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Tropical Cyclones in CAM7:

Assessing the Impact of Prognostic Momentum Fluxes and Convective Parameterization at Global and Storm Scales

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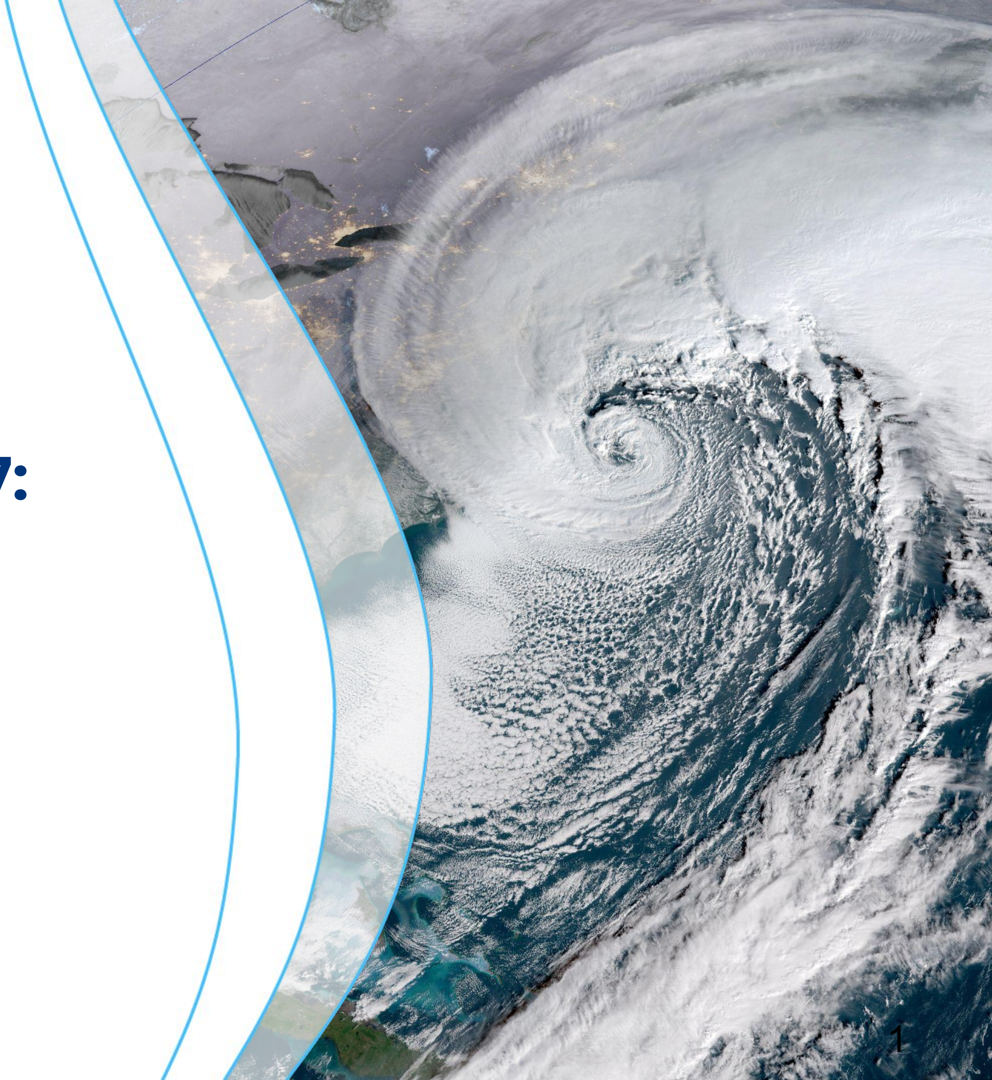

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Tropical cyclones in a development version of CAM7

Some updates for CAM7

- Prognostic momentum fluxes in CLUBB (boundary layer turbulence model). **This development work was done under the Momentum CPT.**
- New processes + new hydrometeor species in microphysics (PUMAS)
- Higher boundary-layer resolution (32 → 58 total levels in low-top model)
- ZM updates: convective gustiness parameterization + accommodations for increased boundary-layer resolution

Model configuration/tests

- We ran quarter-degree (QD), variable resolution (VR), and idealized f-plane aquaplanet tests seeded with a single cyclone
- Initial tests had no additional tuning (i.e., same as 1-degree model)
- **Initial performance promising, but improvements were possible via**
  a. Reducing the Zhang-McFarlane CAPE consumption time scale (i.e. more active deep convection)
  b. Reducing diffusivity in CLUBB (i.e. shallower boundary layer)

Diagnostic vs. prognostic momentum fluxes in CAM/CLUBB

CAM5/CAM6

- CAM5 used a “moist turbulence scheme” with (diagnostic) downgradient diffusion
- CAM6 used CLUBB, but also with diagnostic momentum fluxes (downgradient scheme), where K=Lscale*sqrt(TKE)

$$\overline{u'w'} = -K_m \frac{\partial \overline{u}}{\partial z}$$

$$\overline{v'w'} = -K_m \frac{\partial \overline{v}}{\partial z}$$

CAM7

- Will use CLUBB’s prognostic momentum flux code by default.
- Users can revert to diagnostic momentum fluxes by namelist flag

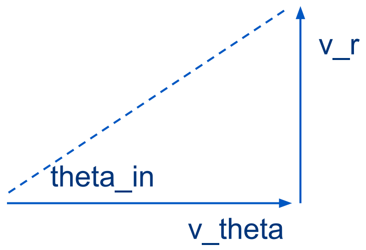
$$\frac{\partial \overline{u'_h w'}}{\partial t} = \underbrace{-\overline{w}\frac{\partial \overline{u'_h w'}}{\partial z}}_{ma} \underbrace{-\frac{1}{\rho_s}\frac{\partial \rho_s \overline{w'^2 u'_h}}{\partial z}}_{ta} \underbrace{-\overline{w'^2}\frac{\partial \overline{u_h}}{\partial z}}_{tp} \underbrace{-\overline{u'_h w'}\frac{\partial \overline{w}}{\partial z}}_{ac} \underbrace{+\frac{g}{\theta_{vs}}\overline{u'_h \theta'_v}}_{bp}$$

$$\underbrace{-\frac{C_6}{\tau}\overline{u'_h w'}}_{pr1} \underbrace{+C_7 \overline{u'_h w'}\frac{\partial \overline{w}}{\partial z}}_{pr2} \underbrace{-C_7 \frac{g}{\theta_{vs}}\overline{u'_h \theta'_v}}_{pr3} \underbrace{+C_{\mathrm{shr}}^{\mathrm{uu}}\overline{w'^2}\frac{\partial \overline{u_h}}{\partial z}}_{pr4}$$

$$\underbrace{+\frac{\partial}{\partial z}\left[(K_{w6}+\nu_6)\frac{\partial}{\partial z}\overline{u'_h w'}\right]}_{dp1}$$

Initial results from CAM7 (DMF vs. PMF)

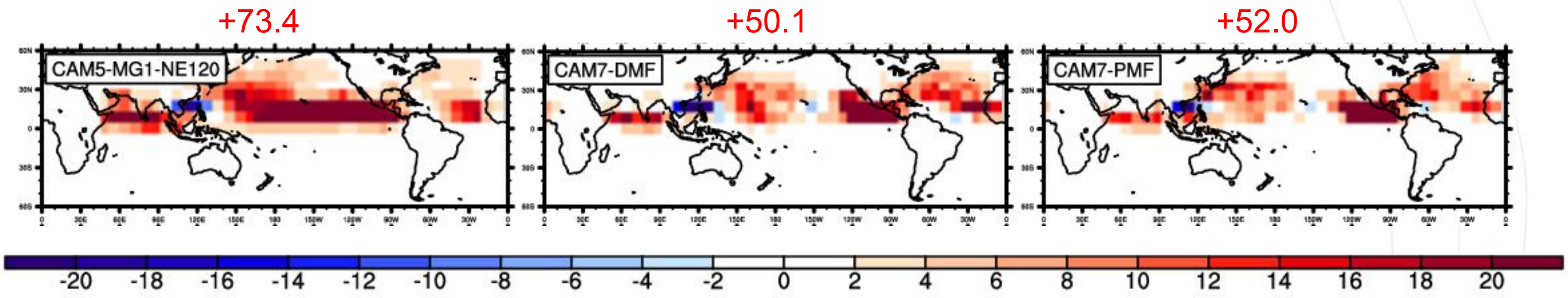
- To start, 10-year quarter-degree (ne120) tests were run using diagnostic and prognostic momentum fluxes
- Strengths
  - TC count and ACE/PACE spatial correlations are improved in DMF over CAM5. PMF further improves on these
  - TC count seasonal correlation is improved in CAM7 DMF/PMF over CAM5
  - Pacific bias improved in both DMF/PMF
- Weaknesses
  - Large-scale: Too many TCs (~2x)
  - Storm scale: inflow angles are small compared to IBTrACS & CAM5, but PMF is better than DMF here



Initial results from CAM7 (DMF vs. PMF)

- Central Pacific bias is improved in the new version of CAM
- But we still overproduce storms by a factor of about 2 in the global mean

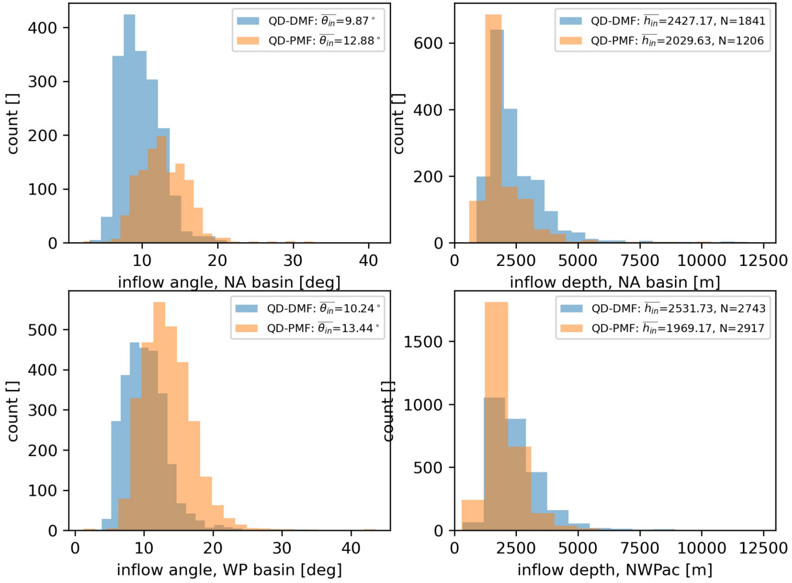
Storm count biases (IBTrACS value: 56.5):

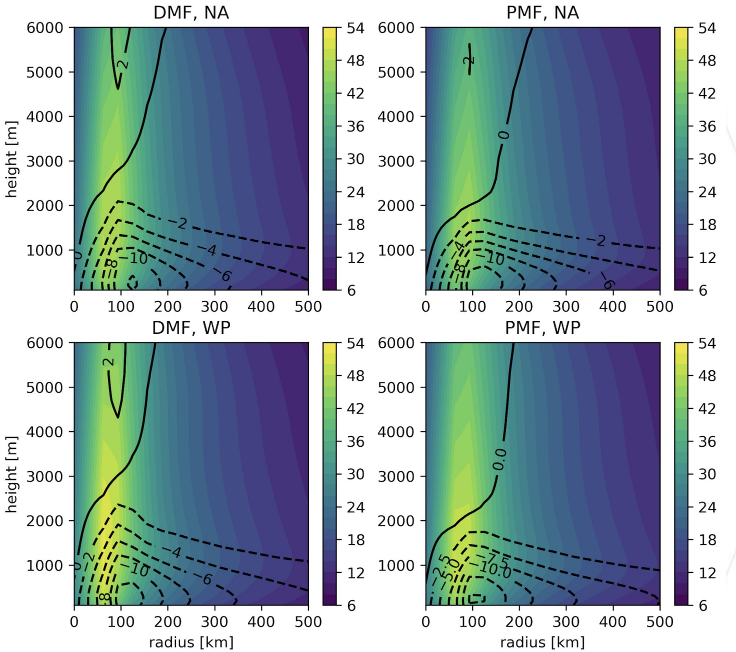


Plots by Colin Zarzycki

Initial results from CAM7 (DMF vs. PMF)

- Inflow angles increase by about 3 degrees with PMF; inflow depths are smaller
- Max tangential winds in contour plots are closer to ground, more concentrated

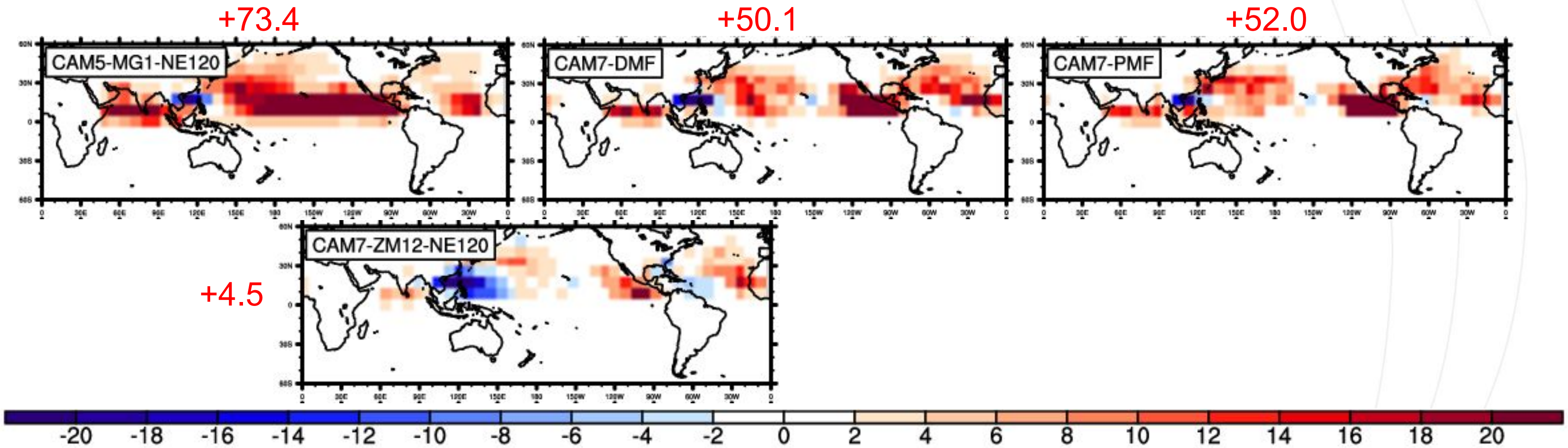




Improvement at the global scale: Reducing CAPE consumption time scale

- Reducing tau_ZM impacts the number of TCs (more active deep convection → less instability → weaker vertical motion → fewer “seeds” for cyclones)
- We bring TC count down by about 40% when reducing tau_ZM from 3600 s to 1200 s.

Storm count biases (obs value: 56.5):



Plots by Colin Zarzycki

Improvement at the storm scale: Reducing diffusivity in CLUBB

- Increasing c_uu_shr improves storm-scale structure (inflow angle, inflow depth)
- Both Larson et al. 2019 and Nardi et al. 2025 find CLUBB to be generally less diffusive with prognostic momentum fluxes than with diagnostic, and…
- Several studies (e.g. Gopalakrishnan et al. 2021 and Bryan 2012) have found less diffusive boundary layers to be associated with enhanced near-surface inflow in cyclones (i.e. larger inward radial winds, hence larger inflow angles)

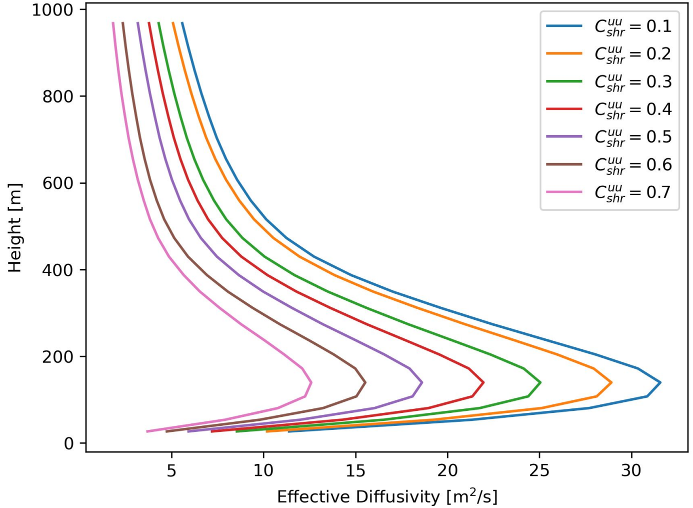
$$\frac{\partial \overline{u_h' w'}}{\partial t} = \underbrace{-\overline{w}\frac{\partial \overline{u_h' w'}}{\partial z}}_{ma} \underbrace{-\frac{1}{\rho_s}\frac{\partial \rho_s \overline{w'^2 u_h'}}{\partial z}}_{ta} \underbrace{-\overline{w'^2}\frac{\partial \overline{u_h}}{\partial z}}_{tp} \underbrace{-\overline{u_h' w'}\frac{\partial \overline{w}}{\partial z}}_{ac} \underbrace{+\frac{g}{\theta_{vs}}\overline{u_h' \theta_v'}}_{bp}$$

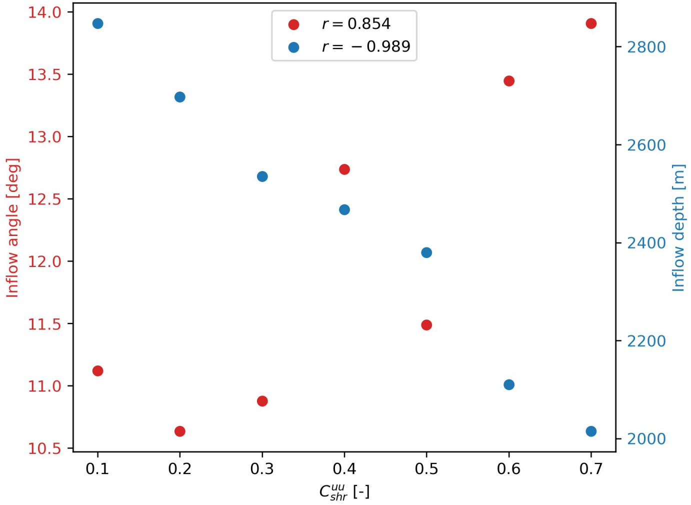
$$\underbrace{-\frac{C_6}{\tau}\overline{u_h' w'}}_{pr1} \underbrace{+C_7\overline{u_h' w'}\frac{\partial \overline{w}}{\partial z}}_{pr2} \underbrace{-C_7\frac{g}{\theta_{vs}}\overline{u_h' \theta_v'}}_{pr3} \underbrace{+C_{\mathrm{shr}}^{\mathrm{uu}}\overline{w'^2}\frac{\partial \overline{u_h}}{\partial z}}_{pr4}$$

$$\underbrace{+\frac{\partial}{\partial z}\left[(K_{w6}+\nu_6)\frac{\partial}{\partial z}\overline{u_h' w'}\right]}_{dp1}$$

Improvement at the storm scale: Reducing diffusivity in CLUBB

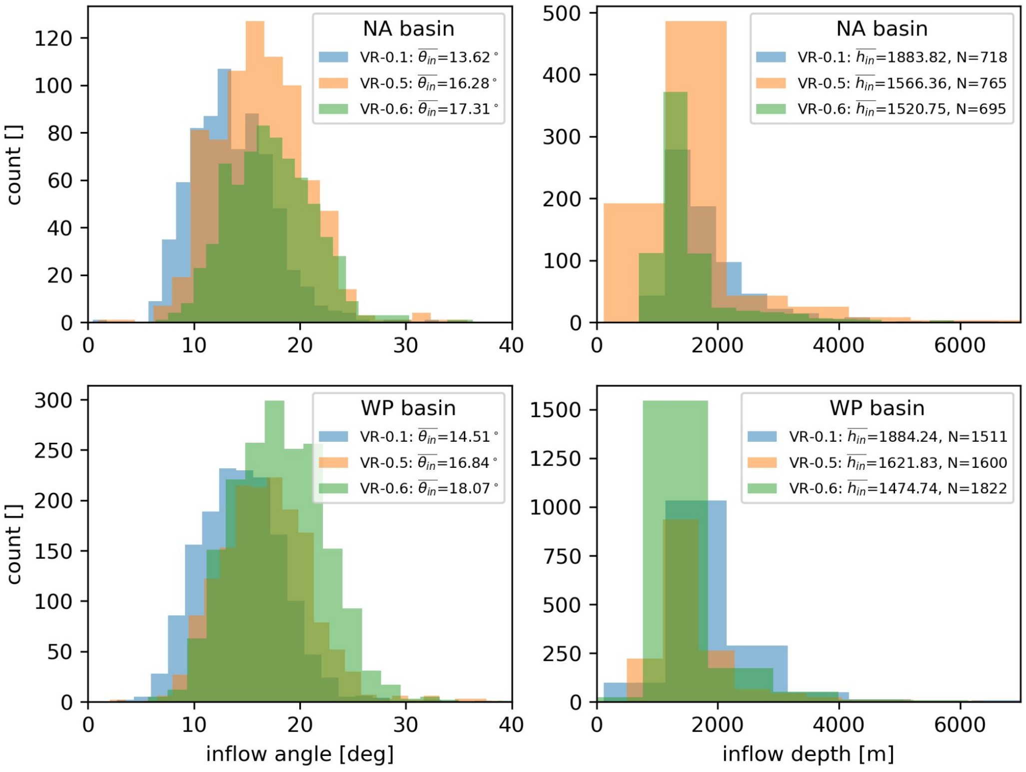
- Idealized f-plane aquaplanet tests with a refined 40x40 region seeded with a single storm show, as c_uu_shr increases:
  - reduced effective diffusivity
  - generally increasing inflow angle (ensembles might make this smoother)
  - decreasing inflow depth





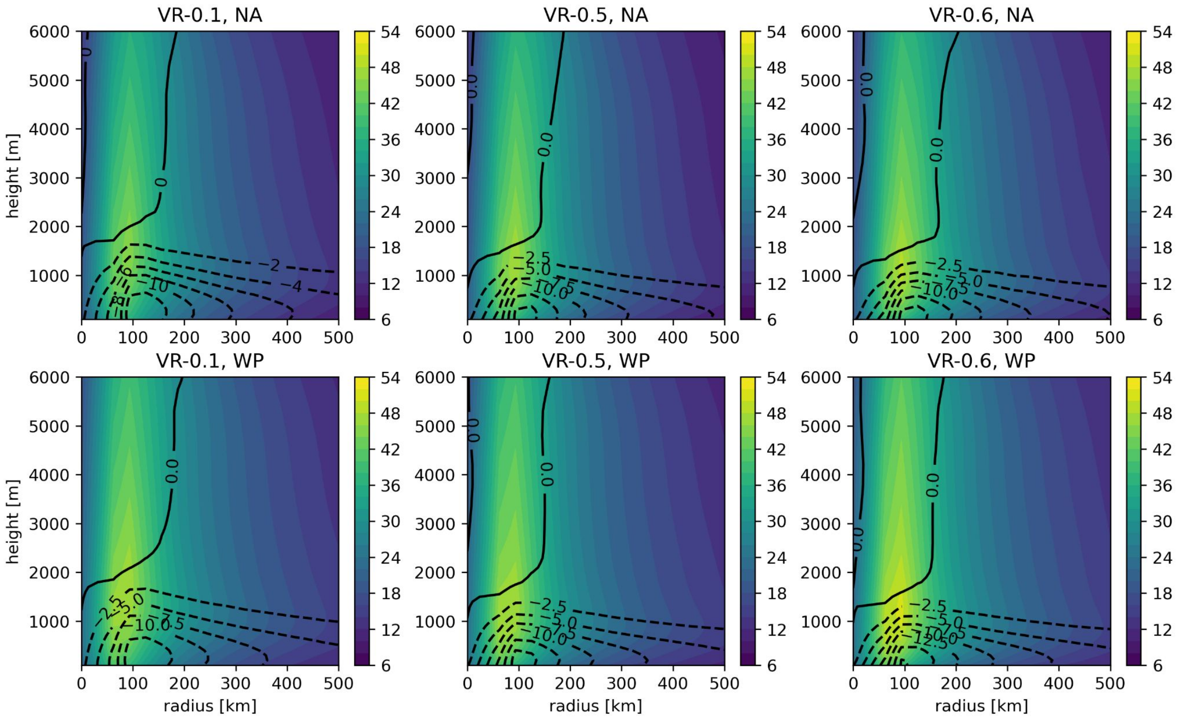
Improvement at the storm scale: Reducing diffusivity in CLUBB

- Variable-resolution tests confirm that in a global model, increasing c_uu_shr improves storm-scale structure
- **Inflow angle increases to the 17-18 degree range as we increase CLUBB's c_uu_shr from 0.1 → 0.6**



Improvement at the storm scale: Reducing diffusivity in CLUBB

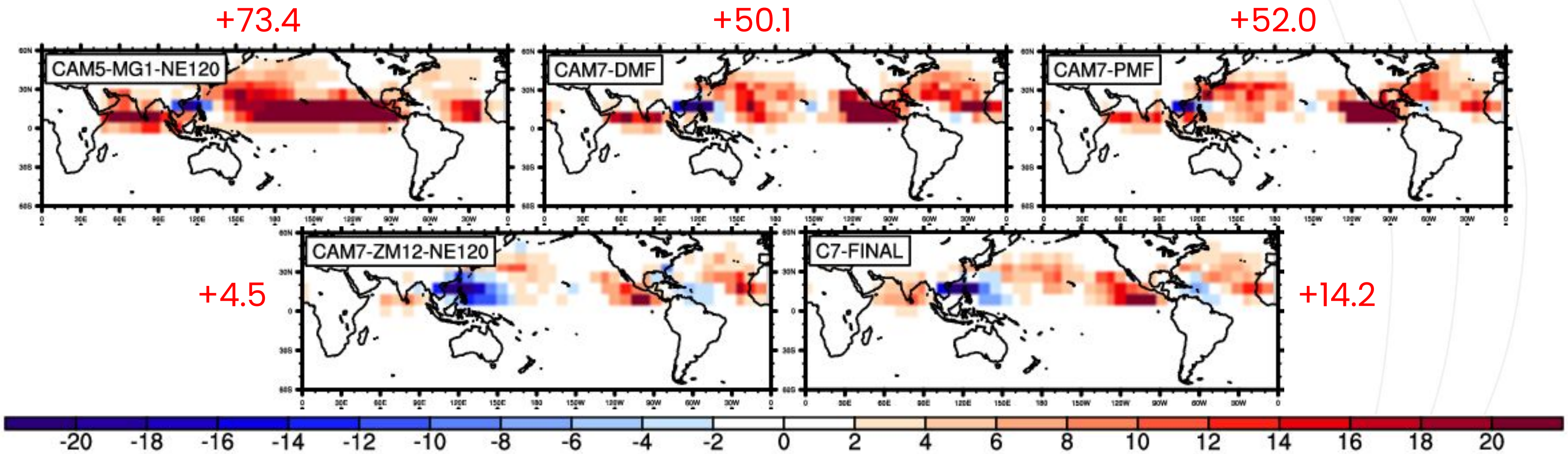
- Variable-resolution tests confirm that in a global model, increasing c_uu_shr improves storm-scale structure
- Inflow angle increases to the 17-18 degree range as we increase CLUBB's c_uu_shr from 0.1 → 0.6
- **Wind contour plots show radial inflow winds closer to the ground (improvement)**



Recent "AMIP" test (run from 1990-2010)

- A longer (21-year) test ("AMIP" test), with tau_ZM=1200 s and c_uu_shr=0.6, shows a much improved storm count and better storm-scale diagnostics

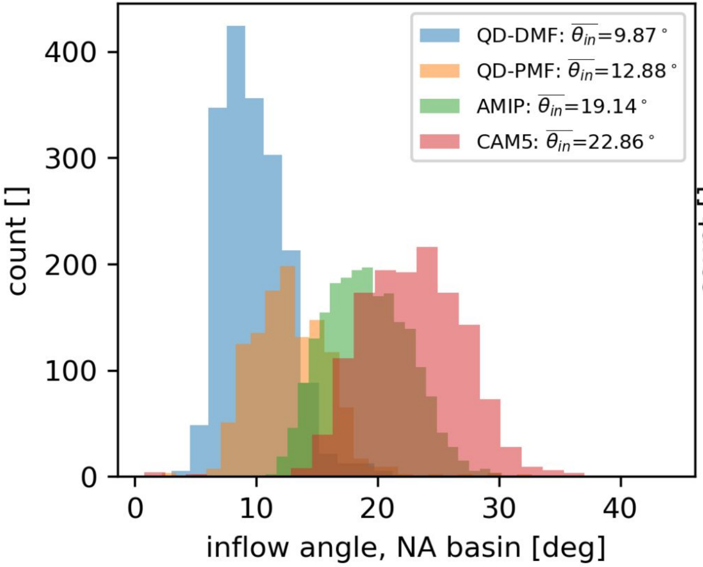
Storm count biases (obs value: 56.5):

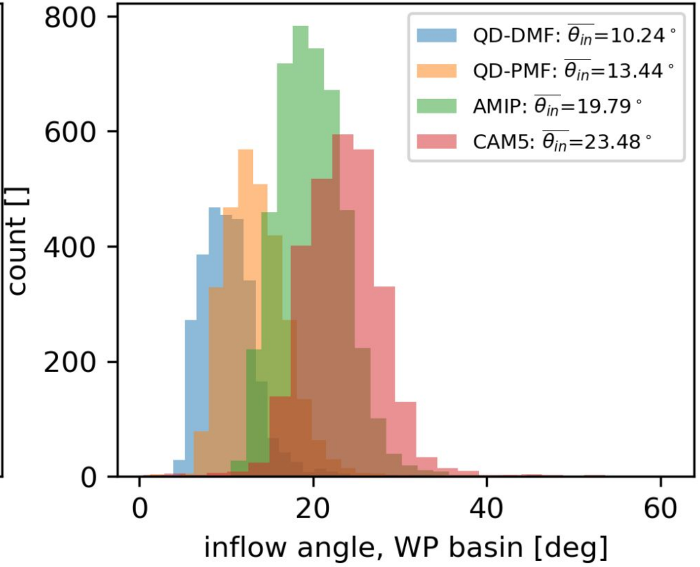


Plots by Colin Zarzycki

Recent "AMIP" test (run from 1990-2010)

- With c_uu_shr=0.6, inflow angles are now between 19-20 degrees
- Didn't save the data to look at wind contours for the AMIP test





Takeaways

Prognostic momentum fluxes improve the representation of TCs

By reducing diffusivity, turning on CLUBB's prognostic momentum flux (PMF) capability improves the storm-scale structure of TCs. Wind contours and inflow angle and inflow depth are improved with PMF.

Decreasing ZM's CAPE consumption time scale effectively reduces TC count

Reducing the Zhang-McFarlane CAPE consumption time scale by 2/3 reduces global mean storm count by about 40%, bringing storm production more closely into line with observations.

Reducing CLUBB's diffusivity improves storm-scale diagnostics

CLUBB's c_uu_shr parameter controls the dissipation of horizontal momentum fluxes. Increasing its value reduces CLUBB's diffusivity. This is associated with improved plots of wind contours and better average inflow angles and inflow depths.

Quarter-degree CAM7 is competitive for studying TCs

When compared to CAM5, the new version of CAM performs well in simulating tropical cyclones, both in large-scale statistics and in storm-scale diagnostics such as inflow angle and inflow depth.

Thank you!

cam7 configs climatological bias (NHEMI)

8° x 8°	$\bar{b}_{clim,count}$	$\bar{b}_{clim,tcd}$	$\bar{b}_{clim,ace}$	$\bar{b}_{clim,pace}$	$\bar{b}_{clim,lmi}$
	#	days	10^4 kn^2	10^4 kn^2	° lat.
OBS	56.5	298.5	482.5	470.2	20.8
ERA5	-7.6	19.3	-309.4	-165.0	3.6
CAM5-MG1-NE120	73.4	674.2	444.5	495.7	-2.9
CAM7-DMF	50.1	353.1	680.0	680.1	-0.2
CAM7-PMF	52.0	333.0	621.4	583.3	0.6
CAM7-ZM12-NE120	4.5	61.2	154.3	175.2	1.7
C7-FINAL	14.2	141.1	255.6	337.1	1.8

cam7 configs spatial correlation (NHEMI)

8° x 8°	$r_{xy,track}$	$r_{xy,gen}$	$r_{xy,u10}$	$r_{xy,slp}$	$r_{xy,ace}$	$r_{xy,pace}$
OBS	1.00	1.00	1.00	1.00	1.00	1.00
ERA5	0.98	0.95	0.61	0.51	0.93	0.97
CAM5-MG1-NE120	0.57	0.52	0.74	0.76	0.78	0.72
CAM7-DMF	0.74	0.51	0.62	0.66	0.81	0.75
CAM7-PMF	0.80	0.58	0.60	0.66	0.87	0.84
CAM7-ZM12-NE120	0.83	0.66	0.58	0.60	0.89	0.84
C7-FINAL	0.85	0.74	0.69	0.71	0.91	0.87

cam7 configs storm mean bias (NHEMI)

8° x 8°	$\bar{b}_{tc,tcd}$	$\bar{b}_{tc,ace}$	$\bar{b}_{tc,pace}$	$\bar{b}_{tc,latgen}$	$\bar{b}_{tc,lmi}$
	days	10^4 kn^2	10^4 kn^2	° lat.	° lat.
OBS	5.3	8.5	8.3	16.5	20.8
ERA5	1.2	-5.0	-2.1	0.2	3.6
CAM5-MG1-NE120	2.2	-1.4	-0.9	-3.5	-3.0
CAM7-DMF	0.8	2.4	2.5	-1.5	-0.2
CAM7-PMF	0.5	1.6	1.4	-0.8	0.6
CAM7-ZM12-NE120	0.6	1.9	2.3	0.3	1.7
C7-FINAL	0.9	1.9	3.1	0.1	1.8

cam7 configs seasonal correlation (NHEMI)

8° x 8°	$\rho_{s,count}$	$\rho_{s,tcd}$	$\rho_{s,ace}$	$\rho_{s,pace}$	$\rho_{s,lmi}$
OBS	1.00	1.00	1.00	1.00	1.00
ERA5	0.97	0.98	0.99	0.94	-0.21
CAM5-MG1-NE120	0.80	0.94	0.97	0.96	0.58
CAM7-DMF	1.00	1.00	0.98	0.97	0.85
CAM7-PMF	0.99	1.00	0.97	0.98	0.56
CAM7-ZM12-NE120	0.93	0.94	0.94	0.94	0.96
C7-FINAL	0.97	0.99	0.99	0.97	0.69

Worse Performance Better Performance

Low bias High bias

Worse Better