Precipitation .

Phil Arkin

Precipitation (?)

Phil Arkin

Global Precipitation Analyses Derived from Satellite and In-situ Observations

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With thanks to Matt Sapiano and Nick Novella, ESSIC, Pingping Xie, Mingyue Chen, Bob Joyce and John Janowiak, NOAA Climate Prediction Center, and many others in the community

- Motivation
- Information Sources
- First Generation Global Analyses
- Climatology and Variability
- Second Generation Global Analyses
- Validation
- Concluding Remarks

Why should we care where and how much precipitation occurs?

- Associated condensation heating drives large-scale atmospheric circulation - critical to weather forecasting
- Effects are crucial to atmosphere-ocean interactions in climate variability - critical to climate monitoring and prediction
- Frequency and intensity – strongly influence surface hydrology (runoff/soil moisture/stream-flow,…)
- Amount largely determines fresh water supply
- Extremes (floods, droughts) - have huge impact on society and natural environment

What are the challenges?

- First of all, what do we actually wish to measure?
  - Water going from atmosphere to surface?
  - Water vapor condensing within the atmosphere?
  - The complete vertical profile of phase changes and velocities?
- Secondly, the time and space scales of precipitation phenomena vary enormously
  - The physics of cloud particles and hydrometeors operate on millimeters and seconds (or less)
  - Atmospheric convection is non-hydrostatic and turbulent
  - And much of the variability of interest is on scales on months to years and thousands of kilometers
- Thirdly, look what we have to work with!
  - Exceedingly limited surface measurements
  - Remotely sensed inferences from surface radars, with fierce arguments over accuracy
  - Satellite-derived inferences, where the arguments are no less fierce, but where no one claims that the results are as good as surface rain radars
- And all elements are the observing system are constantly changing!

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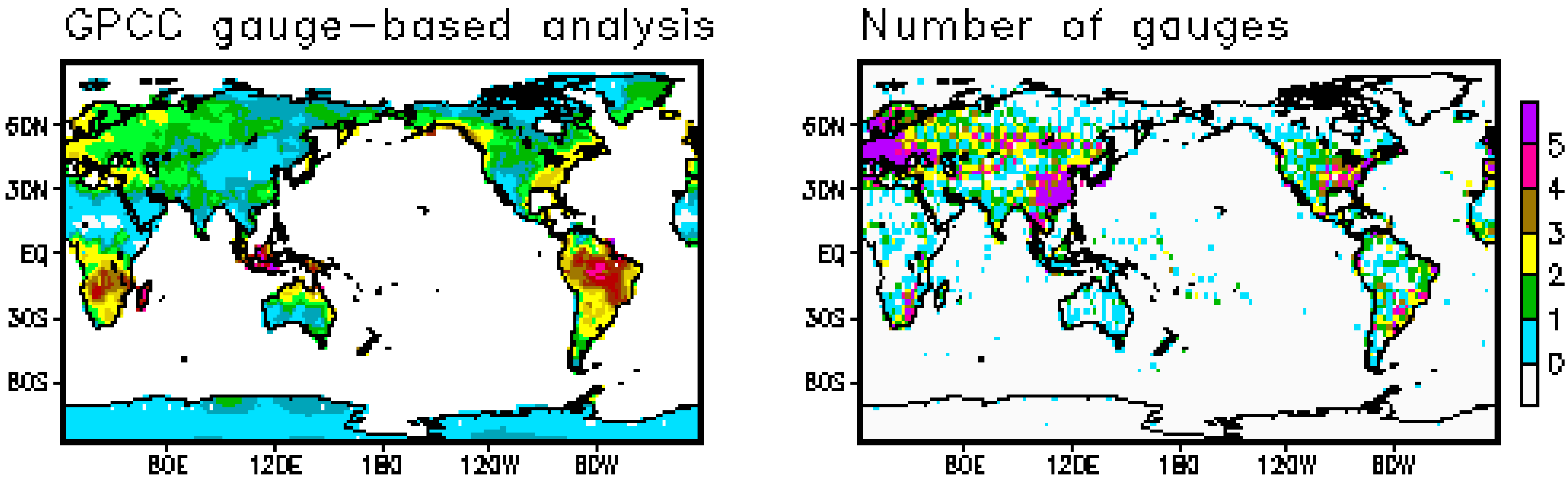
How do we know how precipitation is distributed in space and time?

- Current state of the art depends upon combining information from many sources
  - Rain gauges
  - Surface-based radars
  - Satellite observations: TRMM radar, passive microwave, visible and infrared from geostationary satellites
  - Atmospheric observations – through models
- GPCP (Global Precipitation Climatology Project and CMAP (CPC Merged Analysis of Precipitation) are examples on global scale

Rain gauges

- Catch whatever falls at a given point
- Best absolute accuracy (but not perfect)
- Limited spatial coverage (only where people are, and tough to get data sometimes)
- Both measurement and sampling errors
  - Wind and solid precipitation
  - In mountains, gauges tend to be in unrepresentative locations
- Tough data processing problem – wide variety of formats and media

An Example for January 1994



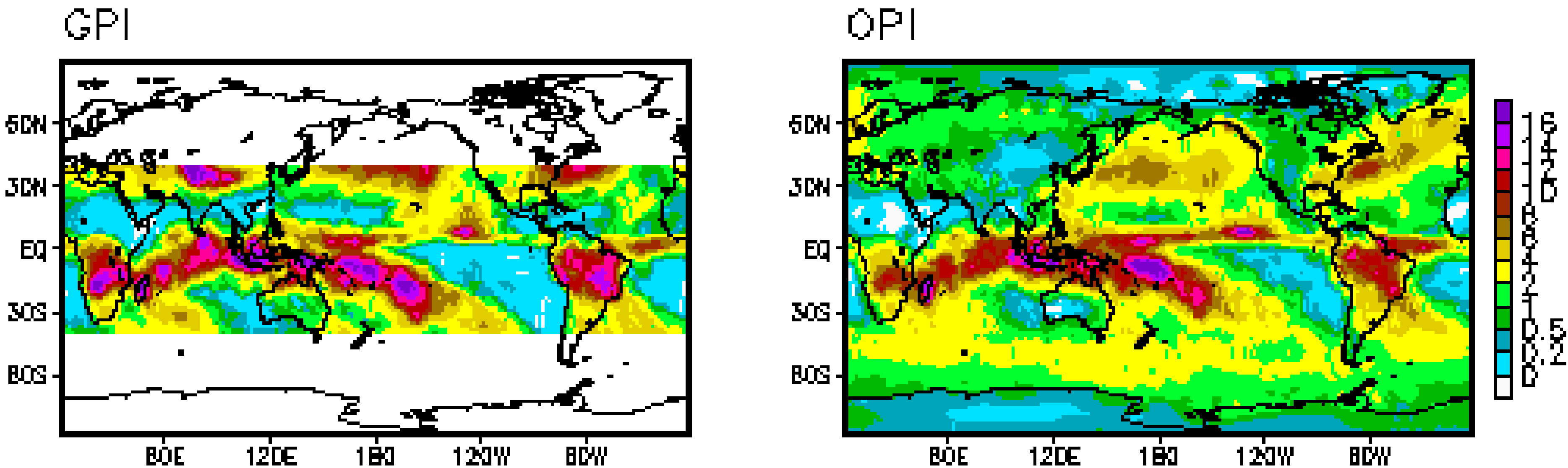
Gauge-based analysis based on about 6500 gauges by Global Precipitation Climatology Centre, DWD

(CMAP - CPC Merged Analysis of Precipitation-Xie and Arkin, 1997, *Bulletin of the American Meteorological Society*)

Satellite-derived estimates *optical*

- Visible and/or infrared (IR)
- Geostationary coverage nearly global (up to 60° latitude)
  - 30 minute temporal sampling
- Highly empirical - you really don't see anything except the tops of the clouds
  - Many years (20 - 30) available
  - Many, many examples - interestingly enough, almost any method seems to work to some extent

An Example for January 1994



IR-based estimates – geostationary and polar orbiting satellite data

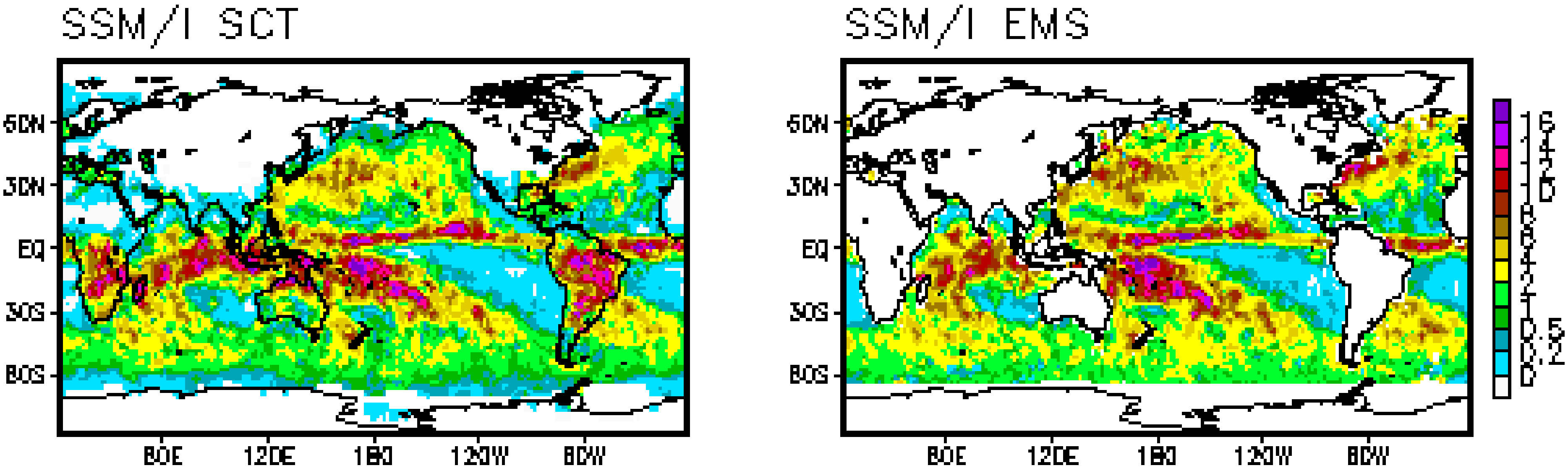
Satellite-derived estimates *passive microwave emission*

- At lower frequencies, raindrops emit like blackbodies over colder-appearing ocean surface
  - Ocean only at present
  - Best way to estimate “warm” rain (not associated with an ice phase)
  - Subject to errors from cold surface water or ice
  - Most direct (physically based) of passive algorithms, but requires assumptions regarding atmosphere (freezing level) and surface emissivity

Satellite-derived estimates *passive microwave scattering*

- At higher frequencies, large ice particles scatter radiation upwelling from the surface
  - Land as well as ocean
  - Good at detecting convective precipitation
  - Subject to errors from cold surface water or ice as well
  - Algorithms more empirical than emission, less so than IR/visible

An Example for January 1994



Passive microwave-based (SSM/I): scattering (Ferraro et al. - left) and emission (Chang and Wilheit - right)

Other satellite-derived estimates *better in principle, but more difficult in practice*

- Inversion - with adequate spectral resolution and a good radiative transfer model, vertical structure of rain/snow can be inferred
  - SSM/I since 1987, AMSU, AMSR-E, TMI
  - Goddard Profiling Algorithm – GPROF, Kummerow
- Radar - in principle, best by far; in practice, only recently possible
  - TRMM, GPM

Model-derived estimates

- Other atmospheric observations contain relevant information
  - Winds, temperature, moisture
- Physically based dynamical models yield precipitation in various ways
  - NWP models forecast precipitation
  - Assimilation of radiances can yield cloud, hydrometeor distributions
- Best where models best - mid, maybe high latitudes
- Examples: atmospheric reanalyses

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Methodology

- This is an "analysis" problem (in the NWP sense: getting a complete gridded field from disparate irregularly distributed observations)
- Microwave-based estimates are most accurate, but their spatial and temporal sampling is mediocre
- Geostationary IR provides much better sampling, but poor accuracy
- Gauges are crucial for calibration and validation
- Two generations of analyses have been produced – one for finer resolution; the other for better accuracy

First Generation Analyses

- GPCP uses a compositing technique: at any location where more than one value is available, use the “best” (in this case, determined a priori)
  - Emission microwave over oceans, scattering over land (both corrected for diurnal sampling errors using geostationary IR), IR-based cloud index from HIRS assimilation over high latitudes
- CMAP uses a weighted average (of inputs similar to GPCP)
  - Weights are proportional to errors, which are estimated over land from comparison with gauge observations and over ocean from earlier validation studies
  - To ensure spatial completeness, CMAP uses an IR-based product derived from anomalies in OLR, and one version uses precipitation from the NCEP reanalysis as an additional input
- Both GPCP and CMAP combine the initial product with a gauge-based analysis over land to reduce systematic errors
- Both are updated a few months behind real time

Characteristics

(see Xie and Arkin, BAMS, 1997 for CMAP, Adler et al, JHM, 2003 for GPCP v.2)

- Monthly and pentad time series: Jan 1979 – Present minus several months
- Spatial resolution: 2.5°x 2.5°, global
- GPCP and CMAP have proven very useful for describing seasonal and interannual variability in tropical and midlatitude precipitation – as of August 2007, 1794 published studies cited the defining papers

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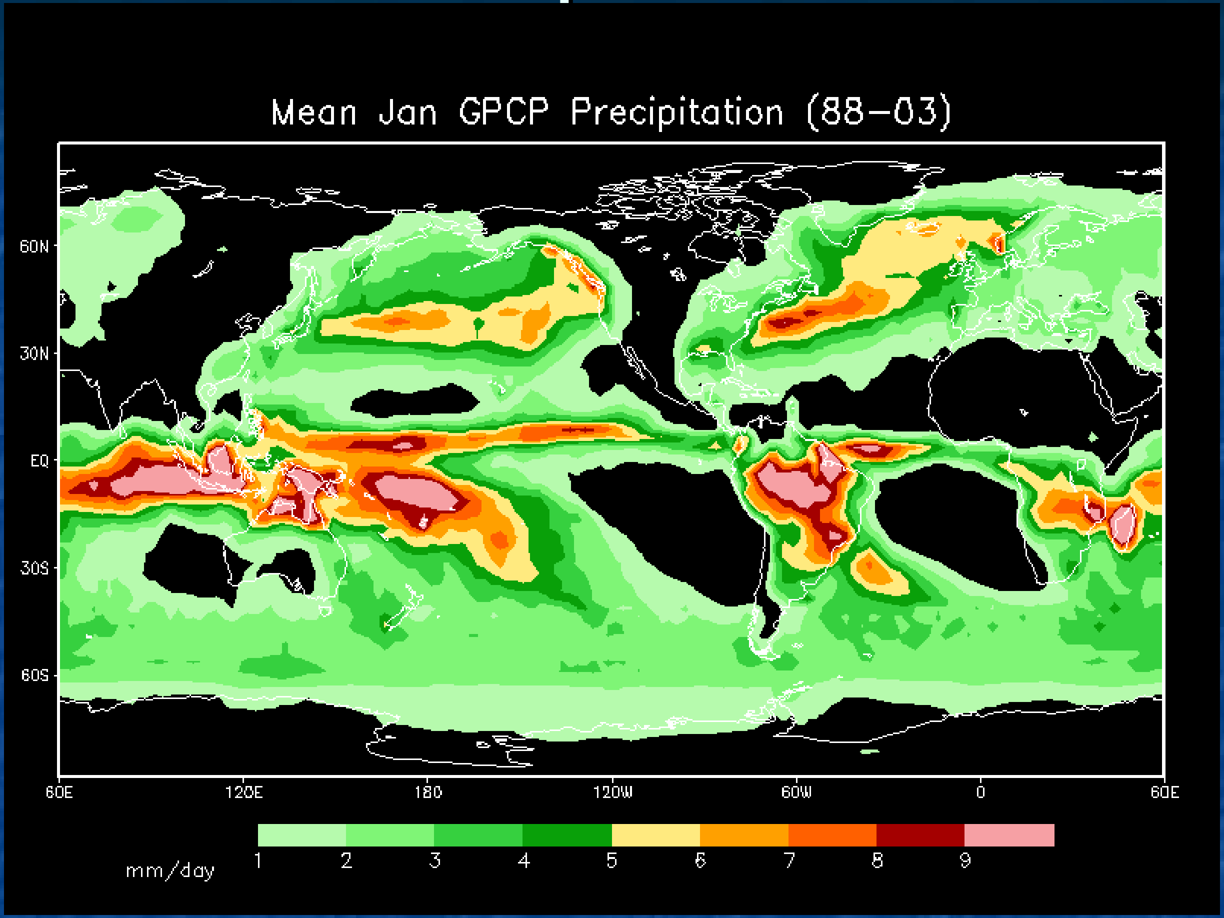
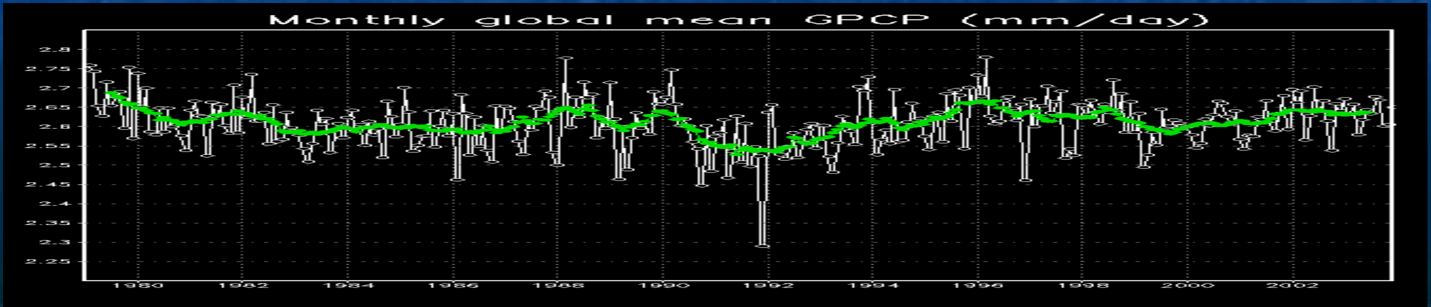
Global Precipitation Climatology Project

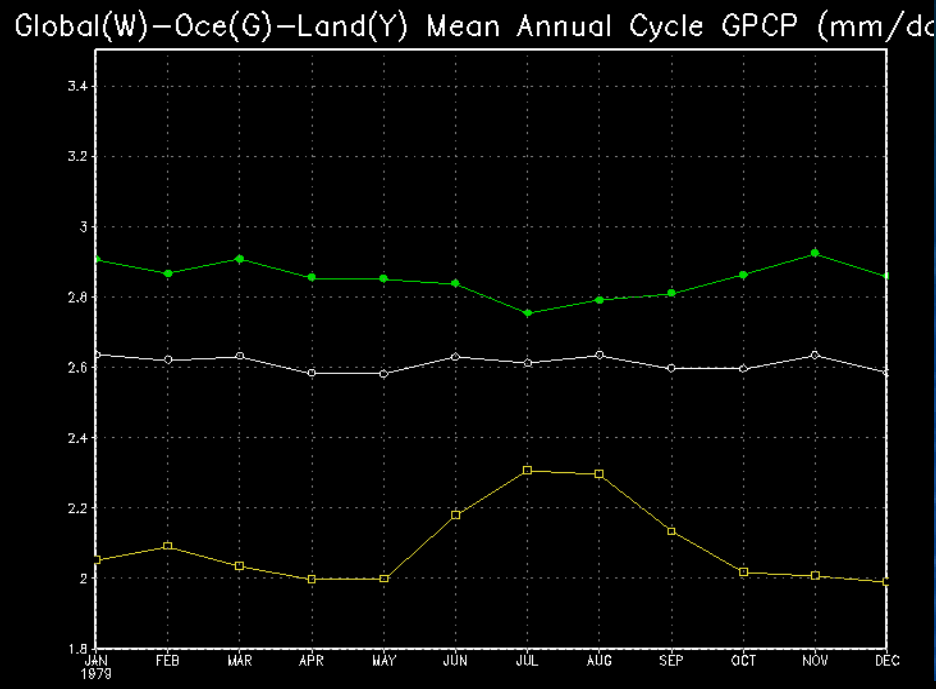


Month and pentad beginning 1979; 2.5° global coverage.

CMAP has similar input data, resolution and coverage

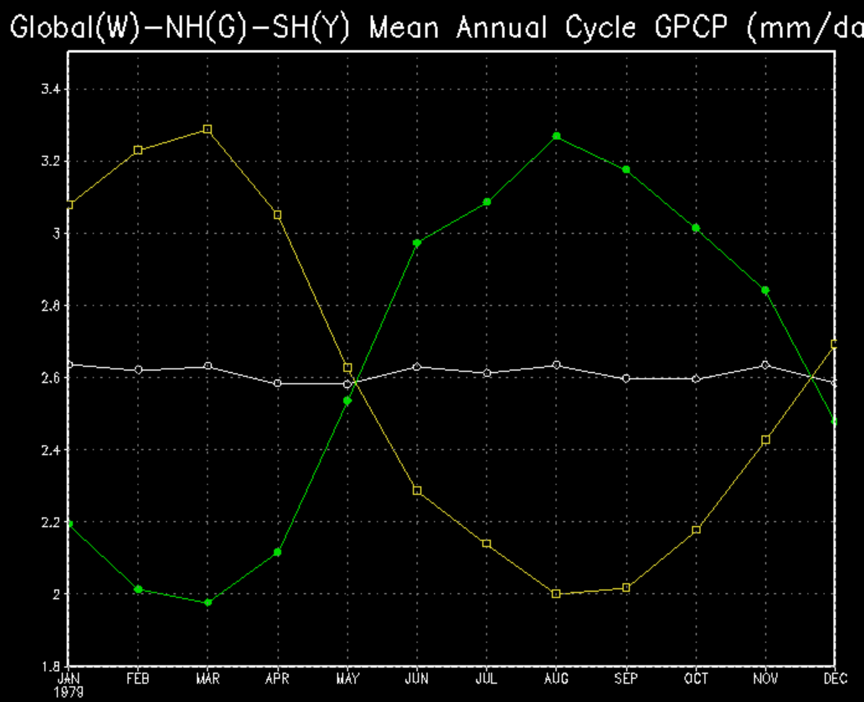
Mean annual cycle (above) and global mean precipitation (below)

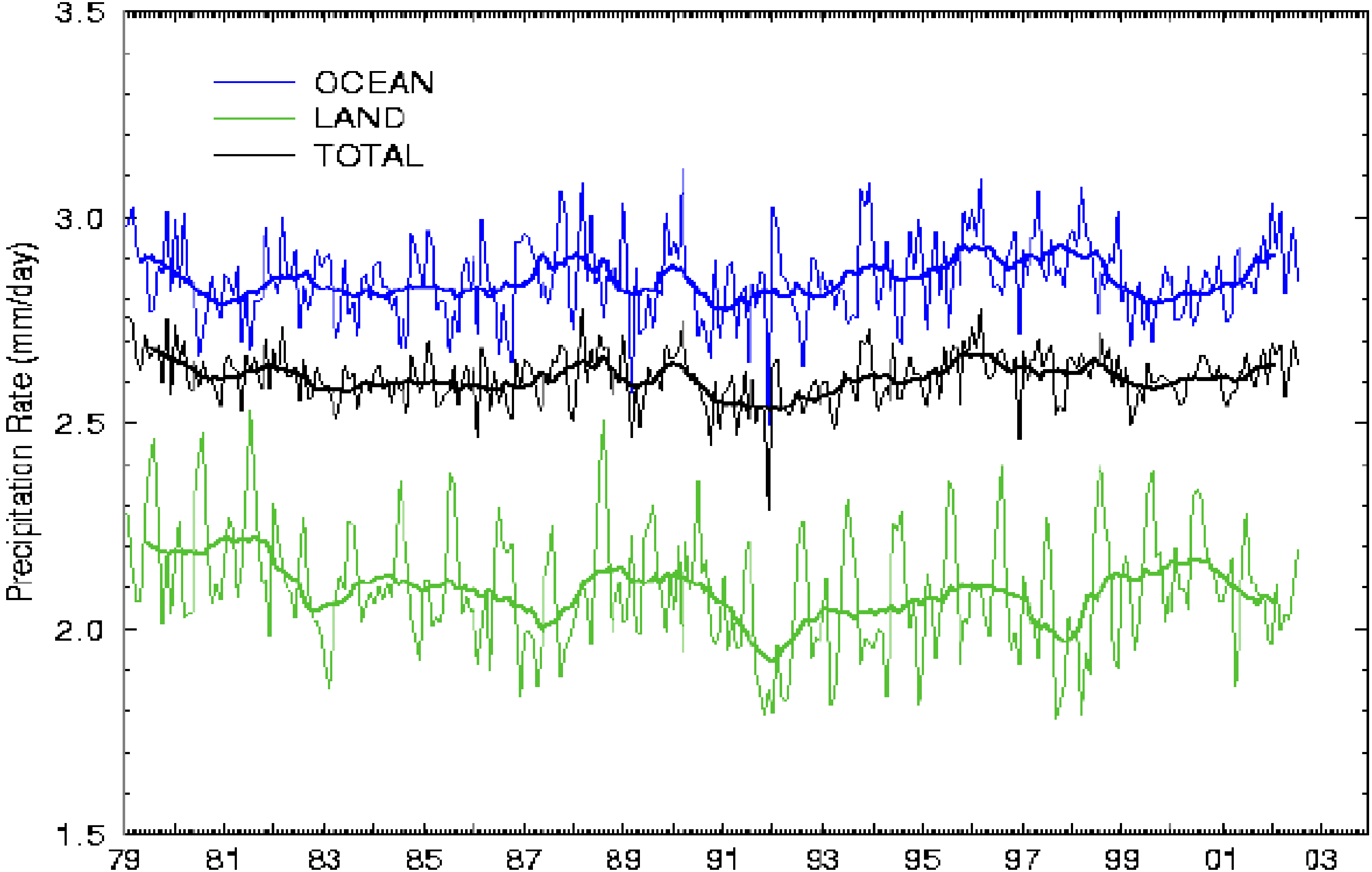




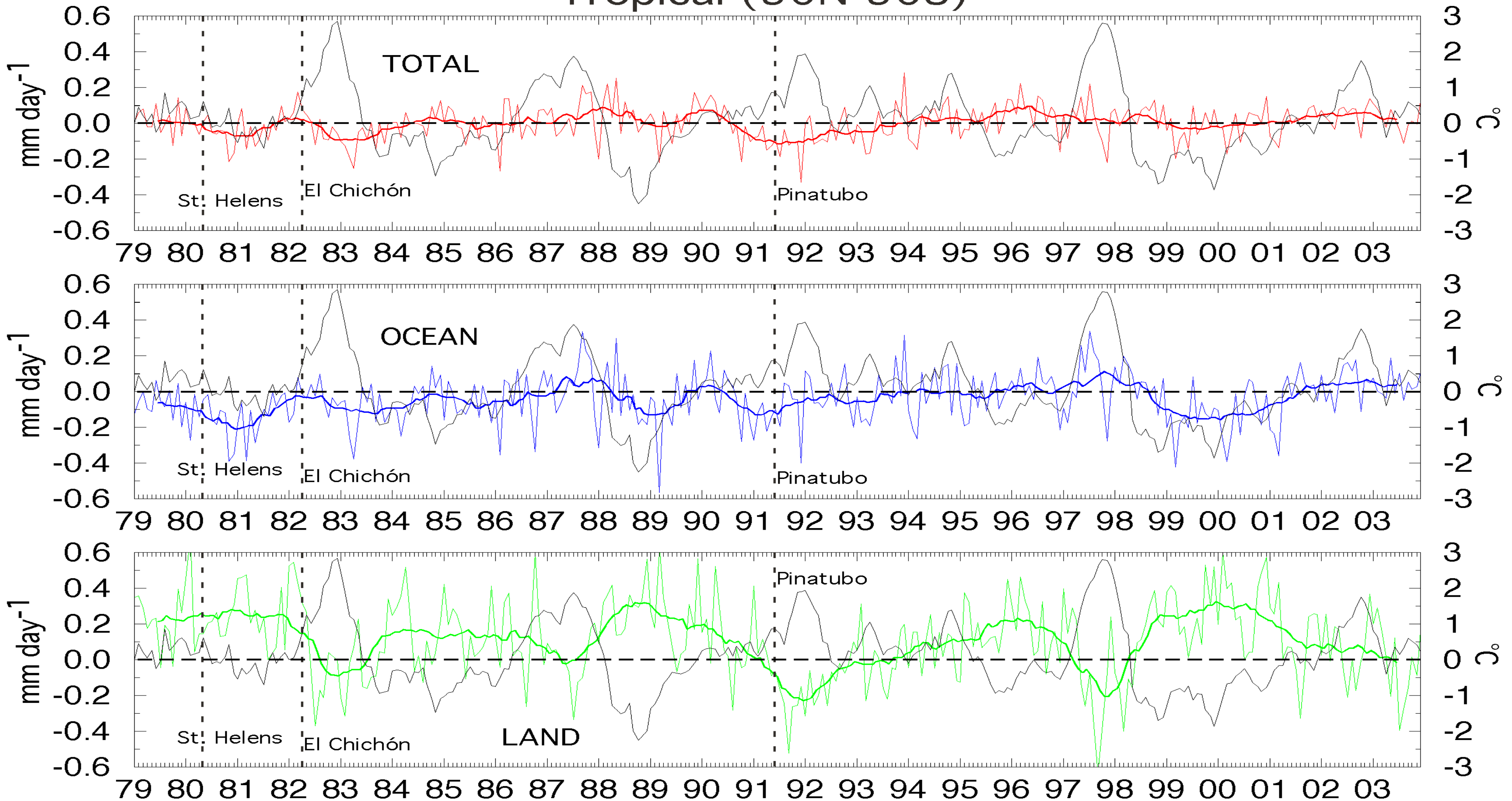
Mean annual cycles – global, ocean and land (left)
- the global mean shows no significant mean annual cycle

Mean annual cycles – global, Northern and Southern Hemispheres (right)

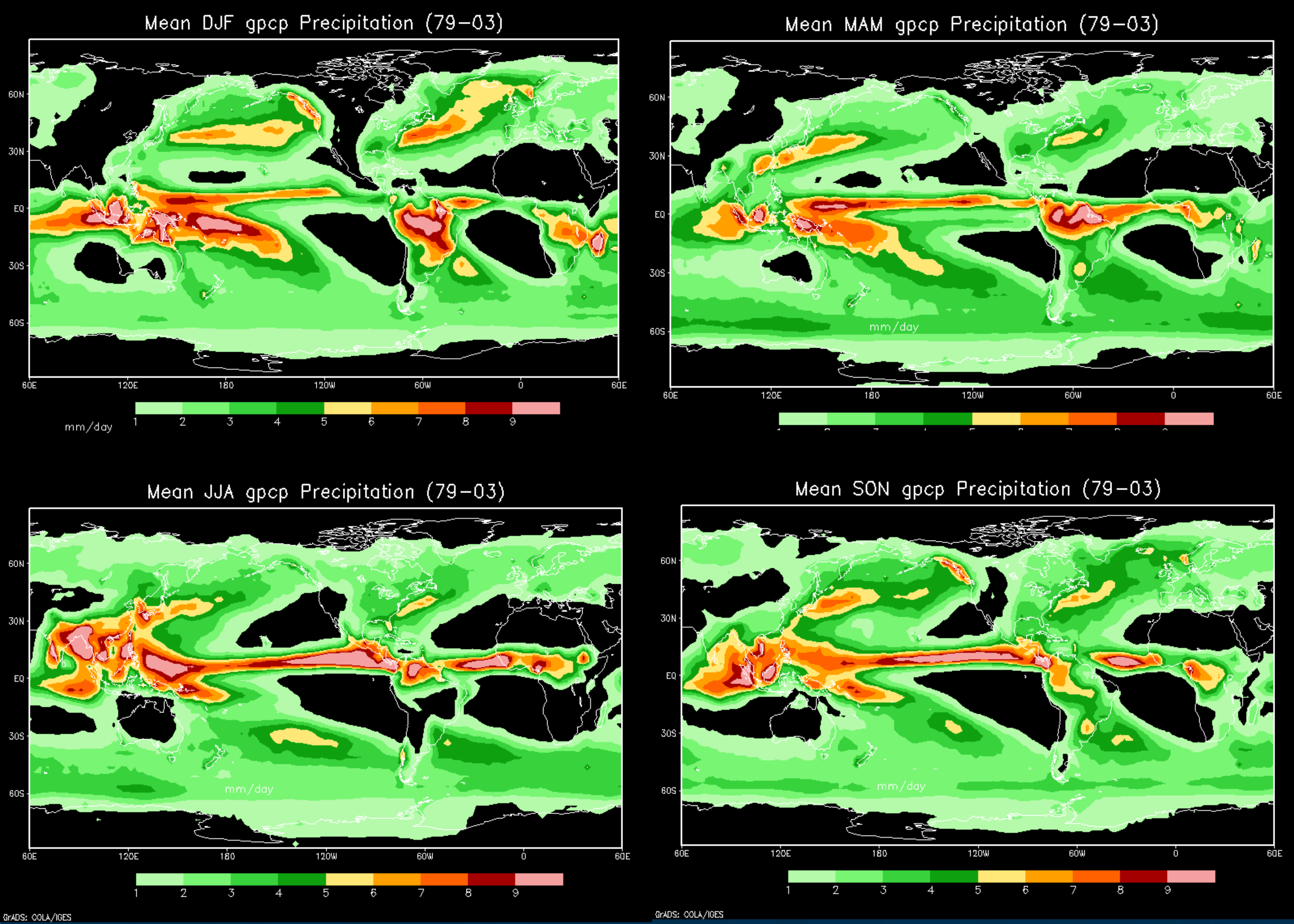




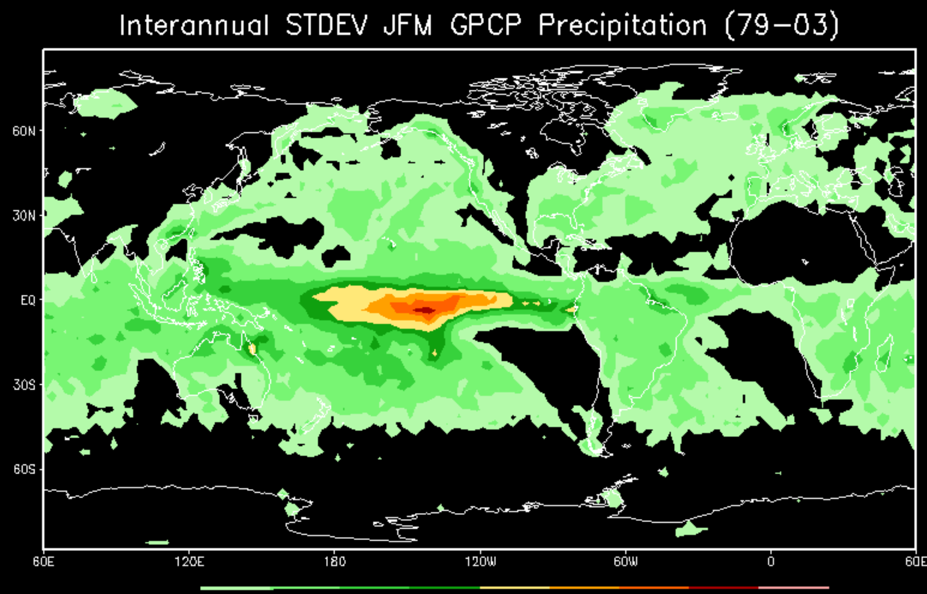
Global averages of monthly precipitation (mm day^{-1}) for ocean, total, and land from Adler et al. 2003.

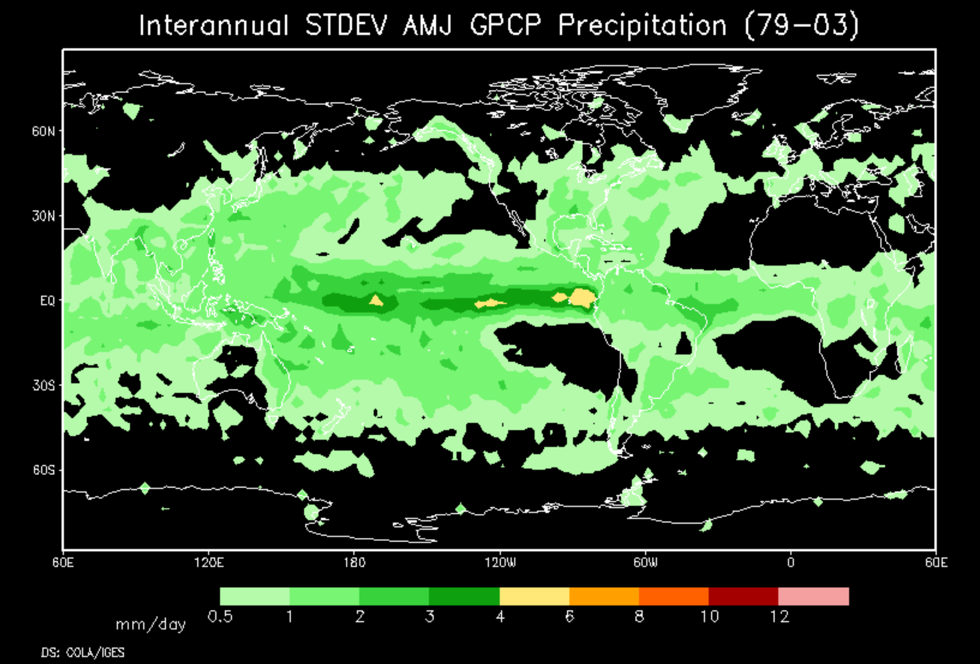


Tropical (30°N-30°S) averages of monthly precipitation anomalies (mm day^{-1}) for (top) total, (middle) ocean, and (bottom) land. Vertical dashed lines indicate the months of significant volcanic eruptions. The thin black curves indicate the Niño-3.4 SST index (°C) (After Adler et al 2003).



Seasonal Means of GPCP for 1979 - 2003


Interannual STDEV JFM GPCP Precipitation (79-03)
60N
30N
EQ
30S
60S
60E
120E
180
120W
60W
0
60E


Interannual STDEV AMJ GPCP Precipitation (79-03)
60N
30N
EQ
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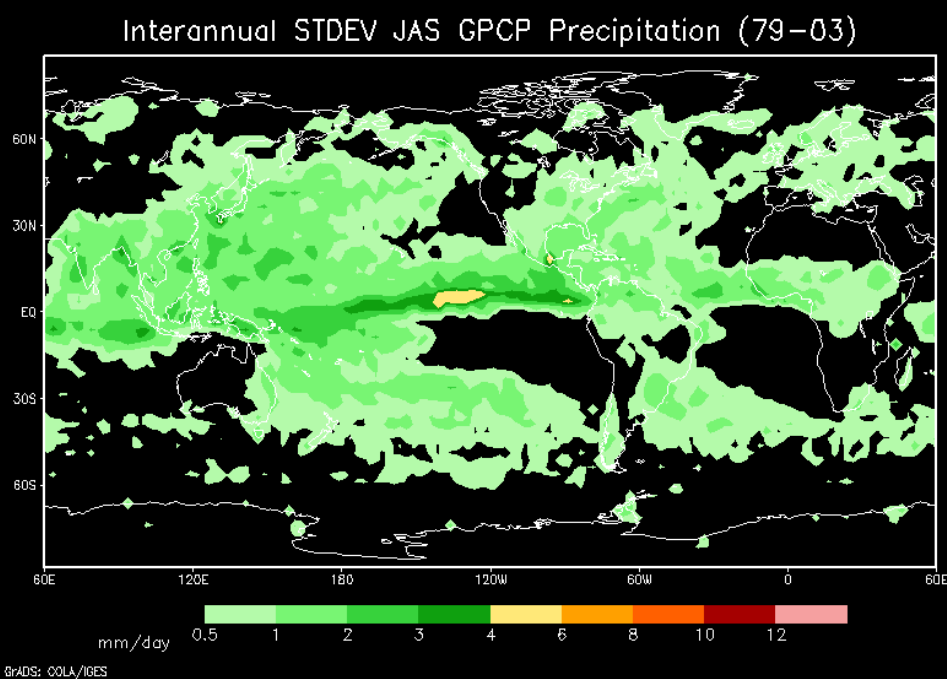
mm/day
0.5 1 2 3 4 6 8 10 12
DS: COLA/IGES


Interannual STDEV JAS GPCP Precipitation (79-03)
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mm/day
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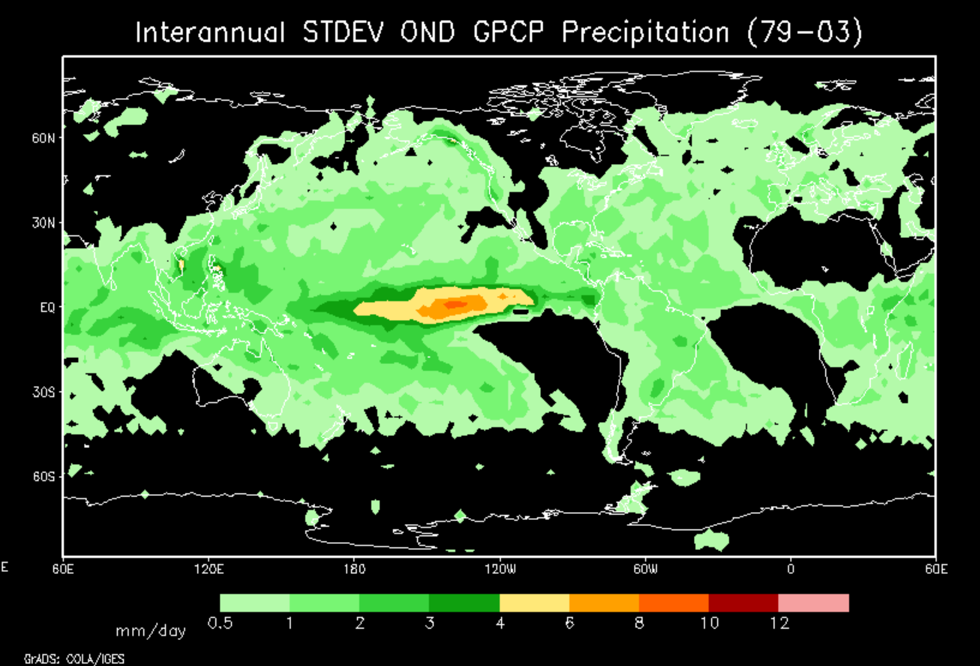
GrADS: COLA/IGES


Interannual STDEV OND GPCP Precipitation (79-03)
60N
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EQ
30S
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120W
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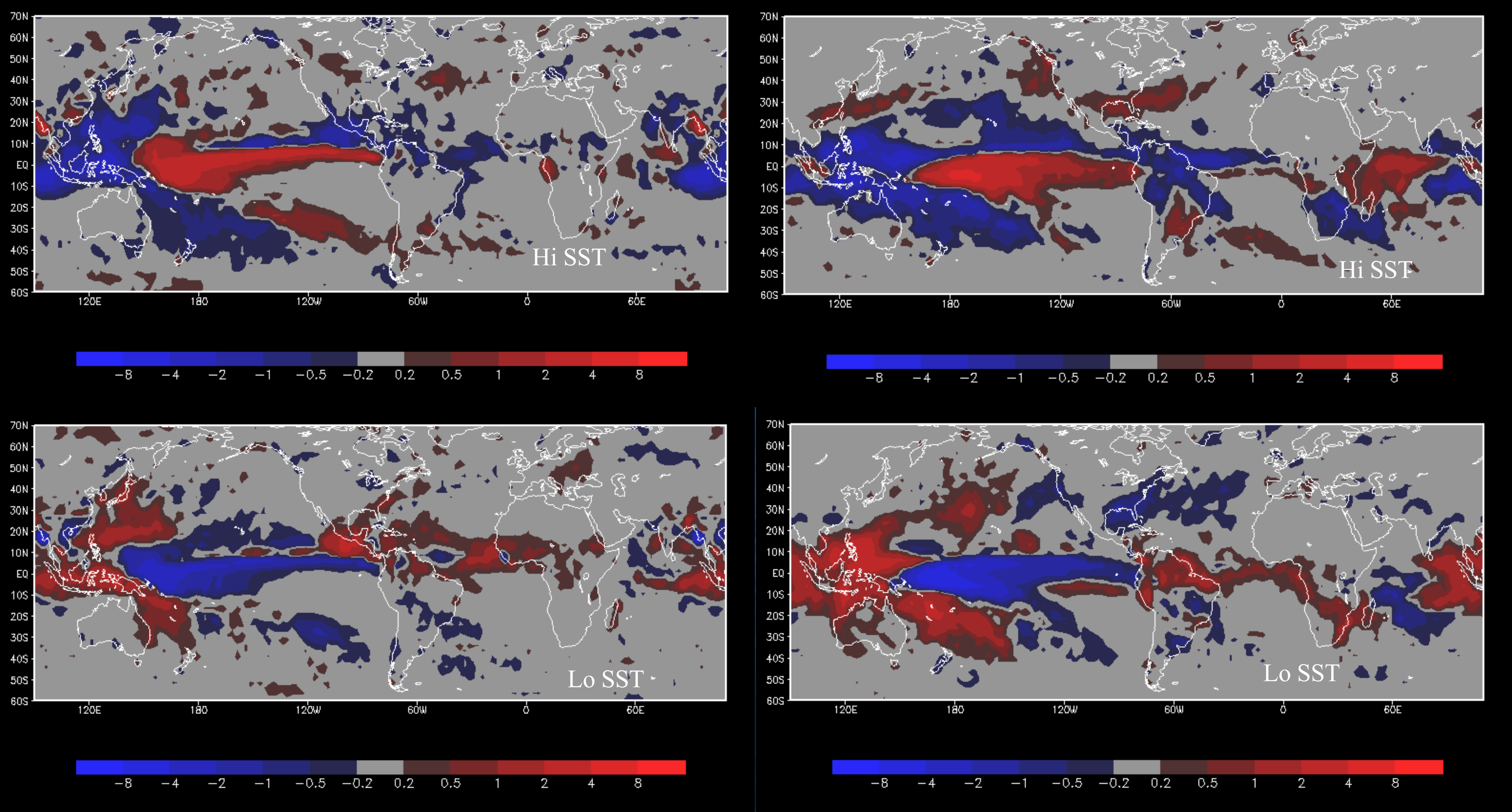
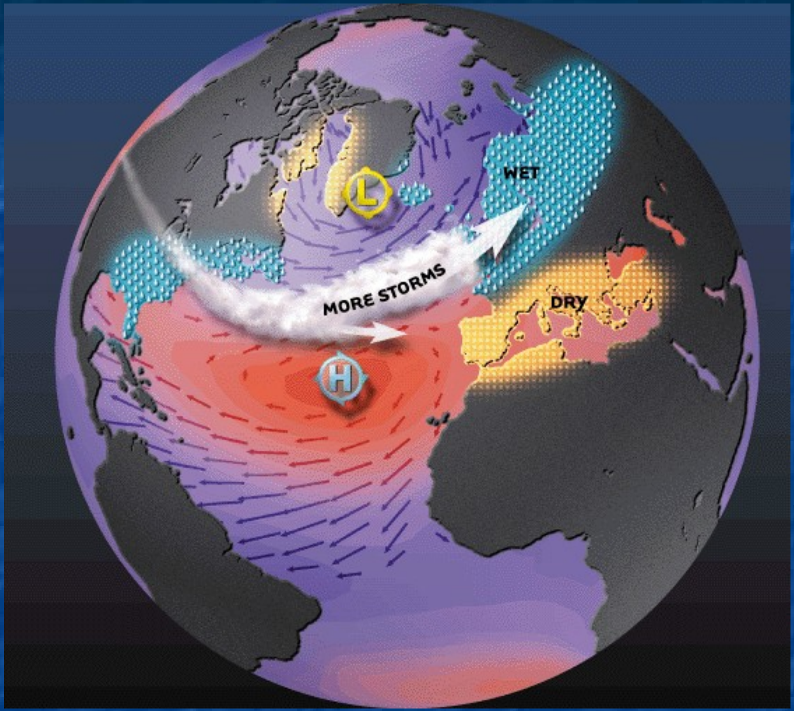
60E
mm/day
0.5 1 2 3 4 6 8 10 12
GrADS: COLA/IGES

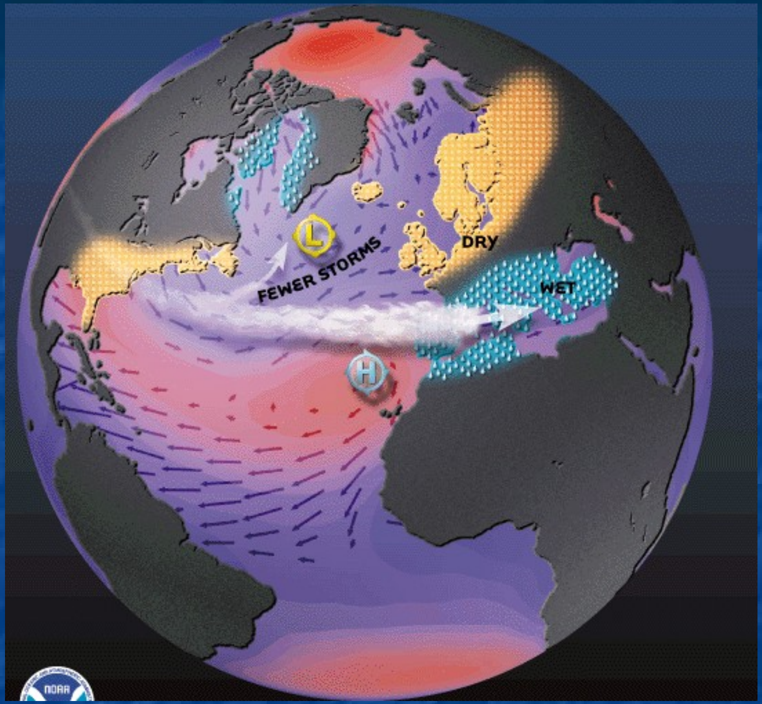
Precipitation anomaly composited on Niño 3.4 Sea Surface Temperature Anomaly (1979-2002)

JJAS DJFM



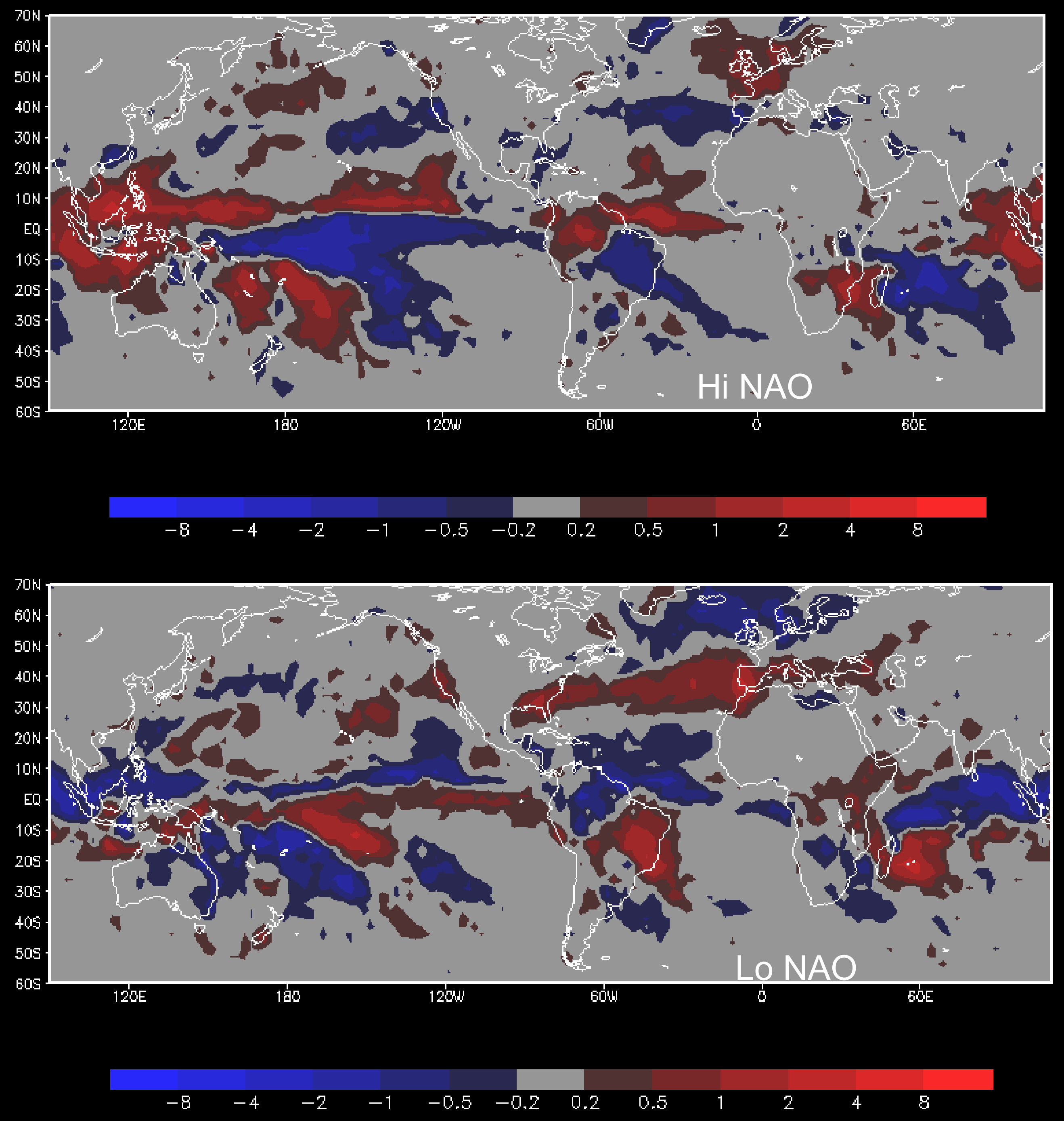
The North Atlantic Oscillation (NAO)





- Dominant mode of climate variability in the Atlantic in winter (van Loon & Rogers, 1972)
- Seesaw of atmospheric mass between subtropical high and subpolar low (Walker and Bliss, 1932)
- **Controls the path and intensity of storm track (Hurrell, 1995) (and precipitation?)**
- Spectral density of NAO weakly exists at 2-3 years (QBO), 7-10 years, also an increasing trend (Hurrell and van Loon, 1997)
- Significant impact on marine and terrestrial ecosystems

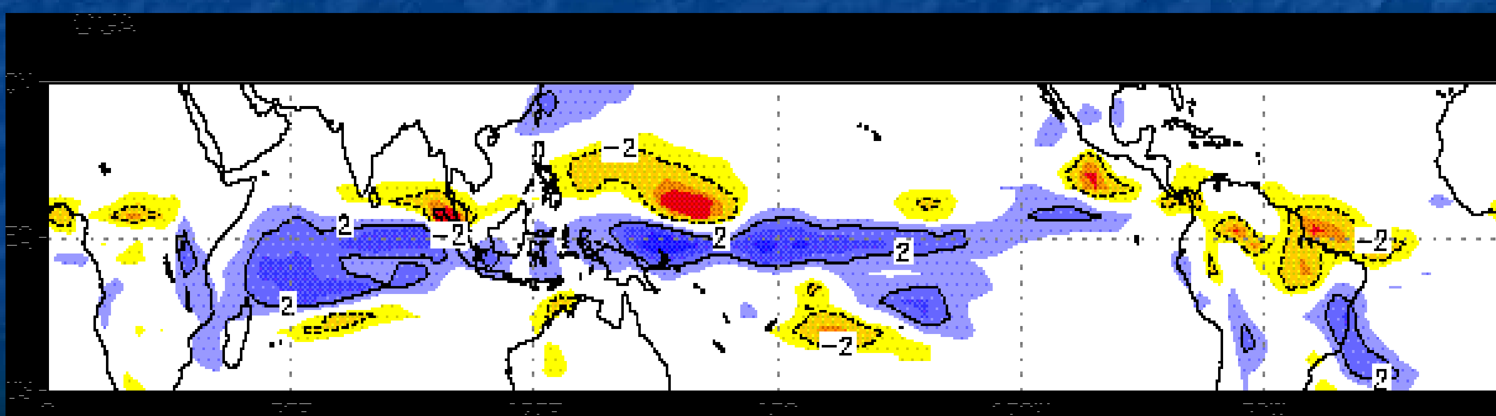
Images courtesy Martin Visbeck



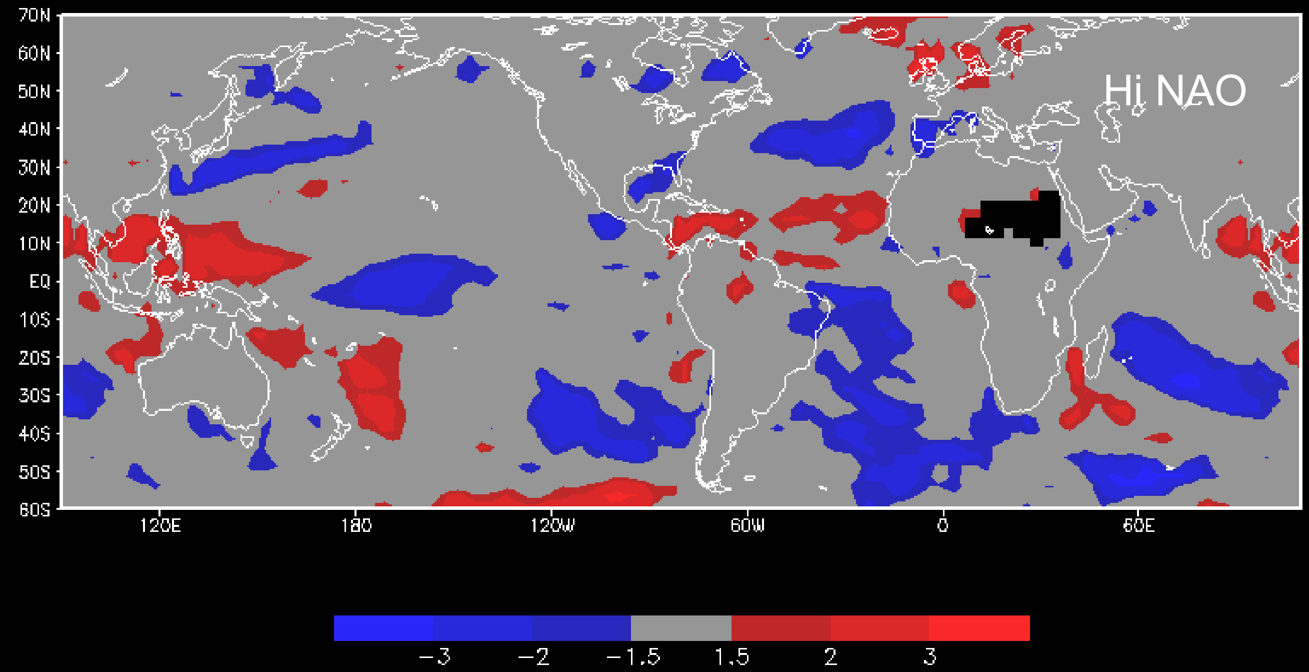
Composite DJFM Precipitation Anomalies from CMAP/A: 1979 – 2002 (Mariotti and Arkin, Climate Dynamics, 2006)

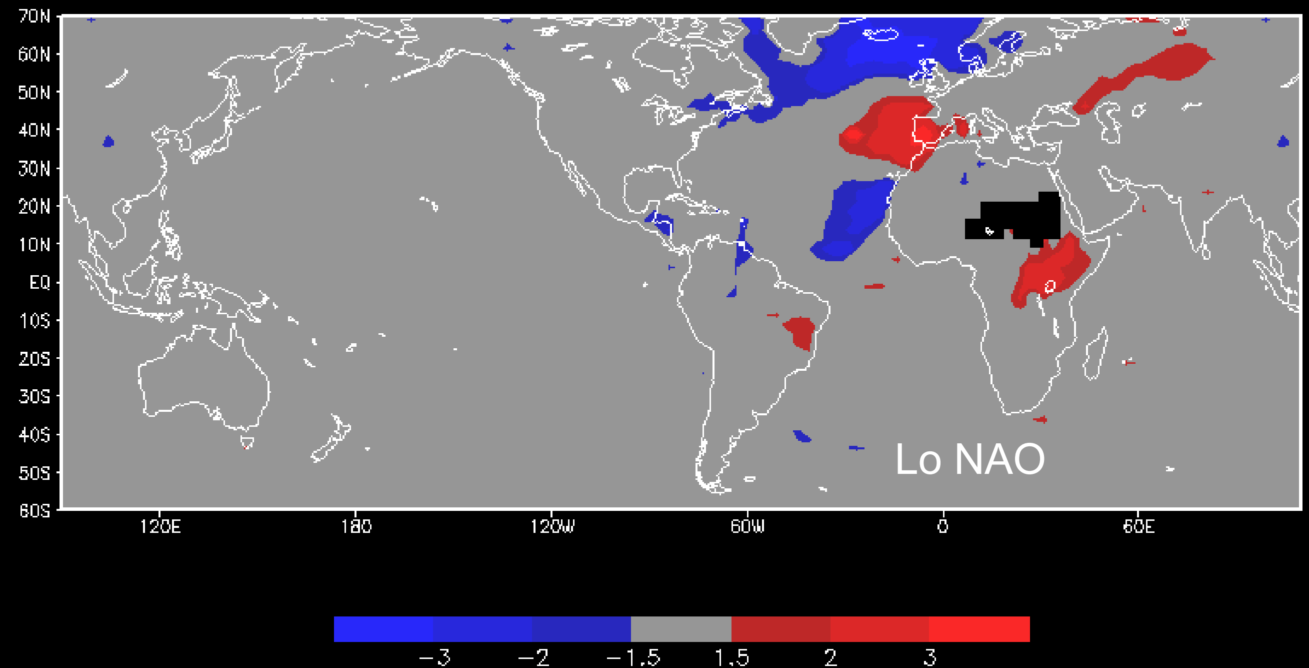
Does the NAO have manifestations outside the North Atlantic Ocean?

- Hoerling et al. (Science, 2001) found that increasing trend in tropical precipitation from 1950-2000 was related to similar trend in NAO
- Our record too short to compare directly, but maybe periods of high/low NAO index are characterized by coherent anomaly patterns away from the Atlantic Ocean



Implication: high NAO index associated with greater Indian/Pacific Ocean tropical precipitation?





Normalized Composite DJFM Precipitation Anomalies (Reconstruction : 1950 – 2002)

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- Both GPCP and CMAP suffer from:
  - Inhomogeneities in input data sets
  - Artifacts in the resulting analyses
  - Records too short to identify trends, too heterogeneous to permit budget calculations
  - Particular problems with high latitude and orographic precipitation
- Many of these associated with observing system gaps/changes (passive microwave, radar, geostationary data)
- Others related to fundamental physical limitations (e.g. snow/ice) and analysis shortcomings (limited physical model input)

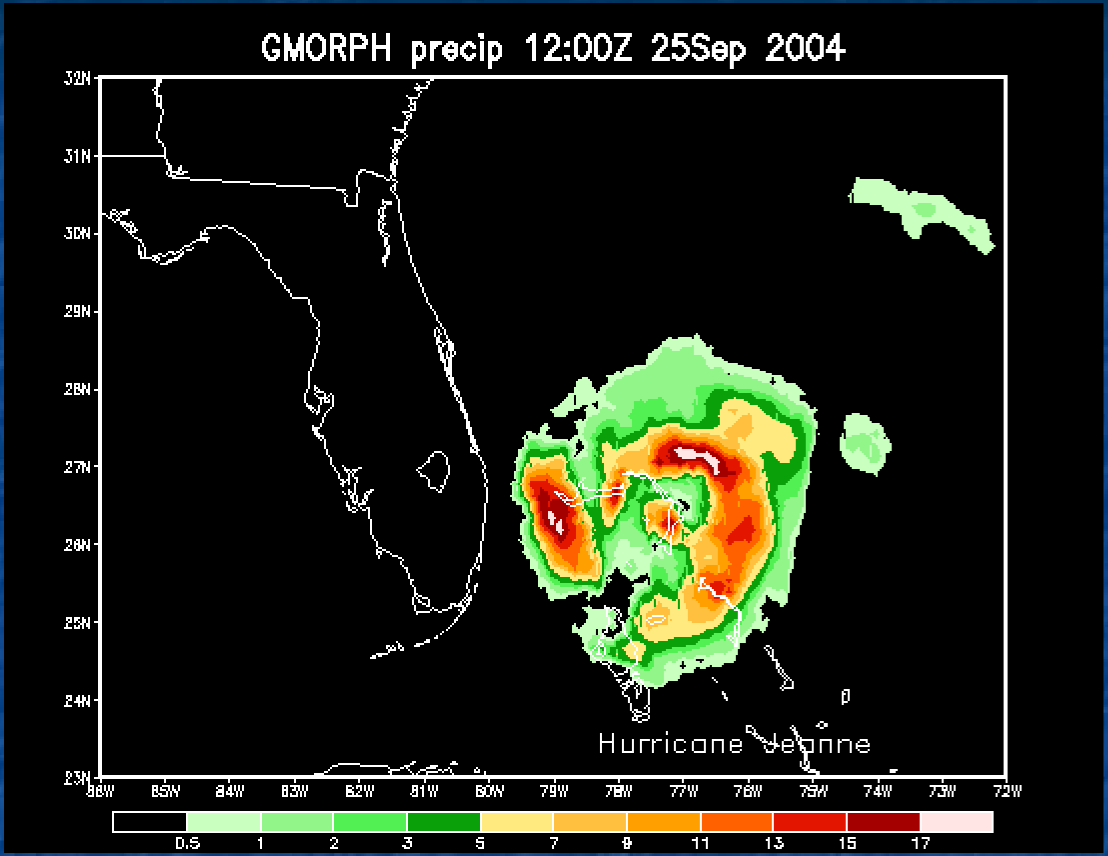
Second Generation Analyses

- At least two pathways are being traveled – one aimed at obtaining finer spatial and temporal resolution, the other at a more homogeneous time series with better understood errors
- The first has led to the high resolution precipitation products such as CMORPH, PERSIANN, TMPA and others
- The second is illustrated by the optimum interpolation analysis being developed in CICS by Sapiano, Arkin and Smith

High Resolution Precipitation Products

- Most scientific and societal applications require fine spatial and temporal resolution
  - Daily or finer
  - 10 – 50 km
- Recent new observations and research have made much higher resolution products possible, and extensive development and implementation has taken place
- The products generally rely on innovative methods that combine geostationary IR observations/estimates with estimates from passive microwave observations
- Time scales of about 3-hourly, spatial resolutions of 0.25°, near-global coverage (60°N-60°S)

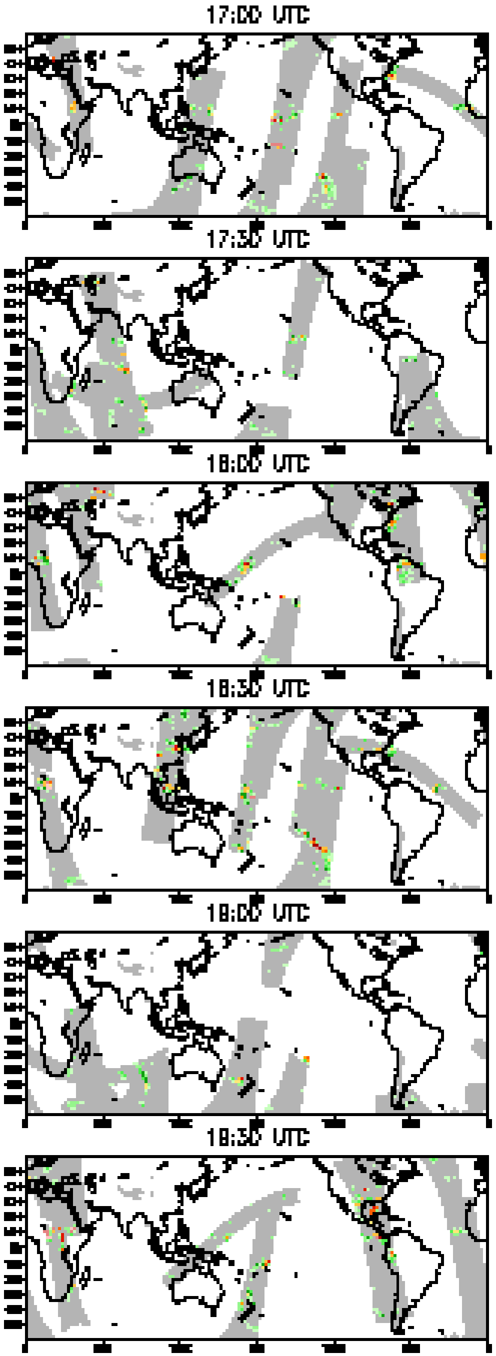
Hurricane Jeanne – September 2004



CMORPH (NOAA USA) uses a combination of precipitation estimates from passive microwave and cloud motion from geostationary IR

CMORPH: A High Time-Space Resolution Global Precipitation Analysis Using Passive Microwave and Infrared Data

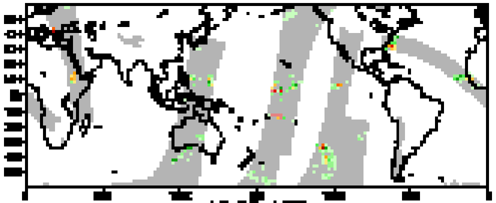
- Team: Bob Joyce, John Janowiak, Pingping Xie (CPC, NOAA)
- Concept:
  - Take maximum advantage of accuracy of microwave estimates and coverage of IR
  - Don't use IR to estimate precipitation – all methods developed so far have significant and difficult-to-quantify errors, particularly on fine scales
  - Use IR to estimate storm motion– errors are smaller/easier to understand
- Input data:
  - Geostationary IR: 30-60 minutes, 8 km at equator
  - Precipitation estimates from passive microwave: TMI, SSM/I, AMSU-B, …
- Product:
  - Global (60°N - 60°S), beginning in December 2002
  - Nominal resolution: 0.0728° (8 km at equator), 30 minutes
  - Usable resolution: hourly, 0.25°
- See Joyce et al., 2004, *J. Hydrometeorology*



At present, precipitation estimates are used from 4 passive microwave sensor types on 8 platforms:

- AMSU-B (NOAA 15, 16, 17)
- SSM/I (DMSP 13, 14, 15)
- TMI (TRMM – NASA/Japan)
- *AMSR/E (Aqua – NASA EOS)*

17:00 UTC



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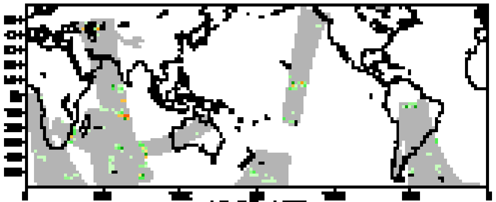

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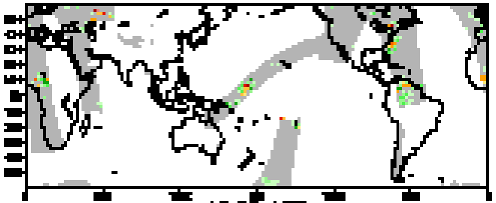
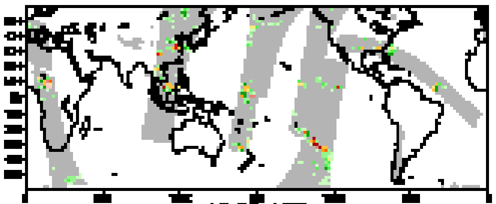


18:30 UTC



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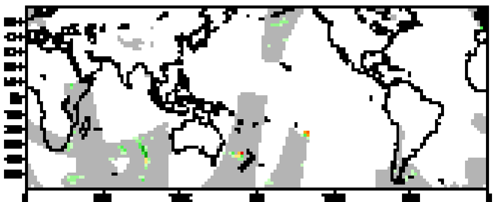
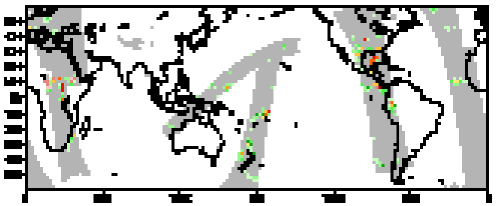
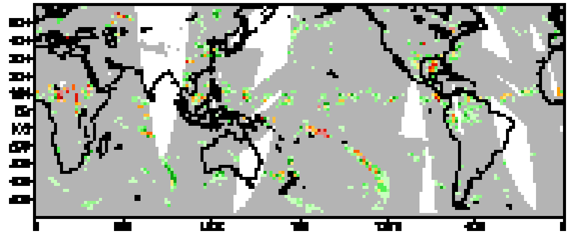


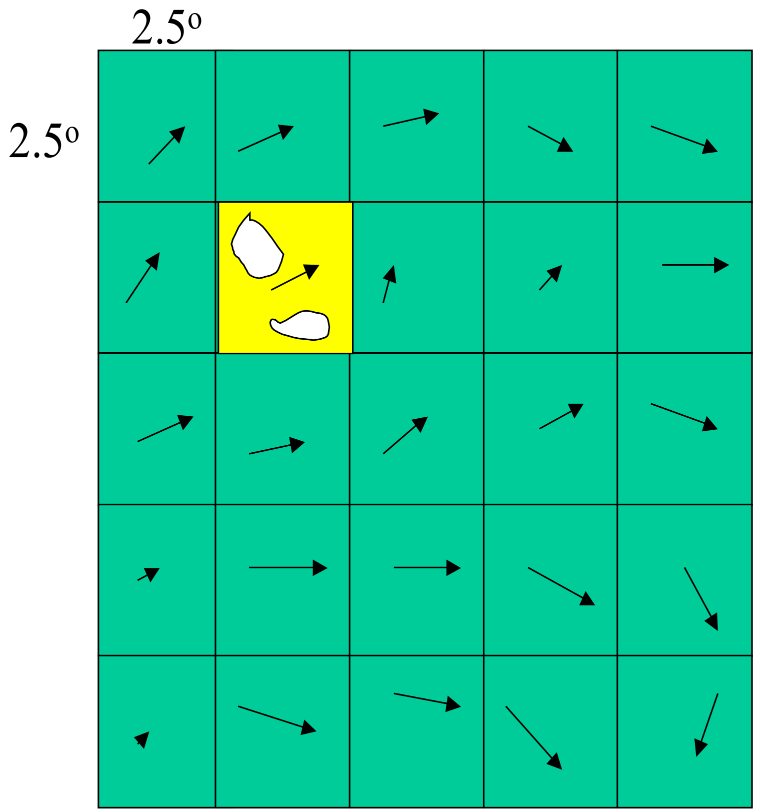
19:30 UTC

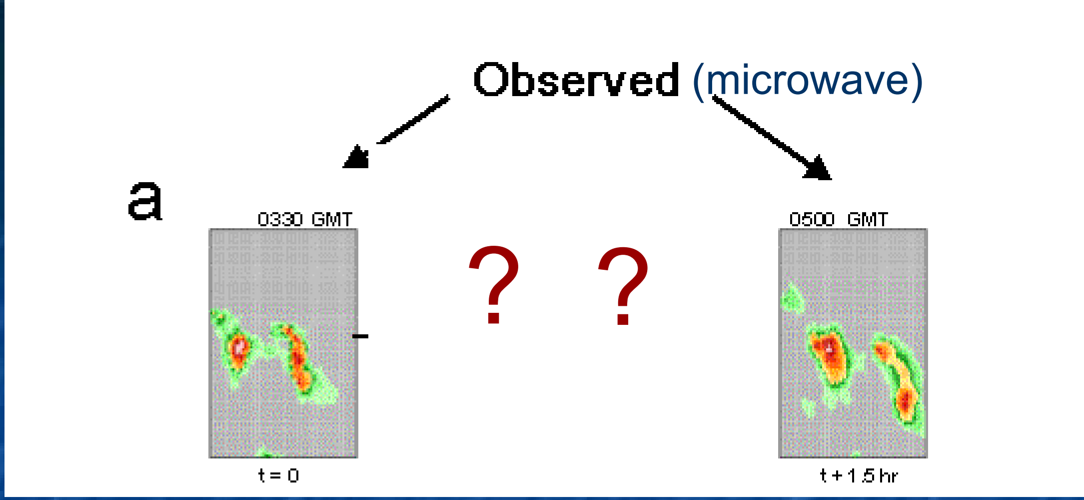


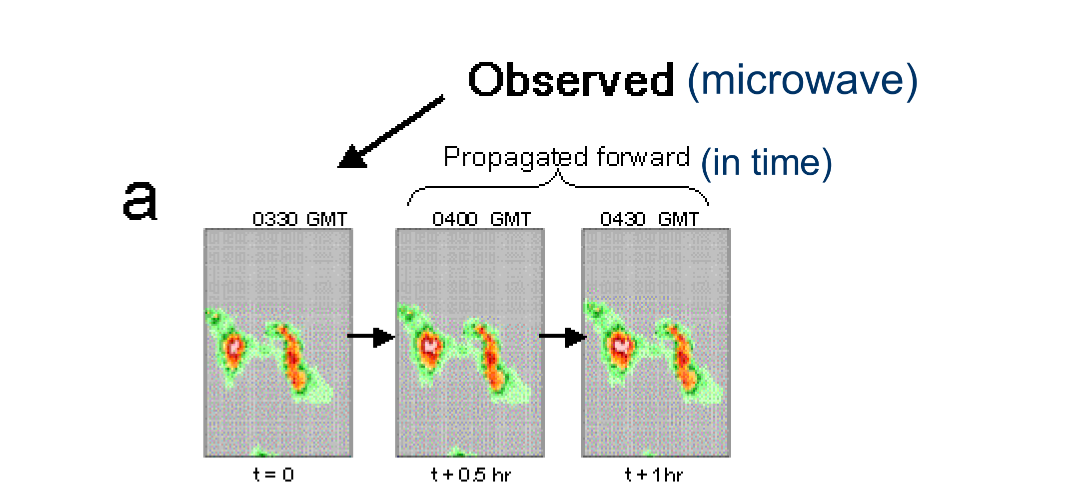
17:00 thru 19:30 UTC

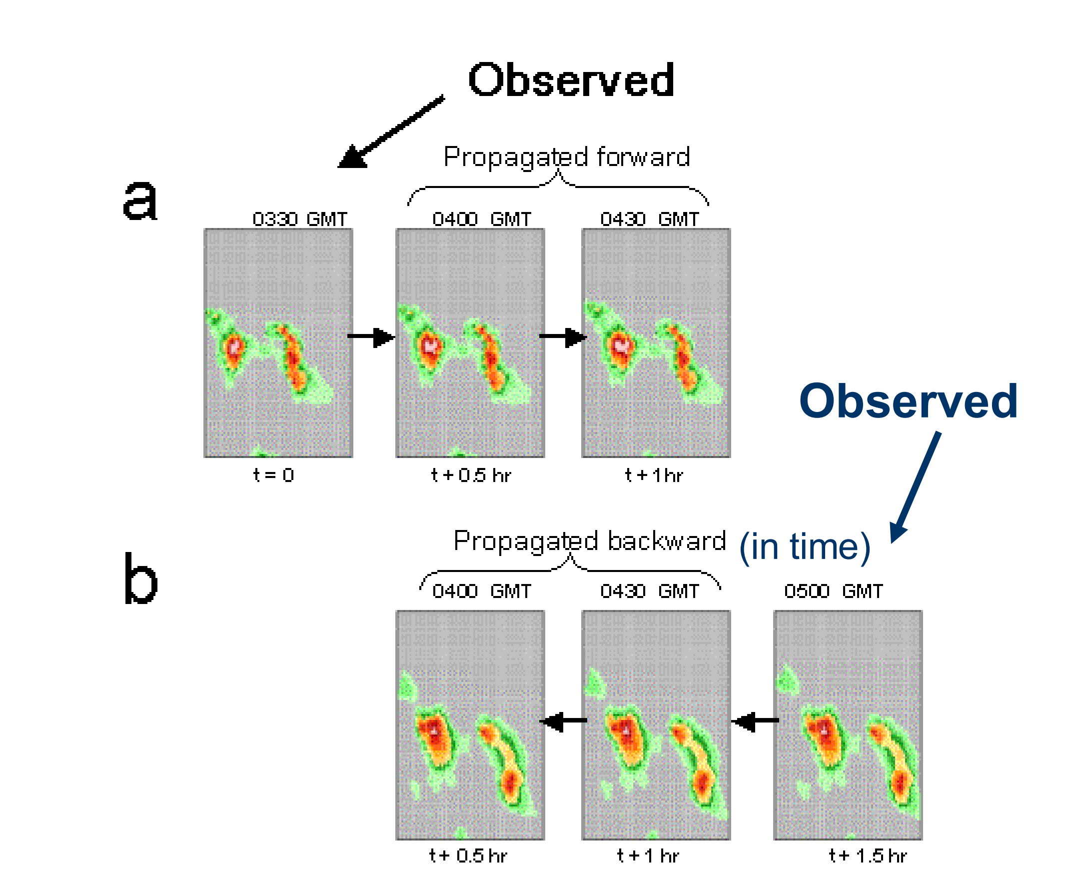


"Advection vectors" are computed from IR for each 2.5°gridbox and ***all microwave pixels*** contained in that grid box ***are propagated in the direction of that vector***

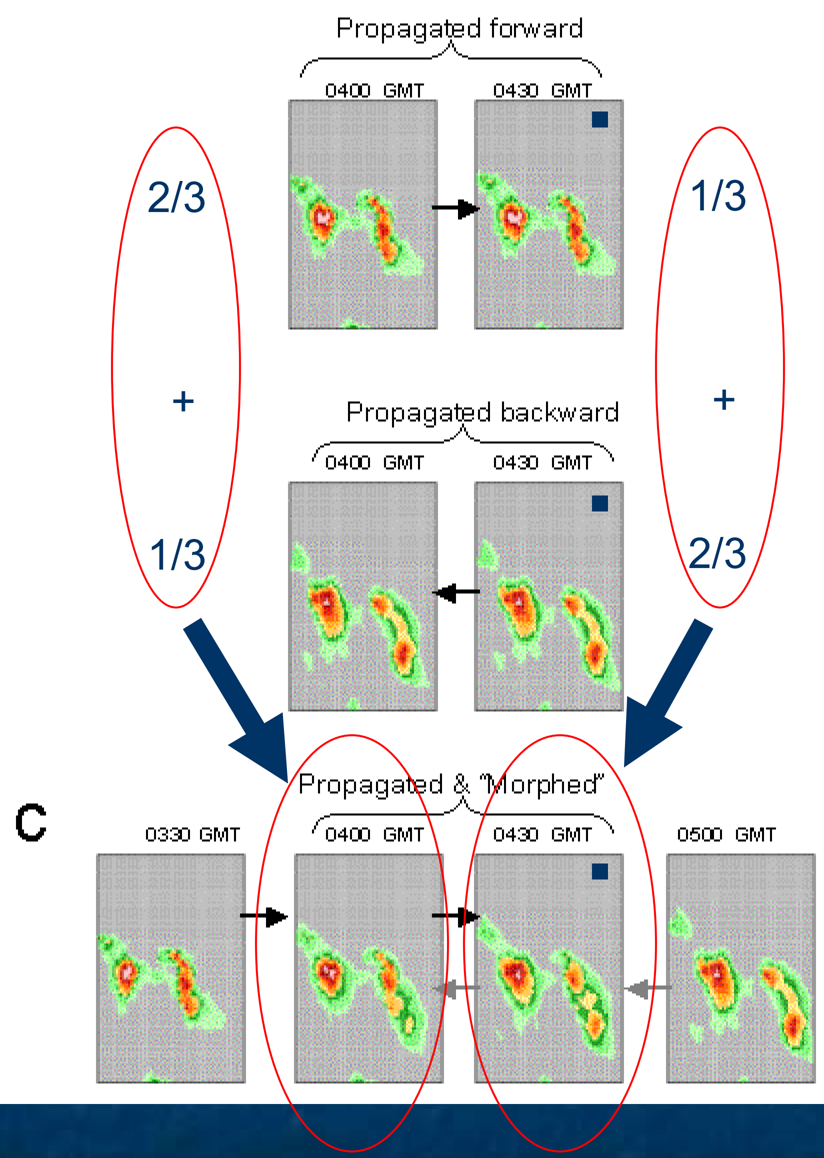



Observed (microwave)
a
0330 GMT
? ?
0500 GMT
t = 0
t + 1.5 hr


Observed (microwave)
Propagated forward (in time)
a
0330 GMT
0400 GMT
0430 GMT
t = 0
t + 0.5 hr
t + 1 hr



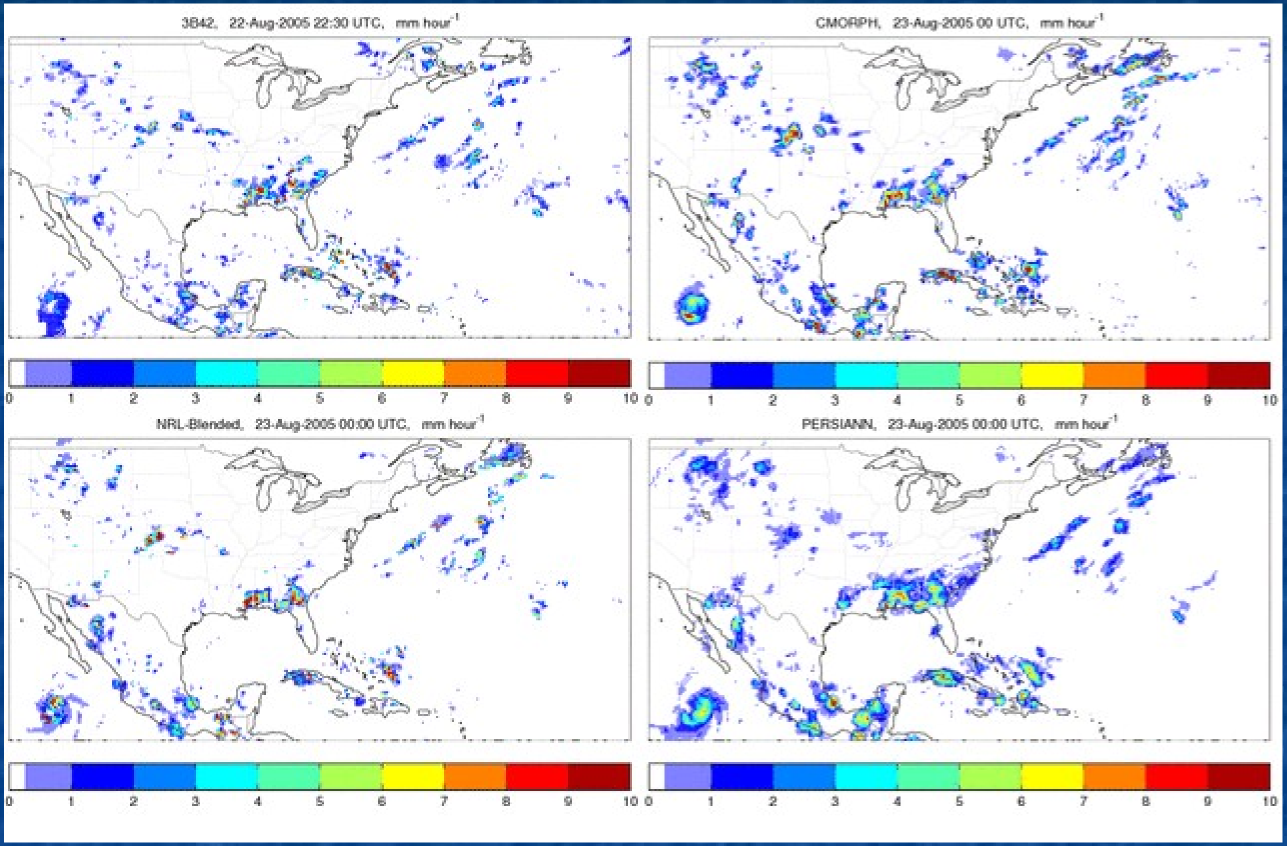
Observed
Propagated forward
a
0330 GMT
0400 GMT
0430 GMT
t = 0
t + 0.5 hr
t + 1 hr
Observed
Propagated backward (in time)
b
0400 GMT
0430 GMT
0500 GMT
t+ 0.5 hr
t + 1 hr
t+ 1.5 hr


Propagated forward
0400 GMT
0430 GMT
2/3
+
1/3
1/3
+
2/3
Propagated backward
0400 GMT
0430 GMT
C
Propagated & "Morphed"
0330 GMT
0400 GMT
0430 GMT
0500 GMT

HRPP Characteristics

- All of these rely on various ways of combining microwave and infrared estimates, sometimes with other information as well – see Matt Sapiano's page (http://essic.umd.edu/~msapiano/PEHRPP/data.html) for some more information
- CMORPH: microwave-based precipitation interpolated using storm motion from IR (Joyce et al., 2004)
- TMPA (TRMM Multi-satellite Precipitation Analysis): microwave estimates where available, supplemented with microwave-calibrated IR threshold estimates where necessary (Huffman et al., 2003)
- Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN): neural-network using IR calibrated with microwave estimates (Sorooshian et al., 2000 and Hsu et al., 1997)
- NRL-Blended: IR threshold calibrated with microwave estimates (Turk, Naval Research Lab, Monterey, CA)
- HydroEstimator: experimental quasi-operational weather-oriented estimate based on IR with NWS model-derived corrections (Kuligowski, STAR, NESDIS/NOAA
- Others being developed: GSMaP (Okamoto, Japan), SCaMPR (Kuligowski)

Hurricane Katrina – August 2005
3-hourly precipitation from TRMM 3B42, CMORPH, NRL, PERSIANN



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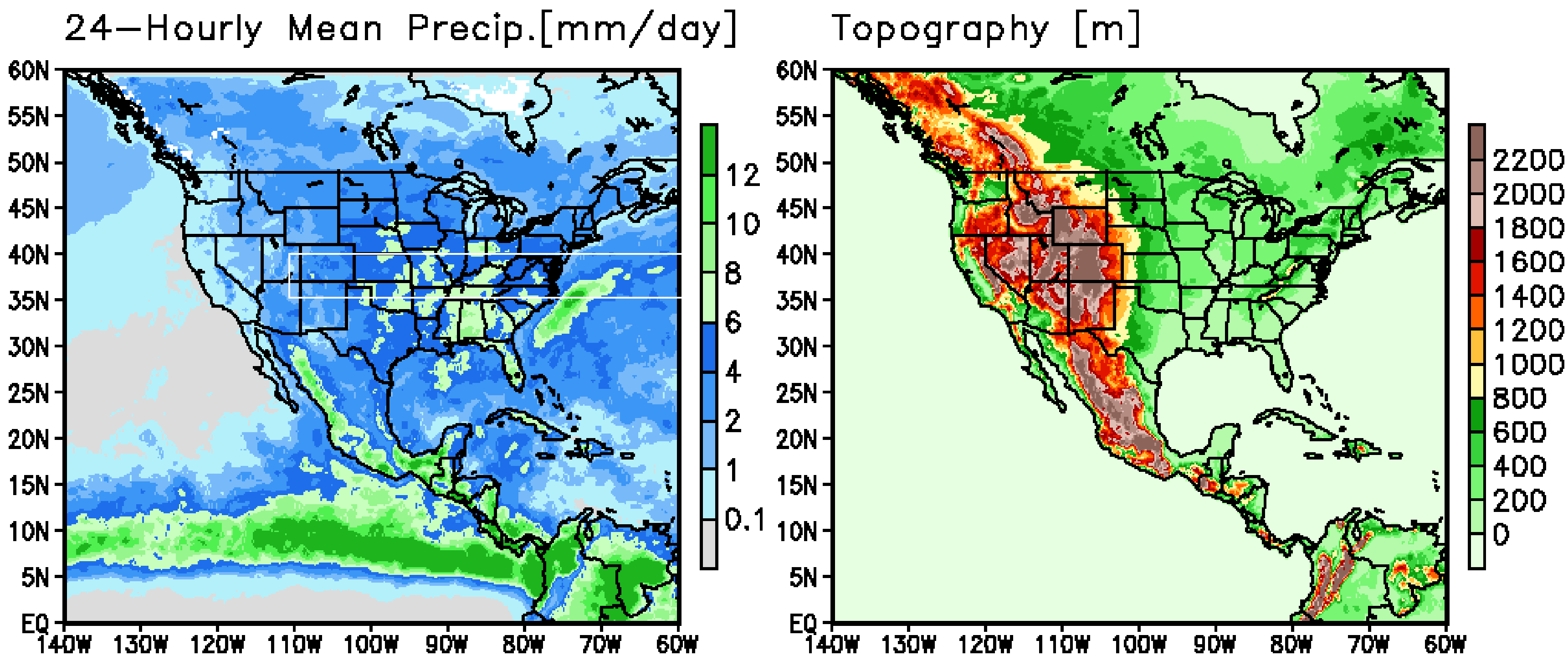
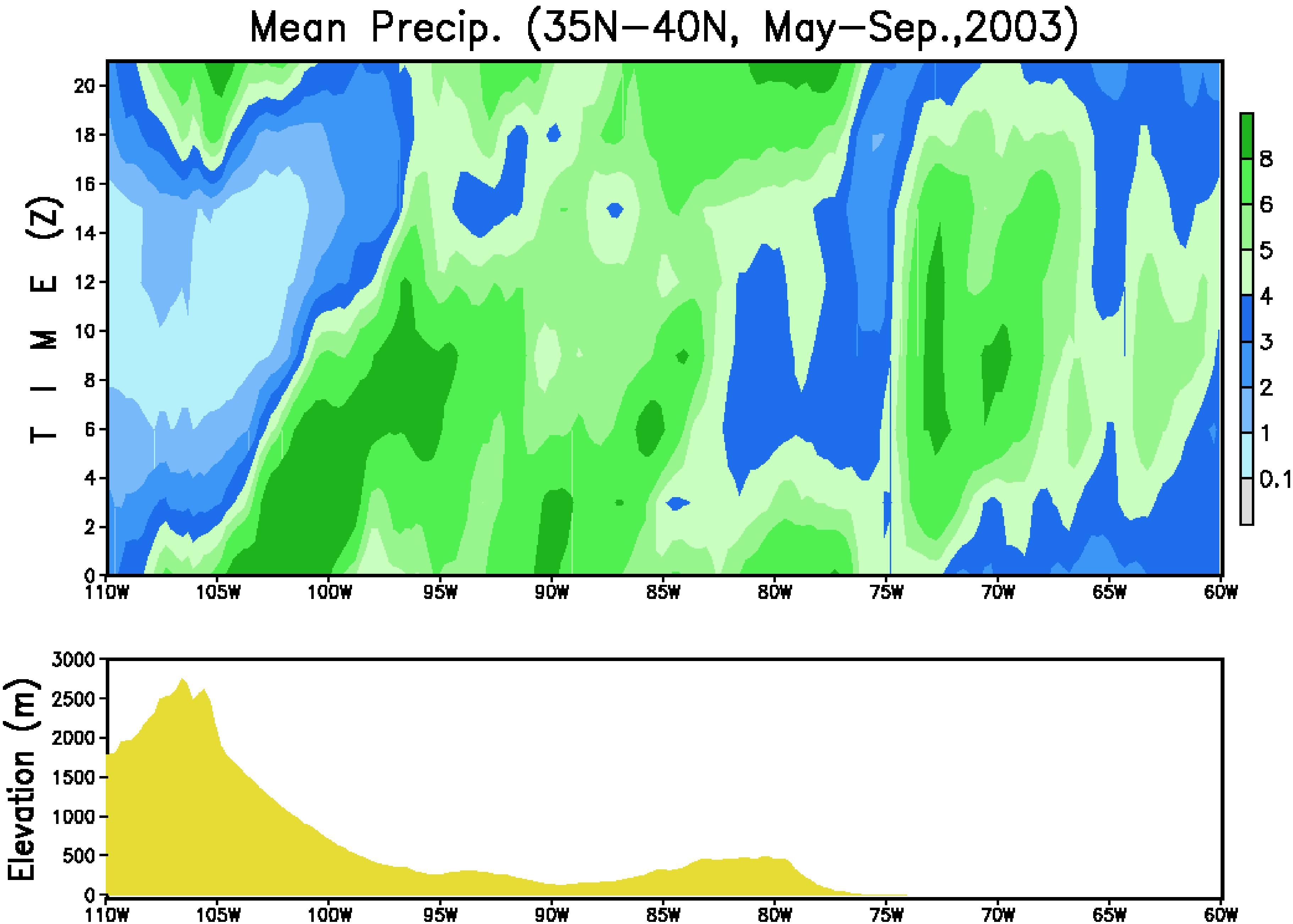
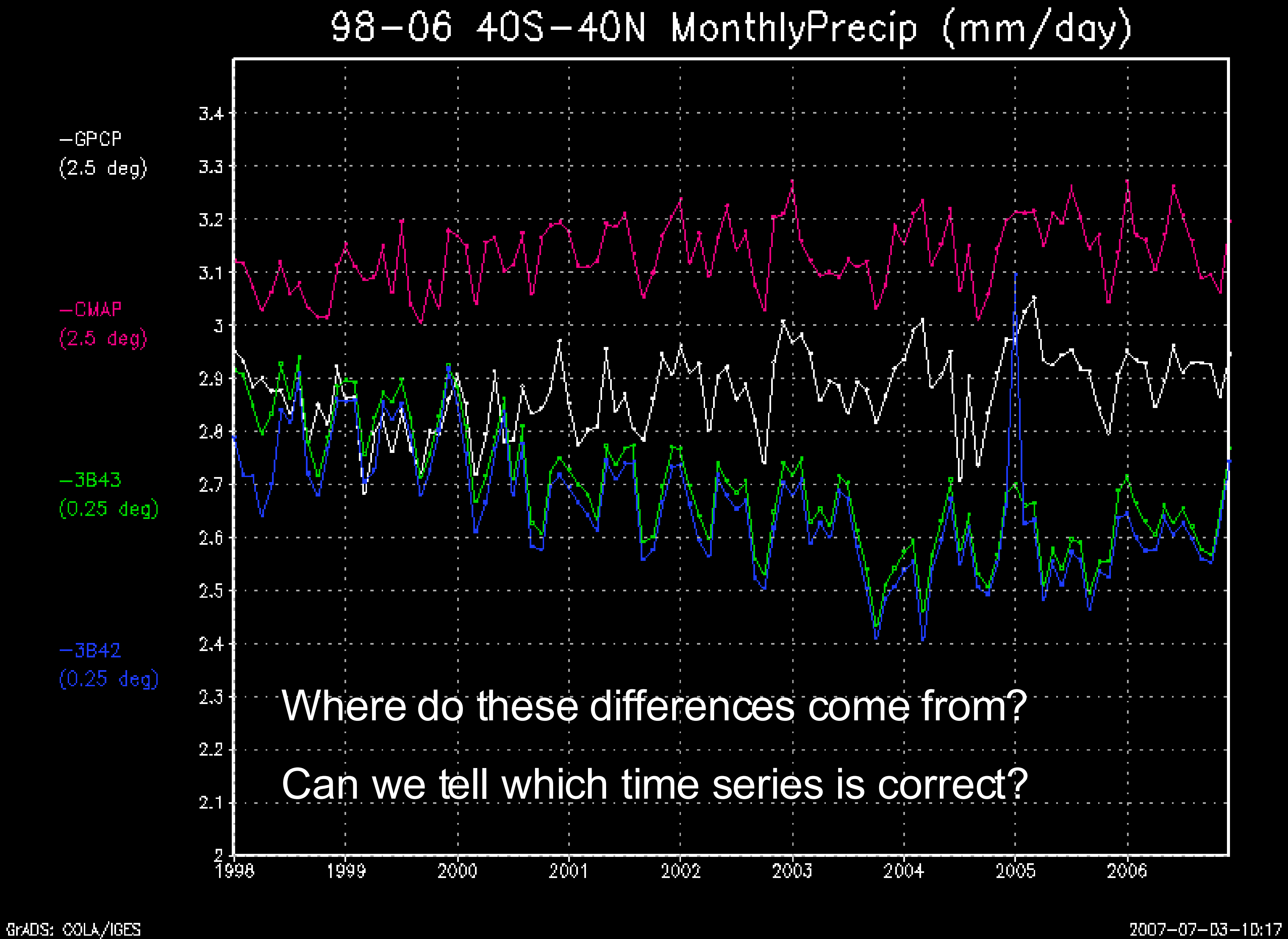


CMORPH / Joyce et al. (2003)


Mean Precip. (35N–40N, May–Sep.,2003)
TIME (Z)
0
2
4
6
8
10
12
14
16
18
20
110W
105W
100W
95W
90W
85W
80W
75W
70W
65W
60W
8
6
5
4
3
2
1
0.1
Elevation (m)
0
500
1000
1500
2000
2500
3000
110W
105W
100W
95W
90W
85W
80W
75W
70W
65W
60W

- CMORPH and the other HRPP are proving to be very attractive for many purposes:
  - Diagnostic studies describing the diurnal cycle and fine scale phenomena previously out of reach for global precipitation products
  - Hydrologists can use them to drive land surface models on scales for which they previously had to use model predictions
  - Real-time forecasts of floods and landslides can be made globally
- However, a different motivation comes from climate change studies:
  - As global surface temperature changes (regardless of the reason for the change), the amount of moisture in the atmosphere should increase (higher sea surface temperature -> higher near-surface absolute humidity)
  - If the total amount of water vapor in the atmosphere is greater, it seems reasonable to hypothesize that total global precipitation would increase as well
  - This reasoning doesn’t tell us anything about regional variations, but given sufficiently accurate global analyses we might be able to test the hypothesis
- Global climate models indicate that total atmospheric water vapor and precipitation do increase with atmospheric temperature, although precipitation doesn’t seem to increase in strict proportion
- However, the observational datasets we have so far (GPCP and CMAP) are too heterogeneous to permit us to test the hypothesis


98-06 40S-40N MonthlyPrecip (mm/day)
-GPCP (2.5 deg)
-CMAP (2.5 deg)
-3B43 (0.25 deg)
-3B42 (0.25 deg)
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1998
1999
2000
2001
2002
2003
2004
2005
2006
Where do these differences come from?
Can we tell which time series is correct?
GrADS: COLA/IGES
2007-07-03-10:17

A New Global Analysis of Precipitation

Matt Sapiano, Phil Arkin and Tom Smith

Cooperative Institute of Climate Studies (CICS), University of Maryland

Project Aims

- Create a global multi-source precipitation analysis which is both long and *homogeneous* for use in climate studies
  - Minimize discontinuities
  - Include reanalysis estimates; hope to improve estimates at high-latitudes
  - *Note on resolution: monthly; 2.5º lat/lon*
- Create a reconstruction of *oceanic* precipitation over a longer period (50-100 years) based on the new merged analysis

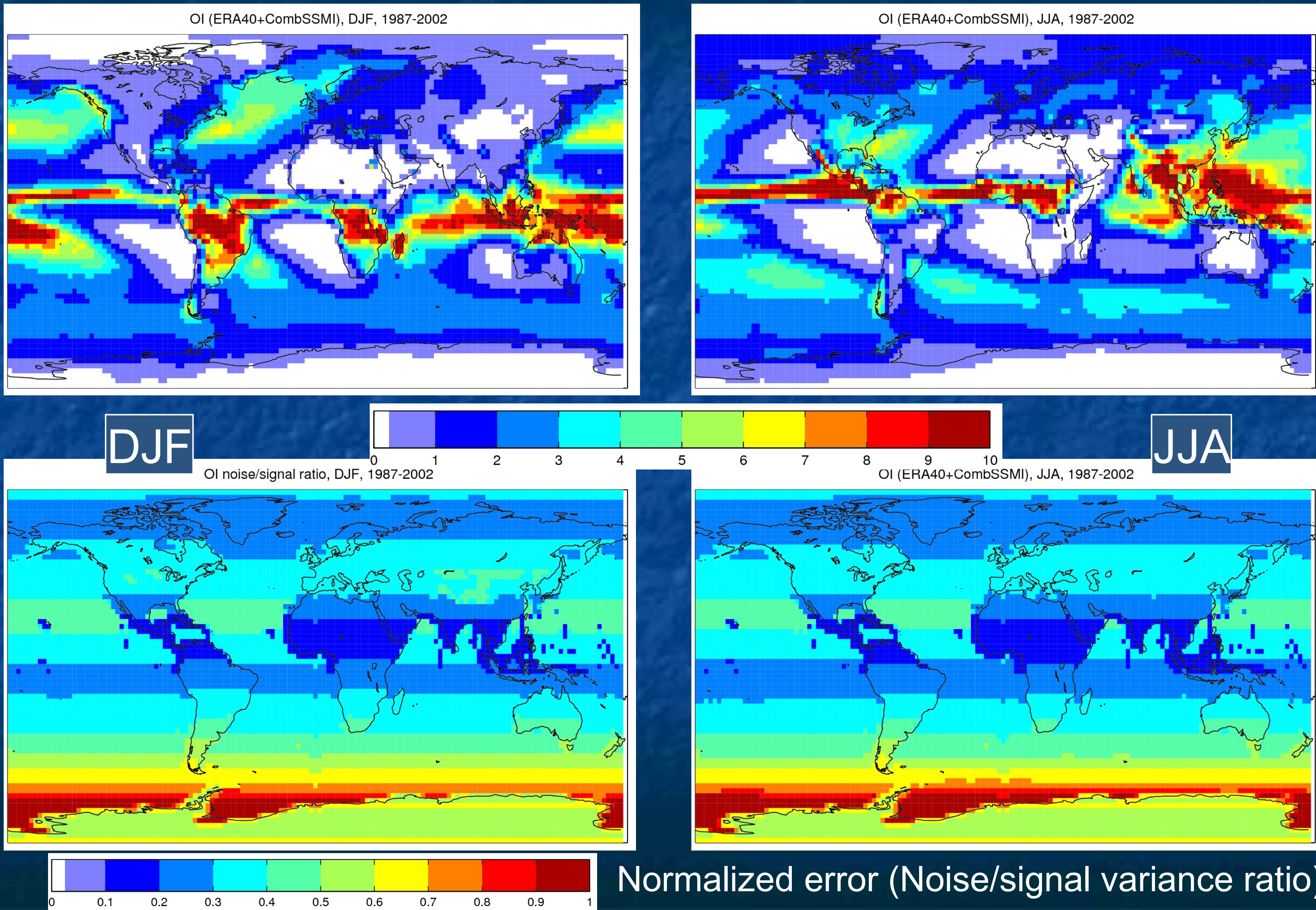
Some hypotheses…

- Satellite data provides the only globally complete estimate of precipitation
  - Need to use satellite precipitation to make estimate over the ocean – definite candidate for analysis
  - Other merged analyses may contain discontinuities due to use of ever-changing inputs (GPCP, CMAP, etc…)
    - Can use single input to get homogeneous estimate
- Reanalysis precipitation ("model data") might provide best estimate in high-latitudes
  - Some evidence of this exists – difficult to prove
  - Probably no worse than anything else in NH high latitudes!
- Want to make an experimental dataset which might be useful for climate studies
  - Might also inform the next generation of merged estimates
  - Use Optimum Interpolation to merge the input datasets
    - Also yields a meaningful estimate of error

→ Make merged estimate from satellite and reanalysis precip

→ Need to decide which satellite estimates to use…

Results: ERA-40 + Combined SSM/I

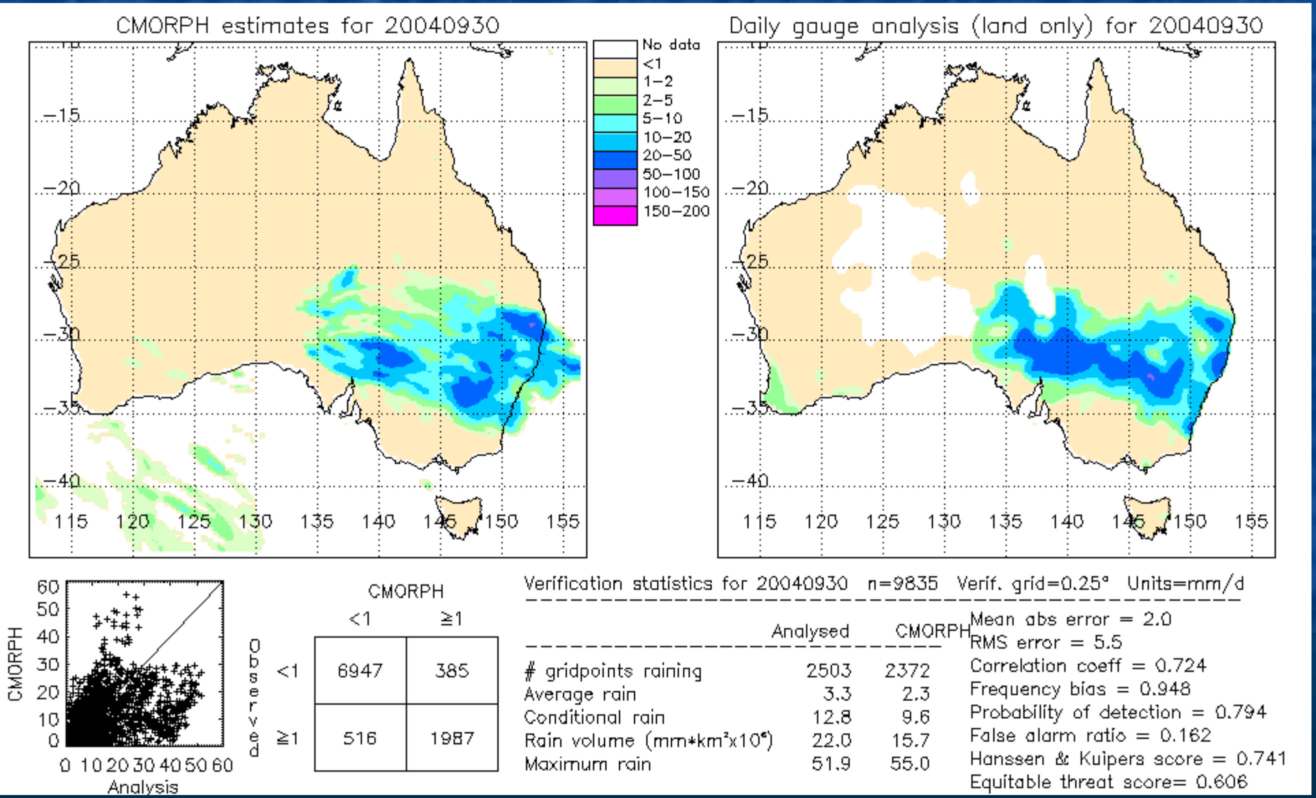


- Motivation
- Information Sources
- First Generation Global Analyses
- Climatology and Variability
- Second Generation Global Analyses
- Validation
- Concluding Remarks

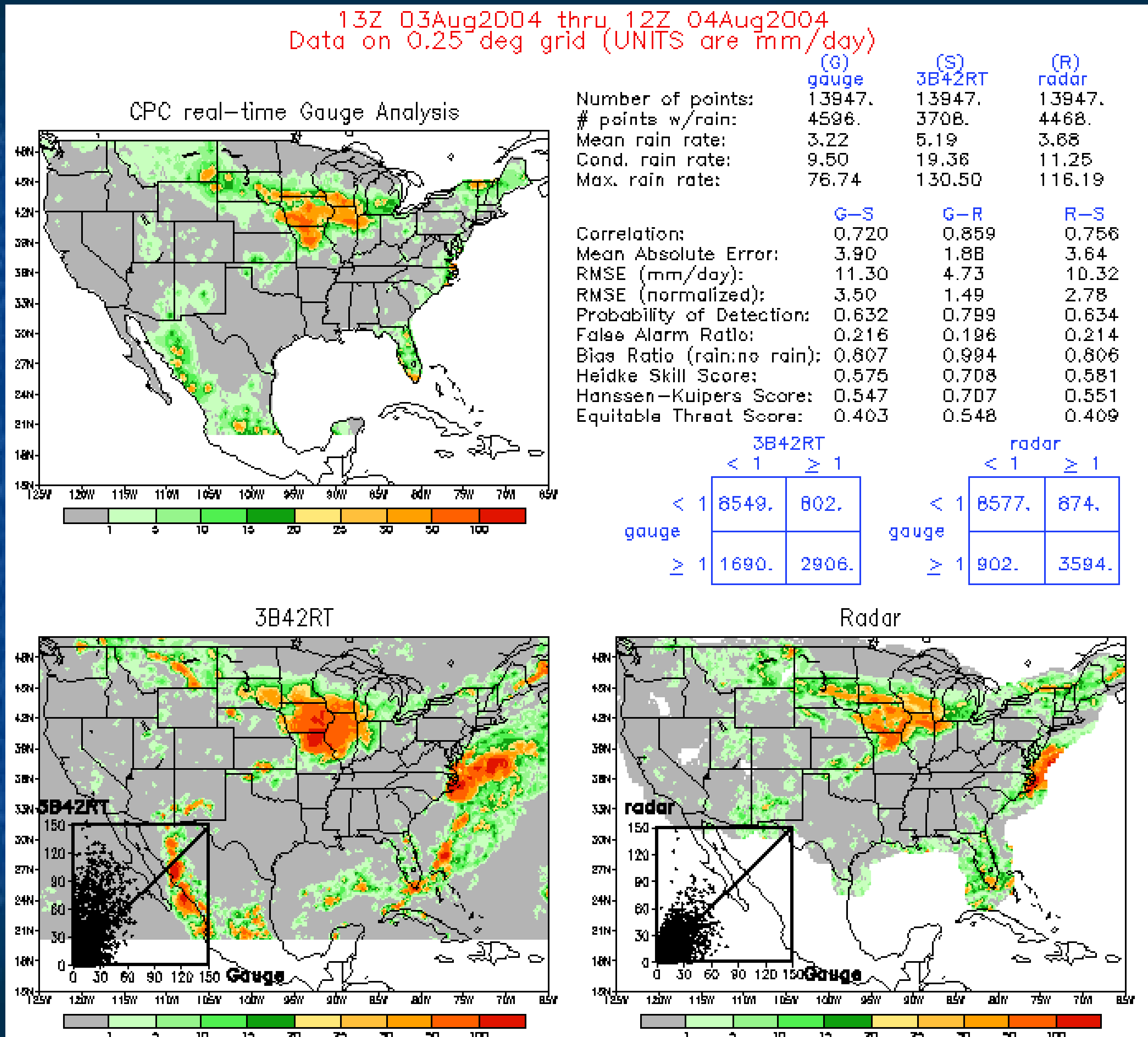
- Everything involved in this process must be validated somehow so that users (scientists and others) can use them with confidence
- Rain gauge measurements continue to be the fundamental link to a specific physical quantity – estimates are always characterized somehow in relation to gauge observations
- Individual estimates derived from satellite observations (just like surface radar-derived estimates) are tied as much as possible to the detailed distribution of falling water and ice and the associated radiation physics – this is sometimes referred to as “physical validation” to distinguish it from statistical validation through correlations and such
- The sorts of analyses I’ve described here must be validated as well, both physically (to the extent possible) and statistically

Continental/Regional Comparisons

- Large areas, long (continuous) time periods
- Daily/0.25°x0.25° areas
- Participants from Australia, U.S., Western Europe, Japan, South Africa, Ethiopia, Argentina, Brazil, South Korea, China, Canada, …
- Utilizing analyses based on national gauge and radar networks



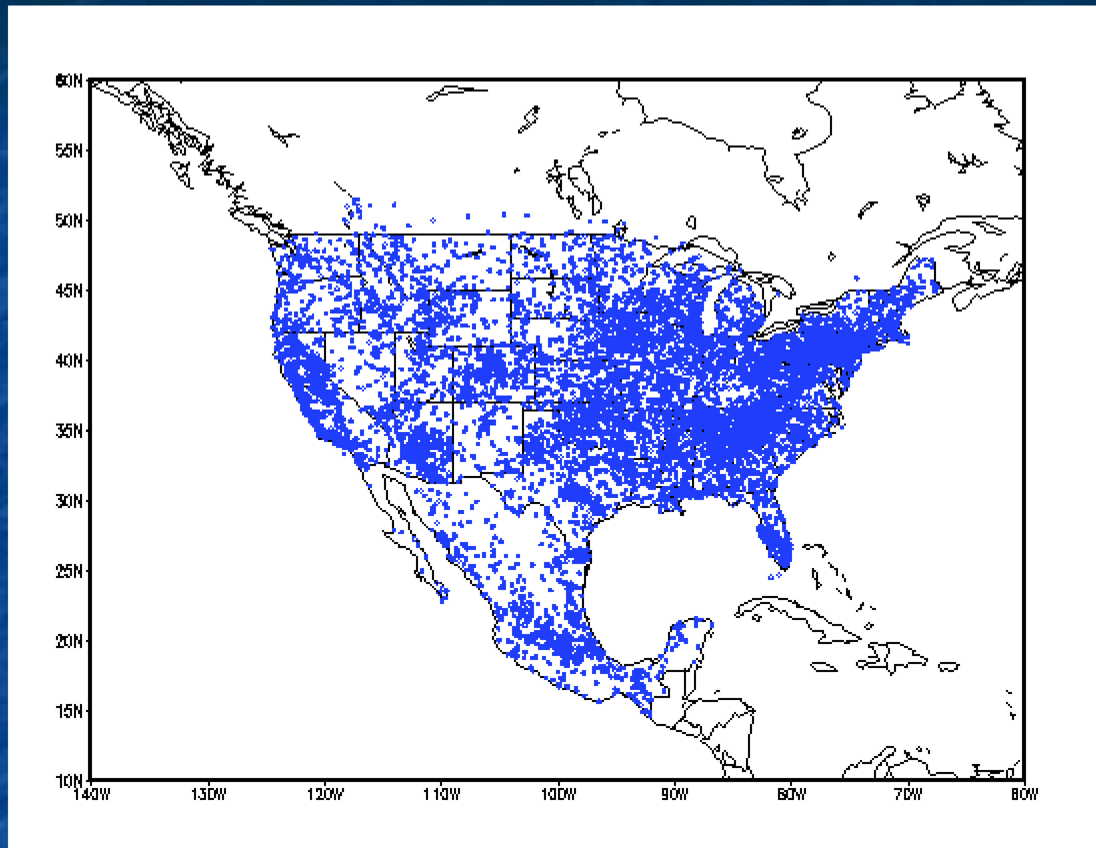
Beth Ebert (BMRC, Australia) originated this technique www.cpc.ncep.noaa.gov/products/janowiak/us_web.shtml



US – Mexico Gauge Analysis

(http://www.cpc.noaa.gov/products/precip/realtime/US_MEX/index.shtml)

Typical Station Distribution

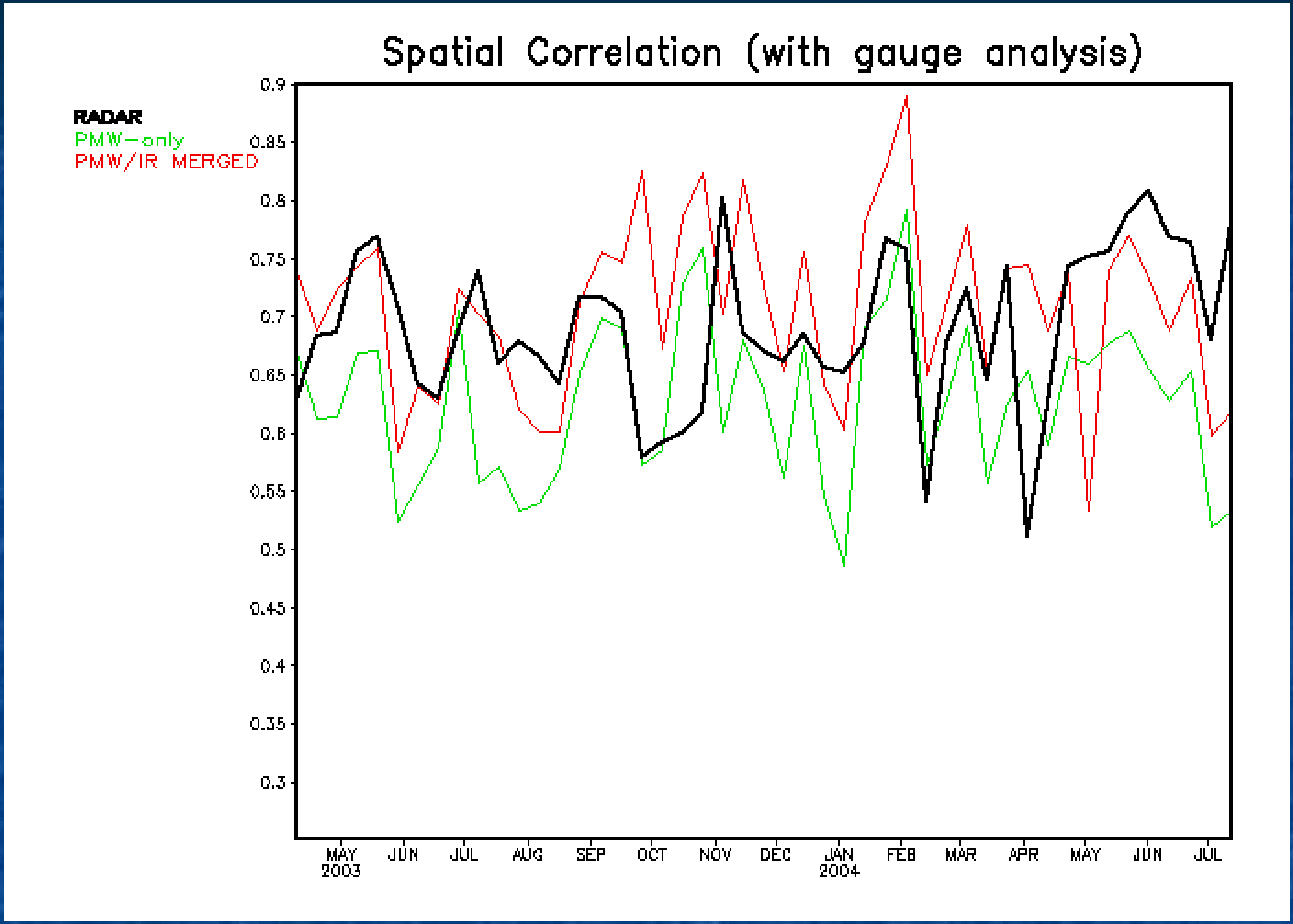


7000+ station reports daily - 12Z – 12Z accumulation period

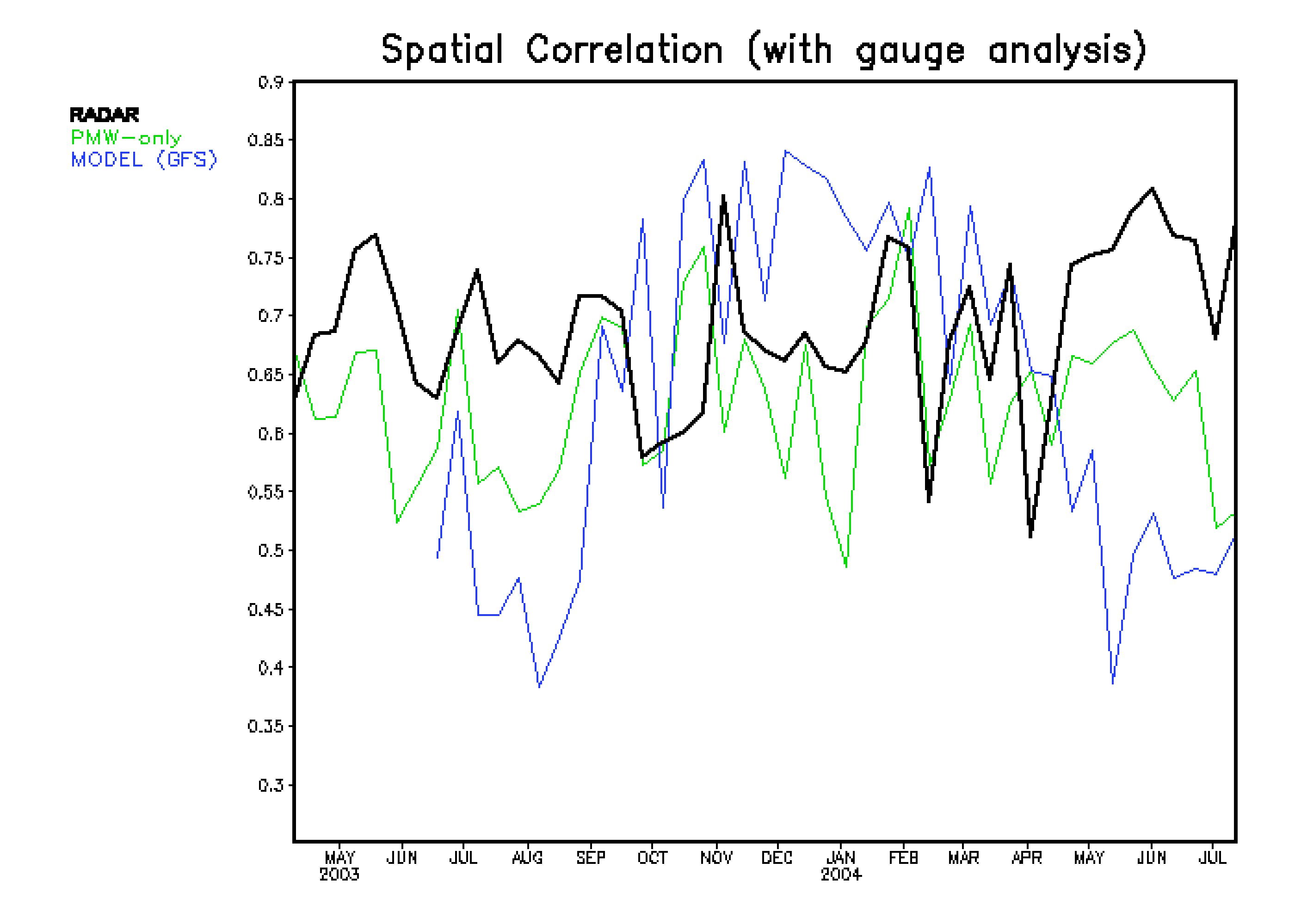
Data analyzed using a Cressman-type scheme

Error characteristics of validation data are ***NOT*** known

Validation area matched for all estimates (if missing in one, made missing in all)



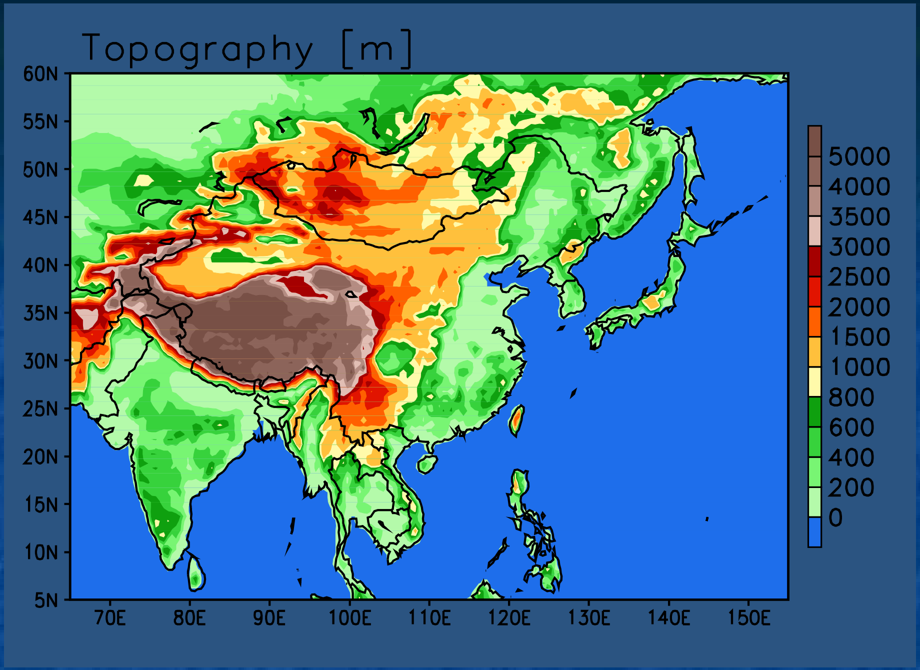
CMORPH consistently correlates better with the gauge analysis than does the composite of all microwave estimates – morphing adds information



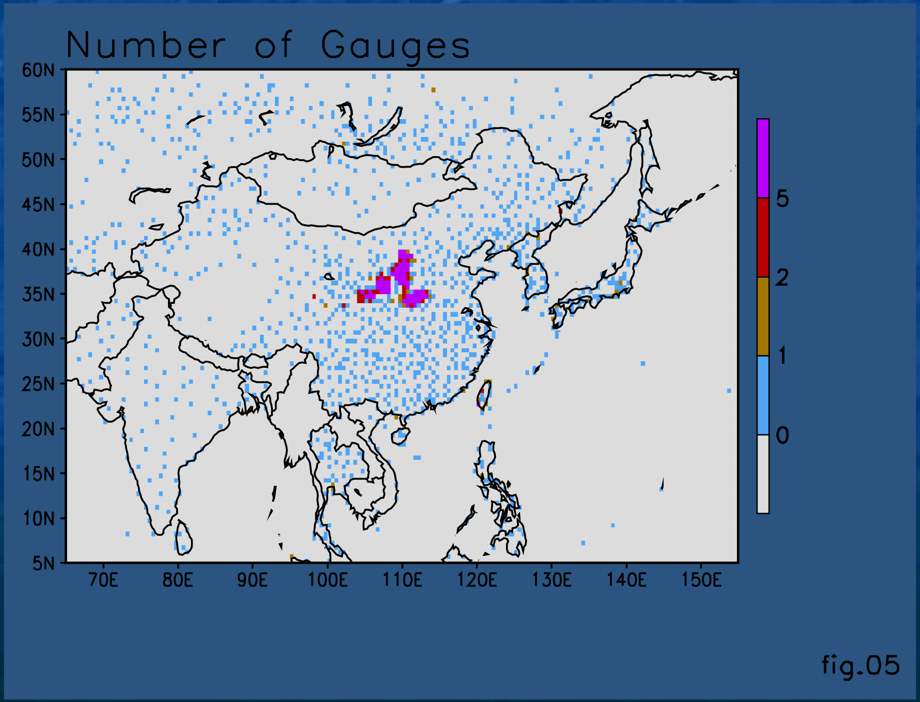
Model precipitation forecasts have strong annual cycle in correlation; in winter, generally better than radar and all satellite-based products – for many applications, model forecasts could be treated as data

East Asian gauge-based analysis

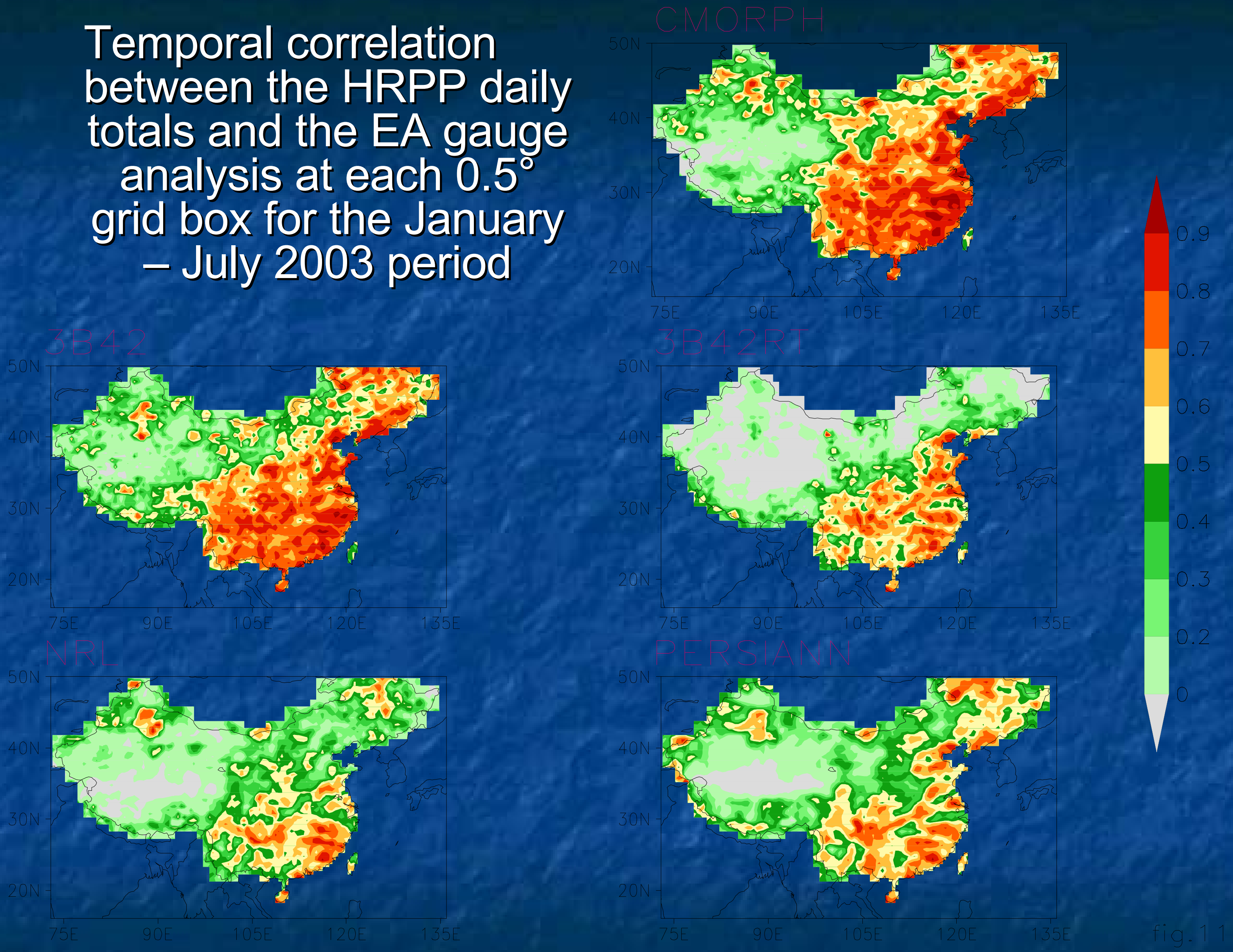
Daily totals on 0.5° latitude /longitude grid based on >2000 stations for 1978 – 2003 with adjustments for orography (Pingping Xie and colleagues)



Typical gauge distribution – note that the dense network in the Yellow River valley is not available for the most recent period



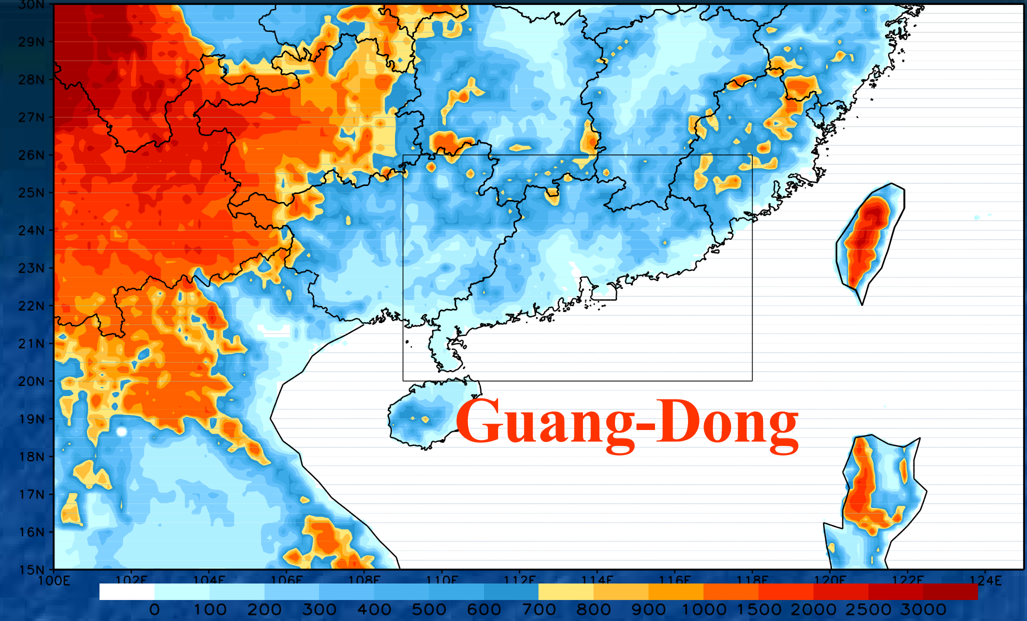
Temporal correlation between the HRPP daily totals and the EA gauge analysis at each 0.5° grid box for the January – July 2003 period

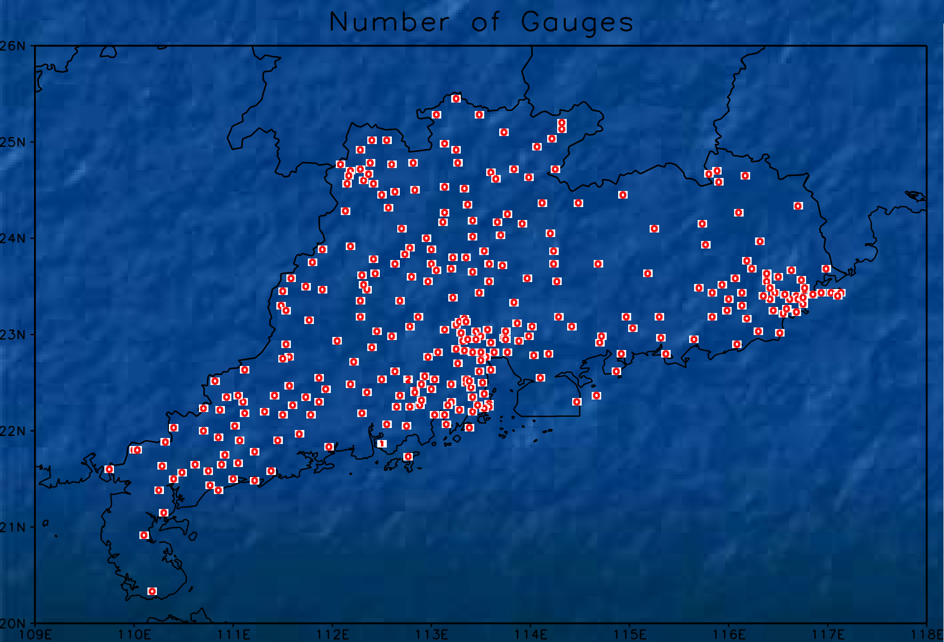


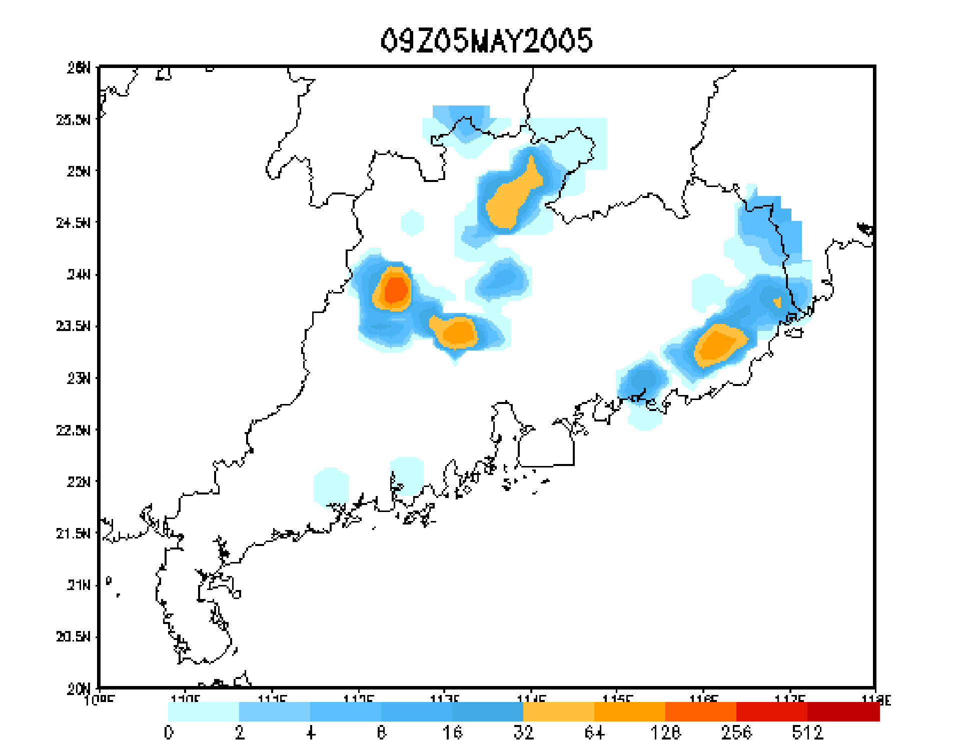
3B42 better than 3B42RT – adding sparse monthly gauge information improves correlations on daily time scale

Guangdong Validation Site:
Jianyin Liang, CMA with Pingping Xie, NOAA

April – June 2005 period of initial data







394 hourly real-time gauges

- Motivation
- Information Sources
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- Second Generation Global Analyses
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- Concluding Remarks

Concluding Remarks

- We still have a wide variety of products without a clear sense of errors and uncertainties
- Better estimates of precipitation from satellite observations are possible from incremental advances
- Much better global analyses are possible
- Validation is crucial
- Combinations of modeled and observed/estimated precipitation are likely to prove extremely valuable in the near future