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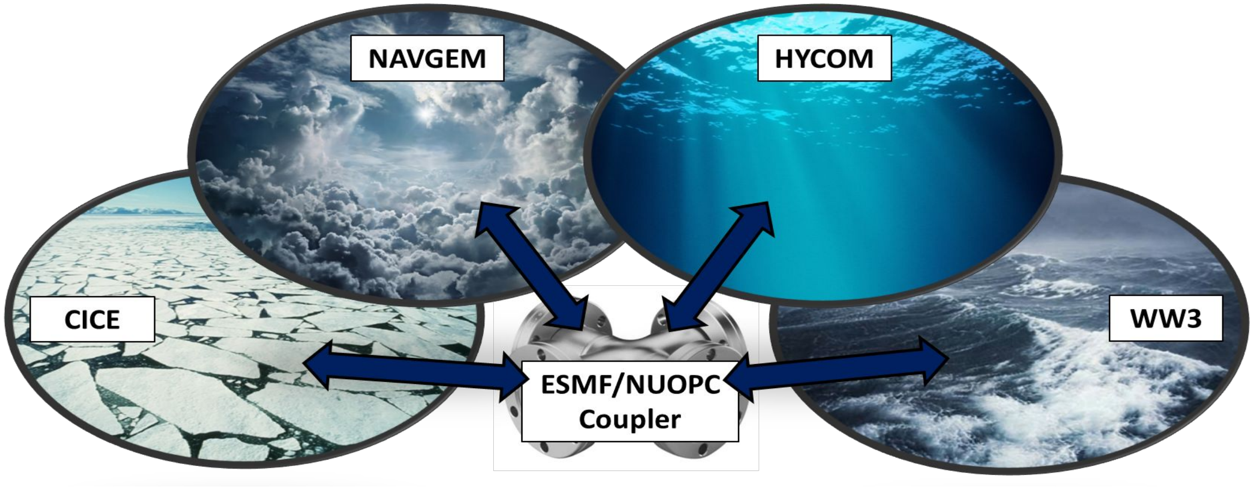
Towards Reduction of Atmospheric Forecast Errors in Navy ESPC


NAVGEM

HYCOM

CICE

WW3

ESMF/NUOPC Coupler

James Ridout[1] (presenter), Carolyn Reynolds[1] , Richard Allard[2], Charlie Barron[2], William Crawford[1], Maria Flatau[1], David Hebert[2], Gregg Jacobs[2], Matthew Janiga[1], Tommy Jensen[2], David Kuhl[3], Fei Liu[4], Jun Ma[3], E. Joseph Metzger[2], Erick Rogers[2], Clark Rowley[2], Stephanie Rushley[1], Jay Shriver[2], Timothy Whitcomb[1]

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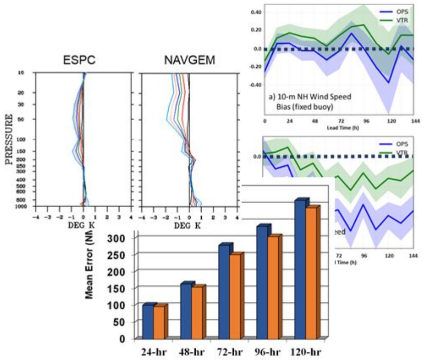
Navy Earth System Prediction Capability (Navy ESPC)



Navy ESPC Operational and Near-Operational Versions

ESPC-D(eterministic) and ESPC-E(nsemble)

Version	Atmosphere NAVGEM	Ocean HYCOM	Sea Ice CICE	Waves WW3	Land Surface	Clim. Aerosol
ESPC-D v2	T681L143 (19 km) HA (middle atmo.)	1/25° (4.5 km) 41 layers with tides	1/25° (1.75 km) CICE V6 w/ landfast Ice	1/8° (12 km)	Module within NAVGEM	Module within NAVGEM
ESPC-E v1	T359L60 (37 km) 60 levels	1/12° (9 km) 41 layers with tides	1/12° (3.5 km) CICE V4		Module within NAVGEM	
ESPC-E v2	T681L143 (19 km) HA (middle atmo.)	1/12° (9 km) 41 layers with tides	1/12° (3.5 km) CICE V6 w/ landfast Ice	1/4° (24 km)	Module within NAVGEM	Module within NAVGEM

Operational

Near-operational (ESPC-D v2), Starting V&V (ESPC-E v2)

NAVGEM Physics Development – General Considerations

Benefit of a dual-timescale perspective

ESPC-D *Model physics development for v2 has focused on the Deterministic system, which is designed for once-per-day forecasts out to 16 days. Atmospheric validation of the system has a dual time-scale perspective, in which both S2S- and NWP time-scale performance are emphasized. It is expected that attention given to weather prediction will benefit the longer time-scales as well.*

Benefit of resolution uniformity between ESPC-D and ESPC-E

***For v1**, we had a higher NAVGEM horizontal resolution for ESPC-D (T681) compared with ESPC-E (T359). This proved unsuccessful due to difficulties adequately addressing performance implications in the time available.*

***For v2**, the NAVGEM configuration is the same in ESPC-D and ESPC-E*, which has precluded the difficulties experienced with v1.

NAVGEM Physics Development – 2-Step Process

NAVGEM physics development for Navy ESPC **has followed an iterative 2-step process,** combining extended range integrations and uncoupled data assimilative (DA) NWP forecasts - **This has been helpful in addressing demands placed by the emphasis on dual-timescale validation testing,** particularly for the ESPC-D system.

1) ***MJO case study coupled hindcasts*** **–** *with verification against satellite rainfall and OLR retrieval data, as well as atmospheric reanalysis and NCODA SST data. Also, regular checks of global-mean values of atmospheric state variables, physics tendencies, cloud cover and radiative fluxes. This work has been largely focused on just one test case from the DYNAMO period, with a start date of 1 Nov 2011.*

2) *NWP uncoupled NAVGEM DA cycling and 5-day forecasts – with evaluation using standard NWP skill metrics.*

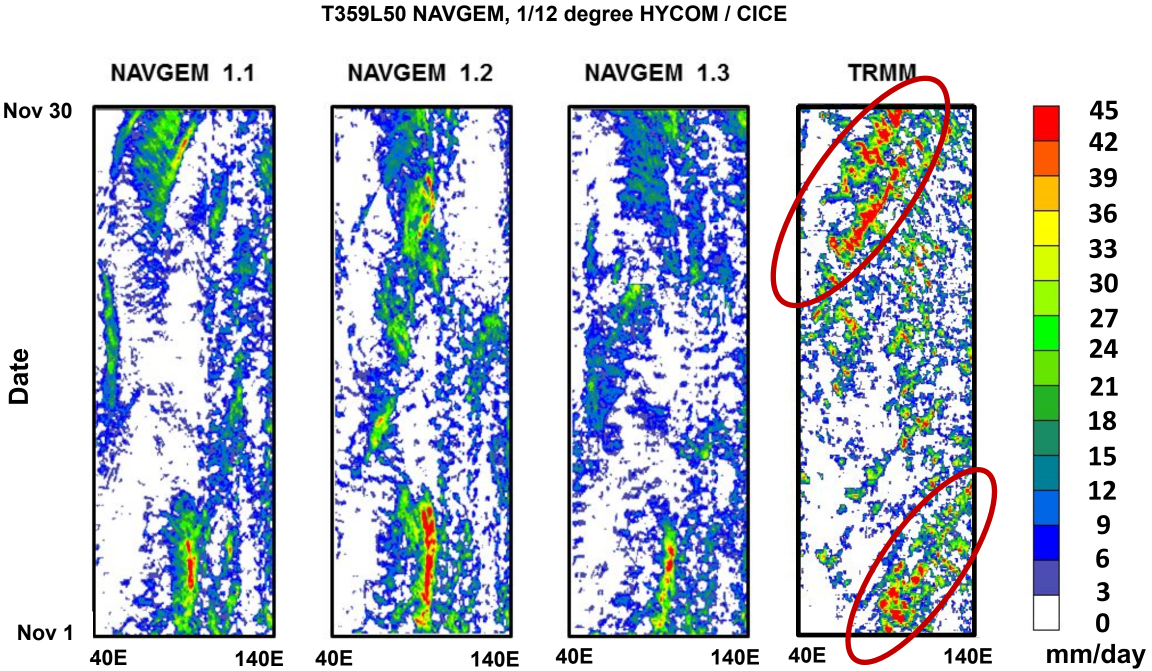
Both steps include physics adjustments to address identified issues. Repeat (1) and (2) as necessary, since small changes made in step 2 can have a significant impact on the MJO.

Step 1 – DYNAMO Case Study Hindcasts

Early Navy ESPC tests using operational NAVGEM showed limited MJO skill

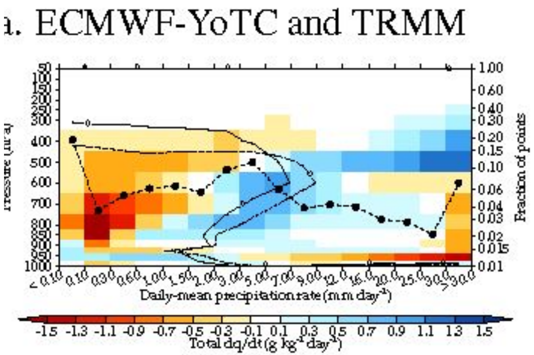
Air-sea coupling in Navy ESPC was not enough to resolve MJO skill deficiencies that had been identified in uncoupled NAVGEM hindcasts.

Rainfall (5N – 5S) Hovmöller Plots (Time/Longitude)



Key MJO Diagnostic - Net Moistening / Rainfall

Adapted from Klingaman et al. 2015

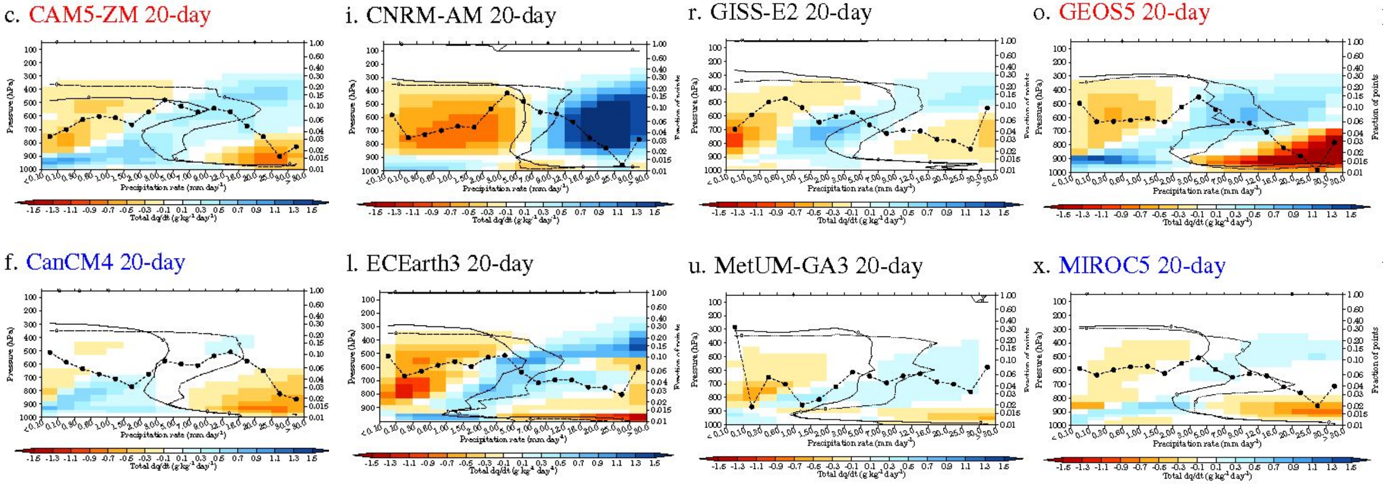


Mean net moistening rate profile versus rainfall rate based on the ECMWF-YOTC 24-hr forecasts and TRMM rainfall.

In 20-day hindcasts for the Year of Tropical Convection (YOTC), the pattern correlation of plots of net moistening rate profile vs rainfall with the one to the left proved to be the strongest single indicator of MJO skill.

The authors hypothesized that the midlevel moistening at moderate rain rates was critical to a reliable representation of the MJO. In ECMWF-YOTC and the high-skill GCMs, this was produced by a combination of the GCM dynamics and physics.

Selected examples



Red indicates good MJO models, **blue** is for poor MJO models

Modified Kain-Fritsch (MKF) Convection

Ridout, J.A., 2023: A modified Kain-Fritsch convection scheme for extended range prediction. *Wea. Forecasting*, 38, 1041-1062. - ***includes:***

Ridout et al. (2005) modifications to the Kain-Fritsch (1990) scheme:

- Closure formulation based mainly on an assumed “cloud-base quasi-balance”, which was supported by cloud-resolving simulations with COAMPS.
- Cloud source level selection following Peng et al. (2004), also supported by COAMPS simulations, and implemented into the Emanuel convection scheme at NRL.

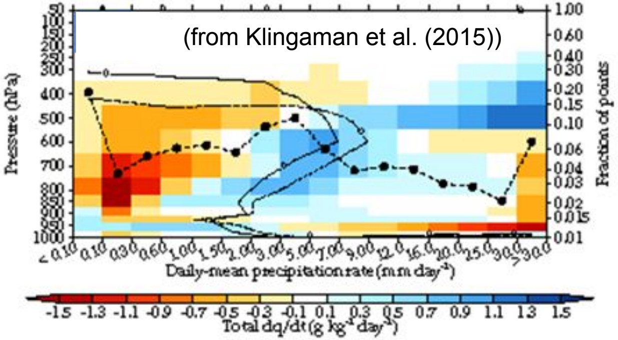
More recent changes, beginning in 2014:

- Turbulence-triggered convection mode coupled with plumes from the NAVGEM EDMF scheme (Sušelj, et al. 2013), incorporating the mixed-layer Richardson number-based trigger of Ridout and Reynolds (1998).
- Updraft entrainment similar to Peng et al. (2004).
- Cloud top condition to enhance sensitivity to parcel buoyancy / entrainment of dry air.
- Explicit sensitivity of updraft entrainment to vertical motion.
- Downdraft scheme based on Kain (2004).

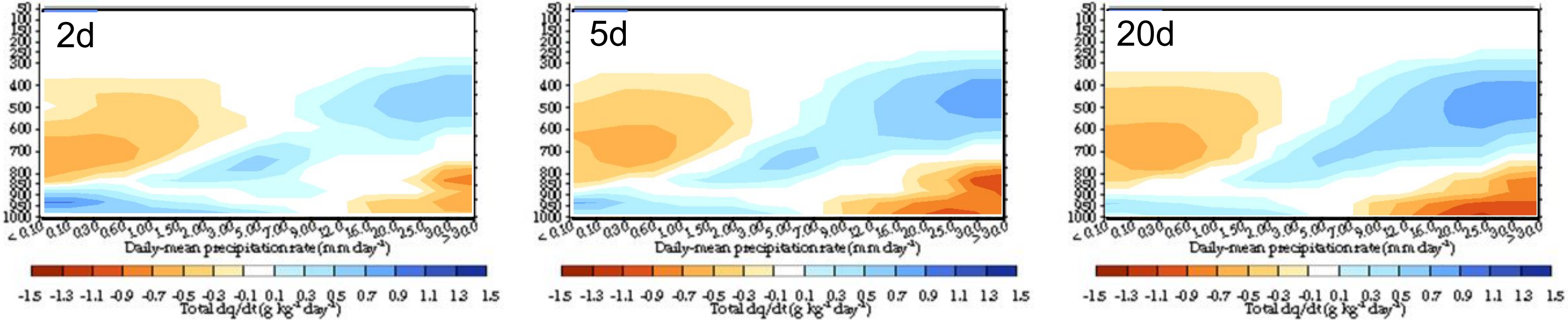
This work benefited considerably from MJO diagnostic efforts by M. Flatau, M. Janiga, C. Reynolds, and also MJO intercomparison studies of Klingaman et al. (2015) and Jiang et al. (2015)

Net Moistening Diagnostic – Navy ESPC with MKF Scheme

The Navy ESPC deficiency with respect to the net moistening diagnostic of Klingaman et al. 2015 was rectified with the MKF convection scheme. Results shown for our DYNAMO test case hindcast, looking at 2-d, 5-d and 20-d hindcast periods.



(from Klingaman et al. (2015))



Vertical cross-sections of net moistening rate as it varied with preciptation rate (horizontal axis) for a region bounded by 10N -10S and 60E – 180E for **top) ECMWF YOTC period analysis** (see Klingaman et al. (2015)) and **bottom) MKF scheme in Navy ESPC 2-d, 5-d and 20-d hindcasts** from 1 Nov. 2011.

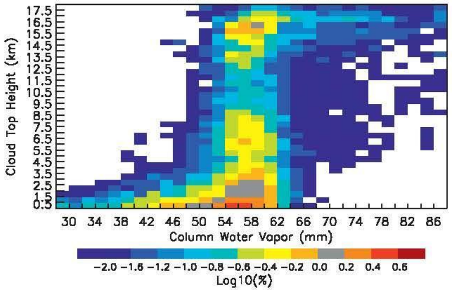
MKF Convection – Cloud top heights

Convective cloud top height – column water vapor relationship in Navy ESPC broadly consistent with satellite observations in the Indo-Pacific region (Ridout - *Wea Forecasting* 2023)

Joint Probability Density Function (pdf) of cloud top height and column water vapor

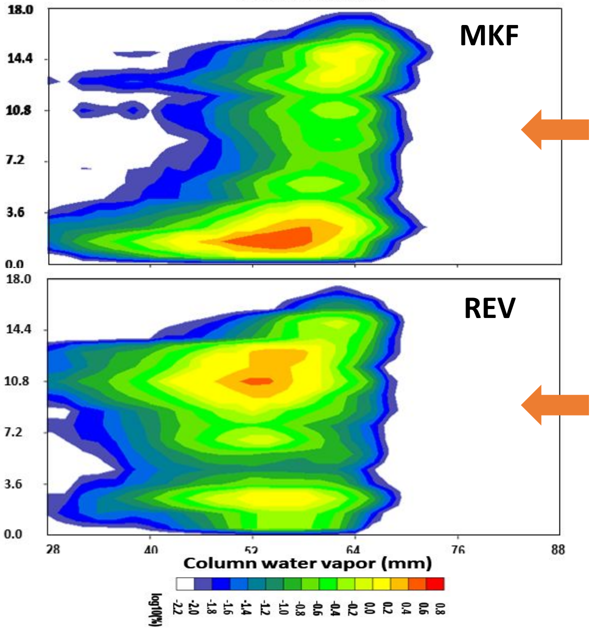
Observations and model results are for convection with source level within 2 km of the surface.

Satellite Retrieval



CloudSat / CALIPSO data presented by Del Genio et al. (2012) for the MJO transition phase to deep convection for a multi-year Sep – May sampling between 5N-10S and 65-170E

Navy ESPC Hindcast (T359L50 NAVGEM)
1 Nov – 15 Dec 2011 – 5N-5S, 40–140E



Modified Kain-Fritch (MKF) convection (Ridout 2023), (implemented with small adjustments for T681L143 NAVGEM in Navy ESPC v2.0)

REVersion to KF of two key features of MKF (removal of impact of near-cloud vertical motion on entrainment, and a modified cloud-top condition)

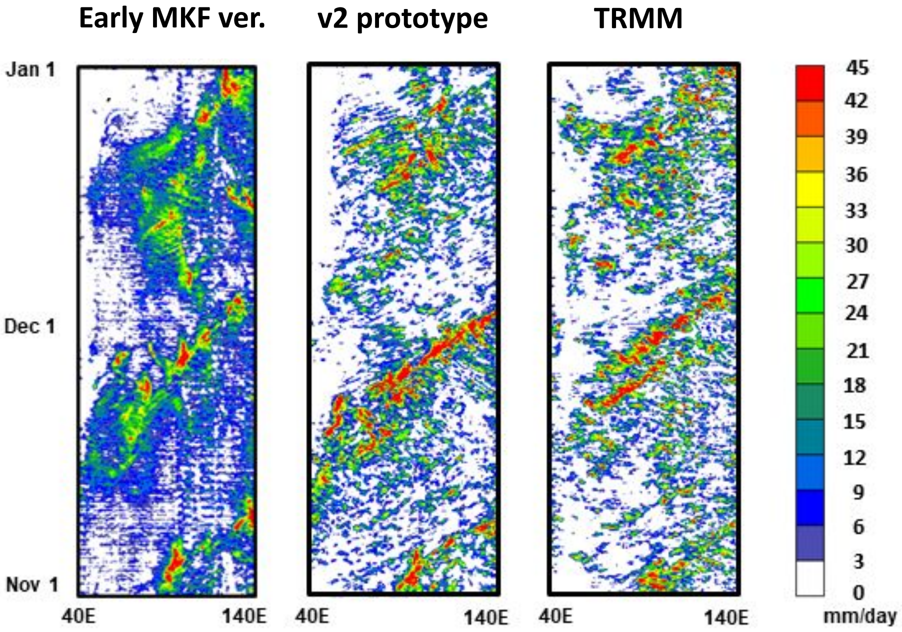
DYNAMO Case Study Hindcasts Extended to 61 days

Physics development for Navy ESPC led to improved equatorial rainfall propagation and variability in our DYNAMO test case

Results shown here with T359L50 NAVGEM (approximate 37-km horizontal resolution).

Development for T681L143 NAVGEM for Navy ESPC v2 required further minor adjustments.

Rainfall (5N – 5S) (Time/Longitude)



T359L50 NAVGEM, 1/12 degree HYCOM / CICE

NAVGEM Physics Development – 2-Step Process (cont)

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1) *MJO case study coupled hindcasts – with verification against satellite rainfall and OLR retrieval data, as well as atmospheric reanalysis and NCODA SST data. Also, regular checks of global-mean values of atmospheric state variables, physics tendencies, cloud cover and radiative fluxes. This work has been largely focused on just one test case from the DYNAMO period, with a start date of 1 Nov 2011.*

2) ***NWP uncoupled NAVGEM DA cycling and 5-day forecasts** – with evaluation using standard NWP skill metrics.*

Both steps include physics adjustments to address identified issues. Repeat (1) and (2) as necessary, since small changes made in step 2 can have a significant impact on the MJO.

Step 2 - Uncoupled NAVGEM NWP Testing

NAVGEM 2.1 vs “NAVGEM 2.2” (Navy ESPC v2 NAVGEM) - Neutral NWP Skill

Scorecard re)sults for a **Summer** period (1 Jun – 30 Sep 2021) and a **Fall/Winter** period (1 Oct 2021 – 29 Jan 2022)

+/- shows win/loss for NAVGEM 2.2 configuration

No points were awarded in the standard TC track error analysis (not shown)

Neutral NWP scorecard for NAVGEM 2.2 reflects significant NAVGEM coupled physics improvements since Navy ESPC v1.

Attaining parity in this respect with operational uncoupled NAVGEM is a milestone for us, reflecting the impact of Step 2 of our error reduction process.

Metrics considered include fixed buoy mean wind speeds, radiosonde mean and RMS errors, self-analysis anomaly correlation and RMS errors, and TC track errors.

Summer Fall/Winter

Reference	Level	Region	Lead time	Variable	Level type	Metric	Weight	Score	Score
Fixed Buoy	None	Northern Hemisphere	96	Wind Speed	surface	Mean Error	2	0	0
Fixed Buoy	None	Tropics	96	Wind Speed	surface	Mean Error	2	0	0
Manual Sfc Land	None	Northern Hemisphere	96	Air Temperature	surface	Mean Error	1	0	0
Radiosondes	100	Global	96	Geopotential Height	pressure	RMS Error	1	+1	+1
Radiosondes	250	Global	96	Air Temperature	pressure	RMS Error	1	0	0
Radiosondes	250	Global	96	Wind	pressure	Vector RMS Error	1	0	0
Radiosondes	500	Global	96	Geopotential Height	pressure	RMS Error	1	0	0
Radiosondes	700	Global	96	Relative Humidity	pressure	Mean Error	1	0	0
Radiosondes	850	Global	96	Air Temperature	pressure	Mean Error	1	0	0
Radiosondes	850	Global	96	Air Temperature	pressure	RMS Error	1	0	0
Radiosondes	850	Global	96	Wind	pressure	Vector RMS Error	1	0	0
Self Analysis	200	Northern Hemisphere	96	Wind	pressure	Vector RMS Error	1	0	0
Self Analysis	200	Southern Hemisphere	96	Wind	pressure	Vector RMS Error	1	0	0
Self Analysis	200	Tropics	96	Wind	pressure	Vector RMS Error	1	0	0
Self Analysis	500	Northern Hemisphere	120	Geopotential Height	pressure	Anomaly Correlation	2	0	0
Self Analysis	500	Southern Hemisphere	120	Geopotential Height	pressure	Anomaly Correlation	1	0	0
Self Analysis	500	Northern Hemisphere	120	Geopotential Height	pressure	RMS Error	2	0	0
Self Analysis	500	Southern Hemisphere	120	Geopotential Height	pressure	RMS Error	1	0	0
Self Analysis	850	Northern Hemisphere	96	Wind	pressure	Vector RMS Error	1	0	0
Self Analysis	850	Southern Hemisphere	96	Wind	pressure	Vector RMS Error	1	0	0
Self Analysis	850	Tropics	96	Wind	pressure	Vector RMS Error	2	-2	0
Self Analysis	1000	Northern Hemisphere	120	Geopotential Height	pressure	Anomaly Correlation	1	0	0
Self Analysis	1000	Southern Hemisphere	120	Geopotential Height	pressure	Anomaly Correlation	1	0	0
Total								-1	+1

NAVGEM Uncoupled NWP – Day-5 10-m Wind Speed Bias

1 Jun 2021- 29 Jan 2022
Twice-daily forecasts

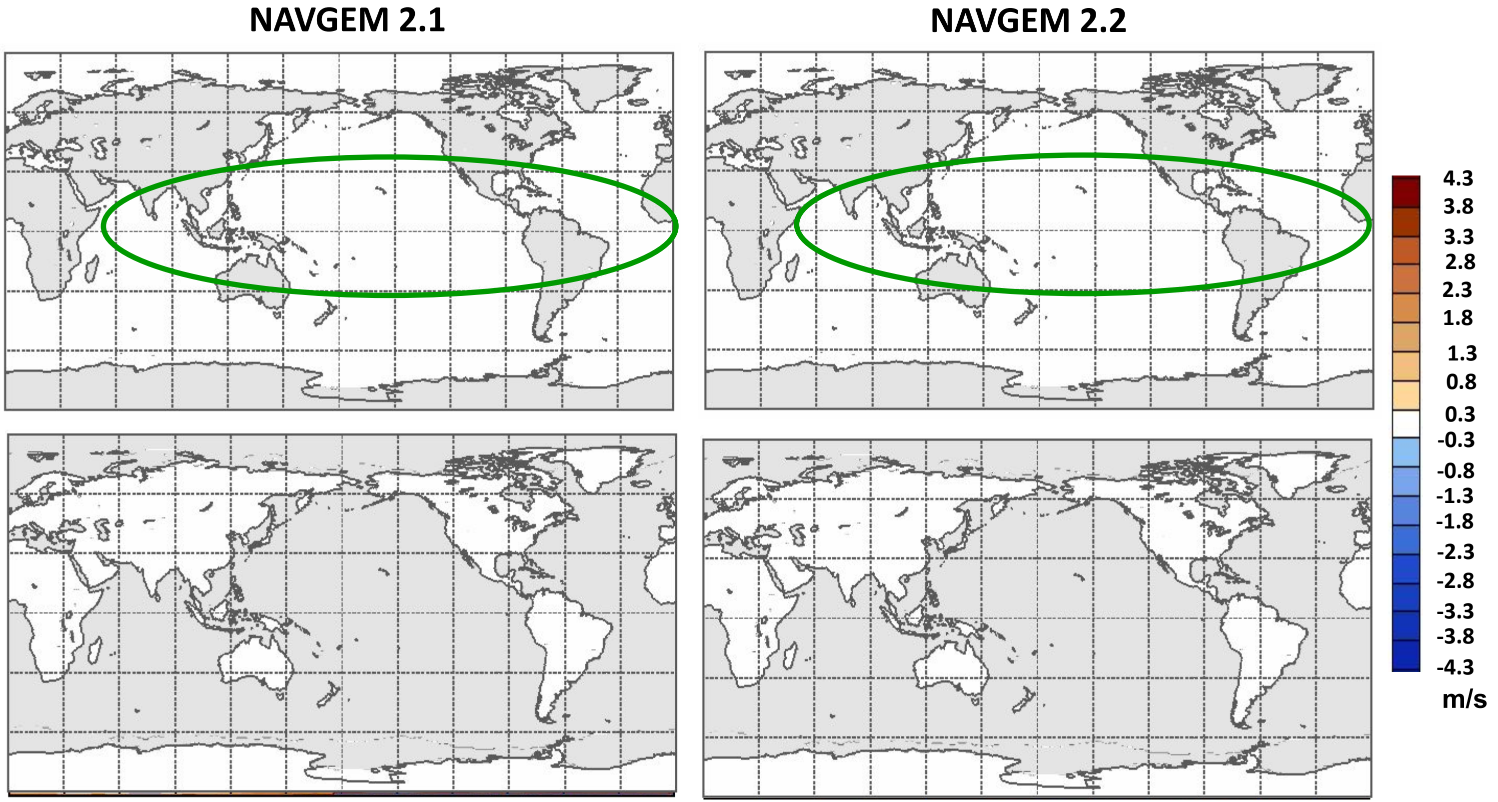
Day-5 10-m wind speed mean error with respect to ERA5 Reanalysis

Oceans - Improvement with NAVGEM 2.2 over the oceanic tropics of 0.25 m/s. Time series of tropical-ocean mean error differences significant at the 99.5% level.

In NAVGEM 2.2, both HYCOM and NAVGEM use the Kara et al. (2005) surface fluxes (efficient approx. to COARE 3.0)

Land - Similar errors with both models.

Both models use Louis et al. (1982) surface fluxes over land – and the same land surface scheme (Hogan)



Navy ESPC Error Reduction Process – Summary Comments

Step 1) MJO case study coupled hindcasts

a) Step (1) targets improved S2S time-scale skill. The DYNAMO case has helped guide development efforts, while providing a useful yardstick of progress. An additional case study would be beneficial.
b) More S2S time-scale three-dimensional field verifications would be helpful.
c) Results sensitive to small changes in the physics – hence the need to iterate the two steps.

Step 2) NWP uncoupled testing

a) Step (2) assists with improvements in regards to early time-scale errors.
b) We include tests over more than a single season.
c) Importance of scorecard metrics and weighting – where should emphasis be placed?
d) Expected to help with S2S skill as well.

Once tests and adjustments are completed for the various model components – we finally get to see how things look with the complete updated Navy ESPC system in an extended coupled forecast validation test – for Navy ESPC-D v2, this consisted of a one-year reanalysis and one 16-day forecast per week.

Navy ESPC-D v2 Validation Test – NAVGEM NWP Results

Validation test NWP Scorecard for Navy ESPC-D v2 vs NAVGEM 2.0 Ops is somewhat better than in our uncoupled test of NAVGEM 2.2 vs NAVGEM 2.1 (current Ops version)

+/- shows win/loss for Navy ESPC-D v2

+5 on the scorecard for Navy ESPC-D v2 vs NAVGEM 2.0 Ops

Significant improvement compared with the -5 score of Navy ESPC-D v1 against NAVGEM v1.4.1 Ops in its validation test

Navy ESPC-D v2 vs NAVGEM 2.0 Ops (forecasts once/week from 9/6/2020 – 8/29/2021)

Reference	Level	Region	Lead time	Variable	Level type	Metric	Weight	Score
Fixed Buoy	None	Northern Hemisphere	96	Wind Speed	surface	Mean Error	2	0
Fixed Buoy	None	Tropics	96	Wind Speed	surface	Mean Error	2	+2
Manual Sfc Land	None	Northern Hemisphere	96	Air Temperature	surface	Mean Error	1	0
Radiosondes	100	Global	96	Geopotential Height	pressure	RMS Error	1	**0**
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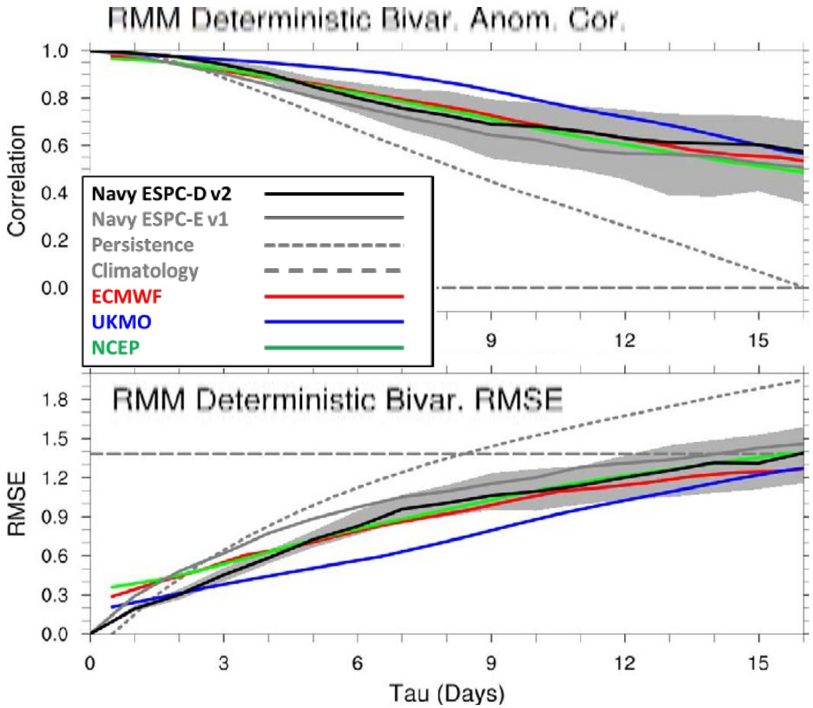
Radiosondes	250	Global	96	Wind	pressure	Vector RMS Error	1	0
Radiosondes	500	Global	96	Geopotential Height	pressure	RMS Error	1	+1
Radiosondes	700	Global	96	Relative Humidity	pressure	Mean Error	1	0
Radiosondes	850	Global	96	Air Temperature	pressure	Mean Error	1	+1
Radiosondes	850	Global	96	Air Temperature	pressure	RMS Error	1	+1
Radiosondes	850	Global	96	Wind	pressure	Vector RMS Error	1	0
Self Analysis	200	Northern Hemisphere	96	Wind	pressure	Vector RMS Error	1	0
Self Analysis	200	Southern Hemisphere	96	Wind	pressure	Vector RMS Error	1	0
Self Analysis	200	Tropics	96	Wind	pressure	Vector RMS Error	1	0
Self Analysis	500	Northern Hemisphere	120	Geopotential Height	pressure	Anomaly Correlation	2	0
Self Analysis	500	Southern Hemisphere	120	Geopotential Height	pressure	Anomaly Correlation	1	0
Self Analysis	500	Northern Hemisphere	120	Geopotential Height	pressure	RMS Error	2	0
Self Analysis	500	Southern Hemisphere	120	Geopotential Height	pressure	RMS Error	1	0
Self Analysis	850	Northern Hemisphere	96	Wind	pressure	Vector RMS Error	1	0
Self Analysis	850	Southern Hemisphere	96	Wind	pressure	Vector RMS Error	1	0
Self Analysis	850	Tropics	96	Wind	pressure	Vector RMS Error	2	**0**
Self Analysis	1000	Northern Hemisphere	120	Geopotential Height	pressure	Anomaly Correlation	1	0
Self Analysis	1000	Southern Hemisphere	120	Geopotential Height	pressure	Anomaly Correlation	1	0
TC Report	SLP	Global	96	Trop. Cyclone		Track Error	2	0
Total								**+5**

Navy ESPC-D v2 Validation Test – MJO Skill

Real-Time Multivariate MJO (RMM) deterministic bivariate anomaly correlation and RMSE for Navy ESPC-D v2 and ESPC-E v1, along with three models from the S2S database (Vitart et al. 2017)



Navy ESPC-D v2 shows improved skill over Navy ESPC-E v1 at all lead times, though the differences here are not statistically significant. UKMO performance stands out as superior in these results.

Plotted values for the ensembles (all of the models except Navy ESPC-D v2) are averages of values computed for the individual ensemble members.

RMM deterministic bivariate (top) anomaly correlation and (bottom) RMSE for the ESPC-D v2 and the operational ESPC-E v1, ECMWF, UKMO, and NCEP ensembles. Deterministic skill for the operational ESPC-E v1, EMCWF, and UKMO ensembles is calculated by averaging the skill of each ensemble member. The 95% uncertainty for ESPC-D v2 (gray shading) is determined from a 1000-member bootstrap resampling.

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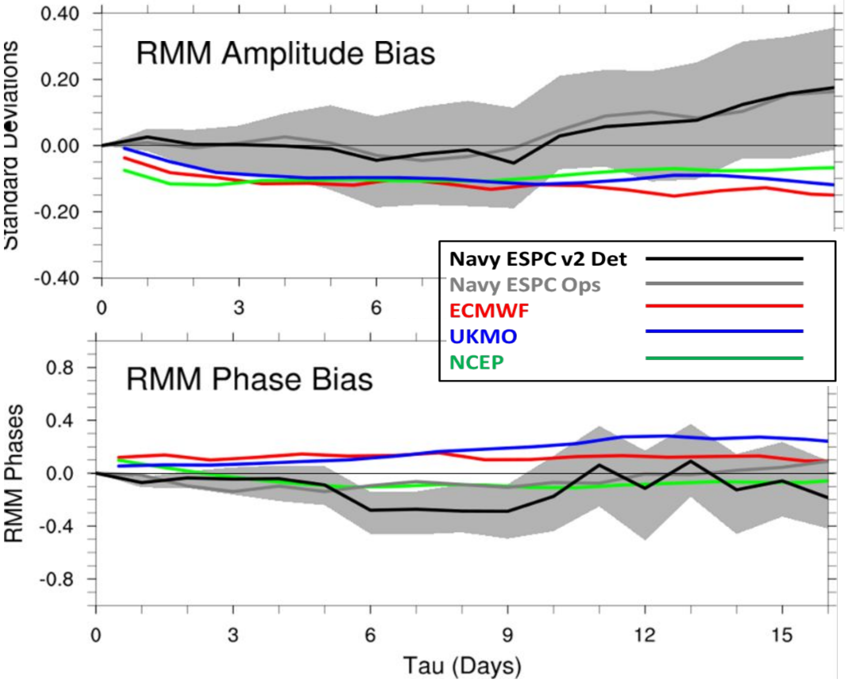
Navy ESPC-D v2 Validation Test – MJO Bias

Real-Time Multivariate MJO (RMM) index amplitude and phase bias for Navy ESPC-D v2 and ESPC-E v1 (Ops), along with three models from the S2S database (Vitart et al. 2017)



Amplitude bias for Navy ESPC-D v2 and for Navy ESPC-E v1 (Navy ESPC Ops) are small compared to the other models for the first 9 days, but then begin to grow.

Phase bias for Navy ESPC-D v2 tends to be somewhat greater than for Navy ESPC-E v1. Like NCEP, the phase error tends to be negative, in contrast to ECMWF and UKMO.

Biases for the ensembles (all of the models except Navy ESPC-D v2) are averages of values computed for the individual ensemble members.

RMM amplitude (top) and phase (bottom) bias for the ESPC-D v2 and the operational ESPC-E v1, ECMWF, UKMO, and NCEP ensembles. For the ensembles, bias is evaluated for each individual ensemble member and then averaged. RMM amplitude bias is the bias in the distance from the origin (standard deviations) and phase bias is the bias in RMM phases at an amplitude of 1 standard deviation. The 95% uncertainty for ESPC-D v2 (gray shading) is determined from a 1000-member bootstrap resampling.

Upcoming Navy ESPC Versions

V2.1 - This will be the final Navy ESPC version with NAVGEM as the atmospheric model component. It will have the same ~19-km horizontal resolution as in v2.0. The model physics in v2.1 will include updates to improve among other things OLR/rainfall comparisons with CERES and TRMM observations.

V3.0 - This version will be a major update, in which the NEPTUNE forecast model will replace NAVGEM as the atmospheric model in Navy ESPC. By virtue of being a nonhydrostatic model, and having superior scaling properties, NEPTUNE will bring the capability for global storm-resolving forecasting to Navy operations. NEPTUNE is configured to use the Common Community Physics Package (CCPP), which will enable easy access for testing impacts of physics variations on model errors.

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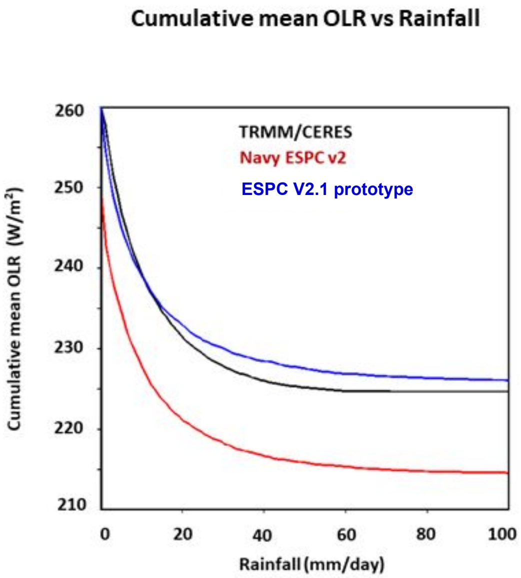
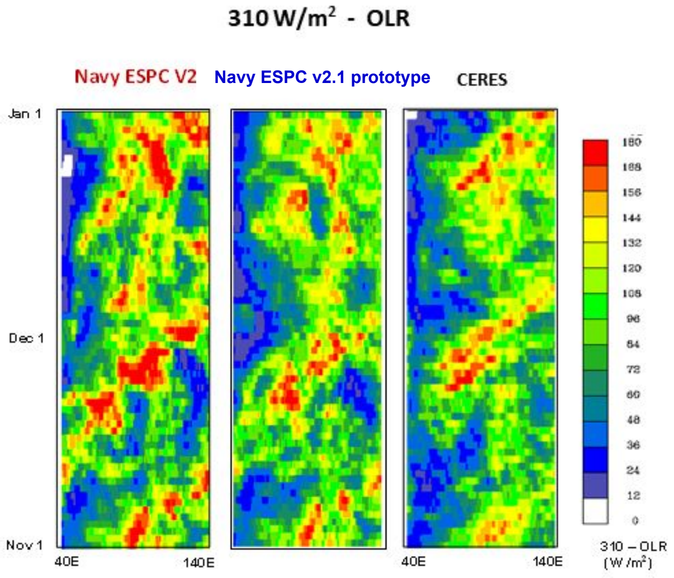
Navy ESPC v2.1 NAVGEM Physics Preparations

The final NAVGEM implementation in Navy ESPC will have the same ~19-km horizontal resolution as in v2.0. The model physics in v2.1 will include updates to improve among other things OLR/rainfall comparisons with CERES and TRMM observations, as shown here for our DYNAMO test case.

v2.1 prototype includes precipitation production rate adjustments in the cloud physics scheme and convective cloud fraction modifications to be more consistent with the convection scheme.

Still under development, but should be completed within a few months.


Cumulative mean OLR vs Rainfall


310 W/m² - OLR

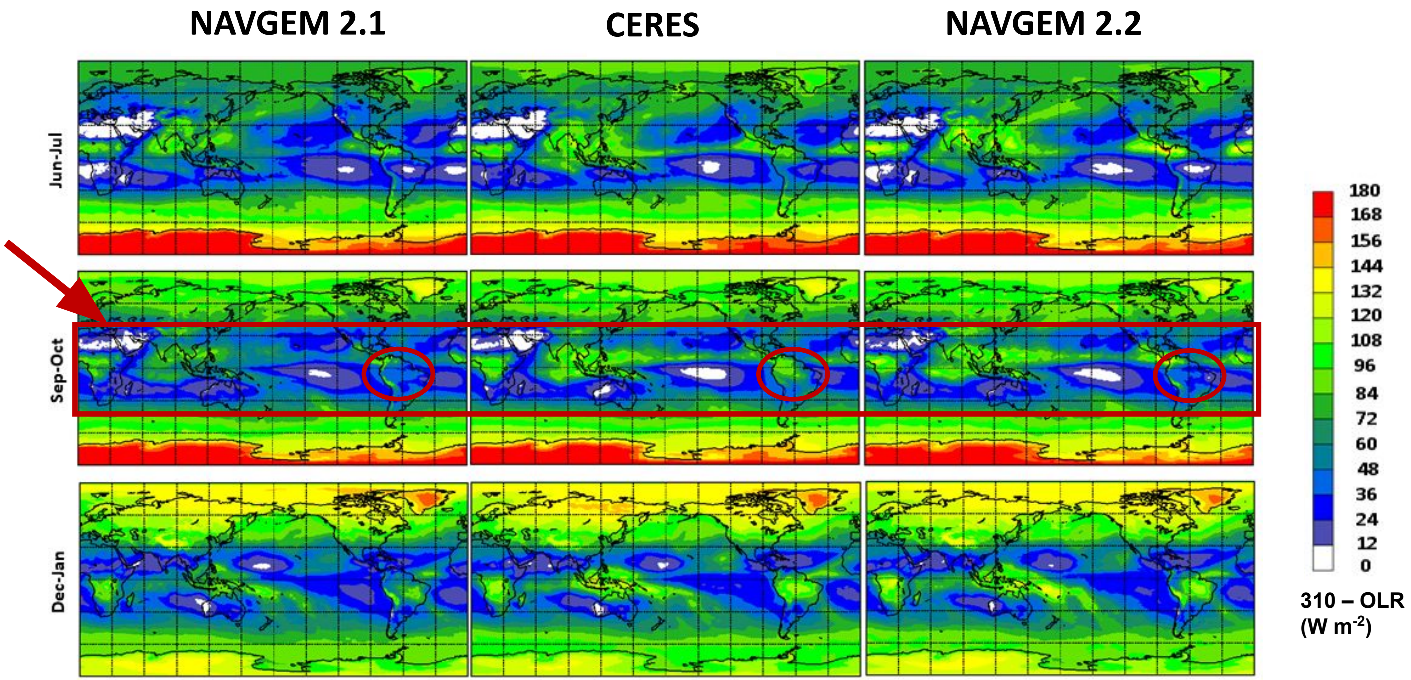
Questions?

Extra Slides

NAVGEM Uncoupled NWP – Day-5 OLR vs CERES

Day-5 NAVGEM OLR evaluation with respect to CERES satellite retrieval

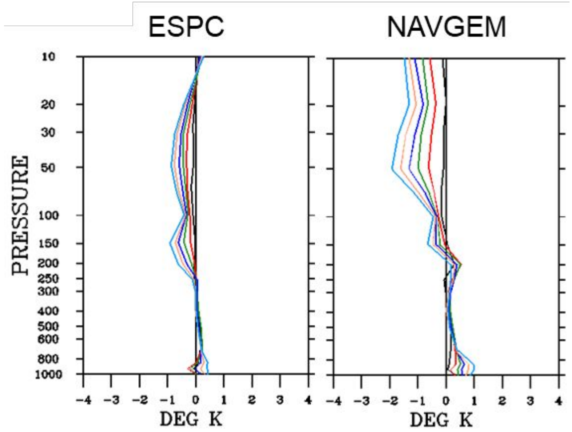
Improved OLR with NAVGEM 2.2 in the equatorial band over the oceans. OLR is not part of our NAVGEM uncoupled scorecard, but this result reflects the emphasis on the tropics (and particularly the MJO) in the Step 1 physics development for Navy ESPC.



Forecast day-5 mean of the quantity 310 – OLR (W m^{-2}) for NAVGEM 2.1 and Navy ESPC v2 NAVGEM configuration runs, along with the corresponding values based on CERES satellite retrieved OLR. Results are shown for three two-month periods (June – July 2021, Sep – Oct 2021, and Dec 2021 – Jan 2022).

Navy ESPC-D v2 Validation Test – NAVGEM NWP Results (cont)

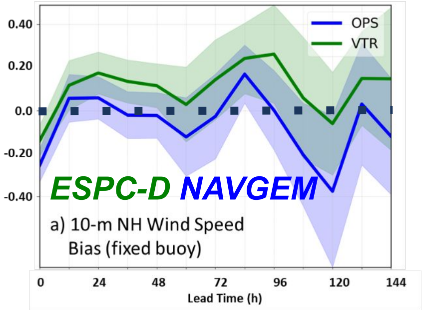
Temperature bias (k) as compared to global radiosonde network at tau=0 h (black) through tau= 120 h (cyan)



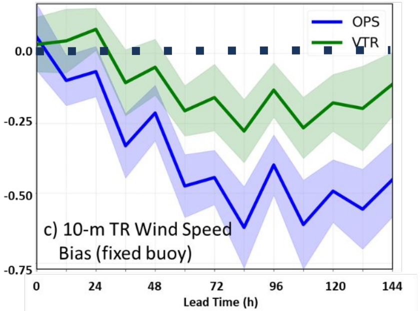
Smaller biases in middle atmosphere and in troposphere (higher top, better physics)

10-m wind speed bias (m/s) against fixed buoys

NH

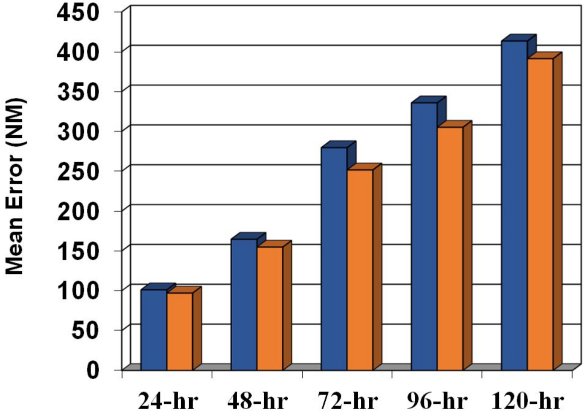


TR



Significant improvement in 10-m wind speed bias in tropics, slightly worse in NH extratropics

*Global Tropical Storm Track Error (NM) for **ESPC-D NAVGEM***



Significant improvement in TC tracks - statistically significant at 60 h and 72 h.

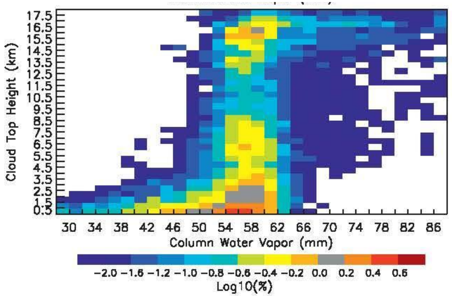
MKF Convection – Cloud top heights

Convective cloud top height – column water vapor relationship in Navy ESPC found to be broadly consistent with satellite observations in the Indo-Pacific region (Ridout - *Wea Forecasting* 2023)

Joint Probability Density Function (pdf) of cloud top height and column water vapor

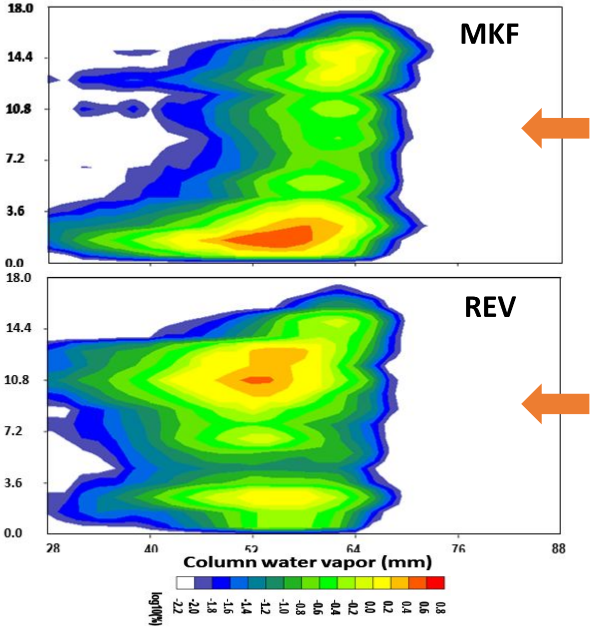
Observations and model results are for convection with source level within 2 km of the surface.

Satellite Retrieval



CloudSat / CALIPSO data presented by Del Genio et al. (2012) for the MJO transition phase to deep convection for a multi-year Sep – May sampling between 5N-10S and 65-170E

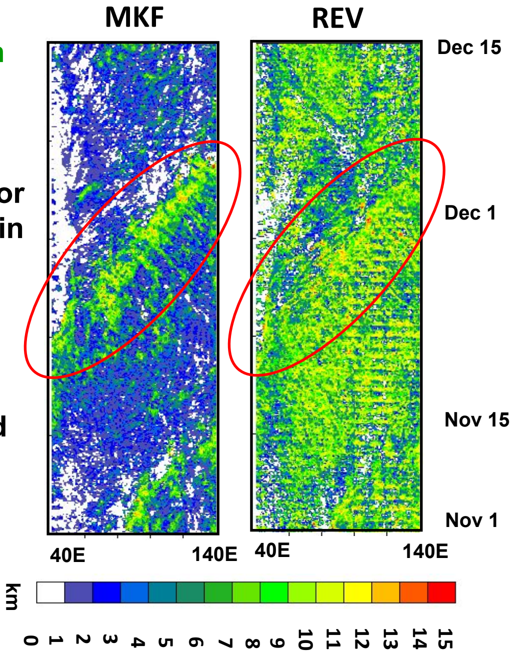
Navy ESPC Hindcast (T359L50 NAVGEM)
1 Nov – 15 Dec 2011 – 5N-5S, 40–140E



Modified Kain-Fritch (MKF) convection (Ridout 2023), (implemented with small adjustments for T681L143 NAVGEM in Navy ESPC v2.0)

REVersion to KF of two key features of MKF (removal of impact of near-cloud vertical motion on entrainment, and of modified cloud-top condition)

MJO phase-dependence of mean convective cloud top height



NWP and NAVGEM Subgrid Vertical Eddy Diffusion - Implication for Air-Sea Coupling Strategy

NWP - Vertical Eddy Diffusion

Vertical eddy diffusion is implemented in NAVGEM in a fully implicit computation along with the surface fluxes, requiring solution of a tridiagonal system. NWP tests had shown that a fully-implicit solution provides benefits to forecast skill, and we have endeavored to retain this formulation in Navy ESPC.

Implication for Surface fluxes in Navy ESPC

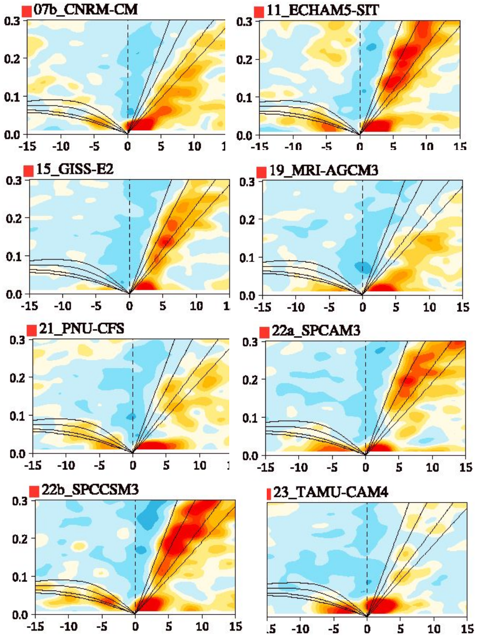
The NAVGEM surface fluxes come out of the fully implicit solution with the vertical eddy diffusion, involving three-dimensional fields every NAVGEM time-step. In Navy ESPC, this should ideally be done on the high-resolution HYCOM grid. To avoid excessive computational and memory requirements, we decided to simply compute the surface fluxes in the component models – and to help limit non-conservation, the Kara et al. (2005) implementation of the COARE 3.0 scheme used in HYCOM was ported to NAVGEM.

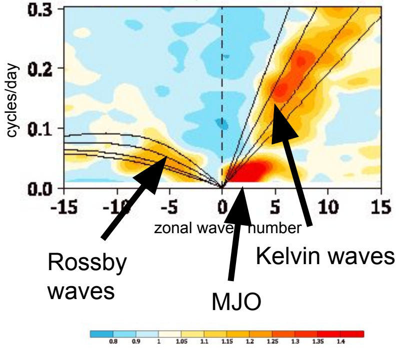
Rainfall Propagation – 20-Year Runs

Adapted from Jiang et al. 2015

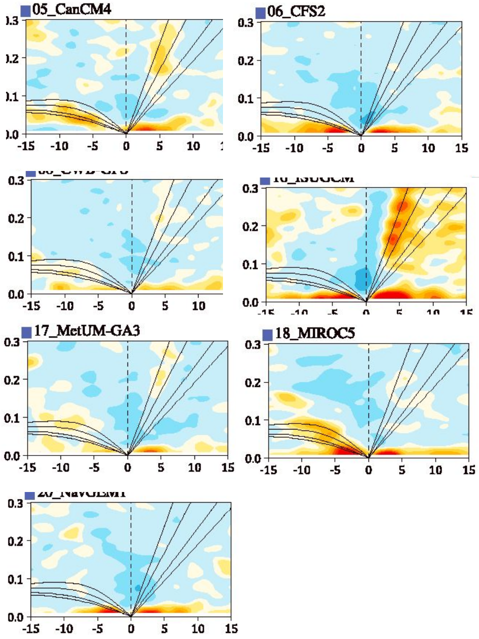
TRMM Rainfall Wave Spectrum
15°S to 15°N, 60°E–180°
Nov – April 1998-2012

Good MJO models





Poor MJO models



Considerable variability in skill in representing the observed rainfall power spectrum in 20-year integrations.

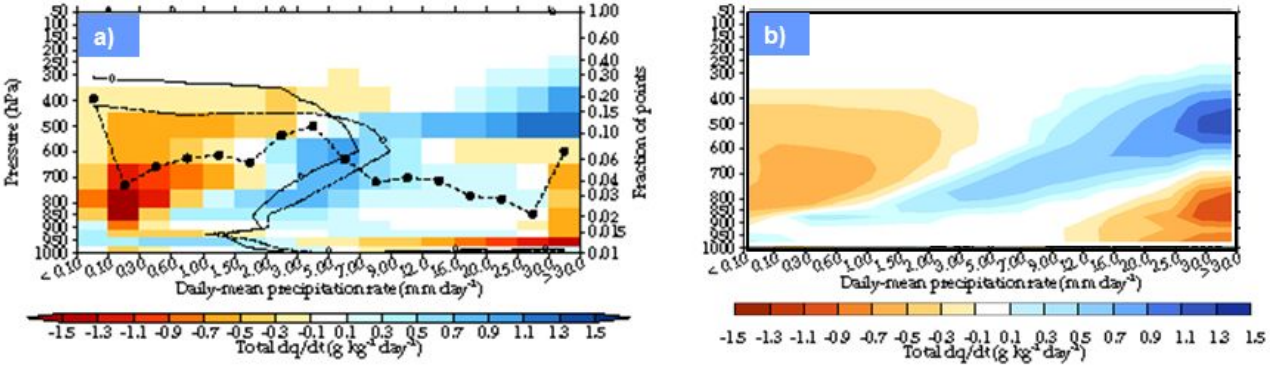
Model data - Nov – April 1991-2010

Wave number-frequency power spectra of the symmetric component of equatorial rainfall (60°E–180°) plotted as the ratio between raw rainfall power and the power in a smoothed red noise background spectrum averaged from 15°S to 15°N.

Key MJO Process-oriented Net Moistening Diagnostic From Klingaman et al. (2015)

NAVGEM 20-day hindcasts with prescribed SSTs (Klingaman et al. 2015) and early Navy ESPC tests were unable to reproduce the relationship between net moistening profiles and rainfall rate observed in a ECMWF YOTC period analysis. Model intercomparison results suggested this was a key diagnostic for MJO skill.

This deficiency was rectified in Navy ESPC tests with the MKF scheme in which a modified cloud top condition was implemented.



Vertical cross-sections of net moistening rate as it varied with preciptation rate (horizontal axis) for a region bounded by 10N -10S and 60E – 180E for **a) ECMWF YOTC period analysis** (see Klingaman et al. (2015)) and **b) MKF scheme in a Navy ESPC 20-day hindcast** from 1 Nov. 2011.