Workshop on High-Resolution Coupling and Initialization to Improve Predictability and Predictions in Climate Models

Initialization in Climate Prediction

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September 30 - October 2, 2015

Summary

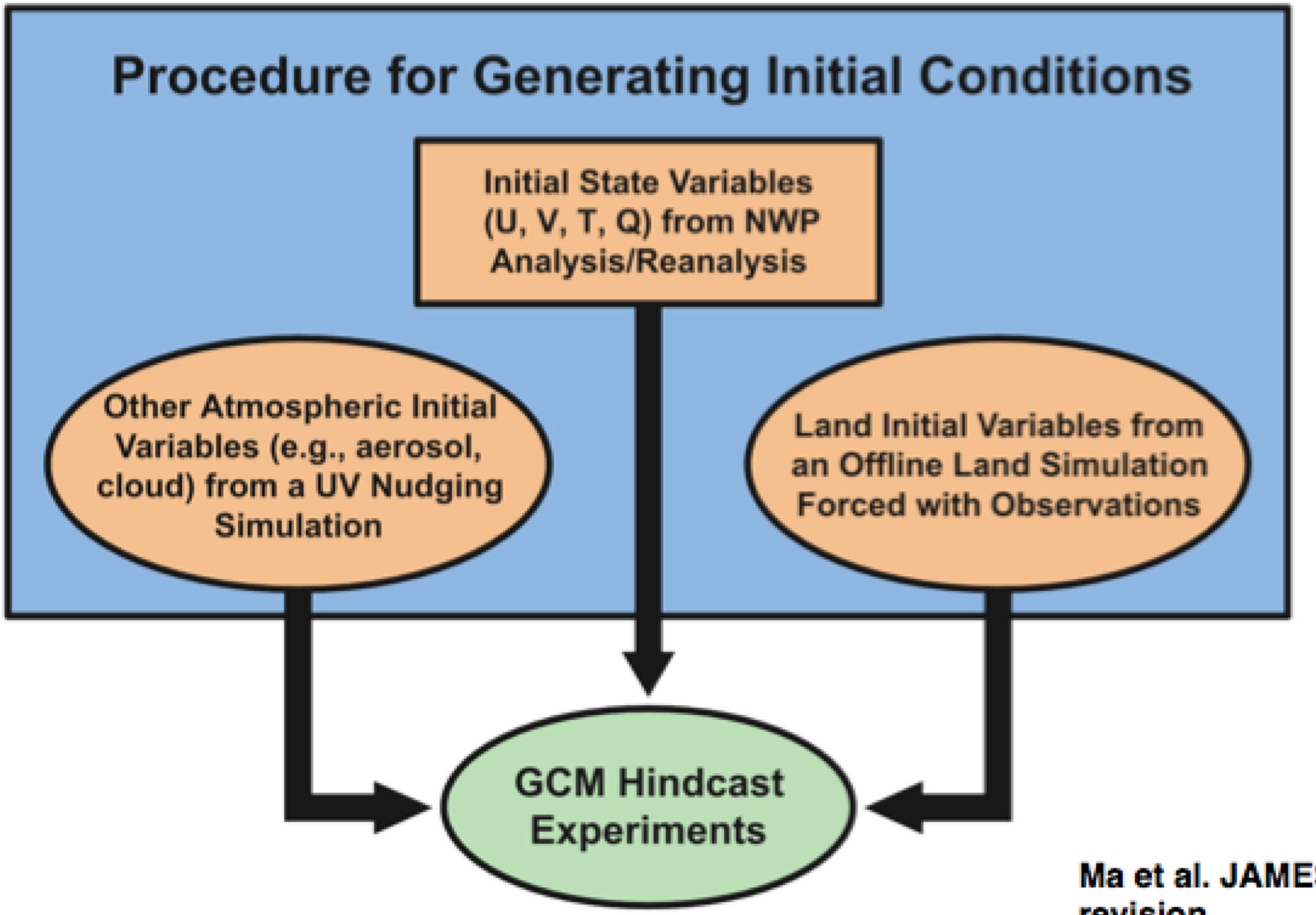
- Traditional climate model initialization
- Coupled Data Assimilation for climate analysis
- Current approaches and Future directions

Traditional Climate Model Initialization

- See review by Meehl et al., (2009) entitled "Decadal Prediction: Can it be Skillful?"
  - Initialization from observations
  - Anomaly initialization
  - Initializing from reanalyses

Meehl, G., and coauthors, 2009: Decadal Prediction: Can it be Skillful? *Bull. Amer. Meteor. Soc.*, Oct., 1467-1485. DOI:10.1175/2009BAMS2778.1

CAPT Initialization Procedure



Ma et al. JAMES, in revision

Initialization of High Resolution Climate Models

- For now, we will define a ‘high-resolution climate model’ as having resolution finer than 1°x1°
- Review *Lawless et al., (2012)* from the ESA International Workshop on Coupled Data Assimilation
- Techniques evolved historically from Numerical Weather Prediction (NWP)
- CFS, 20CR, ERA 20C, MERRA, etc.

Lawless, A., et al., 2012: Coupled Model Data Assimilation, in *Report from Int. Work. Coupled Data Assim.*, Univ. Reading, 10-12 Sept 2012, Reading, England.

As of a few years ago… (c. 2012)

- NCEP CFS (GFS T574/27KM + MOM4 1/2° ocean + SIS ice + Noah land)
- ECMWF (IFS 12-hr 4D-Var, NEMO 10-day 3D-Var)
- Met Office (4DVar 60 km atmos, 3DVar-FGAT 1/4° ocean)
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Assimilation Cycle Lengths

- NCEP-CFS uses 6-hour atmos, 5-day ocean
- ECMWF: 12-hour atmos, 10-day ocean
- Met Office: 6 hour atmos, 24-hour ocean
- JAMSTEC: 9-month, for seasonal/inter-annual prediction
- GFDL: 6-hour atmos, 24-hour ocean (PE after 1-year)
- JMA: 1-month (IAU, ocean only)
- Australia: 1-day

Lawless, A., et al., 2012: Coupled Model Data Assimilation, in *Report from Int. Work. Coupled Data Assim.*, Univ. Reading, 10-12 Sept 2012, Reading, England.

From that workshop, two major coupled DA terms were described, by consensus:

Weak vs. Strong CDA

- **Weak coupling**: background estimates produced by a coupled model, separate analysis updates for each component
- Thus, an observation in one model component cannot directly cause an analysis increment in the other components
  - increments calculated separately - so potentially unbalanced
  - always run coupled model – so background model fields are in balance

- **Strong coupling**: The analysis itself is coupled, so that any observation can affect analysis increments throughout the system
- Strong coupling requires –
  - coupled error covariance models
  - (possibly) well-tuned coupling parameters for mom., buoyancy fluxes
  - (possibly) strong observational constraint for all components

https://www2.cisl.ucar.edu/sites/default/files/Chatterjee_Presentation_CDA.pdf

Highlighting…

- NCEP CFS (GFS + MOM4 ocean + SIS ice + Noah land)
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UK Met Office (c. 2014)

- A *Weakly Coupled data assimilation* (DA) system is being developed to provide improved initial conditions for coupled forecasts.
- the UM is run at 60km horizontal resolution on 85 vertical levels, NEMO is at 25km horizontal resolution on 75 vertical model levels, and CICE is run with 5 thickness categories.
- The coupled model is corrected using two separate 6-hour window DA systems:
  - 4DVAR system for the atmosphere assimilating the standard set of atmosphere data with associated soil moisture content nudging and snow analysis schemes
  - 3DVAR First Guess at Analysis Time (FGAT) NEMOVAR for the ocean and sea-ice.
- The background information in the DA systems comes from a previous 6-hour forecast of the coupled model. The coupling frequency was increased from the 3 hours to 1 hour. This has improved the model representation of the diurnal cycle.

http://coaps.fsu.edu/pub/eric/papers_html/Brassington_et_al_15.pdf

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ECMWF

- Started by integrating separate Amos & Ocean systems:
  - Atmos: IFS, 12-hr 4D-Var cycle, fixed SST
  - Ocean: NEMO, 10-day 3D-Var FGAT IAU
- CERA (Coupled ECMWF Reanalysis System) started as a Weakly Coupled DA system used to:
  - Seek improvement in surface observation assimilation
  - Represent shorter timescale phenomena (diurnal cycle, MJO, etc.)
- Development path: CERA-A, CERA-O, CERA-S—> CERA

ECWMF development

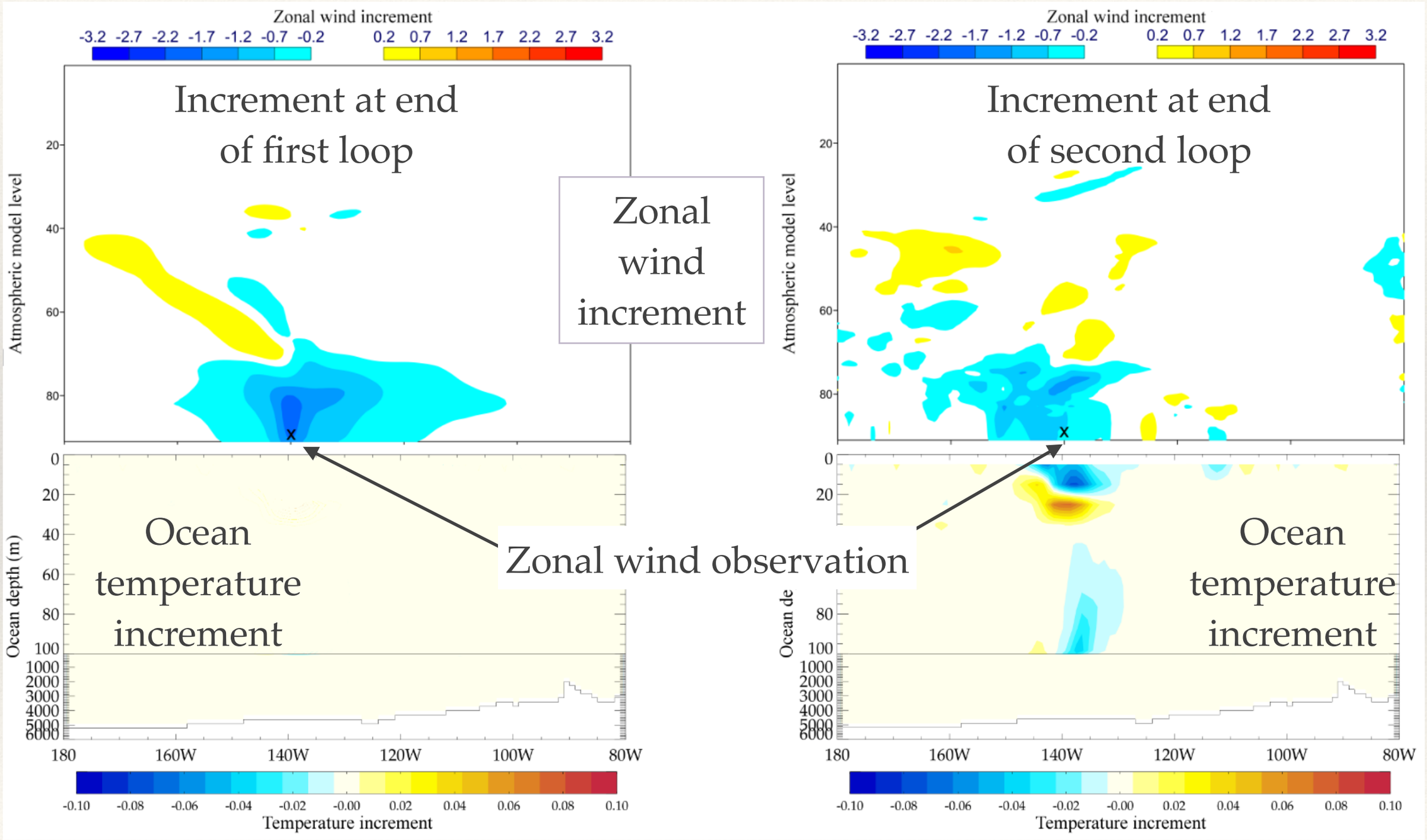
- Weakly coupled DA system: background state from coupled model, increments from separate analyses (4D-Var atmos, OI/3D-Var ocean)
- Investigations including: time-windows, balance of the coupled system, bias correction, coupling frequency
- Longer-term: assess and implement cross-system error covariances, move to higher resolution for NWP
- Looking into diurnal SST analysis system.

ECMWF future

- Moving toward a quasi-strong coupling for climate reanalysis using CERA *(Laloyaux et al., 2015)*
  - The coupled model is used as a constraint in the 4DVar outer loop.
  - Shifted to a common 24-hour window.
  - Uses conventional and satellite obs in atmosphere and T/S profiles in ocean. Relaxation to SST.

Coupled outer loop 4DVar

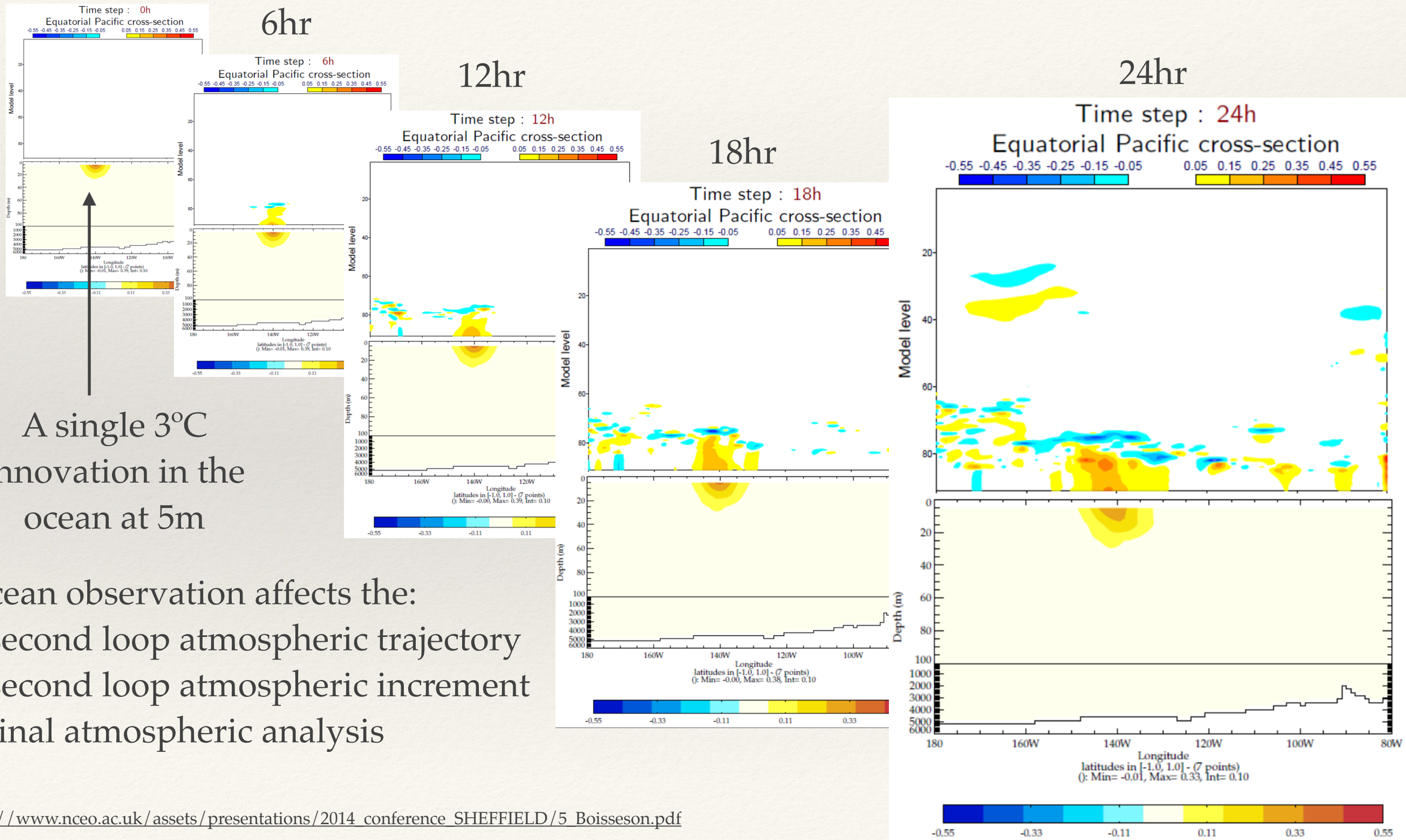
(2 outer loops)



(P. Laloyaux et al., 2015)

Coupled outer loop 4DVar

(2 outer loops)



A single 3ºC innovation in the ocean at 5m

Ocean observation affects the:

- second loop atmospheric trajectory
- second loop atmospheric increment
- final atmospheric analysis

http://www.nceo.ac.uk/assets/presentations/2014_conference_SHEFFIELD/5_Boisseson.pdf

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GFDL

- Ensemble coupled data assimilation (ECDA)
- All coupled components adjusted by observed data through instantaneously exchanged fluxes.
- Minimum initialization shocks
- Focus: seasonal-decadal forecasting (e.g. ENSO and AMOC variability) but considering High-Res implementations
- Analyze pdf rather than single state
- “Assimilation” of NCEP Atmos reanalysis
- Top 50m of ocean temperature influences wind stress

GFDL developments

- Parameter estimation using observations – Coupled data assimilation with enhancive parameter correction
- Strongly Coupled Data Assimilation

Feiyu Lu, Zhengyu Liu, Shaoqing Zhang, and Yun Liu, 2015: Strongly Coupled Data Assimilation Using Leading Averaged Coupled Covariance (LACC). Part I: Simple Model Study. *Mon. Wea. Rev.*, **143**, 3823–3837.
doi: http://dx.doi.org/10.1175/MWR-D-14-00322.1

Lu, F., Z. Liu, S. Zhang, Y. Liu, and R. Jacob, 2015: Strongly Coupled Data Assimilation Using Leading Averaged Coupled Covariance (LACC). Part II: CGCM experiments. *Mon. Wea. Rev.* doi:10.1175/MWR-D-15-0088.1, in press.

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JAMSTEC

- Fully coupled GCM (AFES, MOM3, IARC sea ice, MATSIRO land)
- Adjoint OGCM and adjoint AGCM are coupled [Line by line transformation by TAMC,TAF]
- Long 4D-Var assimilation window (9 month overlapping by 1.5 month at both ends)
- Both atmospheric and oceanic observation data assimilated
- Correction of model climatology by parameter estimation of air/sea fluxes (momentum, sensible heat, latent heat)
- Correction of seasonal to inter-annual trajectory by initialization
- Weather mode is treated as noise: Adjoint AGCM contains damping terms to suppress the strong adjoint sensitivity from weather fluctuations
- Control variables: Ocean initial conditions, bulk parameterizations controlling air-sea fluxes

JAMSTEC (cont.)

- Observational data:
- NCEP BUFR 10-day averages (U,V,T,Q)
- SSM/I sea wind scalar x ERA40 wind direction (10day averages)
- T/P altimeter data(10daily)
- Reynolds SST (10daily)
- WOA data T,S (monthly)
- Ocean Data Assimilation Product T,S(monthly)

JMA

- Weakly-coupled DA system (JMA/MRI-CGCM) only assimilating ocean data
- Observation choice reflects slow variations in the seasonal to inter-annual time scale
- 1-month assimilation, 3D-Var analysis modified by IAU
- Expected negative feedback between SST and precipitation is improved in the weakly-coupled system.
- Balance between zonal wind stress and thermocline should be further improved.

JMA (cont.)

- Future directions:
- Coupled breeding to generate ensemble members
- Imitate NCEP CFS
- A strongly coupled DA to be developed in the future, like JAMSTEC, but maintaining weather modes. Must deal with difference in time scales between weather modes and ocean interior variations.
- Develop scheme that captures relationship between atmos and ocean elements
- New observations:
  - Sea Surface Salinity (more ocean interior information than SST – Fujii et al 2003, precipitation information)
  - Sea Ice Thickness
  - Satellite Gravity data (budget of freshwater mass in the ocean)
  - Land surface constraints from observation data (e.g. soil moisture)

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NRL

- Weakly Coupled DA in Coupled Ocean/Atmosphere Modeling and Prediction System (COAMPS®) modeling and ensemble
- 3D-Var in atmosphere (NAVDAS, Daley and Barker 2001)
- 3D-Var in ocean (NCODA, Cummings 2005)
- Global coupled system is (as of 2015): NAVGEM (T425L60, 31km, 0.04mb), HYCOM, CICE, WWIII

Earth System Prediction Capability

ESPC US Navy Coupled System

Operational Implementation Design

Projected horizontal and vertical resolutions of the individual ESPC system components at the IOC in 2018.

Forecast	Time Scale, Frequency	Atmosphere NAVGEM	Ocean HYCOM	Ice CICE	Waves WW3	Land-Surface NAVGEM-LSM	Aerosol NAAPS
Deterministic short term	0-10 days, daily	20 km 80 levels (T639L80)	1/25° (4.5 km) 41 layers	1/25° (4.5 km)	1/8° (14 km)	3/16° (21 km)	3/16° (21 km)
Deterministic long term	0-30 days, weekly	20 km 80 levels (T639L80)	1/12° (9 km) 41 layers	1/12° (9 km)	1/4° (28 km)	3/16° (21 km)	3/16° (21 km)
Probabilistic long term	0-90 days, weekly	37 km 50 levels (T359L50)	1/12° (9 km) 41 layers	1/12° (9 km)	1/4° (28 km)	1/3° (37 km)	1/3° (37 km)

Earth System Prediction Capability

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Projected horizontal and vertical resolutions of the individual ESPC system components at the IOC in 2018.

Forecast							Aerosol NAAPS
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Initialization:

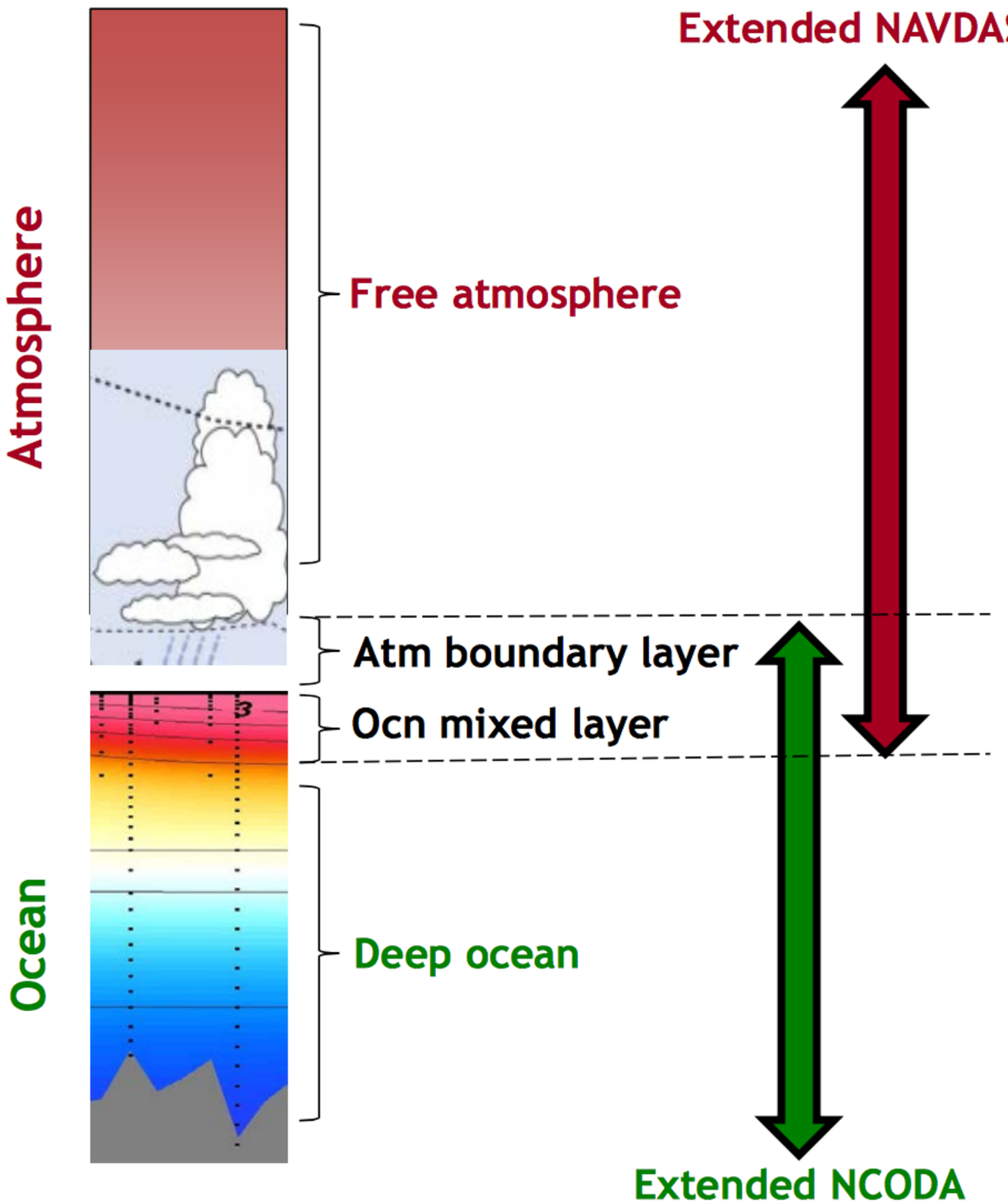
- Joint observational retrievals
- Hybrid DA approaches

ESPC US Navy

- At first, data assimilation will be *weakly coupled* and use operational systems: NAVDAS 4DVar in the atmosphere and aerosol models, NCODA 3DVar in the ocean, sea ice, and wave models.
- Eventually, a *strongly coupled data assimilation system* will be implemented.
  - Direct assimilation of satellite SST radiances using the coupled model atmospheric state.
  - Hybrid ocean data assimilation with NCODA 3DVar that uses information from the ocean ensemble .
  - A new coupled solver approach where covariances from the coupled model ensemble are used to assimilate atmospheric boundary layer observations in the ocean model.

http://www.godae.org/~godae-data/OceanView/Events/DA-TT-workshop-May-2015/3.2-DA-TT_2015.cummings.pdf

Navy Coupled Data Assimilation



Extend Atm DA to include observations in ocean mixed layer

Extend Ocn DA to include observations in atmospheric boundary layer

Assume free atmosphere and deep ocean are uncorrelated

Specify coupled covariances using ensembles

Requires hybrid versions of NAVDAS 4DVar and NCODA 3DVar (in place)

Requires global coupled model ensemble (not in place)

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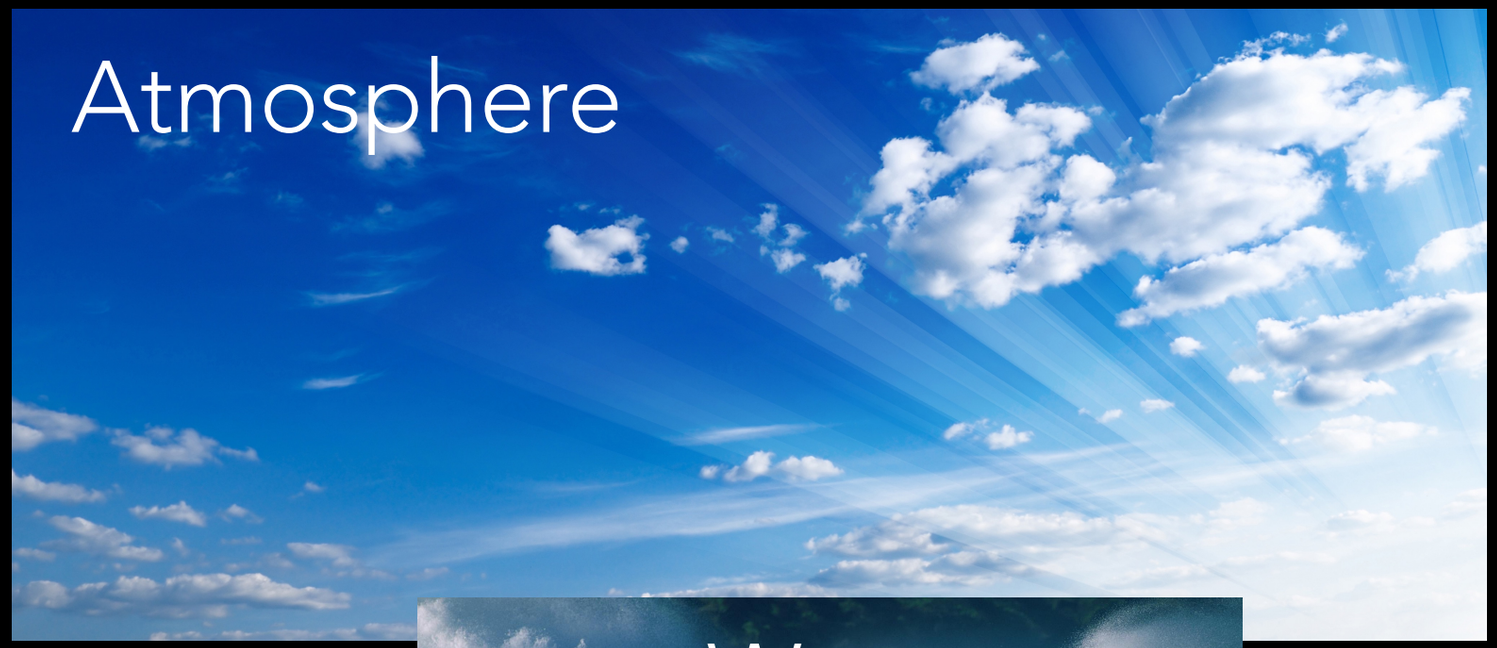
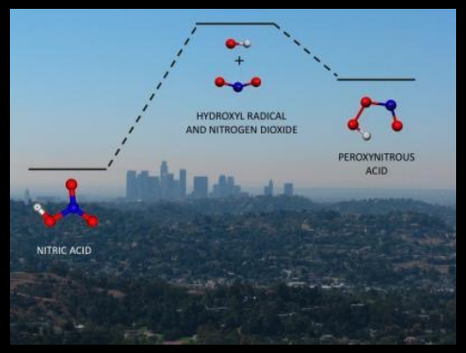
NCEP

- Current CFSv2 DA consists of:
  - GDAS/GSI for atmosphere
  - 3DVar-GODAS for ocean
  - GLDAS for land
  - Nudging for sea-ice
- Next-Gen CFSv3 consists of…

CLIMATE FORECAST SYSTEM V3





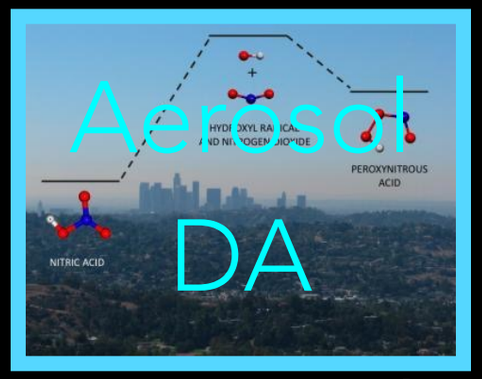
Aerosol

Land

Sea Ice

Current CFSv3 components

WEAKLY COUPLED DATA ASSIMILATION



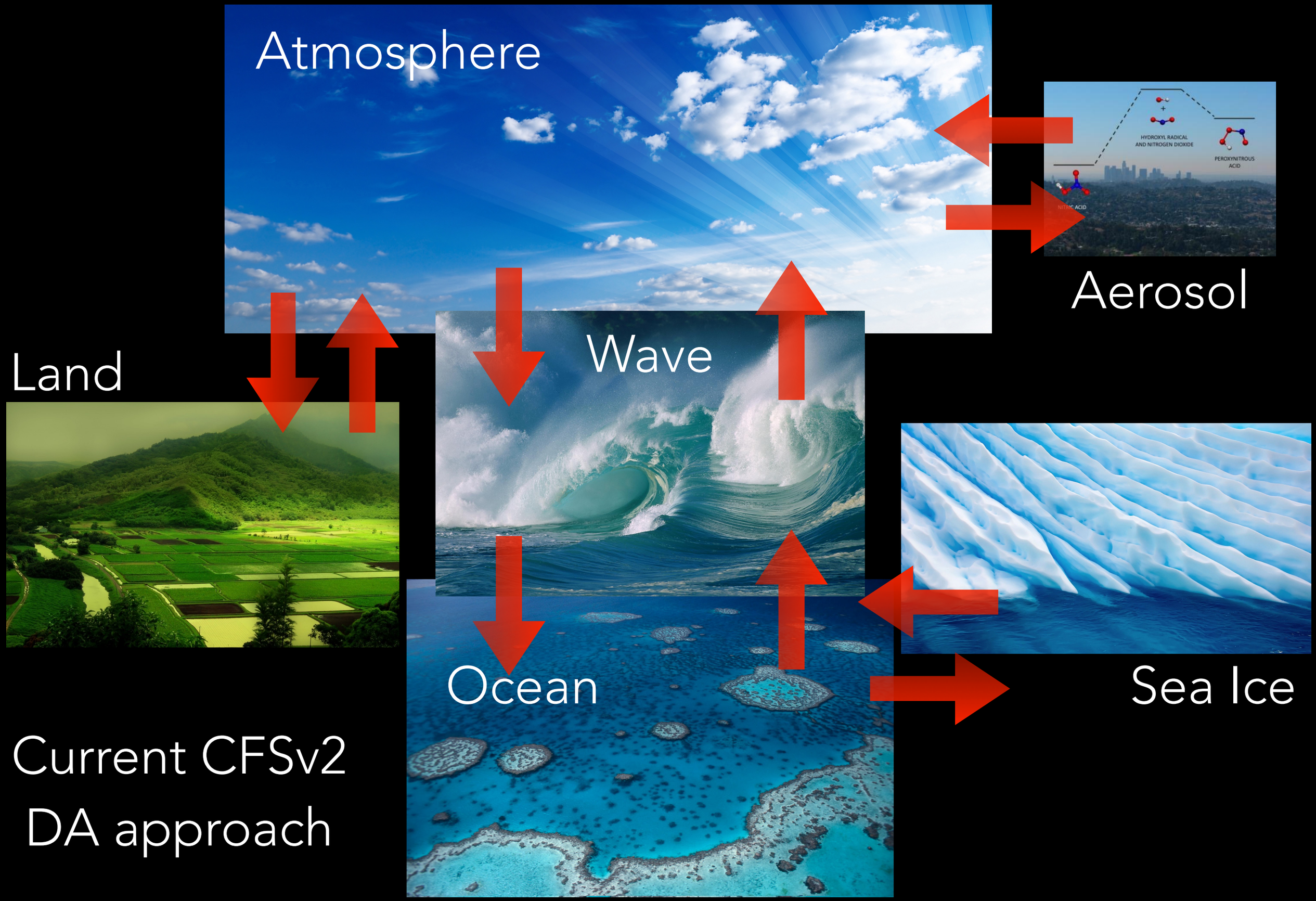
Aerosol

Land

Sea Ice

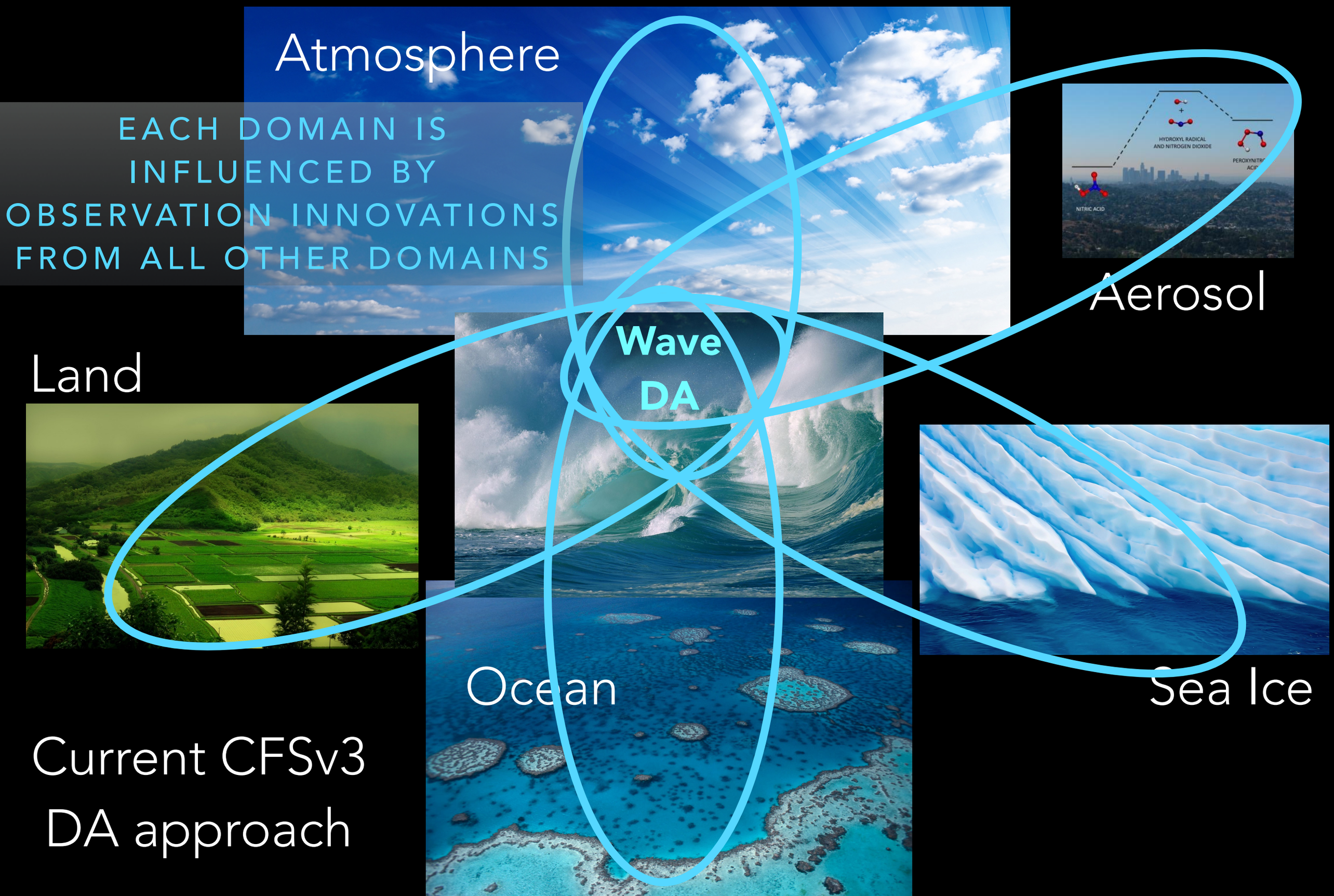
Current CFSv2
DA approach

COUPLING ONLY ON FORECAST



Current CFSv2
DA approach

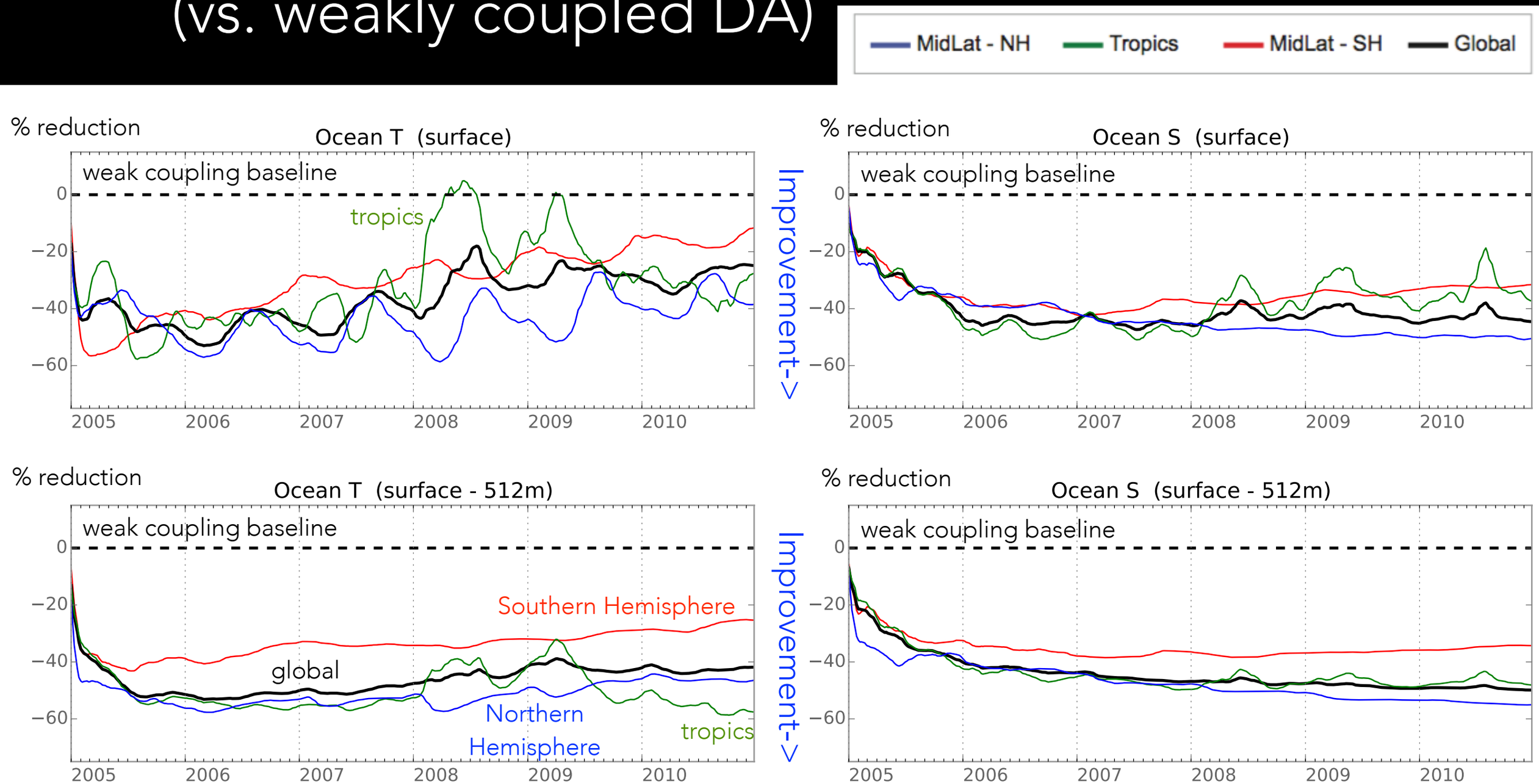
STRONGLY COUPLED DATA ASSIMILATION



Current CFSv3 DA approach

STRONGLY COUPLED DA REDUCES ERRORS (vs. weakly coupled DA)

For example, assimilating only atmospheric observations leads to significant improvements in ocean:



(Note: Observing System Simulation Experiments (OSSEs), not real data)

Sluka, T., S.G. Penny, E. Kalnay, T. Miyoshi, 2015: Using Strongly Coupled Ensemble Data Assimilation to Assimilate Atmospheric Observations into the Ocean. Submitted to GRL.

In Session 4

Day 2, 1:30-5:00pm

- NASA's initialization approach (Bill Putnam)
- Strong Coupling (Eugenia Kalnay's talk)
- Bias Correction at Initialization (Eugenia Kalnay)
- Initialization of global ocean eddy resolving coupled simulation (Ben Kirtman)
- NCAR initialization with DART (Kevin Raeder)