#### Developing regional ocean modeling capabilities with MOM6 for use in UFS



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### Some of the other contributors...

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- Raphael Dussin (GFDL)
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- Dujuan Kang (Rutgers)
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## Background

- Motivation:
  - Coastal regions susceptible to extreme weather events  $\bigcirc$
  - 40% of US population lives in coastal regions •
  - Significant economic contribution from coastal regions (industry, fisheries, tourism)  $\bigcirc$
  - Provide accurate forecasts is paramount for the safety of the population and economic vitality of  $\bigcirc$ coastal regions
  - Global ocean models struggle in coastal regions  $\bigcirc$
- Challenge:
  - Wide range of scales in the dynamics and environments (From sub-tropics to Arctic)  $\bigcirc$
- Approach:
  - Develop a framework for investigating regional weather and climate dynamics via the use of multi- $\overline{}$ scale models



**SST Biases: Models - Observations** lacksquare



NCAR CCSM4 Model (Gent et al., 2011)

### **Climate Model Biases**



GFDL CM2.5 Model (Delworth et al., 2012)

### Space-time scales for some oceanic processes



Haidvogel, Curchitser, Daniflov and Fox-Kemper (2018)

## Evolution of computational power

MIPS per	<b>\$1000</b> (1998 \$)		Evolut	ion of Cor	nputer
Million					
1000					
					Powerl Gateway-48
				Mac	Mac intosh-128K
1				Co Apple DG Eclipse	IBM PC II Sun-2
			DE	CDC 7600 C PDP-10	
1 1000			IBM 7090 Whirlwind	IBM 1130	
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1		Colossus	•		IBM 36
Million			•••/	<b>~</b>	Burroughs 5 3M 1620
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	inve Calculator	•	ASCC	(Mark 1)	
• 1900	• • 192	20 19	940		



## **USF-HFIP** goals

- HFIP: Reduce errors in forecast for TC track, intensity and other quantities
- HFIP working group advocates improved model resolution as the necessary and fundamental advancement needed to improve forecasting (e.g., Gall et al., 2012)
- model as part of HAFS
- Our goal is to address the HFIP requirements for improved regional, high-resolution, ocean modeling capacity with MOM6

NCEP/EMC has adopted GFDL-MOM6 as the next generation ocean

representation of storm parameters by developing and implementing



## What is the MOM6 ocean model?

Community ocean model rooted in climate modeling Structured C-grid, Finite Volume Core Global climate modeling focus; Processes oriented origins Hydrostatic Primitive Equations Conservative, including wetting & drying (ice shelves) Arbitrary Lagrangian Eulerian Method (ALE) General vertical coordinates No vertical CFL limit on timesteps/resolution Reduces numerical diapycnal mixing for some coordinates Efficiencies for biogeochemistry & passive tracers Comprehensive set of physical process parameterizations Required for climate model projections into unobserved states Moving toward energetics-based formulations of params. Many capabilities resulted from extensive collaborations 4 NSF/NOAA sponsored Climate Process Teams

- CVMix shared NCAR/GFDL/LANL vertical mixing code
- CLIVAR CORE/OMIP ocean-climate model comparisons

Neutral mixing params. from Dr. A. Shao of U. Victoria, Canada 4000, 10 20 30 40 50 60 70 80
 Embedding SIS2 sea-ice & GFDL icebergs in MOM6
 Free Community Open Development with deliberate ocean model software design Design drew upon experience from MOM4/5, MITgcm, HIM, GOLD, Poseidon, ...



Slide from presentation by Bob Hallberg



### How to build a regional model? Open Boundary Conditions! Design philosophy: Put "OBCs" anywhere





Boundary conditions on the Arakawa C-grid

- Free surface
- Normal velocity
- **Tangential velocity**
- Tracers
- Layer thickness...would be nice but messy?



vqA. j - 0.5 $\eta$ i-1i - 1.5i - 0.5i-2

## OBC Types currently in MOM6

For the normal velocity:

- SIMPLE (aka clamped), needs user code
- GRADIENT (zero gradient)
- FLATHER barotropic mode
- ORLANSKI radiation for baroclinic mode
- OBLIQUE another radiation
- NUDGED modifier to radiation



For the tangential velocity:

- Strain/Vorticity (Lateral viscosity/Coriolis):
  - Free slip (zero gradient)
  - Specified dv/dx or du/dy from file or radiation condition
  - Computed using velocities from file or radiation condition
  - Zero

## **Boundary conditions:** Barotropic mode

• Flather (needs boundary information for both  $U_{\text{barotropic}}$  and free surface  $\eta$ 



# $\overline{u} = \overline{u}_{ext} + \sqrt{\frac{g}{H}(\eta - \eta_{ext})}$

### **Boundary conditions:** Baroclinic

#### Baroclinic Mode:

velocity if needed)

$$\frac{\partial \phi}{\partial t} = -\left(\phi_{\xi} \frac{\partial \phi}{\partial \xi} + \phi_{\eta} \frac{\partial \phi}{\partial \eta}\right)$$

where  $\phi_{\xi,\eta}$  are the phase speeds

On inflow, either zero gradient nudged to external value (Marchesiello) •



#### • Orlanski or oblique radiation (Raymond & Kuo): Compute local normal phase speed (also used for tangential

### More boundary conditions

#### Tracers

- A reservoir has memory of fluid that has left the domain out of each boundary Can also mix in external values of tracers on inflow
- Mixing lengths set relative contributions of each tracer
- Layer thickness (used in continuity and Coriolis computations)
  - Set to no-gradient
  - With ALE, may be difficult to implement other options



### Boundary conditions: Explicit tidal boundary forcing

- User provides tidal amplitude and phase data along the boundary for elevation and barotropic u and v velocities [for example, derived from TPXO tide model dataset].
- MOM6 calculates tidally varying elevation and velocity from amplitude and phase, which is then superimposed on the boundary data for non-tidal elevation and velocity.
- Includes option to modulate tides by the 18.6 year nodal cycle.
- Can be used alone or in addition to the tidal potential forcing, including self-attraction and loading, already available in MOM6.



## MOM6 Implementation in the Northwest Atlantic

#### Northwest Atlantic (NWA) Domain





## MOM6 Implementations: NW Atlantic

#### **MOM6-NWA Setup**

- Regional MOM6 simulation of Northwest Atlantic (NWA)
  - Grid (converted from ROMS grid of Kang & Curchitser, 2013)
    - Vertical:
- Geopotential (z\*) Hybrid Hycom1 ( $z^* \& \rho$ )
- Forcing
  - Ocean BC & IC: SODA3
  - Atmospheric forcing: JRA55-do
  - Runoff: Dai & Trenberth river discharge
- Computation (1 simulation year)

hycom1 (NK=75) z\* (NK=50) z\* (NK=75) 15x160 = 2400 CPU hrs 19x240 = 4560 CPU hrs 21x240 = 5040 CUP hrs



- Horizontal: ~7 km resolution, 720 x 360 grid points NK=75 & NK=50 NK=75





## Model evaluation: SST





### **Gulf Stream Mean Path**



hycom1

#### Mean Features: z\* vs. hycom1

hycom1



hycom1 - z\*

## Eddy Kinetic Energy (EKE)





## MOM6 Implementations: NW Atlantic temperature transects





### **Different MOM6-NWA Settings**

#### Different parameters in MOM\_input

	Control	SMAG	BBL	Solid
SMAG_BI	0.015	0.06	0.015	0.015
BBL_EFFIC	0.2	0.2	0.01	0.2
CORIOLIS_SCHEME	SADOURNY 75_ENSTRO	SADOURNY 75_ENSTR O	SADOURNY 75_ENERG Y CORIOLIS_ EN_DIS = True	SADOURNY 75_ENSTR O
BC (East, South)	open	open	open	wall

## **Mean EKE: 1982** SMAG\_BI=0.06 BBL\_EFFIC=0.01 Wall BC







### Mean T-profile across Charleston Bump: hycom1



## MOM6: Tidal elevations







## MOM6: Tidal elevations





## Tides: M2 Amplitude/Phase







## Tides: K1 Amplitude/Phase











### **Seasonal EKE using z\*-coordinate**

#### Mesoscale EKE MS: Jan 0.08 - 0.06 300 300 - 0.04 0.02 200 200 0.00 -0.02 100 100 -0.04-0.060 +0 400 600 -0.08 200 200 0 0 EKE MS: May 0.08 - 0.06 300 300 - 0.04 - 0.02 200 200 0.00 -0.02 100 100 -0.04 -0.060 +0 400 600 -0.08 200 200 0 0 EKE MS: Aug 0.08 - 0.06 300 300 - 0.04 - 0.02 200 200 - 0.00 -0.02 100 100 -0.04-0.060 +0 -0.08 200 400 600 200 0 0 EKE MS: Nov 0.08 - 0.06



#### Submesoscale

#### Total



### **Seasonal EKE using z\*-coordinate**

GS along-coast GS



Mesoscale S

### **GS off-coast** Whole domain

Submesoscale

Total

## Other regions in development

MOM6-NEP





MOM6-Arctic

### MOM6-NWA









## (Near) Future directions





Courtesy of A. Wallcraft and E. Chassignet

## Regional Grid Generation Tool (under construction)

Clear Information       GridUtils application initialized.         Plot Grid Setup       Grid Plot Grid Info Local Files Remote Files Manual         Projection Extent Style       Welcome! Please specify         Projection       Velcome! Please specify         Projection       Central Longitude(lon_0) (0 to 360)         230       Central Latitude(lat_0) (-90 to 90)         40       First Parallel(lat_1) (-90 to 90)         40       Latitude of True Scale/lat ts) (-90 to 90)	Information						
Plot Grid Plot Grid Plot Grid Info Local Files Remote Files Manual   Projection   Projection   Nearside Perspective   Central Longitude(lon_0) (0 to 360)   230   Central Latitude(lat_0) (-90 to 90)   40   First Parallel(lat_1) (-90 to 90)   40   Second Parallel(lat_2) (-90 to 90)   40   Latitude of True Scale(lat ts) (-90 to 90)	Clear Information GridUtils application	n initializ	zed.				
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Plot	Plot	-					1



- Interactive Python tool for generating grids
- Allows a user to create a grid, visualize it, and download it as netCDF
- Can be spawned as stand-alone application or run on local machine



## Visualize a Grid

Clear Information Running make_plot(): Running make_plot(): Running make_plot(): Running make_plot():	: done : done
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rojection Spacing Advanced	
Grid Projection Projection	Lambert Conformal Conic: 2
Lambert Conformal Conic	·
Central Longitude(lon_0) (0 to 360)	
300	
Central Latitude(lat_0) (-90 to 90)	
40	
First Parallel(lat_1) (-90 to 90)	
25	
Second Parallel(lat_2) (-90 to 90)	
55	
Latitude of True Scale(lat_ts) (-90 to 90)	
40	22
Tilt (-90 to 90)	
-33	- men
Make Grid	



x30 with -33 degree tilt



Specify projection parameters, grid spacing, and resolution

Click 'Make Grid' and your grid will appear

Easily edit parameters and shift grid to your exact specifications



## **Download Grid as netCDF**

Clear Information	Running make_plot().	iono					
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		y		(nyp, nxp)	float64	31.01 30.84 30.66 4	
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Central Latitude(lat_0)	(-90 10 90)	▼ Attrib	utes:				
40		grid	version :	0.2			
First Parallel(lat_1) (-9	0 to 90)	cod	e_version :	GridTools:	beta		
25		hist	ory:	sometime:	GridToo	ls Conic	
Second Parallel(lat_2)	(-90 to 90)	proj	:	LambertConformalConic +ellps=WGS84 +proj=lcc +lon_0=40.0 +l 55.0 +no_defs			

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\_0=300.0 +x\_0=0.0 +y\_0=0.0 +lat\_1=25.0 +lat\_2=

- Select the Grid Info tab so see a live view of your grid as an xarray object
- Grid angles, area, • etc. are calculated on the fly
- Click 'Download • Grid' and this will be saved to your machine as a netCDF file



## Final remarks

### Regional MOM6 is quickly becoming a reality

- Most desired features have been coded up:
  - Barotropic/Baroclinic OBCs
  - Sponge layers
  - Tracer boundary conditions (including BGC)
  - Tides
- Several implementations are being tested (NWA, CCS/NEP, Arctic, Indian Ocean, Eastern Tropical Pacific...)
- Community is expanding fast (Climate and Fisheries Initiative)
- Ancillary software is being developed (python based)
- New North Atlantic models will be tested starting this summer
- Much remains to be done!



ning a reality coded up:

## Additional slides

### Low-resolution model biases: SST (Model minus Observations of mean SST)

#### (CCSM 3.5 - WOA98)



"Models still show significant errors ... The ultimate source of most is that many important small-scale processes are not represented explicitly in models ..."

Randal et al., 2007.