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Application of an ensemble smoother to precipitation assimilation

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Assimilation of precipitation in a global modeling system poses a special challenge in that the observation operators for precipitation processes are highly nonlinear. In the variational approach, substantial development work and model simplifications are required to include precipitation-related physical processes in the tangent linear model and its adjoint. An ensemble based data assimilation algorithm "Maximum Likelihood Ensemble Smoother (MLES)" has been developed to explore the ensemble representation of the precipitation observation operator with nonlinear convection and large-scale moist physics. An ensemble assimilation system based on the NASA GEOS-5 GCM has been constructed to assimilate satellite precipitation data within the MLES framework. The configuration of the smoother takes the time dimension into account for the relationship between state variables and observable rainfall. The full nonlinear forward model ensembles are used to represent components involving the observation operator and its transpose. Several assimilation experiments using satellite precipitation observations have been carried out to investigate the effectiveness of the ensemble representation of the nonlinear observation operator and the data impact of assimilating rain retrievals from the TMI and SSM/I sensors. Preliminary results show that this ensemble assimilation approach is capable of extracting information from nonlinear observations to improve the analysis and forecast if ensemble size is adequate, and a suitable localization scheme is applied. In addition to a dynamically consistent precipitation analysis, the assimilation system produces a statistical estimate of the analysis uncertainty.

A joint research between
NASA Goddard Space Flight Center and CIRA at Colorado State University

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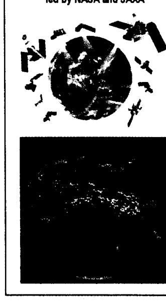
Background

- Precipitation measurements from satellites provide crucial information on the Earth's hydrological cycle with unprecedented temporal and spatial coverage.
- Data assimilation systems can use precipitation data to reduce forecast errors caused by inaccuracies in model precipitation process.
- Innovative data assimilation techniques need to be developed to handle non-linear observation operators for precipitation that consists of complex parameterizations of model physics.

Objective

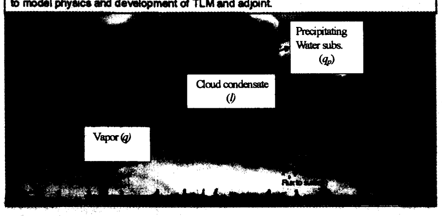
- develop an ensemble smoother capable of extracting information from data with non-linear observation operators
- apply ensemble assimilation technique to assimilation of satellite precipitation data to reduce errors in global precipitation analyses and forecasts.

Global Precipitation Measurements
an international satellite mission
led by NASA and JAXA



Precipitation process in global forecast model and its observation operator

- Precipitation is a highly non-linear physical process, and is represented by physical parameterization in global forecast models.
- TLM and adjoint that includes model physics provide links between observed precipitation and model state variables in assimilation system.
- Ensemble assimilation approach uses covariance of non-linear forward model ensembles to represent precipitation observation operator, which avoids simplifications to model physics and development of TLM and adjoint.



A maximum likelihood estimate framework for the ensemble smoother

Minimize the cost function

$$J(x) = (x-x_b)^T P^{-1} (x-x_b) + (y - H(x))^T R^{-1} (y - H(x))$$

x : estimate of model state at the initial time of assimilation time window
P : background error covariance
- estimated and updated by perturbed ensemble forecasts

Y : observations during the assimilation window (6 hours).
R : observation error covariance
H(x) : first guess by non-linear observation operator
- covariance of non-linear forward model ensemble, instead of representation by TLM and its adjoint

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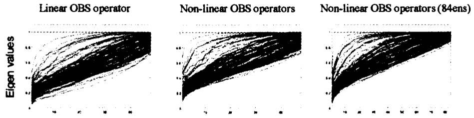
Information matrix in ensemble space with localization

- Information matrix (C) is defined as the covariance of forward model ensembles. The matrix is calculated from an ensemble of first guess observable in each sub-domain in localization scheme.
- Information is extracted from observations via observation operators to reduce the forecast errors in model space.

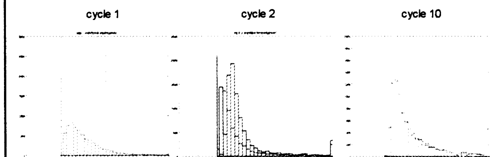
$P_a^{1/2} = P_f^{1/2} [I + C]^{-T/2}$ $C = [R^{-1/2} HP_f^{1/2}]^T [R^{-1/2} HP_f^{1/2}]$

Eigenvalues of $[I + C]^{-T/2}$ at analysis cycle 20



Blue: sub-domains in localization
Red: sub-domain average

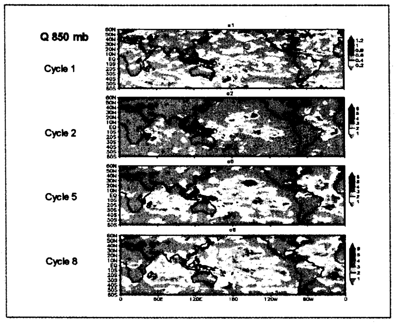
The time-evolving distribution of error standard deviation in forecast error covariance



Red: start with a lagged forecast distribution
Green: start with a uniform distribution

Q at 850 mb g kg $^{-1}$

The evolving spatial structures of error standard deviation in forecast error covariance



Assimilation experiments using precipitation data

Observations

Data used by MLES-G5 (ensemble smoother):
- SSM/I and TMI GPROF rain retrievals
- GSI analysis of dynamical fields as pseudo observations

Data used by GSI-G5 (3D-VAR):
- conventional observations
- satellite observations: ERS, HRS, SSM/I, AMSU
- SSM/I and TMI GPROF rain retrievals

GEOS5 GCM:

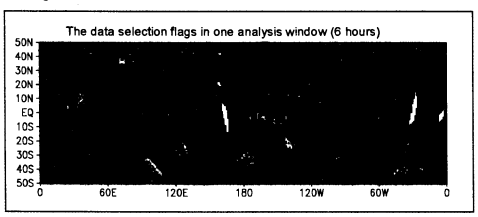
model resolution: horizontal 2° by 2.5°; vertical 72 levels

Observation operators for precipitation:
- 3D-VAR uses TLM/adjoint of simplified NCEP model physics
- MLES-G5 uses full GEOS5 non-linear model physics

Experiment setting:
- Assimilation time window: 6 hours
- **Control:** 3D-VAR assimilation
- **ASSIM:** MLES-G5 assimilation

Precipitation observation selection

The rain innovations are calculated at all valid observation locations
- Non precipitating locations
- Precipitating locations
- Precipitating locations with large differences between observation and first guess



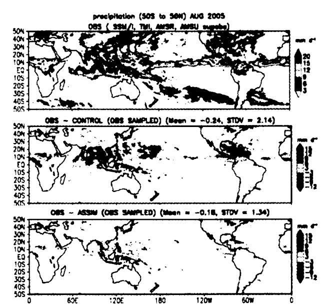
Improvement in global precipitation analysis

Monthly averaged August 2005

Verification data (SSM/I, TMI, AMSR, SMSU)

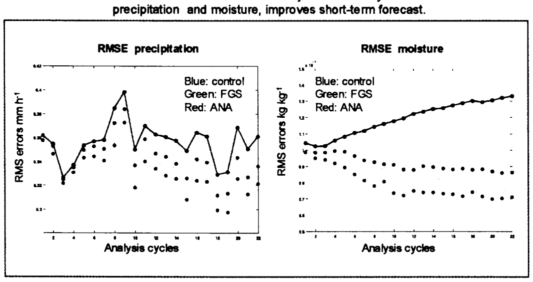
OBS – CONTROL (no precipitation data assimilated)

OBS – ASSIM (precipitation data assimilated)

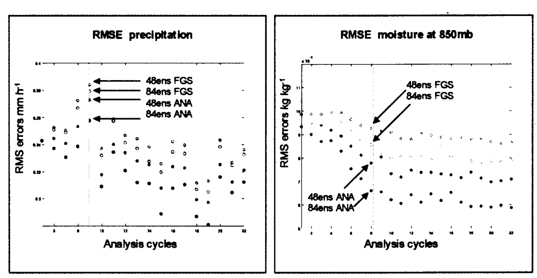


Reduction in forecast and analysis errors in precipitation and moisture

- the ensemble assimilation effectively reduces analysis errors in precipitation and moisture, improves short-term forecast.

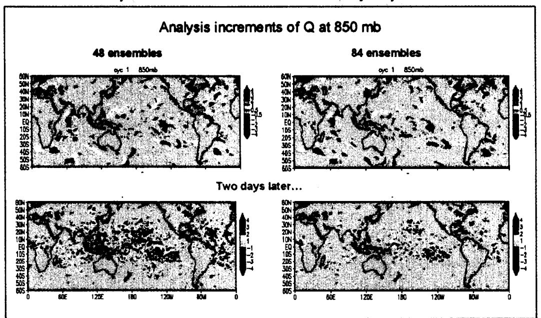


Further improving forecast and analysis by using more ensemble members



Positive impact from using more ensemble members

- analysis increments are smaller after a few analysis cycles



Precipitation observations contain valuable information about forecast errors in global weather prediction and assimilation system

Maximum likelihood ensemble smoother is capable of effectively assimilating precipitation data to reduce errors in global precipitation analysis and forecast

An forward ensemble covariance is used to represent non-linear operator for precipitation observations, and its validity relies on adequate ensemble size and suitable localization scheme