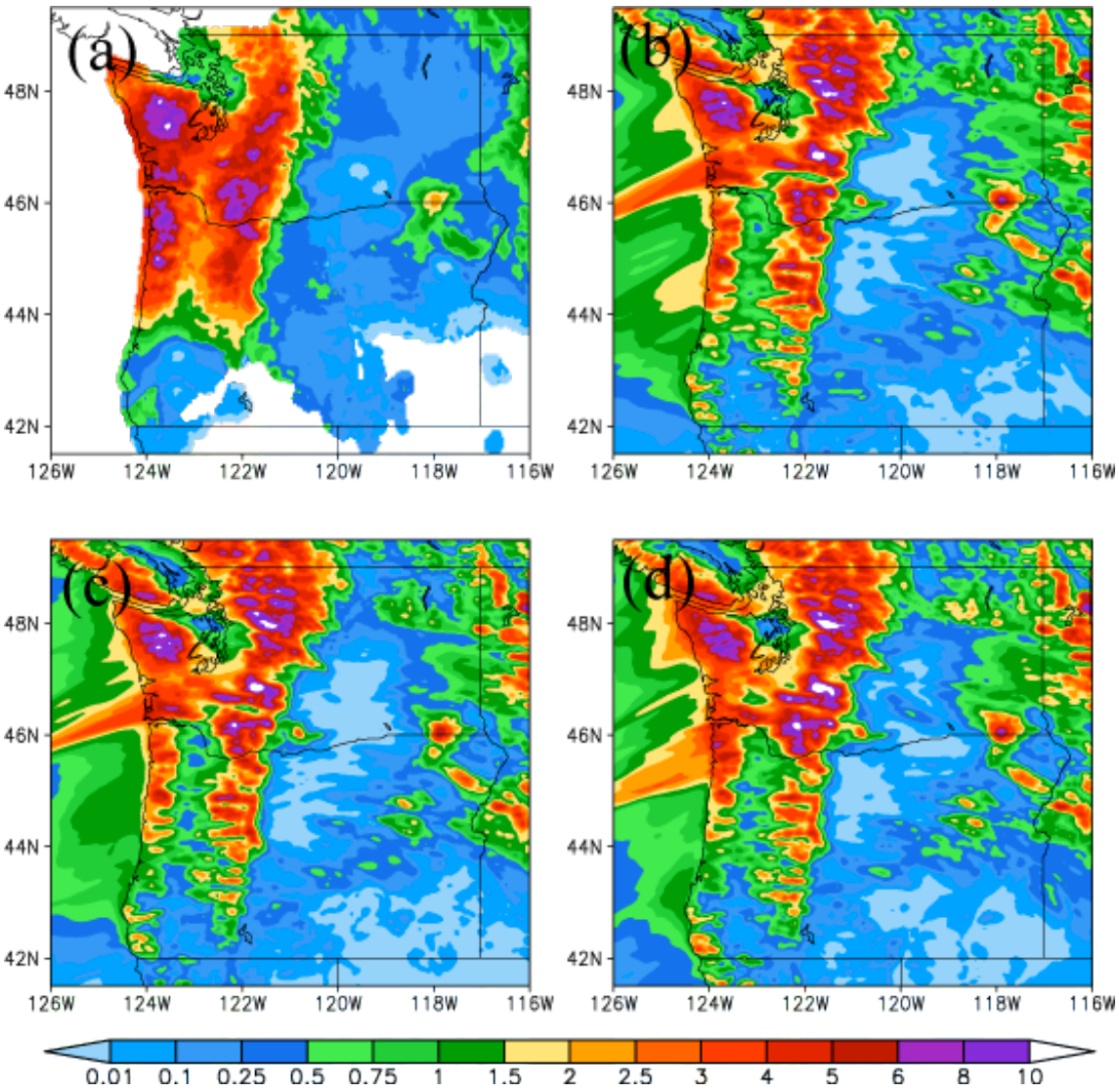
Mean errors as a function of time

	6/15	6/16	6/17	6/18	7/02	7/03	7/04	7/05	AVG
FCST	3 h	4 h	5 h	6 h	14 h	15 h	16 h	17 h	
CNTL	-0.152	-0.231	-0.137	-0.283	-0.303	-0.237	-0.311	-0.179	-0.229
LOCAL	-0.148	-0.243	-0.154	-0.297	-0.274	-0.211	-0.306	-0.176	-0.226
N-LOCAL	-0.163	-0.228	-0.138	-0.276	-0.255	-0.192	-0.291	-0.171	-0.214

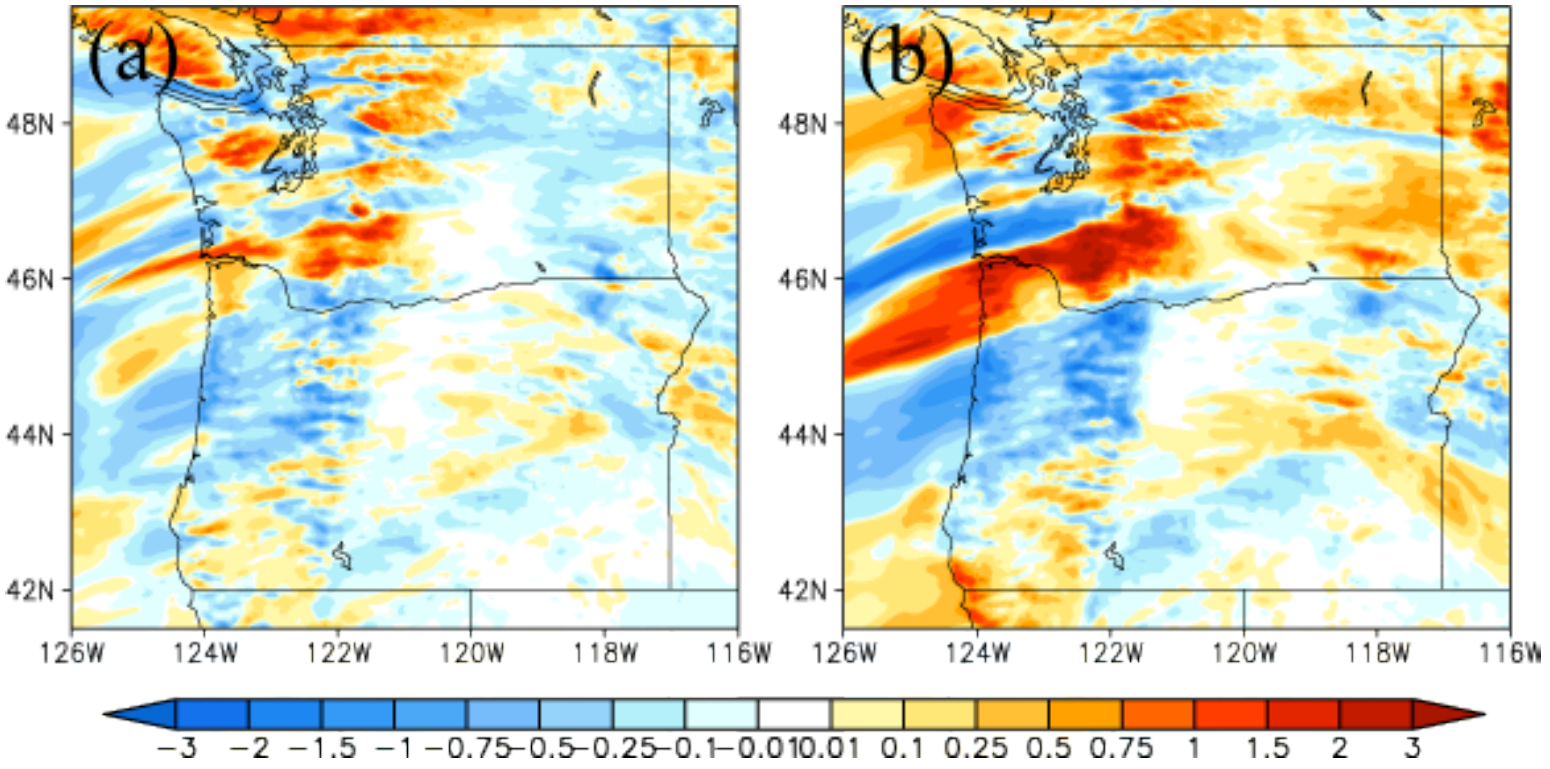
Standard deviations as a function of time

	6/15	6/16	6/17	6/18	7/02	7/03	7/04	7/05	AVG
FCST	3 h	4 h	5 h	6 h	14 h	15 h	16 h	17 h	
CNTL	0.39	0.339	0.331	0.349	0.456	0.443	0.405	0.334	0.381
LOCAL	0.41	0.338	0.339	0.347	0.454	0.432	0.401	0.355	0.385
N-LOCAL	0.40	0.330	0.327	0.332	0.432	0.421	0.378	0.341	0.371

Evaluate 24h Precipitation on domain D3



Evaluate 24h Precipitation on domain D3 …

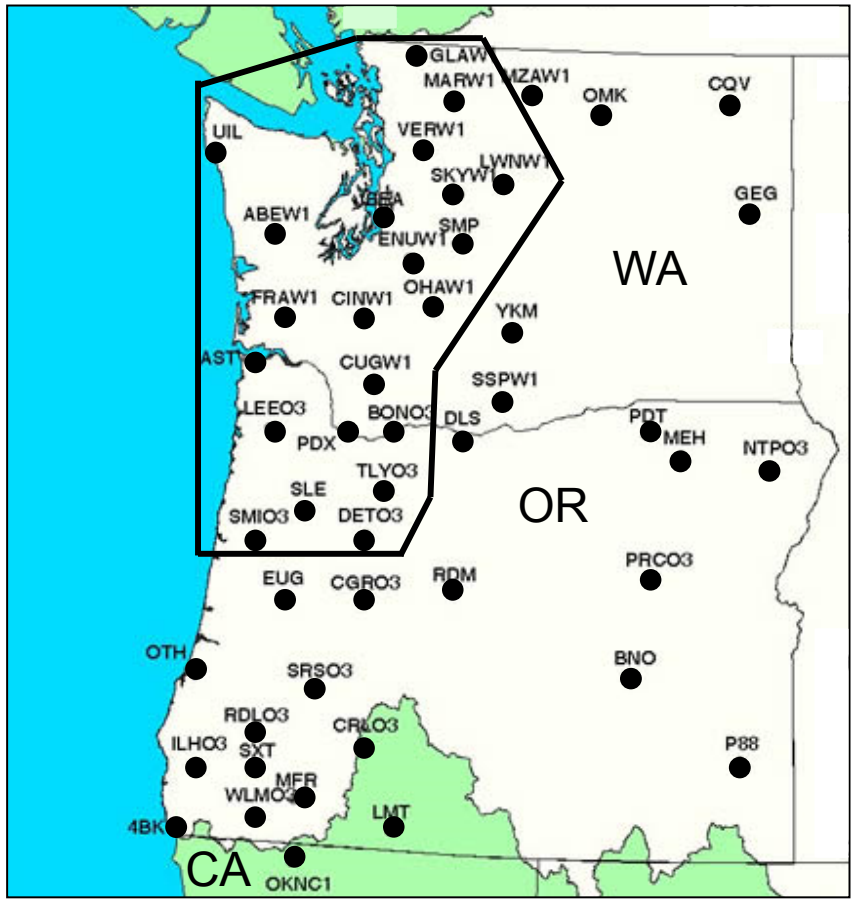


LOC - CTRL **NLOC - CTRL**

The difference of 24h accumulative precipitation ending at 1200 UTC 7 November 2006: (a) LOC minus CTRL and (b) NLOC minus CTRL.

QPF and evaluation data

Verification Region



SITES

- 50 sites in WA, OR, & CA (117” precip. total)
  - 22 sites in “wet” region (107” precip. total)
  - 28 sites in “dry” region (10” precip. total)

DATA

- 1200 UTC 6 Nov. to 1200 UTC 7 Nov. 2006
- Model quantitative precipitation forecast (QPF)
  - –Forecasts made from 12 Z to 12 Z
  - –Resolution of 4 km
- Quantitative precipitation estimates (QPE)
  - –From NWRFC
  - –Gauge-based
  - –12 Z to 12 Z
  - –Resolution of 4 km

Site Forecast and Observed Data

All 50 sites (wet area and dry area)				
		24 h COSMIC QPF (in)		NWRFC (in)
	CTRL	LOCAL	NONLOCAL	Observed
Avg Precipitation	**1.72**	**1.72**	**1.86**	**2.33**
Avg Bias	**0.74**	**0.74**	**0.80**	

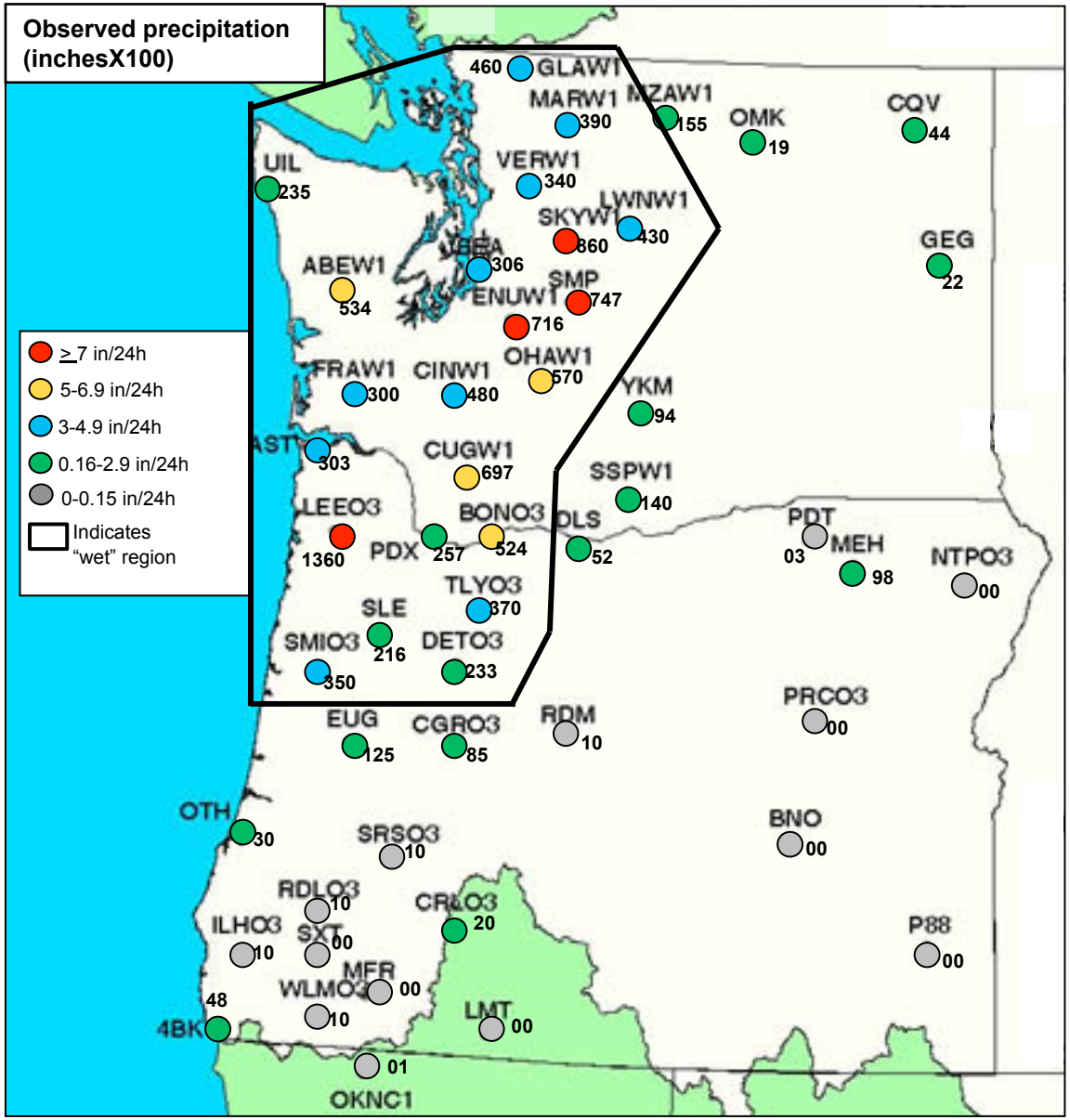
"Wet" region sites

			24 h COSMIC QPF (in)		NWRFC (in)
	Site ID	CTRL	LOCAL	NONLOCAL	Observed
Astoria, OR	AST	2.07	2.44	4.87	3.03
Frances, WA	FRAW1	4.40	4.60	2.69	3.00
Cinebar, WA	CINW1	3.69	4.20	4.84	4.80
Cougar, WA	CUGW1	5.42	6.59	8.52	6.97
Packwood, WA	OHAW1	4.52	4.88	6.02	5.70
Aberdeen, WA	ABEW1	4.31	4.17	3.77	5.34
Enumclaw, WA	ENUW1	3.18	2.90	3.16	7.16
Glacier, WA	GLAW1	3.42	3.78	3.36	4.60
Leavenworth, WA	LWNW1	3.23	3.03	3.16	4.30
Marblemount, WA	MARW1	5.97	6.26	5.40	3.90
Seattle, WA	SEA	1.74	1.40	1.70	3.06
Skykomish, WA	SKYW1	3.76	3.97	4.20	8.60
Stampede Pass, WA	SMP	2.85	3.05	3.78	7.47
Quillayute, WA	UIL	2.28	1.92	3.37	2.35
Verlot, WA	VERW1	7.54	7.61	8.51	3.40
Bonneville Dam, OR	BONO3	2.96	2.46	2.24	5.24
Detroit Dam, OR	DETO3	2.24	2.36	1.75	2.33
Lees Camp, OR	LEEO3	3.10	3.09	3.69	13.60
Portland, OR	PDX	1.07	0.79	0.94	2.57
Three Lynx, OR	TLYO3	1.84	1.86	1.26	3.70
Salem, OR	SLE	1.15	0.79	0.52	2.16
Summit, OR	SMIO3	2.03	1.34	1.15	3.50
	Avg ppt	**3.31**	**3.34**	**3.59**	**4.85**
	Avg Bias	**0.68**	**0.69**	**0.74**	

"Dry" region sites

			24 h COSMIC QPF (in)		NWRFC (in)
	Site ID	CTRL	LOCAL	NONLOCAL	Observed
Brookings, OR	4BK	0.33	0.33	1.08	0.48
Burns Airport, OR	BNO	0.43	0.35	0.22	0.00
Cougar Dam, OR	CGRO3	1.24	1.13	1.42	0.85
Colville, WA	CQV	0.17	0.12	0.26	0.44
Crater Lake, OR	CRLO3	1.58	1.54	1.82	0.20
The Dalles, OR	DLS	0.07	0.02	0.00	0.52
Eugene, OR	EUG	1.06	0.68	0.68	1.25
Spokane, WA	GEG	0.64	0.49	0.76	0.22
Agness, OR	ILHO3	0.96	0.60	0.78	0.10
Klamath Falls, OR	LMT	0.14	0.08	0.02	0.00
Meacham, OR	MEH	0.55	0.68	0.26	0.98
Rogue Valley, OR	MFR	0.09	0.15	0.30	0.00
Mazama, WA	MZAW1	1.44	1.99	1.16	1.55
Enterprise, OR	NTPO3	0.20	0.22	0.30	0.00
Oak Knoll, CA	OKNC1	0.02	0.13	0.24	0.01
Omak Airport, WA	OMK	0.49	0.31	0.50	0.19
North Bend, OR	OTH	1.09	0.97	0.83	0.30
Owyhee, NV	OWYN2	0.06	0.00	0.02	0.01
Rome, OR	P88	0.01	0.00	0.01	0.00
Pendleton, OR	PDT	0.06	0.06	0.01	0.03
Prairie City, OR	PRCO3	0.83	0.89	1.37	0.00
Riddle, OR	RDLO3	0.01	0.05	0.13	0.10
Redmond Roberts, OR	RDM	0.00	0.00	0.00	0.10
Glide, OR	SRSO3	0.29	0.33	0.49	0.10
Goldendale, WA	SSPW1	1.16	1.21	1.17	1.40
Sexton Summit, OR	SXT	0.05	0.11	0.03	0.00
Williams, OR	WLMO3	0.08	0.08	0.09	0.10
Yakima, WA	YKM	0.00	0.00	0.03	0.94
	Avg	**0.47**	**0.45**	**0.50**	**0.35**
	Avg Bias	**1.32**	**1.27**	**1.42**	

Observed precipitation at 50 evaluation sites



Comparison of QPF bias for forecasts with ("non-local") and without ("control") COSMIC data

* Numerical values represent difference between the two forecasts in inches, normalized by the total observed precipitation at that site. It is expressed as a percentage.

*Color fill represents which forecast had smallest bias:

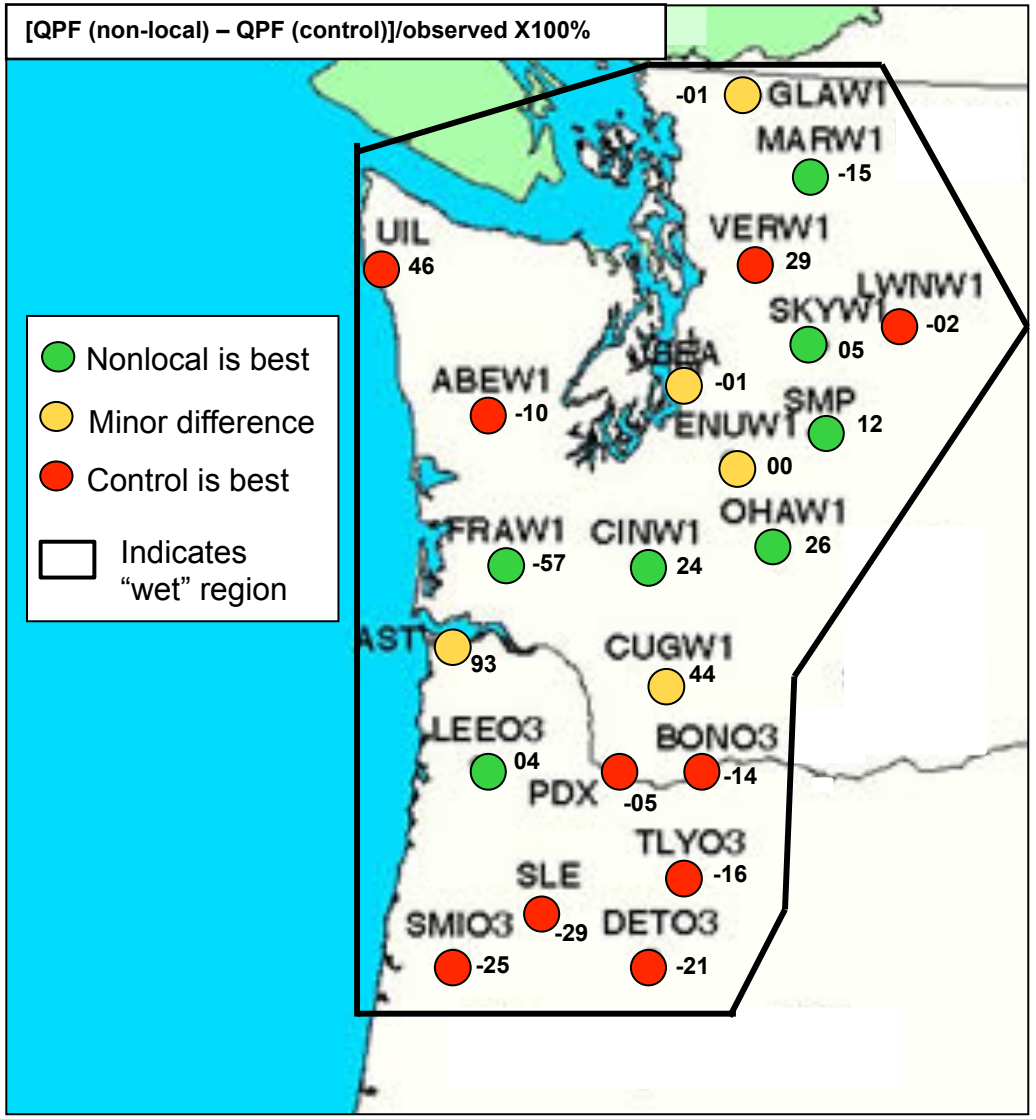
-green: COSMIC data improved the forecast

-red: Control run without COSMIC is still best

-yellow: Differences were minor

*****The COSMIC data improved the QPF at sites where the heaviest rain fell.**

NOLOCAL performs better than LOCAL.



Summary and Conclusions

- COSMIC GPS RO soundings successfully assimilated with NCEP regional GSI system using both local and nonlocal observation operators.
- Assimilation of COSMIC data improved regional analysis and prediction of the atmospheric river event:
  - Better fit to independent observations (e.g., SSM/I, rainfall data)
- Nonlocal observation operator performs better than local observation operator:
  - Significantly reduces dry bias in precipitation forecast
  - improves QPF at sites where the heaviest rain fell
- More case studies are needed to substantiate the results.

Comparing COSMIC GPS RO Data with Large-Scale Analyses in Clear-sky and Cloudy Atmospheric Conditions

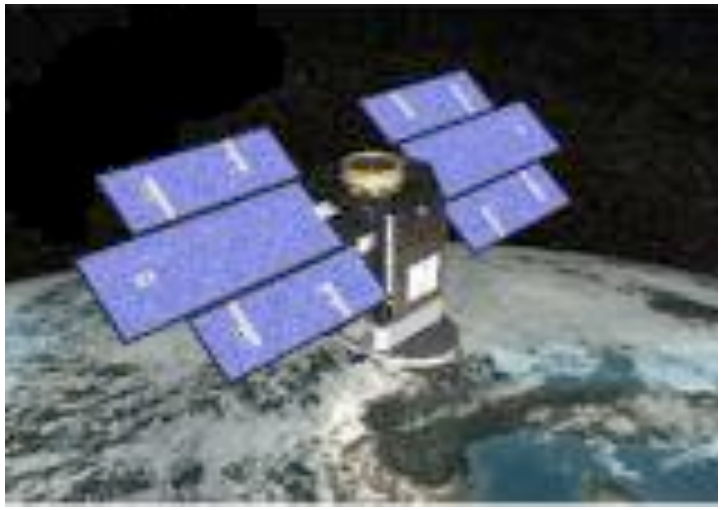
L. Lin, X. Zou, R. A. Anthes, Y.-H. Kuo

Motivations

GPS RO data are globally available, not affected by clouds, and of high vertical resolution, making them ideally suitable for studying clouds.

This study uses GPS RO data to examine the observed vertical structures of the atmosphere within and outside clouds and compare them with large-scale analyses.

CloudSat



Instrument: 94-GHz profiling radar

Launch time: April 28, 2006

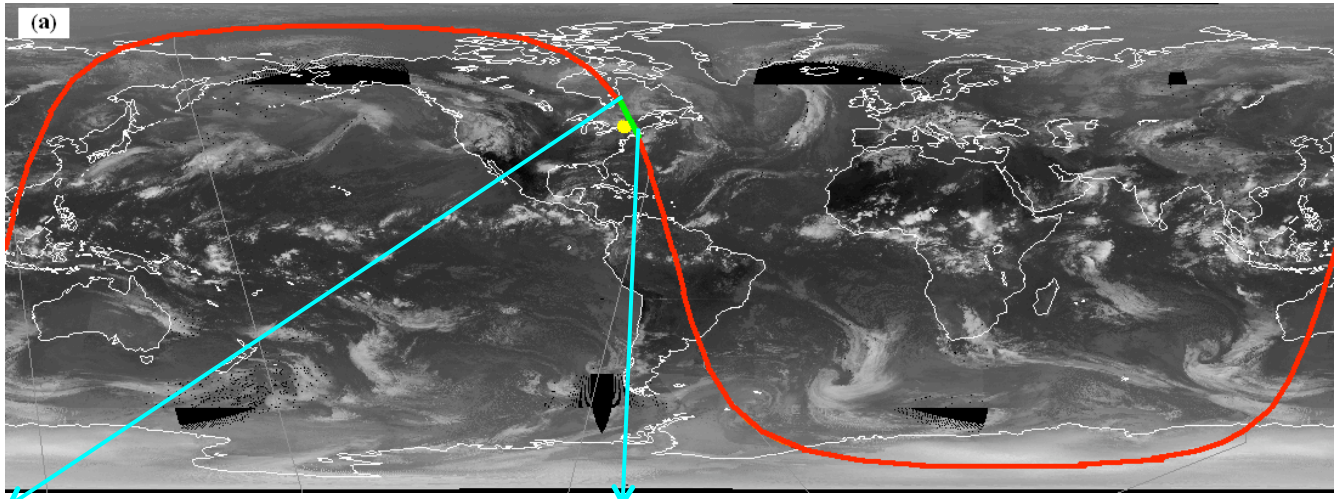
One orbital time: ~1.5 hours

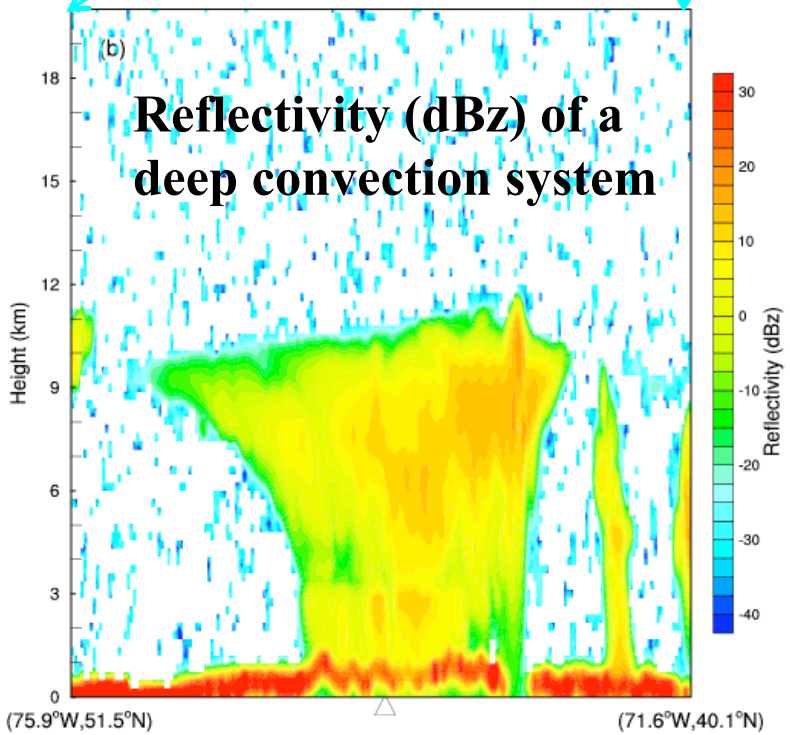
Along-track resolution: ~1.1 km

Track width: ~1.4 km

Observed variables:
- reflectivity
- liquid/ice water content
- cloud top height
- cloud base height
- cloud types

A CloudSat Orbital Track and a Collocated GPS RO





One granule of CloudSat orbital track:
17:02:24 UTC June 5, 2007

A collocated GPS sounding:
(72.98°W, 43.79°N)

Data Selection

- **Time periods of data search:**

  (1) June-September 2006, June 2007

  (2) September 2007 to August 2008

- **Collocation of CloudSat and COSMIC data:**

  Time difference < 0.5 hour

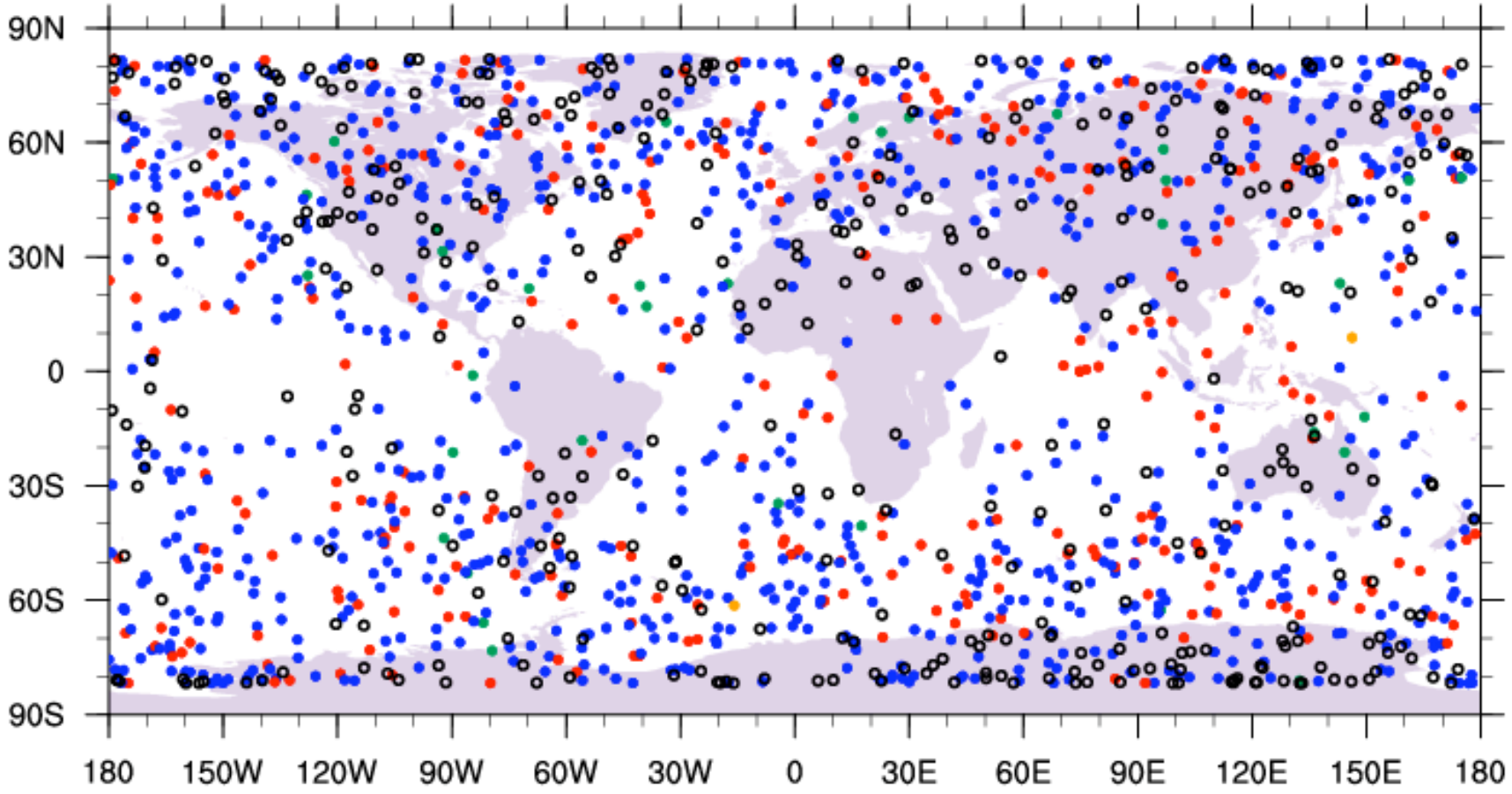
  Spatial distance < 30 km

  Cloud top >2 km

Collocated Cloudy and Clear-Sky Sounding Numbers

	Total cloudy profiles	Total clear-sky profiles
Four-month period	147	86
One-year period	1198	386

Spatial Distribution of Clear-Sky and Cloudy GPS ROs

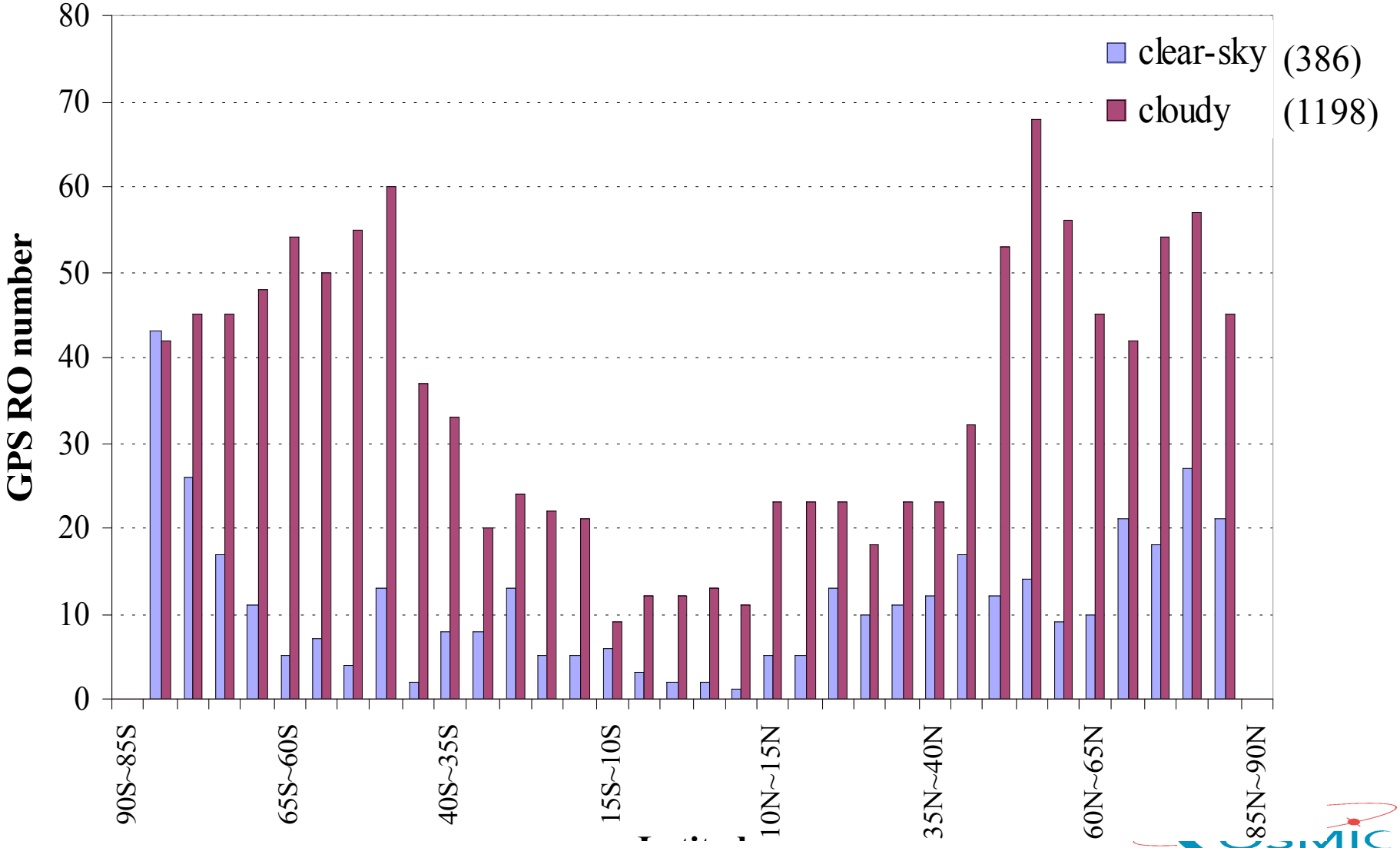


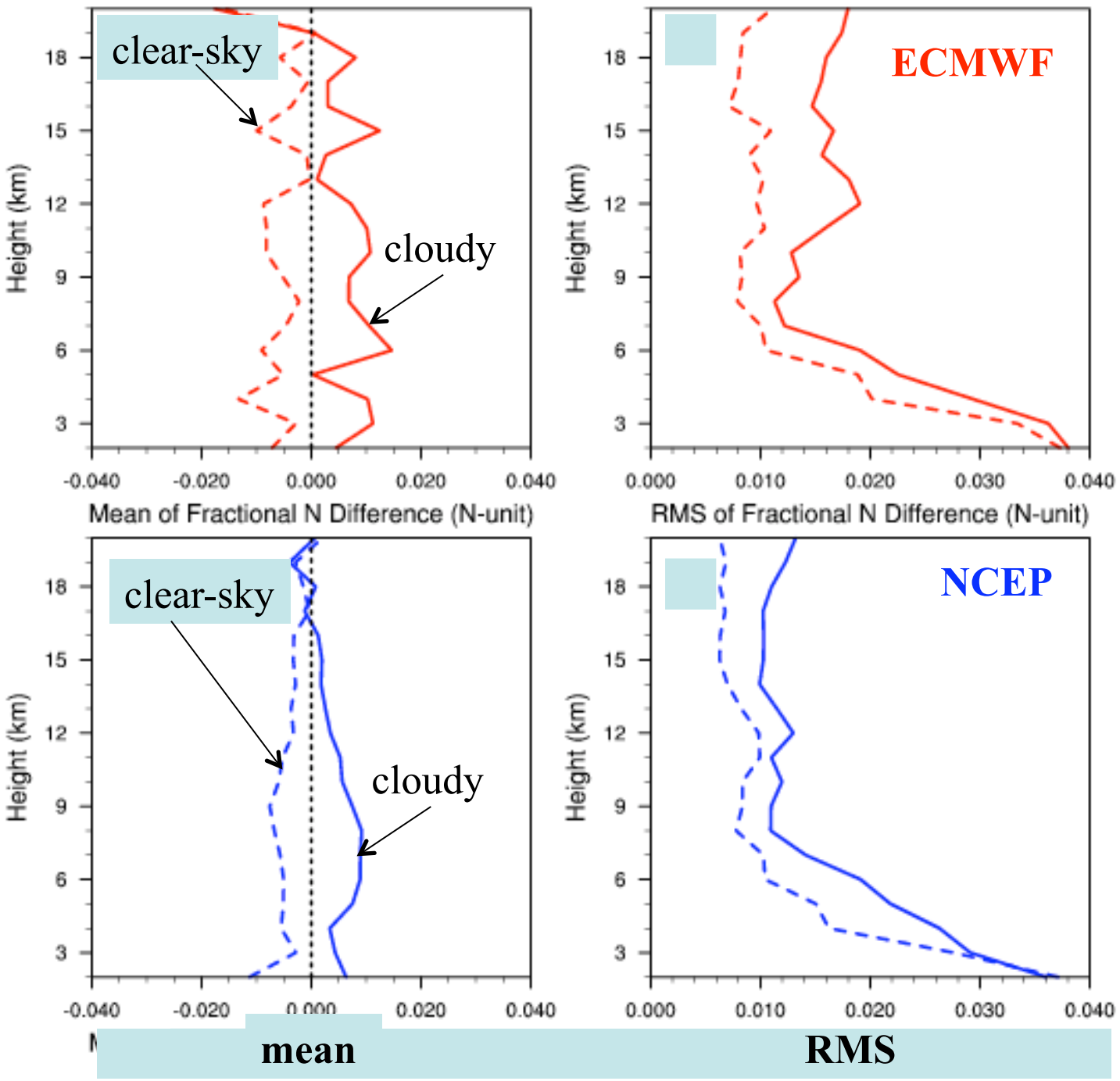
Single-layer cloud Two-layer cloud

Three-layer cloud Four-layer cloud

Clear-sky ROs

Latitudinal Distribution of Clear-Sky and Cloudy GPS ROs

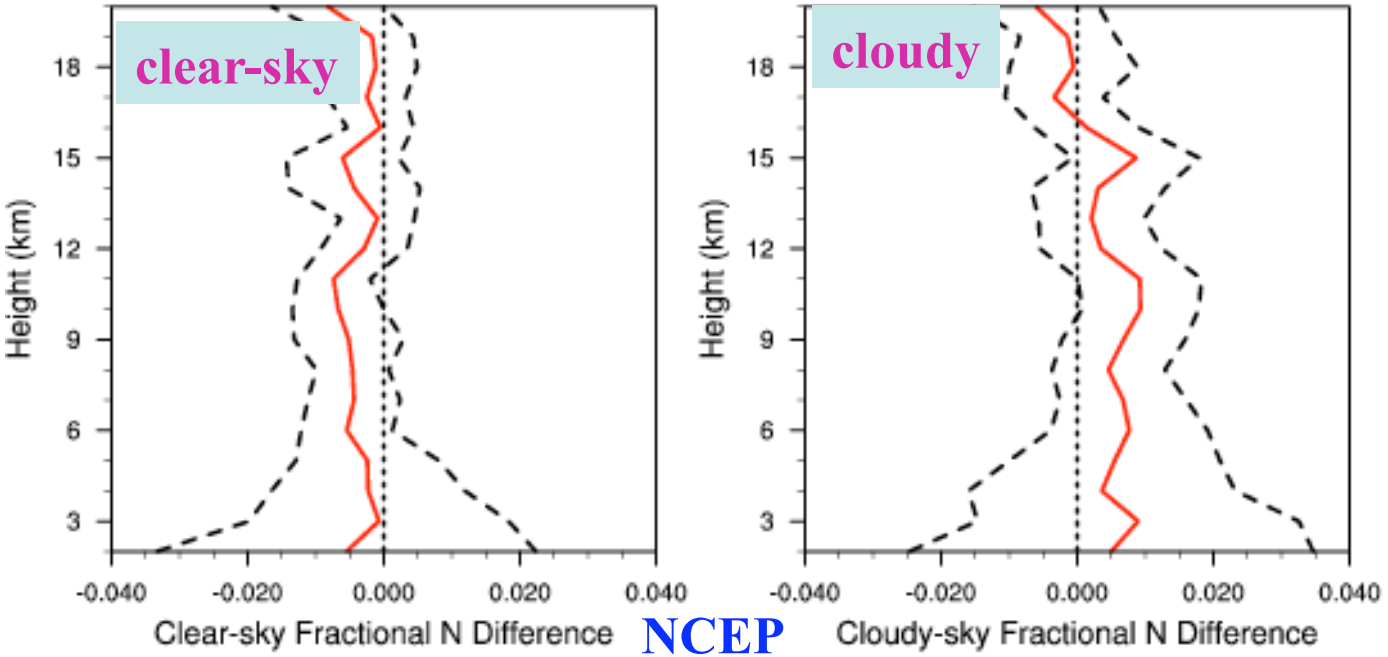




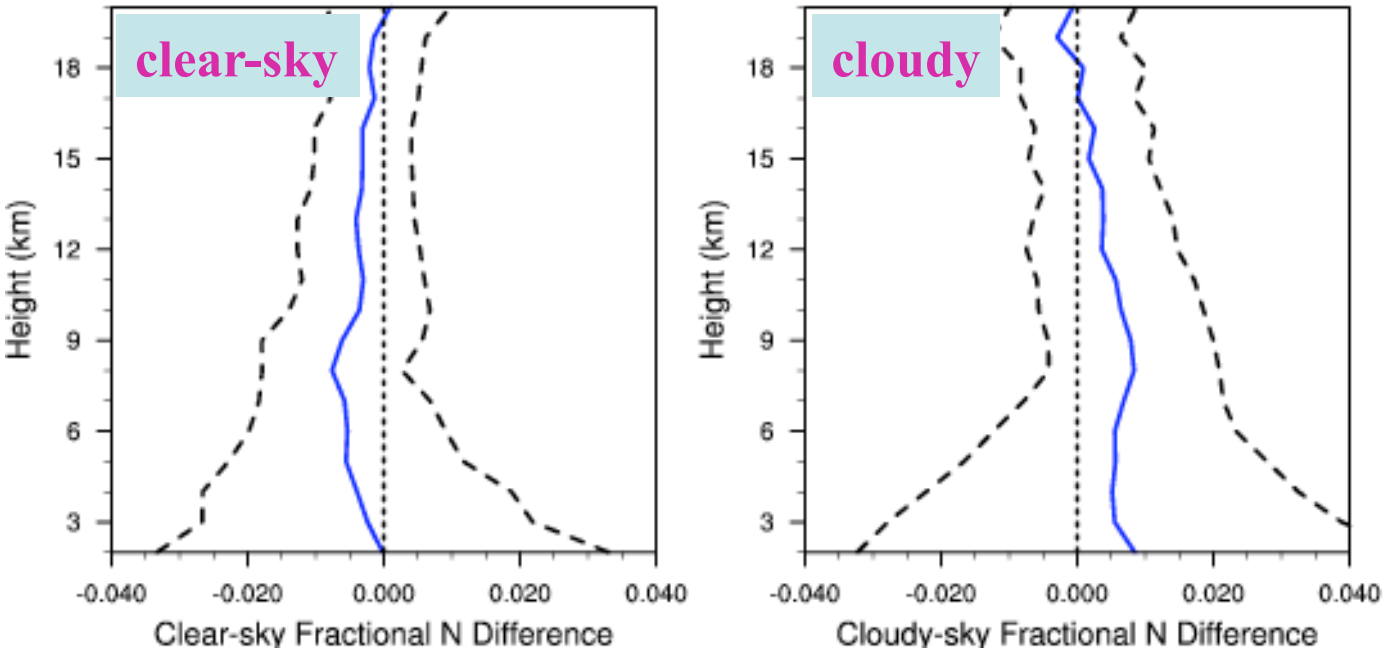
Mean/RMS of Fractional *N* Differences

Four-month period

ECMWF



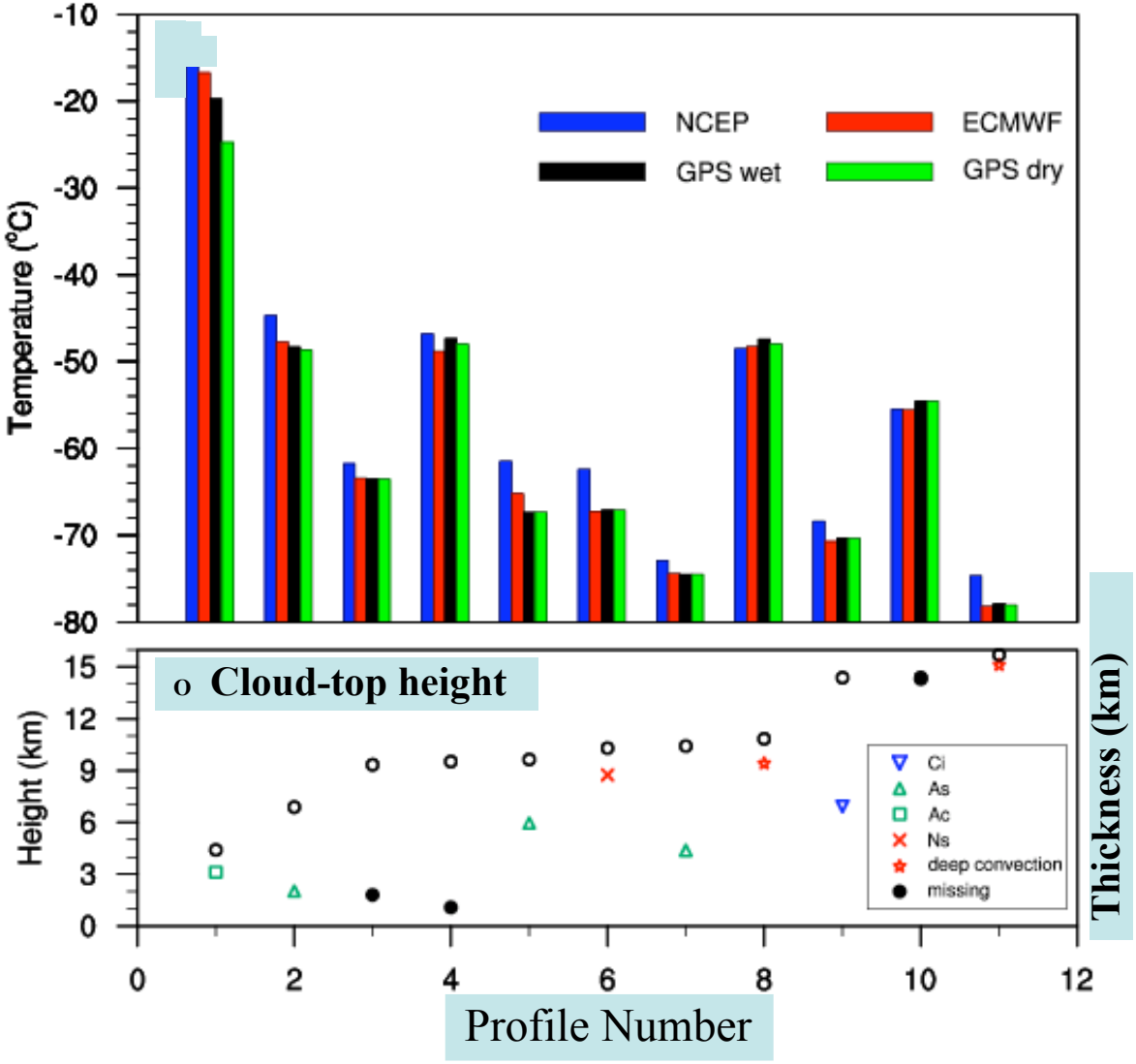
NCEP



Mean/RMS of Fractional *N* Differences

One-year period

Cloud-Top Temperature (data in June 2007)

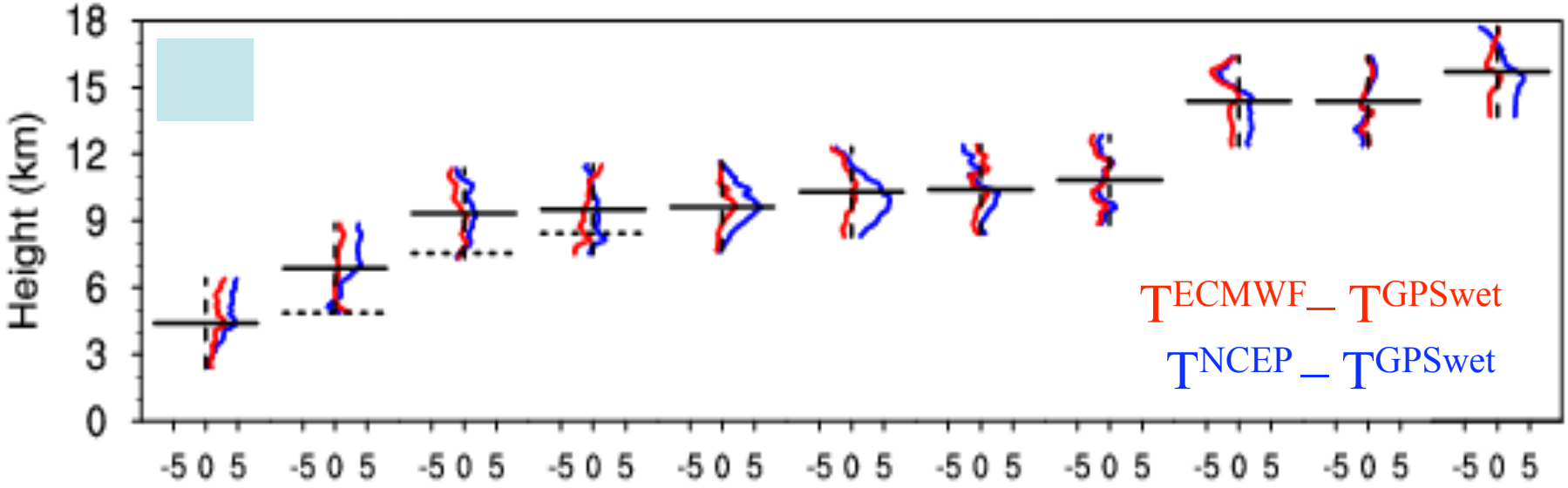


NCEP analysis is warmer than both GPS and ECMWF

ECMWF compares more favorably with GPS than NCEP

GPS dry retrieval is several degrees colder than other data for low cloud (z<5km)

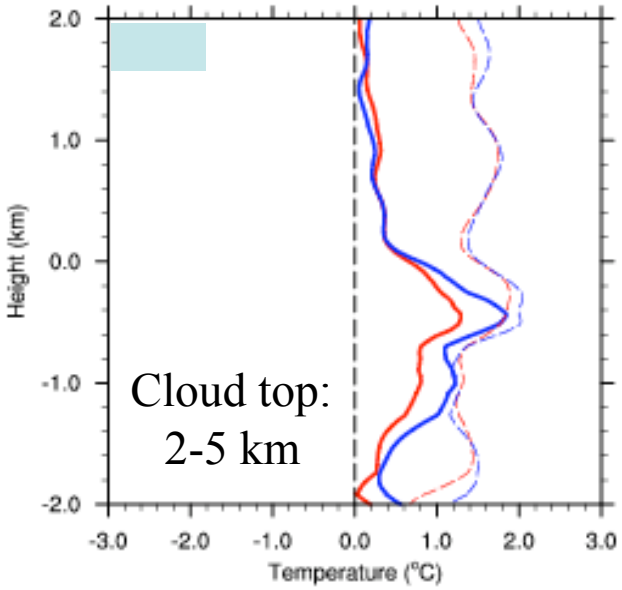
Temperature near the Cloud-Top (June 2007)

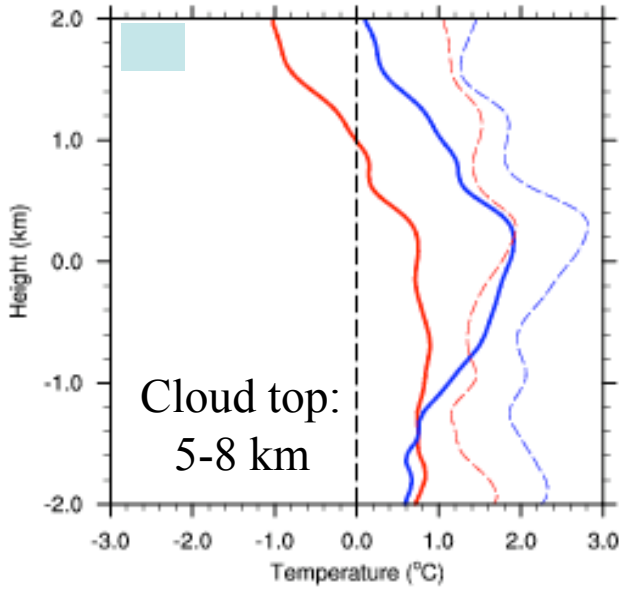


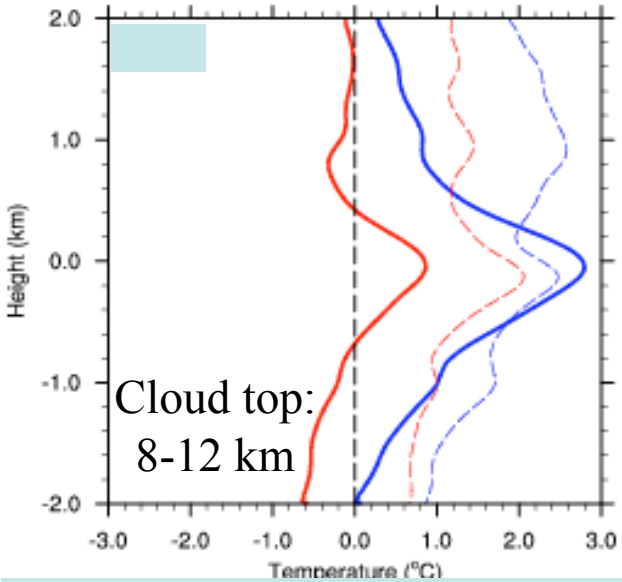
Cloud top is indicated by solid horizontal (black) line.

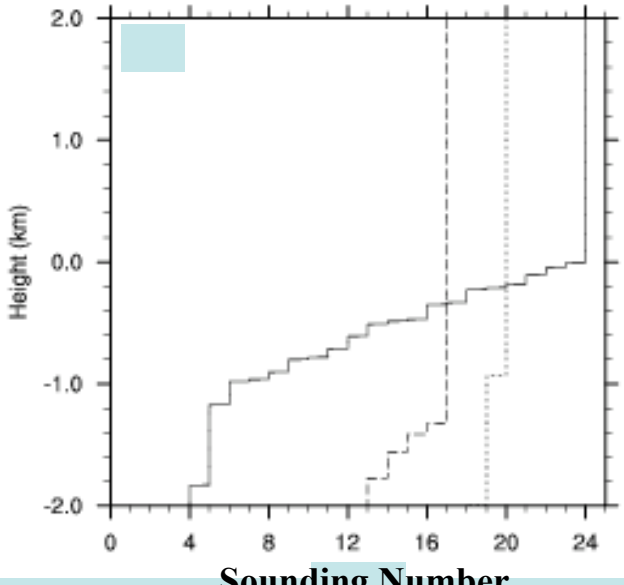
Cloud base is indicated by dotted line for those clouds whose thickness is < 2 km.

Temperature near the Cloud-Top (all data)









$T^{ECMWF} - T^{GPSwet}$

$T^{NCEP} - T^{GPSwet}$

Summary

1. A new cloudy retrieval algorithm is developed.

2. GPS ROs are compared with large-scale analysis separately in cloudy and clear-sky environment for the first time.

3. CloudSAT data are combined with GPS RO data for studying clouds.

Summary

Major Findings:

- Positive *N*-bias are found for cloudy soundings

  Negative *N*-bias for clear-sky conditions

- ECMWF temperature compares more favorably with GPS retrieved temperature than NCEP