Scientific Background

Emergent Phenomena
<table>
<thead>
<tr>
<th>IN THE ATMOSPHERE</th>
<th>Dynamical or Physical Regime</th>
<th>IN THE OCEAN</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>LAMINAR / BAROTROPIC</td>
<td></td>
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<tr>
<td></td>
<td>BAROCLINIC RESOLVING</td>
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<tr>
<td></td>
<td>CYCLOSTROPHIC / SUBMESOSCALE</td>
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<tr>
<td></td>
<td>SMALL-SCALE THERMODYNAMICS</td>
<td></td>
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<tr>
<td>Dynamical or Physical Regime</td>
<td>IN THE ATMOSPHERE</td>
<td>Increasing resolution →</td>
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</table>
Dynamical or Physical Regime

IN THE ATMOSPHERE

LAMINAR / BAROTROPIC

BAROCLINIC RESOLVING

CYCLOSTROPHIC / SUBMESOSCALE

SMALL-SCALE THERMODYNAMICS

IN THE OCEAN

Increasing resolution →
Dynamical or Physical Regime

LAMINAR / BAROTROPIC
BAROCLINIC RESOLVING
CYCLOSTROPHIC / SUBMESOSCALE
SMALL-SCALE THERMODYNAMICS

IN THE ATMOSPHERE

IN THE OCEAN

Increasing resolution →
Dynamical or Physical Regime

IN THE ATMOSPHERE

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SMALL-SCALE THERMODYNAMICS

IN THE OCEAN

Increasing resolution →
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IN THE ATMOSPHERE

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SMALL-SCALE THERMODYNAMICS

IN THE OCEAN

Increasing resolution →

Increasing resolution →
Dynamical or Physical Regime

IN THE ATMOSPHERE

LAMINAR / BAROTROPIC
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IN THE OCEAN

Increasing resolution →

Increasing resolution →
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IN THE ATMOSPHERE

LAMINAR / BAROTROPIC
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CYCLOSTROPHIC / SUBMESOSCALE
SMALL-SCALE THERMODYNAMICS

IN THE OCEAN

Increasing resolution →

Increasing resolution →
Dynamical or Physical Regime

**LAMINAR / BAROTROPIC**

**BAROCLINIC RESOLVING**

**CYCLOSTROPHIC / SUBMESOSCALE**

**SMALL-SCALE THERMODYNAMICS**

*IN THE ATMOSPHERE*

*IN THE OCEAN*

Increasing resolution →

Increasing resolution →
IN THE ATMOSPHERE

Horizontal resolution

Dynamical or Physical Regime

LAMINAR / BAROTROPIC
BAROCLINIC RESOLVING
CYCLOSTROPHIC / SUBMESOSCALE
SMALL-SCALE THERMODYNAMICS

IN THE OCEAN

Horizontal resolution
IN THE ATMOSPHERE

Dynamical or Physical Regime

LAMINAR / BAROTROPIC

BAROCLINIC RESOLVING

CYCLOSTROPHIC / SUBMESOSCALE

SMALL-SCALE THERMODYNAMICS

Horizontal resolution

~10° latitude/longitude

1° latitude/longitude

100 – 1 km

> 100 m

~1° latitude/longitude

0.1° latitude/longitude

1 km – 100 m

> 10 m

IN THE OCEAN

Horizontal resolution

~1° latitude/longitude

0.1° latitude/longitude

1 km – 100 m

> 10 m
Software Components

Community Earth System Model + Data Assimilation Research Testbed
Model Hierarchy

Parallel Ocean Program (POP) in Eddy-Resolving and Eddy-Parameterizing Configurations
<table>
<thead>
<tr>
<th>IN THE ATMOSPHERE</th>
<th>IN THE OCEAN</th>
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<tbody>
<tr>
<td><strong>Horizontal resolution</strong></td>
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<tr>
<td>~10° latitude/longitude</td>
<td>1° latitude/longitude</td>
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<td><strong>Dynamical or Physical Regime</strong></td>
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<tr>
<td>1° latitude/longitude</td>
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</tr>
<tr>
<td>100 – 1 km</td>
<td>1 km – 100 m</td>
</tr>
<tr>
<td>&gt; 100 m</td>
<td>&gt; 10 m</td>
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<td>Dynamical or Physical Regime</td>
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<td>-----------------------------</td>
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<td>LAMINAR / BAROTROPIC</td>
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<td>1 km – 100 m</td>
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IN THE OCEAN
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<tr>
<td>Horizontal resolution</td>
<td>1° latitude/longitude</td>
<td>0.1° latitude/longitude</td>
<td>1 km – 100 m</td>
<td>&gt; 10 m</td>
</tr>
<tr>
<td>Low Resolution Ocean</td>
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<td>Low Resolution Ocean</td>
</tr>
<tr>
<td>Configuration (g17 grid)</td>
<td>Low Resolution Ocean</td>
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<td>Low Resolution Ocean</td>
<td>Low Resolution Ocean</td>
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</tbody>
</table>
High Resolution Ocean Configuration (t13 grid)

Horizontal resolution

1° latitude/longitude

1 km – 100 m

Dynamical or Physical Regime

LAMINAR / BAROTROPIC

BAROCLINIC RESOLVING

CYCLOSTROPHIC / SUBMESOSCALE

Low Resolution Ocean Configuration (g17 grid)

Horizontal resolution

1° latitude/longitude

1 km – 100 m

> 10 m

< 10 m
High Resolution Ocean Configuration (t13 grid)

Horizontal resolution
1° latitude/longitude 0.1° latitude/longitude

Dynamical or Physical Regime
LAMINAR / BAROTROPIC BAROCLINIC RESOLVING

Horizontal resolution
1° latitude/longitude 0.1° latitude/longitude

Low Resolution Ocean Configuration (g17 grid)

Horizontal resolution
1° latitude/longitude 0.1° latitude/longitude

PARAMETERIZED PARAMETERIZED PARAMETERIZED
Detecting Model Error

Using Data Assimilation to Diagnose where the Model Physics Produce Improbable Outcomes
High Resolution Ocean Configuration (t13 grid)

Horizontal resolution: 1° latitude/longitude
Dynamical or Physical Regime: LAMINAR / BAROTROPIC

Low Resolution Ocean Configuration (g17 grid)

Horizontal resolution: 1° latitude/longitude
Dynamical or Physical Regime: LAMINAR / BAROTROPIC

Horizontal resolution: 0.1° latitude/longitude
Dynamical or Physical Regime: BAROCLINIC RESOLVING

Horizontal resolution: 0.1° latitude/longitude
Dynamical or Physical Regime: CYCLOSTROPHIC / SUBMESOSCALE

Horizontal resolution: 0.1° latitude/longitude
Dynamical or Physical Regime: SMALL-SCALE THERMODYNAMICS

Resolution:
- 1° latitude/longitude: 1 km – 100 m
- 0.1° latitude/longitude: > 10 m
Dynamical or Physical Regime

LAMINAR / BAROTROPIC

BAROCLINIC RESOLVING

CYCLOSTROPHIC / SUBMESOSCALE

SMALL-SCALE THERMODYNAMICS

High Resolution Ocean Configuration (t13 grid)

Horizontal resolution

1° latitude/longitude

0.1° latitude/longitude

1 km – 100 m

> 10 m

Low Resolution Ocean Configuration (g17 grid)

Horizontal resolution

1° latitude/longitude

0.1° latitude/longitude

PARAMETERIZED

PARAMETERIZED

PARAMETERIZED

PARAMETERIZED

PARAMETERIZED

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PARAMETERIZED
Scientific Workflow

Data Assimilation Cycling
Ensemble Data Assimilation 101
Ensemble Data Assimilation 101
Ensemble Data Assimilation 101
Ensemble Data Assimilation 101
Ensemble Data Assimilation 101

25°C

15°C

5°C

Prior

Observation
Ensemble Data Assimilation 101
Ensemble Data Assimilation 101
Ensemble Data Assimilation 101
Ensemble Data Assimilation 101
DART Overview

General-purpose codebase
Interfaces with atmospheric, oceanographic, cryospheric, land surface & space weather models.

Works with any type of observation
Satellites, weather balloons, undersea gliders, radar stations, GPS, etc. Each type can pose unique challenges.

Range of users
Can be compiled without MPI for use on laptops; can be compiled with MPI for running on thousands of nodes

Written in FORTRAN
Implements algorithms currently used in weather forecasting and experimental techniques
Accommodates huge state vectors; one-way MPI communications

https://dart.ucar.edu
Computational Background

Experimental Setup
### High Resolution Ocean Configuration (t13 grid)

<table>
<thead>
<tr>
<th>Horizontal resolution</th>
<th>Dynamical or Physical Regime</th>
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<td></td>
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<td></td>
</tr>
<tr>
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</tr>
<tr>
<td>1 km – 100 m</td>
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<tr>
<td>&gt; 10 m</td>
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### Low Resolution Ocean Configuration (g17 grid)

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# Model Configuration

<table>
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<tr>
<th>Model Configuration</th>
<th>Low-resolution (g17)</th>
<th>High-resolution (t13)</th>
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</thead>
<tbody>
<tr>
<td>Model Grid</td>
<td>Offset Greenland</td>
<td>Poseidon Tripole</td>
</tr>
<tr>
<td>Grid points in 1 instance</td>
<td>5,160,960</td>
<td>535,680,000</td>
</tr>
<tr>
<td>Derecho CPU hours</td>
<td>135,924</td>
<td>44,142,416</td>
</tr>
<tr>
<td>Long term archiving</td>
<td>3.7 TB</td>
<td>87.9 TB</td>
</tr>
<tr>
<td>Forcing</td>
<td>CAM6 Reanalysis (f09)</td>
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</tr>
</tbody>
</table>
Team Experience

Precursor Projects
Two long-term integrations of POP in its high-resolution, eddy-resolving configuration were completed using the Yellowstone ASD period and a University Large Allocation using roughly 5M core hours on Yellowstone.

These experiments are described in Bryan and Bachman (2015) and Johnson et al. (2016). The output has been heavily studied and the experiments are colloquially known as the "ASD Runs" in CGD's Oceanography Section.
Raeder et al., (2021) completed a 10-year atmospheric reanalysis using DART and the atmospheric component of CESM, the Community Atmosphere Model 6.

- Required roughly 17M CPU hours on Cheyenne.
- Revealed inefficiencies in model build scripts due to directory locking.
KiloCAM Experiment

• Johnson and Gharamti are conducting a thousand-member CAM6 ensemble experiment to test DART algorithms on Shaheen II, a Cray XC40 at King Abdullah University of Science and Technology.

• Shaheen II has 6174 nodes with Intel Haswell processors and can theoretically compute 7.2 Pflop/s. The thousand-member experiment uses up to 3000 nodes at one time, nearly 50% of the system’s nodes.
Closing Remarks

Desired Outcomes
Desired Outcomes

- Produce a hierarchical reanalysis spanning four complete years, 2012-2015, that encompasses the termination of the 2012 La Niña event, the transition of PDO from its cool to warm phase in 2014 and the onset of the subsequent 2015 El Niño event.
- Allow for enhanced understanding of mode water formation, continuing the work of Johnson et al. (2016)
- Sensitivity testing of adaptive inflation algorithms, continuing the work of Gharamti (2018)
- Studying interannual variability of the Equatorial Pacific Cold Tongue, continuing the work of Deppenmeier et al. (2021)
- Improved parameterization of mesoscale eddies, continuing the work of Grooms and Kleiber (2019).


Photo Credits

- Trade wind and loop current schematics produced by NOAA. Cropped and resized to fit within the slides.
- Nor’Easter, tornado and cloud photos produced by NOAA. Cropped and resized to fit within the slides.
- Mesoscale eddy figure produced by NASA-GSFC. Public domain.
- Photos of Shaheen II and Campus Library © King Abdullah University of Science and Technology.
- Offset Greenland and Poseidon Tripole Grid schematics © UCAR.
- All remaining DART figures and schematics © UCAR.
Thanks For Your Attention

Any Questions?