Application for Federal Assistance

ID:	3020705
Applicant Name:	George Mason University
Project Title:	Beyond the “Big-Leaf” Model at NOAA: Use of Novel Satellite Data and In-Canopy Processes to Improve U.S. Air Quality Predictions
Project Period:	08/01/2022 - 07/31/2025
Federal Funding Requested:	$685,217.00
Non-Federal Funding Requested:	$0.00
Fiscal Year of Funding Requested:	2022
Federal Application Receipt Date:	11/16/2021
Submitted for:	FY2022 Weather Program Office Research Programs
Notice of Funding Opportunity Number:	NOAA-OAR-WPO-2022-2006969
CFDA Number:	11.459

Application Documents for Review

This Application Report was produced by DoC Grants Online (https://grantsonline.rdc.noaa.gov) on 11/16/2021 02:35 PM EST

a. Title Page

Proposal title: *Beyond the "Big-Leaf" Model at NOAA: Use of Novel Satellite Data and In-Canopy Processes to Improve U.S. Air Quality Predictions*

Competition name: FY2022 NOAA-OAR-WPO Funding Opportunity. Atmospheric Composition (AC) Competition

Competition number: 2006969

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Collaborators: Dr. Barry Baker, George Mason University; Dr. Youhua Tang, George Mason University; Dr. Fanglin Yang, NOAA Environmental Modeling Center; Dr. Raffaele Montuoro, Cooperative Institute for Research in Environmental Sciences/NOAA Global Systems Laboratory; Dr. Rick Saylor, NOAA Air Resources Laboratory; Dr. Paul Makar, Environment and Climate Change Canada.

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Funding date: 08/01/2022 – 07/31/2025

Funded Institutions	**Year 01**	**Year 02**	**Year 03**	**Total**
George Mason University*	$152,529	$264,619	$268,070	$685,217

*Funding is requested for a George Mason University Post-Doctoral Research Scholar (TBD).

Beyond the "Big-Leaf" Model at NOAA: Use of Novel Satellite Data and In-Canopy Processes to Improve U.S. Air Quality Predictions

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b. Abstract

The proposal, *Beyond the "Big-Leaf" Model at NOAA: Use of Novel Satellite Data and In-Canopy Processes to Improve U.S. Air Quality Predictions*, is submitted to the FY2022 NOAA-OAR-WPO Funding Opportunity, specifically the Atmospheric Composition (AC) Competition. In this three-year project, we propose to advance the next-generation Rapid-Refresh Forecast System (RRFS)-Community Multiscale Air Quality (CMAQ) model beyond its "Big-Leaf" canopy approximation by using forest canopy processes and novel satellite data that can ultimately improve ozone predictions in the U.S. This work has implications for the RRFS-CMAQ, and other next-generation, Unified Forecast System-based Atmospheric Composition-Limited Area Model (AC-LAM) predictions at NOAA, while further providing necessary scientific advancements to improve chemical transport models in the scientific community. This project follows a three-step/year integrated process centered on improving RRFS-CMAQ:

1. Advanced development of observation- and theoretically-based forest in-canopy parameterizations that include photolysis attenuation, turbulence effects, and emissions/scalar transport (Years 1-2).
2. Incorporation and testing of novel satellite-based land surface/vegetation data from the Global Ecosystem Dynamics Investigation (GEDI), which includes updated forest canopy heights, to further advance the canopy parameterizations (Year 2).
3. Full-year simulations and evaluation using both 2D and 3D observations to demonstrate model performance changes and readiness for R2O transition (Year 3).

The development of NOAA's AC-LAMs in this project includes priorities focused on the area of model development and advances in using satellite observations of the surface/vegetation. The Readiness Level (RL) is currently at four (based on canopy parameterizations in an experimental version of the current National Air Quality Forecast Capability; NAQFC), and the expected RL at project completion is eight. The future development will continue to leverage both NOAA and GMU computer resources, and the codes are available through NOAA ARL's GitHub page. The in-canopy advancements in NOAA's AC-LAMs will improve air quality forecasts/predictions that have implications for the overarching UFS project, and will undergo a R2O transition that aligns well with the details of this funding opportunity: "*NOAA will support new air quality observing and forecasting applications, including better statistical or dynamic forecast models and techniques*".

c. Background and Problem Statement

As an alternative to single-layer canopy representations in land surface models (LSMs), multilayer canopy models can resolve vertically varying profiles and microclimates in canopies (Baldocchi and Harley, 1995; Ogée et al., 2003; Chang et al., 2018; Bonan et al., 2021). The vertical distribution of leaf area has substantial impacts on the microclimate, leaf morphology, and leaf physiology in forest canopies, which in turn drives the dynamic/kinematic (e.g., wind speed profiles), thermodynamic (e.g., daytime/nighttime air temperatures), and chemical (e.g., trace gas/scalar transport) characteristics of the sub-canopy layer (see Bonan et al., 2021 and references found within). The use of a single-layer, "big-leaf" approach in LSMs neglects such in-canopy profiles and their consequences with the belief that big-leaf approaches to the canopy can adequately reproduce the behavior of multi-layer canopies when deriving the evapotranspiration and gross primary production. While the big-leaf simplification has over time proven useful in the sense that it is computationally efficient and can provide reasonably accurate fluxes, it can only be assumed to be "correct" under certain applications, namely large scale influences of vegetation on large-scale climate (i.e., it is a "useful" approach). However, to understand how large-scale climate manifests in the local microclimate with vegetation requires the use of in-canopy parameterizations or full multi-layer canopy (MLC) models. Furthermore, **MLCs are needed to simulate the chemistry and scalar transport in forest canopies** (Boy et al., 2011; Wolfe and Thornton, 2011; Bryan et al., 2012; Saylor, 2013; Ashworth et al., 2015; Bonan et al., 2021). Overall, in-canopy capabilities can better handle the natural complexity of trace gas and aerosol fluxes between the surface, vegetation, and atmosphere that are known to be important to Earth System, biogeochemical budgets (Braghiere et al., 2019).

Multilayer canopy models have been incorporated in research versions of regional (e.g., Weather Research and Forecasting Model; Xu et al., 2017) and global (Community Land Model; Bonan et al., 2014, 2018) weather and climate models, and have generally shown that the more detailed canopy representations can increase the model accuracy in evapotranspiration. The understanding of the impact of the multilayer canopy on turbulence, chemistry, and scalar transport has been long known (Raupach 1989), and has been applied to one-dimensional canopy models that show good agreement with observations (Makar et al., 1999; Stroud et al.; 2005; Saylor, 2013; Gordon et al., 2014; Ashworth et al., 2015). Only more recently have the effects of multilayer canopy models been demonstrated in regional scale air quality forecast (AQF) models (Makar et al., 2017); however, such processes are not yet represented in the current operational or next-generation AQF models at NOAA. **It is our contention that now is the time to develop and parameterize MLCs into the development of the next-generation, regional AQF system at NOAA.** Development of in-canopy effects in next-generation models at NOAA will improve the biological, physical, and chemical consistency when coupled to other model components (e.g., atmosphere/chemistry ←→ land/canopy). The combination of improved in-canopy models with novel observations of vegetation/canopy cover from space will improve the predictions of ozone, trace gases, and particulate matter now being developed at higher horizontal (e.g., 3 km) *and* vertical (e.g., 127 layers) spatial scales at NOAA.

The latest advancements of NOAA's National Air Quality Forecast Capability (NAQFC) continues to **generate systematic ozone overpredictions in the eastern U.S. during the photochemical summer ozone season** (e.g., July-August), which are consistent with positive ozone biases for many other regional-scale chemical transport models (CTMs) used across the scientific community. This includes next-generation, Unified Forecast System (UFS)-based Atmospheric Composition-Limited Area Models (AC-LAMs) at NOAA. The UFS-based, Short-

[Range Weather (SRW) Application's](#) Rapid Refresh Forecast System (RRFS)-Community Multiscale Air Quality (CMAQ) model will become the future NWS/NOAA operational National Air Quality Forecast Capability (NAQFC) for the U.S. The large summertime ozone bias plaguing both the operational NAQFC and next-generation RRFS-CMAQ (Figure 1 below) indicates missing key model processes.

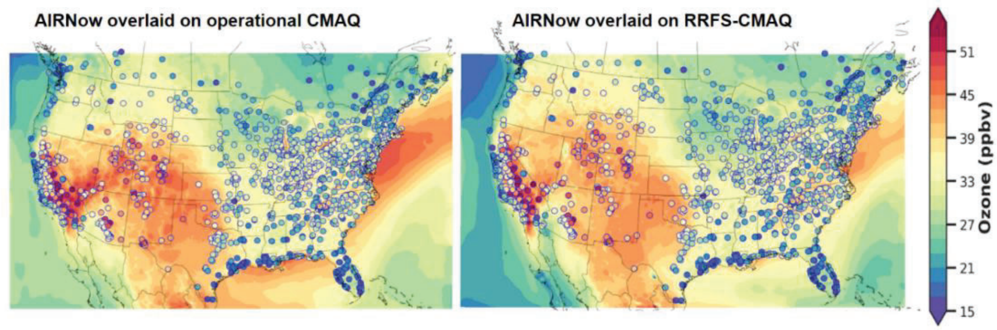

Figure 1. Average August 2019 hourly ozone (ppb) AirNow observations (circles) overlaid on the prior operational NAQFC (left panel) (used before July 20, 2021) and a recent experimental version of RRFS-CMAQ (right panel). Note the widespread overpredictions in ozone for both the NAQFC and RRFS-CMAQ in the Eastern regions of the U.S.

This overprediction issue has been observed across multiple regional /air-quality modelling systems, and is linked to distinct vertical gradients of ozone measured within dense forest canopies of the U.S. (Makar et al. 2017). NOAA and other agencies tasked with air quality forecasting cannot capture such details, as they continue to rely on the incorrect big-leaf model to represent the canopy interactions with chemistry and scalar transport (Makar et al., 2017; Bonan et al. 2021). It has been shown that simulated tropospheric ozone is significantly reduced through the combined effects of forest canopy shading (about a ⅓ effect) and modified turbulence (about a ⅔ effect), where **inclusion of these in-canopy processes largely corrects the long-standing positive bias in forecasts of near surface ozone in the eastern U.S.** (Figure 2 on the left; from Makar et al., 2017).

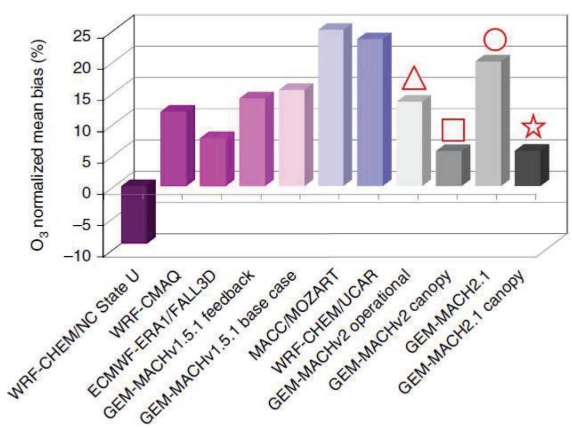

Figure 2. Normalized mean biases in ozone for North America for previous multiple model comparisons (Solazzo et al., 2012) for July 2010 (p.p.b.v.) against the [GEM-MACH](#) canopy simulations in Makar et al. (2017) (shown as light grey/dark grey column pairs overlaid with red symbols; triangle and square: GEM-MACHv2; circle and star: GEMMACHv2.1.).

Simple parameterizations of such in-canopy effects of reduced photolysis and modified turbulence have also been tested by PI Campbell in an experimental version of the current advanced NAQFC (based on an offline-coupled Global Forecast System Version 16-CMAQv5.3.1 model at 12-km horizontal resolution; Campbell et al., 2021). Comparison of the preliminary results against the [U.S. EPA AirNow](#) monitoring network shows that there is about a 50% reduction in the average summer (e.g., August 2019) positive mean biases (MB) of near-surface ozone forecasts, and an improved agreement for the diurnal ozone pattern in an example Mid-Atlantic region of the U.S. (Figure 3 below).

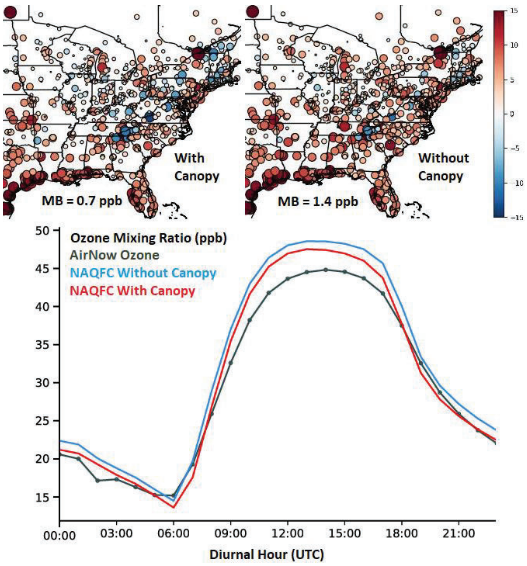

Figure 3. (Top) Spatial mean bias plots of averaged August 2019 ozone for an experimental NAQFC model against the AirNow network with (left) and without canopy effects (right). The average MB values shown in the panels represent the entire CONUS average. (Bottom) Average August 2019 diurnal ozone mixing ratios for AirNow (grey line w/symbols), without canopy (blue), and with canopy (red) averaged over only the U.S. EPA Mid-Atlantic (R3) region.

These initial tests showed "proof-of-concept" and that even simple parameterizations incorporating these effects in CMAQ can improve the NAQFC forecast results. However, a more detailed and focused effort is needed, to improve the representation of in-canopy processes and parameterizations/algorithms, improve the representation of the canopy itself, and to comprehensively test and evaluate the impacts of in-canopy effects to improve the air quality predictions in the next-generation RRFS-CMAQ system at convection-allowing scales (3 km grid scale resolution).

d. Objectives and Project Outputs/Products

The primary objectives from this work include a three-step integrated process focused on 1) development and implementation of algorithms to parameterize the in-canopy effects and tests of more explicitly defined MLC models, 2) improved canopy representation using satellite observations, and 3) comprehensive tests and evaluations of in-canopy effects on predictions of ozone, trace gas, and particulate matter in the RRFS-CMAQ. The major products from Year's 1 and 2 (first half) tasks include the in-canopy model parametrizations and algorithms that are computationally efficient and can approximate the behavior of MLC models (e.g., photolysis attenuation and turbulent transport of scalars). This includes more explicitly defined MLC model implementations to compare their ability to be used under a computationally constrained, operational AQF environment (e.g., Makar et al., 2017). This is particularly important during the development of a high-resolution, computationally expensive RRFS-CMAQ system. These algorithm products are predominantly in FORTRAN and can be readily implemented into the air quality model (AQM) and other RRFS-CMAQ physics components via the Common Community Physics Package (CCPP) framework (see Section f1 for more details). At least one scientific publication and technical presentation will be produced from the model development and application of in-canopy parameterizations and tests of MLC models in RRFS-CMAQ. The CMAQ model is widely used in the operational, regulatory, and scientific research communities worldwide; however, the latest CMAQv5.3.3 has yet to include such in-canopy effects and still relies on the big-leaf approximation.

The performance of the in-canopy parameterizations on chemistry and scalar transport in regional scale AQF models relies heavily on an accurate representation of both the 2D and 3D characteristics (e.g., forest canopy height and vertical leaf area density) of major forest canopies across the model domain, in this case across the RRFS-CMAQ domain covering the contiguous U.S. (CONUS). The release of the Global Ecosystem Dynamics Investigation (GEDI) provides novel high-resolution Light Detection and Ranging (LIDAR) observations of Earth's forests from the International Space Station (ISS) (Potapov et al., 2020). GEDI provides detailed information on the current spatial and vertical characteristics of the forest canopy and has spatial coverage across the experimental RRFS-CMAQ CONUS domain (Figure 1). Thus, the major outputs of Year 2 will include development of RRFS-CMAQ model-ready products from GEDI (e.g., Gridded Level 3 Land Surface Metrics; Dubayah et al., 2021) to improve the representation of the canopy used with the in-canopy parameterizations/algorithms developed during Year 1 tasks (see Section f2 for more details). This has many "co-benefits", such as improving the data used for biogenic emissions and deposition, both of which are vegetation/canopy dependent. At least one publication and technical presentation will be produced on the novel use of high-resolution satellite observations of the forest horizontal and vertical distribution to improve in-canopy chemistry and scalar transport in an operational AQF model framework for the U.S.

The impacts of in-canopy effects on chemistry and scalar transport in RRFS-CMAQ has an inherent seasonal dependence (e.g., higher leaf area index, LAI, during summer; lower LAI during winter), and thus it is paramount that these impacts are tested during the different seasons in the U.S. The products from Task 3/Year 3 are comprehensive RRFS-CMAQ simulation test outputs and evaluations during all seasons for three general simulation cases (see Section f3 for more details). The main RRFS-CMAQ simulation/evaluation design includes a 1) base simulation with no in-canopy effects, 2) a sensitivity simulation with in-canopy parameterizations (and explicit MLC model tests) and climatological forest canopy inputs (e.g., LAI/canopy height), and 3) a second sensitivity run with in-canopy effects + improved GEDI canopy representation and inputs. Both sensitivity cases can be compared to the base case to determine the impacts of in-canopy effects and improved canopy representation on the RRFS-CMAQ ozone, trace gas, and PM predictions. We note that such vegetation/canopy inputs are used in several places in the RRFS-CMAQ codes. Thus, we plan to also break the third set of sensitivity simulations into sub-tests on the impacts on biogenic emissions, deposition, and then canopy processes, to distinguish contributions of each in changing the chemical predictions.

The Readiness Level (RL) is currently at level four. This is based on successful developments, implementation, and demonstrative (i.e., proof-of-concept) tests of in-canopy effects in an experimental version of the current NAQFC operational environment (see Figure 3 and Section f1 below). The NAQFC system is also based on an offline version of the CMAQ code, and thus, these prototype in-canopy parameterizations can be readily transferred for initial implementation and testing in RRFS-CMAQ.

The expected RL at project completion is eight. This estimate is based on the successful transfer of in-canopy parametrizations from the NAQFC operational environment to similar (but more robust) developmental tasks and tests within the integrated RRFS-CMAQ framework, as well as with improved GEDI canopy data. The subsystem in-canopy components will be delivered in FORTRAN, have a pathway to be fully integrated and documented in the RRFS-CMAQ, and will function in an operational environment at NOAA. We note that the PI Campbell has experience in lead research and development of the advanced version of the operational NAQFC at NOAA, which resulted in a significant science advancements and improvements in AQF model performance compared to the previous operational NAQFC.

e. Benefits of the Project and Outcomes/Impact

Addition of in-canopy effects and improved canopy representation will leverage the UFS-based coupling strategy between the meteorological, land, and chemistry model components in a more physically consistent fashion within the RRFS-CMAQ framework. In this way, for example, the land surface model component can be directly coupled (e.g., LAI) with the in-canopy parameterizations in the integrated physics and chemistry model components in RRFS-CMAQ. The addition of GEDI canopy information (e.g., canopy height) is also particularly important for operational NOAA AQF models. This is because of 1) relatively high complexity and spatial resolutions needed to accurately represent land cover and vegetative characteristics, 2) inclusion of comprehensive atmospheric chemistry and aerosol formation components in RRFS-CMAQ, and 3) interactions of 1 and 2 via atmosphere-biosphere exchange, chemistry, and scalar transport that are critical to chemical and aerosol predictions.

NOAA's NAQFC improves the lives of Americans and saves billions of dollars a year. The inclusion of in-canopy effects will improve the accuracy of the next-generation operational AQF system at NWS/NOAA, and will have immediate impacts on society and human heath across the entire U.S. The major end-users of the advanced RRFS-CMAQ are state and local stakeholder offices that disseminate the advancing NWS/NOAA AQF products to the public. These improved AQF predictions affect other endpoints such as ecosystem health, which is significantly impacted by changes to the atmospheric deposition and critical loads to sensitive land/watershed regions.

The sub-grid, in-canopy parametrizations (and more explicit MLC models) developed in this proposal will more consistently couple atmosphere-biosphere exchange processes to improve NOAA AQF accuracy and advance UFS models within NOAA's FV3 dynamical core. The advancements gained in this project will also allow for more flexibility in the inclusion of different land use/vegetation data sets and treatments of in-canopy chemistry and transport for trace gases and aerosols. The milestones achieved in this proposal will further allow for robust development of in-line coupling across horizontal *and* vertical scales that may also lead to improvement between other weather prediction model components (e.g., atmosphere, ocean, land surface) within the R2O initiative's five-year plan to upgrade and unify AC-LAMs at NOAA. The development of in-canopy effects in RRFS-CMAQ further opens the door to a myriad of new scientific collaborations and advancements that span across the atmosphere, chemistry, and land model components in the UFS framework.

The understanding of the in-canopy effects on the regional-scale in RRFS-CMAQ will have further implications for the widespread forests globally and the in-canopy processes that affect near-surface atmospheric chemistry and scalar transport. Furthermore, the sub-grid in-canopy parameterizations, explicit MLC models, and improved canopy/vegetation representation (e.g., vertical leaf area and biomass density) outputs/products described above have further implications for evapotranspiration modeling, wildfire modeling and smoke emissions, and related air quality forecasting. For example, in-canopy processes can trap the smoldering phase fire emissions closer to the surface, which affects the vertical distribution and transport of smoke. These aspects are strongly relevant to NOAA's mission in generating UFS-based, next-generation global AC models of higher skill and accuracy. Furthermore, integration between in-canopy parametrizations and GEDI in this project will have far-reaching implications for climate change and land use interactions, which fundamentally alter Earth's tropical and temperate forests and have feedback effects on AC and weather-related processes.

f. Methods and Activities

1. Development of in-canopy parameterizations and MLC models in RRFS-CMAQ

Year 1 and 2 (in part) of this project consists of continued development and implementation of sub-grid, in-canopy parameterizations and tests of more explicitly defined MLC models in RRFS-CMAQ completed by PI Campbell. The efforts put forth by PI Campbell will benefit greatly from collaborations with Dr. Raffaele Montuoro (lead RRFS-CMAQ developer), Dr. Fanglin Yang (Chief, EMC-Model Physics) and Drs. Paul Makar and Rick Saylor (in-canopy research and development; e.g., Saylor, 2013; Makar et al., 2017). Here we will start with the in-canopy parameterizations implemented and tested by PI Campbell in the current advanced version of the NAQFC based on CMAQv5.3.1 (Figure 3), and apply these methods to the coupled AQM and physics components in RRFS-CMAQ. The parameterizations are based on simplified formulations for the attenuation of light and modified vertical turbulence/diffusivity due to a contiguous forest canopy from Makar et al. (2017).

The first step in parameterization of in-canopy effects is to determine whether a model grid cell is defined as having a contiguous canopy with sufficient foliage to warrant defining a canopy column and correction. As a start in this proposal, a grid cell does *not* have a forest canopy if, for that grid cell (Makar et al., 2017):

- The LAI is relatively small (i.e., less likely to have canopy shading or turbulence changes).
- The forest canopy height (FCH) is so small in vertical extent that it will be a small fraction of the resolved meteorological model's lowest layer depth.
- The population (POP) is high enough to indicate the grid cell represents a large city.
- The forest fraction (FRT) suggests that a contiguous forest canopy is unlikely (e.g., only half of the land use in the grid cell is forested).
- Too much of the incident light (solar zenith angle; θ) makes it to the ground and the canopy is relatively short (i.e., minimal shading and turbulence changes).

The conditional parameters (i.e., LAI, FCH, POP, and FRT) and an additional one known as the "forest clumping index" (CLU) can be derived from combination of satellite observations (e.g., Visible Infrared Imaging Radiometer Suite) and bottom-up forest/land use databases (e.g., Biogenic Emissions Landuse Database). These are used to define the grid cells that include a contiguous forest canopy (Figures 4a-e), and may be further expanded upon in this project.

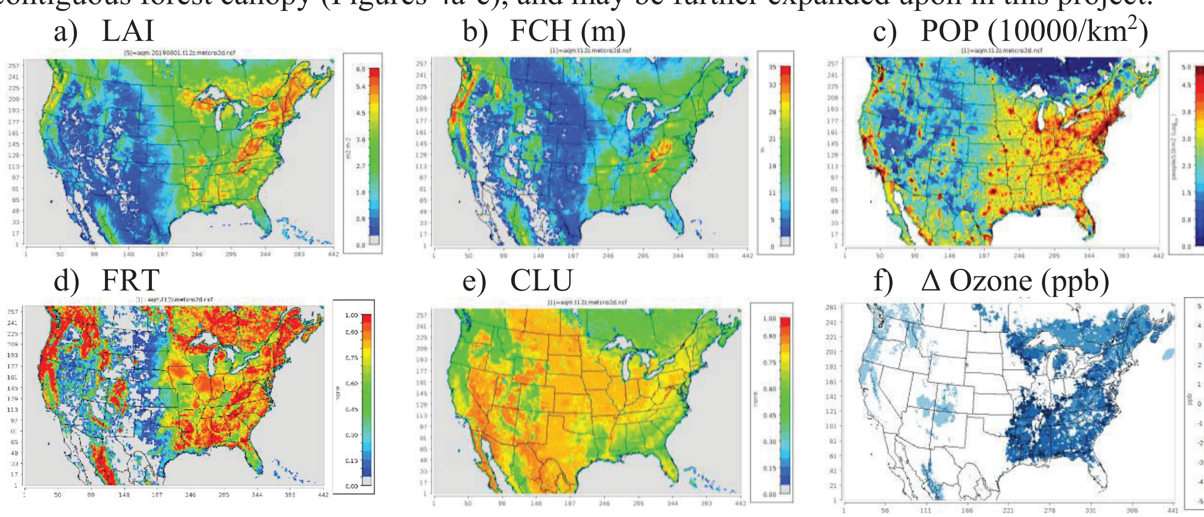

Figure 4. Spatial distribution plots for average August 2019 LAI, FCH, POP, FRT, CLU, and the combined photolysis attenuation and modified turbulence/diffusivity on near-surface ozone concentrations (Δ Ozone (ppb) = with canopy effects – no canopy effects) in an experimental version of the NAQFC/CMAQv5.3.1 (blue shading = decreases).

Using representative canopy conditions, the impact of attenuation of light due to a contiguous forest canopy can be parameterized in the RRFS-CMAQ in the following way:

$$P(\theta,z) = \frac{\int_{z_{j-\frac{1}{2}}}^{z_{j+\frac{1}{2}}} \exp(-\frac{G(\theta)CLU(\theta)LAI(z)}{\cos(\theta)})dz}{z_{j+\frac{1}{2}} - z_{j-\frac{1}{2}}}, \quad (1)$$

where $P(\theta, z)$ is the probability of beam penetration (i.e., fractional light penetration; Nilson, 1971; Monsi and Saeki, 1953), and depends on the LAI, leaf projection (G; for spherical assumption = 0.5), CLU, and solar zenith angle (θ). For the NAQFC application by PI Campbell, the LAI, FCH, and FRT are derived offline using satellite and ground observations. However, these parameters (if available) can be directly coupled (i.e., imported using the "AQM-NUOPC Cap") from the UFS-SRW LSM component (e.g., using the GFS or future RRFS physics packages) and passed to the RRFS-CMAQ photolysis schemes. For consistency, the impacts of the offline calculations of these parameters will be tested against using available RRFS-CMAQ inputs directly from the LSM component (e.g., GSD-RUC, Noah, and/or Noah-MP). We note that to parameterize the integral effect of $P(\theta, z)$, we multiply the total LAI in the grid cell by a set of gridded cumulative LAI fractions between the height of the canopy (FCH) and different heights within the canopy, thus deriving the $P(\theta, z)$, height-dependent photolysis attenuation factor. Linear interpolation between these attenuation values thus gives the attenuation profile below the canopy height, FCH. We note that everything above the FCH will have a correction factor value of unity, where we have tested this parameterization for a sub-grid, in-canopy vertical resolution of Δz = 0.5 m. The integrated correction factor is then used to modify the bulk photolysis rates used in the chemistry gas solver, which in part affects the subsequent predictions of ozone (Figure 4f), trace gas, and particulate matter concentrations.

In the NAQFC and RRFS-CMAQ, the near-surface scalar transport in the vertical is based Monin-Obukhov (M-O) similarity theory and calculation of the eddy diffusivity coefficient (K_z). Neglecting the presence of in-canopy effects, this calculation is based on the resolved meteorology in the first model layer; however, the fluxes and profiles in and above rough plant canopies deviate from M-O similarity theory due to presence of roughness sublayer, where scalar transport is dominated by localized turbulence rather than large-scale advection (i.e., M-O cannot be used). Following the Makar et al. (2017) application of the Raupach (1989) near-field theory, we have also adapted a methodology for parameterizing in-canopy effects on turbulence/diffusivity in RRFS-CMAQ using in general the following two equations:

$$K_{can}(z) = \frac{\int_{z_{j-\frac{1}{2}}}^{z_{j+\frac{1}{2}}} \frac{K_{mod}(z_1)}{K_{est}(\frac{z_1}{FCH})} K_{est}(\frac{z}{FCH})dz}{z_{j+\frac{1}{2}} - z_{j-\frac{1}{2}}} \;, \text{ and} \quad (2)$$

$$K_{est}\left(\frac{z}{FCH}\right) = \sigma_w^2(\frac{z}{FCH})T_L(\frac{z}{FCH}) \;, \quad (3)$$

where z is the height above the Earth's surface, z_1 is the height of the lowest model layer before in-canopy parameterization, σ_w^2 the variance in Eulerian vertical velocity, T_L the Lagrangian turbulence timescale, and $K_{mod}(z_1)$ the model resolved vertical diffusivity coefficient in the bottommost layer. We note that σ_w^2 and T_L are dependent on the resolved friction velocity and atmospheric stability conditions from the driving meteorological model (see Eqs. 4-9 in Makar et al., 2017), and that the effective in-canopy diffusivity, $K_{can}(z)$, is normalized to allow a smooth transition to K values for the resolved first model layer, $K_{est}\left(\frac{z_1}{FCH}\right)$. The calculated values of $K_{can}(z)$ are integrated downward through the sub-grid canopy at Δz = 0.5 m, and the result can reduce the vertical transport of species that build up and titrate ozone formation (e.g., nitrogen dioxide; NO_2). The modification to the eddy diffusivity term, K, will be handled interchangeably for model 'canopy columns' in the coupled RRFS-CMAQ chemistry-physics codes that handle the tracer transport (e.g., the local turbulent eddy-diffusivity mixing schemes; Han and Bretherton, 2019) following the CCPP framework. This modified vertical diffusivity can in part further reduce predicted ozone concentrations (Figure 4f). We note that the in-canopy photolysis attenuation and turbulence/scalar transport parametrizations add negligible computation time to the CMAQ routines in NAQFC and will have minute computational impacts on RRFS-CMAQ.

The test results shown in Figures 3 and 4 are hindered by a relatively coarse first model layer (~40m) in the offline NAQFC system, which is always larger (in some cases significantly) compared to FCHs (Figure 4b) across the U.S. This skews the in-canopy effects when scaled to the first meteorological model layer above the canopy ($K_{est}\left(\frac{z_1}{FCH}\right)$). RRFS-CMAQ has a shallower first model layer (~20 m) that is based on the native RRFS meteorological model configuration. This will result in a larger impact of the $K_{can}(z)$ values on scalar transport when scaled to the resolved driving meteorological model, and will further improve the ozone predictions (i.e., 'with canopy' diurnal ozone pattern closer to observations in Figure 3).

As time and resources allow, we will compare results from the computationally efficient, sub-grid, in-canopy parametrizations described above with MLC model developments in RRFS-CMAQ. Rather than integrating downward through a virtualized (i.e., sub-grid) canopy, this will involve explicitly adding multiple canopy layers inside the RRFS-CMAQ model framework, and requires further steps to be taken to account for spatially discontinuous in-canopy model layers (after canopy vs. no-canopy grid cells are identified) in the horizontal dimension. This can be accounted for by redistributing the mass from the advected model layers back to the canopy layers each subsequent model time step (Makar et al., 2017). One approach is to temporarily add the MLC levels at the start and end of each model time step through the RRFS-CMAQ chemistry and physics codes, which allows the processes to operate at even a higher vertical resolution using a MPI "gather-scatter" approach for canopy versus no-canopy columns.

After the successful addition of vertical layers in RRFS-CMAQ, we will test the impact of these (and possible other 1D canopy model theories, e.g., Makar et al., 1999; Stroud et al.; 2005; Saylor, 2013; Gordon et al., 2014; Ashworth et al., 2015) MLC forms of Eqs. (1)-(3) (i.e., no integration approximations) to the in-canopy parameterization methodology described above for their effects on modifying predicted ozone, trace gas, and particulate matter concentrations. We will also test the additional computational expense of MLC formulations in RRFS-CMAQ, and determine if 1) the impacts of MLC on RRFS-CMAQ have improved model performance compared to the sub-grid in-canopy parameterizations, and 2) if so, how can the MLC formulations be optimized (e.g., reduced number of in-canopy layers) to improve computational performance in RRFS-CMAQ? Estimating the increase in processing time due to additional canopy layers (e.g., 3 additional layers) can be done by simply taking the fraction of the domain that contains canopy columns and multiplying its CPU time by (NZ +3)/NZ, where NZ is the original number of model layers. If the model performance results are similar between the two methods, the simpler sub-grid in-canopy parametrizations will be suggested for RRFS-CMAQ implementation, as there are negligible computational costs in using this method.

Any additional time will allow for further research by PI Campbell on the implications of adding in-canopy and MLC parameterizations for other important RRFS-CMAQ processes that are affected by the presence of contiguous forest canopies (e.g., in-canopy biochemical dry deposition/flux processes; Meyers et al., 1998; Wu et al., 2003). It is envisioned that the development of in-canopy models in this proposal will further lead to an advanced coupled *and* stand-alone (i.e., offline diagnostic tool), ESMF-compliant column model used for gridded chemistry and physics model processes (i.e., with its own NUOPC "cap"). This process-based, in-canopy column model can be both coupled within NUOPC/CCPP-based models and align with other similar, but separate "urban-canopy" model development efforts. Such topics may form future research projects for novel, next generation AC-LAM developments at NOAA.

2. *Improving the canopy representation in RRFS-CMAQ using novel satellite observations*

Vegetation and surface/soil characteristics that are more realistic have shown to improve modeled meteorology, chemistry, and surface-atmosphere exchange processes in regional, coupled meteorological-chemical models (e.g., Ran et al., 2016; Campbell et al., 2019).

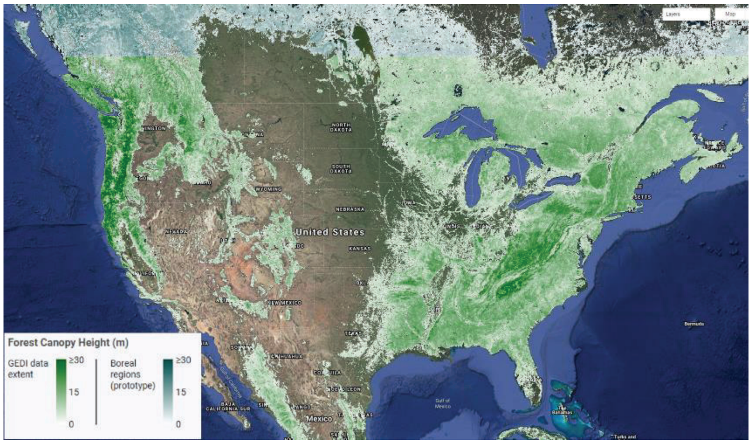

Figure 5. GEDI 30-m spatial resolution global forest canopy heights. Image was derived from the Google Earth Engine App, and is based on the GLAD-UMD-GEDI data download website.

Thus, the majority of the latter half of Year 2 tasks by PI Campbell and a TBD post-doc (in collaboration with Dr. Barry Baker) in this project will further advance the developments in Task 1 (Section f1) by improving the canopy representation using novel GEDI Gridded Level 3 Land Surface Metrics across the RRFS-CMAQ domain. The GEDI datasets include high spatial resolution (30-m) canopy heights spanning across the U.S. (Figure 5 above).

The GEDI datasets will be used to compare against VIIRS/BELD derived FCH (Figure 4b) and for the in-canopy parameterizations and MLC models implemented in Year 1 and 2 (in part) tasks. The in-canopy parameterizations and MLC models are highly sensitive to FCH, and thus the most accurate, high-resolution data sets are pivotal to the spatially high-resolution (3x3 km) RRFS-CMAQ system. The gridded (1x1 km) GEDI L3 data, however, are in 8-bit unsigned LZW-compressed GeoTiff format and have inherent data gaps (see the GEDI Spatial Data Access Tool). The GEDI output is also extrapolated in the boreal regions (beyond the GEDI data range, 52°N to 52°S) to create the global forest height prototype map (Figure 5; Potapov et al., 2020). Due to the challenges in processing/gap filling the GEDI L3 data for RRFS-CMAQ model ready inputs to the in-canopy parameterizations, further work is necessary to develop methods for integrating and testing the updated GEDI L3 canopy datasets into the near-real time AQF framework in RRFS-CMAQ. This may include efforts to coordinate with the (already closely collaborating) RRFS-CMAQ data assimilation team (e.g., Dr. Youhua Tang), thus leveraging the Joint Effort for Data Assimilation (JEDI) capabilities that have the ability to assimilate meteorological, land, and chemical observations. Under the guidance of PI Campbell, a post-doctoral researcher who has experience in some, if not all the following areas, will largely complete the tasks of assimilating GEDI data for RRFS-CMAQ: atmosphere-biosphere interactions, satellite data processing/assimilation, and atmospheric-chemical modeling. We note that if GEDI products do not become part of the NOAA operational stream for use in the RRFS-CMAQ in-canopy models, results from these tasks will inherently lead to development of a climatological, model-ready/gridded dataset that can be ingested externally into the model system.

3. Comprehensive assessment and R2O plan for in-canopy effects in RRFS-CMAQ

Year 3 tasks includes comprehensive assessments of the RRFS-CMAQ model performance changes due to in-canopy effects (against no canopy effects) during all calendar seasons. The all-season testing and evaluation of RRFS-CMAQ is paramount as canopy effects exhibit a strong seasonality that is driven (in part) by LAI (Figure 4a) changes. This will include tasks done by the funded post-doctoral researcher (TBD) under the supervision of the PI Campbell. The PI Campbell has extensive experience in meteorological-chemical modeling, simulations, and evaluation to perform this collaboration and supervision.

Both the PI Campbell and funded post-doc will collaborate to perform comprehensive meteorological and chemical evaluations using the suite of observation networks and measurements available across the U.S. Specifically, we will evaluate the RRFS-CMAQ output against 2D surface chemical networks (e.g., U.S. EPA Air Quality System and near-real-time AirNow observations), high resolution Tropospheric Monitoring Instrument (TROPOMI) satellite observations, and 3D column/profile/aircraft measurements (e.g., NOAA/NASA FIREX-AQ, NASA Pandora Project). The high resolution NOAA/NCEP Meteorological Assimilation Data Ingest System (MADIS) surface observation network will be used to perform the surface, RRFS meteorological evaluation, while other networks such as NOAA/ESRL/GSL Radiosonde database, provide observations to evaluate the modeled atmospheric profile. Statistical measures typically used to evaluate coupled meteorological-chemical/air quality models include the normalized mean bias (NMB), normalized mean error (NME), Root Mean Square Error (RSME), Pearson's correlation coefficient, R, and Index of Agreement (IOA). We will extend this evaluation of the in-canopy effects to more AQF-relevant statistical calculations, which include the Critical Success Index (CSI), Equitable Threat Score (ETS), and the Heidke Skill Score (HSS) for ozone and fine particulate matter ($PM_{2.5}$) predictions that are important for human health and exposure. A model spatial and statistical (NME vs. NMB) comparison of the tropospheric column $HCHO/NO_2$ ratio (Martin et al., 2004), which is a typical photochemical indicator species for ozone formation, will also be assessed using both satellite and the Pandora column measurements.

While other studies have shown the significant impacts of in-canopy effects on ozone concentrations, they have not yet evaluated the detailed effects on ozone formation regimes in AQF-CTMs. These robust observational datasets and RRFS-CMAQ model outputs may be further extended to evaluation of the ozone production efficiency (OPE) near urban centers downstream from major forest canopies, which can demonstrate the impact of in-canopy effects on ozone production and its sensitivity due to precursor NO_x and VOC changes (Mazzuca et al., 2016). The in-canopy effects on chemistry can extend both vertically throughout the atmospheric boundary layer, and horizontally downstream from major forests (Makar et al., 2017). These simulations and evaluations will be completed for the following general simulation design: 1) RRFS-CMAQ with no canopy effects, 2) RRFS-CMAQ with canopy effects (both sub-grid and MLC formulations), and 3) RRFS-CMAQ with canopy effects (both sub-grid and MLC formulations) + GEDI L3 canopy observations. Such a comprehensive evaluation of RRFS-CMAQ will ensure a full understanding of the in-canopy impacts on ozone, trace gases, and PM changes, such that the developments lead to the "right answers for the right reasons".

The resulting model performance statistics for meteorology, trace gases, and particulate matter will be compared against benchmarks found in numerous works (e.g., Emery et al., 2001; Kemball-Cook 2005; Zhang et al., 2006; McNally 2009; Emery et al., 2017; Campbell et al., 2018). The publicly available U.S. EPA Atmospheric Model Evaluation Tool (AMET) and the NOAA/ARL Model and Observation Evaluation Toolkit (MONET) developed by collaborator Dr. Barry Baker

(Baker et al., 2017) will be used to perform much of the RRFS-CMAQ chemical and meteorological analyses. We note that MONET is currently being used to evaluate RRFS-CMAQ.

Following the comprehensive evaluation during Year 3, a R2O transition plan of the in-canopy effects in RRFS-CMAQ for NWS will be formulated and leverage the existing NWS frameworks, infrastructure, and operations. The PI Campbell has experience in R2O transition during his recent lead development of NOAA's advanced NAQFC that is currently operational.

g. Timelines, Milestones, and RL Progression

Table 1 shows the proposal's relevant key activities/milestones, products, and RL progression (at each year's completion) for this project. The project will start at a RL of four, where in-canopy parameterizations have already been developed, demonstrated, and evaluated by PI Campbell as a "proof-of-concept" in an experimental version of the advanced NAQFC. This application was performed in an operational NWS/NOAA environment, and is similarly based on CMAQ. Thus, the code development is readily transferable to the RRFS-CMAQ system. By the end of Year 1, the RL will reach five, and RRFS-CMAQ in-canopy parameterizations will be developed, implemented, and stored on NOAA-ARL GitHub repositories. By the end of Year 2, the RL will reach seven, as the in-canopy parametrizations and improved canopy representation will be implemented, tested, and published. At the end of Year 3, the RL will reach eight, and a finalized and comprehensively evaluated in-canopy system in RRFS-CMAQ will be demonstrated, documented, and published.

Table 1. Relevant key activities/milestones, products, and RL progression (at year's end).

Year	Activities	Products	RL
Year 1	Development and implementation of sub-grid, in-canopy parametrizations in RRFS-CMAQ	RRFS-CMAQ in-canopy parameterizations, code repositories	5
Year 2 (1st half)	Preliminary tests and evaluations of in-canopy parametrizations, and further MLC model development and comparisons in RRFS-CMAQ	RRFS-CMAQ in-canopy and MLC models/stand-alone components/data, codes, data, and paper(s)	6
Year 2 (2nd half)	Improving canopy representation with GEDI Gridded Level 3 Land Surface Metrics and more robust test comparisons and evaluations for in-canopy effects in RRFS-CMAQ	RRFS-CMAQ model-ready GEDI L3 datasets, and data and paper(s)	7
Year 3	Comprehensive, all-season simulations and evaluation of in-canopy effects in RRFS-CMAQ, and R2O demonstration of in-canopy RRFS-CMAQ model system for NWS operations	RRFS-CMAQ in-canopy model outputs, evaluations, and full documentation	8

h. Additional Information

i. High-Performance Computing Request and Additional Resources

Development and testing of RRFS-CMAQ in this project will continue to leverage available NOAA resources (e.g., WCOSS/WCOSS2, Hera, Orion); however, additional computational resources (over 2,000 cores and 500 TBs of data) have already been granted to PI Campbell and a TBD post-doc on high performance computing clusters such as the George Mason University's "Hopper" cluster. The comprehensive all-season evaluation of the in-canopy RRFS-CMAQ system during Year 3 will likely require at least ~ 50,000 core hours and ~ 50-100 TB of data in an NOAA/NCEP operational environment. Additional funding to cover additional CPUs and data storage costs are included in this proposal's budget.

ii. NOAA Federal Collaborator Acknowledgement Forms and Support Letters

FY22 WEATHER PROGRAM OFFICE NOTICE OF FUNDING OPPORTUNITY

STANDARD FORM FOR ACKNOWLEDGEMENT OF FEDERAL COLLABORATION

DATE: 11/4/21

MEMORANDUM FOR: NOAA/OAR Weather Program Office Competition Manager

FROM: Rick D. Saylor

SUBJECT: Federal Collaboration on WPO Proposal

Rick D. Saylor acknowledges federal collaboration with the Principal Investigator(s) listed below on the development of proposal listed below. The applicants have sufficiently coordinated the development of this proposal, including any relevant infrastructure costs and/or plans for proposed testbed activities.

Principal Investigator(s): Patrick Campbell

Proposal Title: Beyond the "Big-Leaf" Model at NOAA: Use of Novel Satellite Data and In-canopy Processes to Improve U. S. Air Quality Predictions

Our role in this collaborative project will include (check all that apply):

X Providing (unfunded) research and development support

X Providing equipment, office space, or computer access to non-federal PIs

___ Providing operational guidance to support the eventual transition of this project

___ Coordinating NOAA Testbed activities for this project

___ Other: ____

Any additional information, comments, or concerns about federal collaboration on this proposal are listed below.

RDSaylor

Signature
(Name, Title, Organization)

Rick D. Saylor
Physical Scientist
NOAA Air Resources Laboratory

FY21 WEATHER PROGRAM OFFICE NOTICE OF FUNDING OPPORTUNITY

STANDARD FORM FOR ACKNOWLEDGEMENT OF NOAA COLLABORATION

DATE: 12/28/2021

MEMORANDUM FOR: NOAA/OAR Weather Program Office Competition Manager

FROM: Fanglin Yang

SUBJECT: NOAA Collaboration on WPO Proposal

__NOAA/NWS/NCEP/EMC__ acknowledges NOAA collaboration with Principal Investigator(s) _Patrick C. Campbell__ on the development of proposal titled __Beyond the "Big-Leaf" Model at NOAA: Use of Novel Satellite Data and In-Canopy Processes to Improve U.S. Air Quality Predictions___. The applicants have sufficiently coordinated the development of this proposal, including any relevant infrastructure costs and/or plans for proposed Testbed activities.

Our role in this collaborative project will include (check all that apply):

__X Providing (unfunded) research and development support

___ Providing equipment, office space, or computer access to non-federal PIs

__x Providing operational guidance to support the eventual transition of this project

___ Coordinating NOAA Testbed activities for this project

___ Other: ____

Any major comments or concerns are listed below.

The model development tasks of adding in-canopy parameterizations to RRFS-CMAQ will likely require modifications to the FV3 model physics component(s) in some way. Considering this aspect of the proposal, I support these developments as the POC in the NOAA/NWS/NCEP-EMC Model Physics Group

YANG.FANGLIN.1393204105 Digitally signed by YANG.FANGLIN.1393204105 Date: 2021.10.28 10:54:46 -04'00'

Fanglin Yang, Ph.D.
Chief, Model Physics Group
Modeling and Data Assimilation Branch
NOAA/NWS/NCEP Environmental Modeling Center

Air Quality Research Division
4905 Dufferin Street
Toronto, Ontario
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November 5, 2021

Re: Letter of Support for Patrick Campbell, FY2022 NOAA-OAR-WPO Funding Opportunity, Atmospheric Composition (AC) Competition 2006969

To Whom It May Concern:

I am writing in support of Dr. Patrick Campbell's entry to competition number 2006969, *Beyond the "Big-Leaf" Model at NOAA: Use of Novel Satellite Data and In-Canopy Processes to Improve U.S. Air Quality Prediction*. I have been working with Patrick and NOAA collaborator Dr. Rick Saylor on the "proof of concept" stage of this work, and will be delighted to continue in an advisory capacity, as well as in sharing model code developed at ECCC with NOAA, to help start off the main phase of this project.

In the proof-of-concept stage, Patrick has tested some of the key features of the ECCC forest canopy parameterization published in *Nature Communications* in 2017– in his work, he has shown that NOAA's CMAQ O_3 forecast bias in the eastern USA may be greatly improved (halved) using simple parameterizations based on, and confirming, that earlier work. Patrick's proposed project will refine and thoroughly evaluate further developments of the NOAA canopy turbulence and shading parameterization. He will also create improved satellite-based model inputs, for NOAA's air-quality forecast platform.

The model code and input fields resulting from Patrick's proposal will represent a significant advancement NOAA's air-quality forecasting capabilities. Most air-quality models to date treat forests as a single Big Leaf, not taking into account the vertical extent of the canopy, and the lower levels of turbulence and light present there. Together, these two factors change the chemical environment, reducing ozone production below the foliage. Patrick's initial work has already confirmed that an improved treatment of the forest canopy in CMAQ can reap significant benefits in forecast accuracy, removing a long-standing performance bias in CMAQ's forecasts.

I have been delighted to see these early results, which confirm my own early work with ECCC's GEM-MACH air-quality forecast model. I'm also delighted to support this proposal: in addition to the benefits to NOAA, CMAQ's very broad user community will benefit from this new science being ported to CMAQ. I will take part in the work through in-kind donations of my time to monthly research meetings, on-going advice, and exchanges of model code between ECCC and NOAA to aid in the project.

Best Regards,

Paul Makar,
Senior Scientist (RES-05)
Environment and Climate Change Canada

iii.   Reference List

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- Zhang, Y., Liu, P., Pun, B., and Seigneur, C. (2006). A comprehensive performance evaluation of MM5-CMAQ for the summer 1999 southern oxidants study episode, Part I. Evaluation protocols, databases, and meteorological predictions. *Atmos. Environ*. 40. https://doi.org/10.1016/j.atmosenv.2005.12.043.

i. Outreach and Education

The project progress will share the developmental code with the general public and scientific community through our NOAA-ARL GitHub page. Examples of such code sharing are shown in the NOAA-EPA Atmospheric Chemistry Coupler (NACC) repository, developed by PI Campbell, and which formed the advanced NAQFC. As milestones are achieved in this project, the results will be disseminated in peer-reviewed journal articles and at internationally renowned technical/professional conferences (e.g., AMS, AGU, CMAS, IWAQFR, etc.).

j. Diversity and Inclusion

All people, irrespective of their economic background, race, religion, sexual orientation, or gender identity deserve equal treatment in the workplace. Nevertheless, some groups remain underrepresented in the geosciences, especially at more senior positions. This makes it difficult for students and more junior researchers from these groups to envision themselves succeeding, overcome negative biases, and find acceptance and success. Because of this, efforts made now to correct inequality can be viewed as an excellent investment; it is critical that we work harder and faster to enhance diversity and achieve greater equity in the sciences. These themes are already on display at GMU and NOAA-ARL, and will continue to be applied during the post-doc hiring process funded under this collaborative project.

k. Data Management Plan

Previously developed in-canopy parameterizations have already been made publicly available via the experimental NOAA-ARL's NAQFC repository in the "canopy shade" branch (based on offline CMAQv5.3.1). This will form the basis of initial development in RRFS-CMAQ, and similar NOAA-ARL GitHub repositories will be generated upon project inception. This will allow for continuous integration of code developed by internal and external collaborators on this project, as well as by the greater scientific community. The RRFS-CMAQ codes will remain a publicly available repository both during and after the proposed three-year project span.

The types of data created in this project include the developed RRFS-CMAQ FORTRAN code base, Python codes, shell scripts, and ASCII-based text files used to drive the model codes, and gridded NetCDF input files from GEDI used to test the improved canopy representation in the canopy parameterizations (available via the NOAA-ARL GitHub site). All RRFS-CMAQ production simulations and their output files will be stored on NOAA/NCEP and GMU/Hopper local and external High Performance Storage Systems (HPSS), and will be made available to the public upon request, or following completion of the three-year project on publicly available data repositories such as the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC). As the size of annual RRFS-CMAQ model simulations may result in data sizes on the order of 100s TBs, high speed transfer of the data is paramount, and may be implemented using a high-speed file transfer service such as Globus. The PI Campbell has significant experience in performing such large-scale simulations, while making such code and data available to the scientific and public communities.

The developed RRFS-CMAQ code will be immediately made available on NOAA-ARL's GitHub site by simply "forking" (i.e., copying) the repository, and "cloning" (i.e., downloading) the appropriate branch of model development and compiling using different compilers. The RRFS-CMAQ in-canopy codes will be standardized as FORTRAN 90 compliant, are based on the ESMF/NUOPC and CCPP infrastructure frameworks, and all input/output data in RRFS-CMAQ will be standardized based on the NetCDF Cooperative Ocean/Atmosphere Research Data Service (COARDS) data file convention.

l. Curriculum Vitae

Dr. Patrick C. Campbell
Research Assistant Professor
Center for Spatial Information Science and Systems
George Mason University
Cooperative Institute for Satellite Earth System Studies (CISESS)
National Oceanic and Atmospheric Administration, Air Resources Laboratory Affiliate

5830 University Research Court
College Park, Maryland 20740
T: 307-760-5178
E: patrick.c.campbell@noaa.gov

EDUCATION

- University of Wyoming *2008 - 2013*
  Doctor of Philosophy in Atmospheric Science
  Dissertation: "The Climatology, Extent, and Impact of Stratospheric Condensation Nuclei, including their formation in polar regions"
- University of Massachusetts at Lowell *2004 - 2006*
  Master of Science in Environmental Studies – Atmospheric Science Concentration
  Thesis: "A Short Range Ensemble Forecast Experiment on Jet Streaks to Improve Forecasters' Model Diagnoses 2004 – 2006"
- University of Massachusetts at Lowell *2000 - 2004*
  Bachelor of Science in Meteorology

AWARDS & DISTINCTIONS

- NOAA OAR Certificate of Accommodation (2021), For Implementing and Upgrading NOAA's NAQFC
- Top Paper Download for *Campbell et al.* (2018), JAMES, 2018-2019
- NRC Research Fellowship Award, NAS, 2016
- Research Spotlight for *Campbell et al.* (2014), AGU, 2014
- Antarctic Service Medal of the United States of America, NSF, 2012

AREAS OF SPECIALIZATION

- Coupled (meteorology-chemistry) air quality model development.
- Emissions and surface-atmosphere exchanges of heat, moisture, gases, and aerosols.
- Atmospheric composition model predictions, applications, and forecasting.

SELECT/RELEVANT EXPERIENCE (< 3 years)

<u>Research Assistant Professor</u>. Center for Spatial Information Science and Systems/Cooperative Institute for Satellite Earth System Studies, George Mason University, ARL/NOAA Affiliate, College Park, MD, *2019 - Current.*

<u>Post-Doc Research Associate.</u> Department of Atmospheric and Oceanic Science/Cooperative Institute for Climate and Satellites-Maryland, University of Maryland, ARL/NOAA Affiliate, College Park, MD, *2018 – 2019*

- Lead developer of the Global Forecast System (GFS)-driven NOAA-EPA Atmosphere Chemistry Coupler (NACC) for the Advanced National Air Quality Forecasting Capability (NAQFC) (Codes: https://github.com/noaa-oar-arl/NACC; https://github.com/noaa-oar-arl/NAQFC)

- Research and development on the NOAA Emission and eXchange Unified System (NEXUS) and connections with next-generation regional and global atmospheric aerosol and composition forecast models (Code: https://github.com/noaa-oar-arl/NEXUS)
- Research on emissions, atmospheric deposition and composition, air quality, and air-surface exchange processes, which includes in-canopy processes
- Research on coupled meteorological, photochemical, and chemical transport/air quality modeling

SELECT/RELEVANT PUBLICATIONS (< 3 years)

- **Campbell, P. C.**, et al., (2021). An Improved National Air Quality Forecasting Capability Using the NOAA Global Forecast System. Development and evaluation of an advanced National Air Quality Forecast Capability using the NOAA Global Forecast System version 16, under review.
- Ma, S., D. Tong, L. Lamsal, J. Wang, Y. Tang, R. Saylor, T. Chai, P. Lee, **P. C. Campbell**, B. Baker, S. Kondragunta, L. Judd, and I. Stajner (2021). Improving predictability of high ozone episodes through dynamic boundary conditions, emission refresh and chemical data assimilation during the Long Island Sound Tropospheric Ozone Study (LISTOS) field campaign. Atmospheric Chemistry and Physics, in press.
- **Campbell, P. C.**, et al., (2021). Impacts of the COVID-19 Economic Slowdown on Ozone Pollution in the U.S. Atmospheric Environment, https://doi.org/10.1016/j.atmosenv.2021.118713.
- Chen, X., Y. Zhang, K. Wang, D. Q. Tong, P. Lee, Y. Tang, J. Huang, **P. C. Campbell**, J. T. McQueen, H. O. T. Pye, B. N. Murphy, D. Kang. 2020. Evaluation of the offline-coupled GFSv15-FV3-CMAQv5.0.2 in support of the next-generation National Air Quality Forecast Capability over the contiguous United States. Geoscientific Model Development, Preprint. https://doi.org/10.5194/gmd-2020-272.
- Tang, Y., H. Bian, Z. Tao, L. D. Oman, D. Q. Tong, P. Lee, **P. C. Campbell**, B. Baker, S. Lu, L. Pan, J. Wang, J. T. McQueen, I. Stajner. 2021. Comparison of Chemical Lateral Boundary Conditions for Air Quality Predictions over the Contiguous United States during Intrusion Events. Atmospheric Chemistry and Physics Discussions. https://doi.org/10.5194/acp-21-2527-202.
- Uttamang, P., **P. C. Campbell**, V. P. Aneja, A. F. Hanna, 2019, A multi-scale model analysis of ozone formation in the Bangkok Metropolitan Region, Thailand, Atmospheric Environment, 229, 117433. https://doi.org/10.1016/j.atmosenv.2020.117433
- **Campbell, P. C.** et al., 2019, Projections of Atmospheric Nitrogen Deposition to the Chesapeake Bay Watershed, J.Geophys. Res. Biogeosci., 124. https://doi.org/10.1029/2019JG005203
- **Campbell, P. C.**, Bash, J. O., & Spero, T. L., 2018, Updates to the Noah land surface model in WRF-CMAQ to improve simulated meteorology, air quality, and deposition. Journal of Advances in Modeling Earth Systems, 11. https://doi.org/10.1002/2018MS001422
- **Campbell, P. C.**, F. Yan, Z. Lu, Y. Zhang, and D. Streets, 2018, Impacts of Transportation Sector Emissions on Future U.S. Air Quality in a Changing Climate. Part I: Projected Emissions, Simulation Design, and Model Evaluation, Environmental Pollution, 238, 903-917, doi: 10.1016/j.envpol.2018.04.020.
- **Campbell, P. C.**, F. Yan, Z. Lu, Y. Zhang, and D. Streets, 2018, Impacts of Transportation Sector Emissions on Future U.S. Air Quality in a Changing Climate. Part II: Air Quality Projections and the Interplay between Emissions and Climate Change, Environmental

Pollution, 238, 918-930, doi: 10.1016/j.envpol.2018.03.016.

SELECT/RELEVANT CONFERENCE PRESENTATIONS (< 3 years)

- Tang, Y., **P.C. Campbell**, et al. (2021). An Improved National Air Quality Forecasting Capability Using the NOAA Global Forecast System. Part II: Comparisons with WRF/CMAQ. 2021 Meteorology and Climate - Modeling for Air Quality Conference (Virtual). September, 2021
- **Campbell, P.C.** et al. (2021). An Improved National Air Quality Forecast Capability Using the NOAA Global Forecast System. Part I: Model Development and Community Application. 2021 Meteorology and Climate - Modeling for Air Quality Conference (Virtual). September, 2021.
- **Campbell, P.C**. et al. (2021). An Improved National Air Quality Forecasting Capability Using the NOAA Global Forecast System. 2nd Annual NOAA General Modeling Meeting and Fair (Virtual). April, 2021.
- **Campbell, P.C**. et al. (2021). Impacts of the COVID-19 Economic Slowdown on Ozone Pollution in the U.S. NOAA OAR Senior Management Meeting (Virtual). January 11, 2021.
- **Campbell, P. C.**, et al. (2020). An Improved National Air Quality Forecasting Capability Using the NOAA Global Forecast System. Part I: Model Development and Community Application. 19th Annual CMAS Conference, Chapel Hill, NC, Oct. 2020.
- Baker, B., **P. C. Campbell**, D. Tong, and R. Saylor (2020). Development of a NOAA Emissions and eXchange Unified System (NEXUS) for UFS Atmospheric Chemistry and Composition Models. 1st Annual Unified Forecast System Workshop, College Park, MD, Jul 2020.
- **Campbell, P.C.**, B. Baker, R. Saylor, D. Tong, Y. Tang, P. Lee, S. McKeen, G. Frost, and C. Keller (2020). Initial Development of a NOAA Emissions and eXchange Unified System (NEXUS). 100th Annual AMS Conference, Boston, MA. Jan 2020.
- Tang, Y., Tong, D., P. Lee, B. Baker, **P. C. Campbell**, J. McQueen, H.-C. Huang, L. Pan, J. Huang, J. Torado, and I. Stanjner (2019). Development of a Fast Fire Emission Processor and Its application with HMS-Bluesky and GBBEPx Inventories. 18th Annual CMAS Conference, Chapel Hill, NC, Oct. 2019.
- Tong, D., B. Baker, K. Schepanski, S. Kondragunta, P. Ciren, Y. Tang, P. Lee, **P. C. Campbell**, and R. Saylor (2019). Implementation of new satellite-based source maps in the FENGSHA dust module and initial application with the CMAQ-based NAQFC system. 18th Annual CMAS Conference, Chapel Hill, NC, Oct. 2019.
- **Campbell, P. C.**, B. Baker, R. Saylor, D. Tong, Y. Tang, and P. Lee (2019) Initial Development of a NOAA Emissions and eXchange Unified System (NEXUS). 18th Annual CMAS Conference, Chapel Hill, NC, Oct. 2019.
- **Campbell, P. C.**, D. Tong, Y. Tang, B. Baker, and P. Lee (2019). Updates of Satellite Applications in National Air Quality Forecasting. HAQAST6 Meeting, Pasadena, CA., Jul. 2019.

m. Current and Pending Support

Dr. Patrick C. Campbell
Current Federal support*:
Title: CISESS: GMU Air Surface Exchange and Atmospheric Composition Research; PI: Patrick C. Campbell; Sponsor: NOAA; Total Amount: $242,126; Period of Performance: 8/1/2021 – 7/31/2022; Commitment: 12 calendar months *Salary support only

Pending Federal support:
Title: Beyond the "Big-Leaf" Model at NOAA: Use of Novel Satellite Data and In-Canopy Processes to Improve U.S. Air Quality Predictions; PI: Patrick Campbell; Sponsor: NOAA; Total Amount: $685,217; Period of Performance: 8/1/2022 – 7/31/2025; Commitment: 12 calendar months

Title: Develop the Combined Chemical Data Assimilation and Emission Inversion System for NOAA Regional Full-Chemistry Forecast System; PI: Youhua Tang; Sponsor: NOAA; Total Amount: $615,879; Period of Performance: 8/1/2022 – 7/31/2025; Commitment: 2.04 calendar months

Title: Transitioning GMU Weather-Aware Emission Modeling Capability (WAEMC) to Support National Air Quality Forecast Capability Operations; PI: Bok Haeng Baek; Sponsor: NOAA; Total Amount: $598,383; Period of Performance: 9/1/2022 – 8/31/2025; Commitment: 1.2 calendar months

George Mason University
Budget Summary

A. PERSONNEL	Person Months		Base Sal.	Effort %	Period 1 08/01/22-07/31/23	Period 2 08/01/23-07/31/24	Period 3 08/01/24-07/31/25	TOTAL
Patrick Campbell	12	Calendar	$79,800.00	100.00%	$79,800	$82,194	$84,660	$246,654
TBD PostDoc	12	Calendar	$60,000.00	100.00%	$0	$61,800	$63,654	$125,454
TOTAL PERSONNEL					**$79,800**	**$143,994**	**$148,314**	**$372,108**
B. FRINGE BENEFITS								
Faculty, Academic & Calendar				31.80%	$25,376	$45,790	$47,164	$118,330
TOTAL FRINGE					**$25,376**	**$45,790**	**$47,164**	**$118,330**
C. TRAVEL								
1. Domestic Travel					$2,894	$5,788	$5,788	$14,470
TOTAL TRAVEL					**$2,894**	**$5,788**	**$5,788**	**$14,470**
E. SUPPLIES								
1. Computers					$3,000	$3,000	$0	$6,000
2. Other					$5,000	$5,000	$5,000	$15,000
TOTAL SUPPLIES					**$8,000**	**$8,000**	**$5,000**	**$21,000**
H. OTHER DIRECT COSTS								
1. Publications					$3,000	$3,000	$3,000	$9,000
TOTAL OTHER					**$3,000**	**$3,000**	**$3,000**	**$9,000**
I. TOTAL DIRECT COSTS					**$119,070**	**$206,572**	**$209,266**	**$534,908**
J. FACILITIES & ADMINISTRATIVE COSTS	Rate	Rate Type						
Research Off-Campus Adjacent	28.1%	**MTDC**			$33,459	$58,047	$58,803	$150,309
TOTAL COSTS					**$152,529**	**$264,619**	**$268,069**	**$685,217**

Personnel **Total Requested $372,108**

Dr. Patrick Campbell will serve as the PI of this proposal and will dedicate 12 calendar months in each year to administer the project and supervise the postdoctoral researcher.

TBD Postdoctoral researcher will be hired to assist Dr. Campbell and will dedicate 12 calendar months in years two and three of the project.

MERIT INCREASES

Mason provides annual merit increases to Faculty and Staff. An escalation factor of 3% has been included for all personnel each year.

FRINGE BENEFITS **Total Requested $118,330**

George Mason University's negotiated fringe benefit rates for Fiscal Year 2022 are applied as follows:

Faculty (Admin, Teaching, & Post-Docs)	31.8%
FICA Only (summer, adjunct, non-student wages)	7.2%

The rates quoted above shall, at the time of funding, be subject to adjustment, if superseding Government approved rates have been established. Salaries, wages and fringe benefits are estimates only and will be paid and billed in accordance with University policy.

TRAVEL **Total Requested $14,470**

$14,470 in funds are requested for travel All travel will be in accordance with University travel regulations and mileage will be charged at the current rate on the date of travel. Travel estimates are based on costs that were incurred on previous projects of a similar nature for federal and state agencies. Funds are requested and based upon travel to the 5-day annual AGU Fall Meeting held in San Francisco, CA. Travel estimates are for 1 trip each year, with 1 participant in year 1 and 2 participants in years 2 & 3. Costs include transportation, lodging, per diem, and other related expenses.

Domestic Travel per person to AGU Conference, California

Airfare:	1 trip x $750	= $750
Lodging:	1 trip x 4 nights x $288	= $1152
Per diem:	4.5 days x $76/day x 1 trip	= $342
Car Rental:	1 trip x 5 days x $30/day	= $150
Conference Fee:	1 fee x $500	= $500

SUPPLIES **Total Requested $21,000**

$6,000 in funds are requested to include the purchase of two laptop computers, one in year one for the PI and one in year two for the post-doc. $15,000 in funds are requested for, annual maintenance and computational/CPU costs, software purchases, and data storage fees per year.

OTHER – PUBLICATIONS **Total Requested $9,000**

$9,000 in funds are requested for publications to pay for journal page fees and for publishing colored figures.

Total Direct Charges **Total Requested $534,908**

A. Personnel $372,108
B. Fringe $118,330
C. Travel $14,470
D. Equipment $0
E. Supplies $21,000
F. Contractual $0
G. Construction $0
H. Other $9,000
I. Total Direct Costs $534,908

Indirect Costs **Total Requested $150,309**

George Mason University has an F&A rate of 28.1%, Modified Total Direct Costs (MTDC), Predetermined by the Office of Naval Research, and is computed on the following direct cost base:

Total Base	$ 534,908
Multiplied by Indirect Cost Rate 28.1%	
Total Indirect Costs	$ 150,309
Total project budget requested	**$ 685,217**

DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
875 NORTH RANDOLPH STREET
SUITE 1425
ARLINGTON, VA 22203-1995

IN REPLY REFER TO:

Agreement Date: December 15, 2020
Supersedes Agreement Dated: June 24, 2020

NEGOTIATION AGREEMENT

INSTITUTION: **GEORGE MASON UNIVERSITY**
FAIRFAX, VA 22030

The Facilities and Administrative (F&A) Cost rates contained herein are for use on grants, contracts and/or other agreements issued or awarded to the George Mason University by all Federal Agencies of the United States of America, in accordance with the provisions and cost principles mandated by 2 CFR Part 200. These rates shall be used for forward pricing and billing purposes for the George Mason University Fiscal Years 2021through 2023. This rate agreement supersedes all previous rate agreements/determinations related to these rates for Fiscal Years 2021 through 2023.

Section I: RATES - TYPE: PREDETERMINED (PRED)

Type	From	To	Rate	Location	Base	Applicable to
PRED.	7/1/20	6/30/21	57.0%	On Campus	(a)	Organized Research (1)
PRED.	7/1/20	6/30/21	26.0%	Off Campus Remote *	(a)	Organized Research (1)
PRED.	7/1/20	6/30/21	27.7%	Off Campus Adjacent **	(a)	Organized Research (1)
PRED.	7/1/20	6/30/21	59.7%	On Campus	(a)	Organized Research (2)
PRED.	7/1/20	6/30/21	28.7%	Off Campus Remote *	(a)	Organized Research (2)
PRED.	7/1/20	6/30/21	31.0%	Off Campus Adjacent **	(a)	Organized Research (2)
PRED.	7/1/20	6/30/21	54.3%	On Campus	(a)	Instruction
PRED.	7/1/20	6/30/21	26.0%	Off Campus Remote *	(a)	Instruction
PRED.	7/1/20	6/30/21	37.9%	Off Campus Adjacent **	(a)	Instruction
PRED.	7/1/20	6/30/21	40.0%	On Campus	(a)	Other Sponsored Activities
PRED.	7/1/20	6/30/21	26.0%	Off Campus Remote *	(a)	Other Sponsored Activities
PRED.	7/1/20	6/30/21	27.3%	Off Campus Adjacent **	(a)	Other Sponsored Activities
PRED.	7/1/20	6/30/21	9.0%	All	(a)	IPA ***

Type	From	To	Rate	Location	Base	Applicable to
PRED.	7/1/21	6/30/23	58.9%	On Campus	(a)	Organized Research (1)
PRED.	7/1/21	6/30/23	26.0%	Off Campus Remote *	(a)	Organized Research (1)
PRED.	7/1/21	6/30/23	28.1%	Off Campus Adjacent **	(a)	Organized Research (1)
PRED.	7/1/21	6/30/23	69.5%	On Campus	(a)	Organized Research (2)
PRED.	7/1/21	6/30/23	36.6%	Off Campus Remote *	(a)	Organized Research (2)
PRED.	7/1/21	6/30/23	38.7%	Off Campus Adjacent **	(a)	Organized Research (2)
PRED.	7/1/21	6/30/23	54.0%	On Campus	(a)	Instruction
PRED.	7/1/21	6/30/23	26.0%	Off Campus Remote *	(a)	Instruction
PRED.	7/1/21	6/30/23	37.7%	Off Campus Adjacent **	(a)	Instruction
PRED.	7/1/21	6/30/23	40.0%	On Campus	(a)	Other Sponsored Activities
PRED.	7/1/21	6/30/23	26.0%	Off Campus Remote *	(a)	Other Sponsored Activities
PRED.	7/1/21	6/30/23	27.3%	Off Campus Adjacent **	(a)	Other Sponsored Activities
PRED.	7/1/21	6/30/23	10.0%	All	(a)	IPA ***

*Off-Campus Remote – activities performed outside the commuting area of the university.
**Off-Campus Adjacent/Vicinity – off campus activities performed within the commuting area of the university.
***Intergovernmental Personnel Act

DISTRIBUTION BASE

(a) Modified total direct costs, consisting of all direct salaries and wages, applicable fringe benefits, materials and supplies, services, travel, and up to the first $25,000 of each subaward (regardless of the period of performance of the subawards under the award). Equipment, capital expenditures, charges for patient care and tuition remission, rental costs, scholarships, and fellowships, participant support costs as well as the portion of each subaward in excess of $25,000 shall be excluded from modified total direct costs.

APPLICABLE TO

(1) Applies to DOD contracts awarded before November 30, 1993, all Non-DOD Instruments, and all DOD grants and other agreements (See Section II, paragraph E). (Capped)

(2) Applies to only DOD contracts awarded on or after November 30, 1993 in accordance with and under the authority of DFARS 231.303(1) (See Section II, paragraph E). (Uncapped)

SECTION II - GENERAL TERMS AND CONDITIONS

A. **LIMITATIONS**: Use of the rates set forth under Section I is subject to availability of funds and to any other statutory or administrative limitations. The rates are applicable to a given grant, contract or other agreement only to the extent that funds are available and consistent with any and all limitations of cost clauses or provisions, if any, contained therein. Acceptance of any or all of the rates agreed to herein is predicated upon the following conditions: (1) that no costs other than those incurred by the institution were included in this indirect cost pool as finally accepted and that such costs are legal obligations of the institution and allowable under governing cost principles; (2) that the same costs that have been treated as indirect costs are not claimed as direct costs; (3) that similar types of costs have been accorded consistent accounting treatment; and (4) that the information provided by the institution which was used as a basis for acceptance of the rates agreed to herein, and expressly relied upon by the Government in negotiating and accepting the said rates is not subsequently found to be materially incomplete or inaccurate.

B. **ACCOUNTING CHANGES**: The rates contained in Section I of this agreement are based on the accounting system in effect at the time the agreement was negotiated. Changes to the method(s) of accounting for costs, which affect the amount of reimbursement resulting from the use of these rates require the prior written approval of the authorized representative of the cognizant agency for indirect costs. Such changes include but are not limited to changes in the charging of a particular type of cost from indirect to direct. Failure to obtain such approval may result in subsequent cost disallowances.

C. **PREDETERMINED RATES**: The predetermined rates contained in this agreement are not subject to adjustment in accordance with the provisions of 2 CFR Part 200, subject to the limitations contained in Part A of this section.

D. **USE BY OTHER FEDERAL AGENCIES**: The rates set forth in Section I are negotiated in accordance with and under the authority set forth in 2 CFR Part 200. Accordingly, such rates shall be applied to the extent provided in such regulations to grants, contracts, and other agreements to which 2 CFR Part 200 applies, subject to any limitations in part A of this section. Copies of this document may be provided by either party to other federal agencies to provide such agencies with documentary notice of this agreement and its terms and conditions.

E. **APPLICATION OF INDIRECT COST RATES TO DEPARTMENT OF DEFENSE (DOD) CONTRACTS**: In accordance with DFARS 231.303, no limitation may be placed on the reimbursement of otherwise allowable indirect cost incurred by an institution of higher education under a DoD contract awarded on or after November 30, 1993, unless the same limitation is applied uniformly to all other organizations performing similar work. It has been determined by DoD that such limitation is not being uniformly applied. Accordingly, the rates cited (2) of Section I, as explained under the title, "APPLICABLE TO" do not reflect the application of the 26% limitation on administrative indirect costs imposed by 2 CFR Part 200, whereas (1) does so.

F. **DFARS WAIVER**: Signature of this agreement by the authorized representative of George Mason University and the Government acknowledges and affirms the University's request to waive the prohibition contained in DFARS 231.303(1) and the Government's exercise of its discretion contained in DFARS 231.303(2) to waive the prohibition in DFARS 231.303(1) for the Instruction and Other Sponsored Activities rates. The waiver request by George Mason University is made to simplify the University's overall management of DoD cost reimbursements under DoD contracts.

Accepted:

FOR GEORGE MASON UNIVERSITY:

Deb Dickenson
Vice President for Finance

12/15/2020

Date

FOR THE U.S. GOVERNMENT:

WOOD.LINDA.MORGAN.1514688946 Digitally signed by WOOD.LINDA.MORGAN.1514688946 Date: 2020.12.16 09:46:01 -05'00'

Linda Morgan Wood
Contracting Officer

12/16/20

Date

For information concerning this agreement contact:

Linda Morgan Wood
Office of Naval Research

Phone: (703) 588-2254
E-mail: linda.m.wood@navy.mil

BUDGET INFORMATION - Non-Construction Programs

OMB Number: 4040-0006
Expiration Date: 02/28/2022

SECTION A - BUDGET SUMMARY

Grant Program Function or Activity (a)	Catalog of Federal Domestic Assistance Number (b)	Estimated Unobligated Funds Federal (c)	Estimated Unobligated Funds Non-Federal (d)	New or Revised Budget Federal (e)	New or Revised Budget Non-Federal (f)	New or Revised Budget Total (g)
1. NOAA-OAR-WPO-2022-2006969	11.459	$ 0.00	$ 0.00	$ 152,529.00	$ 0.00	$ 152,529.00
2. NOAA-OAR-WPO-2022-2006969	11.459	0.00	0.00	264,619.00	0.00	264,619.00
3. NOAA-OAR-WPO-2022-2006969	11.459	0.00	0.00	268,069.00	0.00	268,069.00
4.						
5. Totals		$ 0.00	$ 0.00	$ 685,217.00	$ 0.00	$ 685,217.00

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SECTION B - BUDGET CATEGORIES

6. Object Class Categories	GRANT PROGRAM, FUNCTION OR ACTIVITY				Total
	(1) NOAA-OAR-WPO-2022-2006969	(2) NOAA-OAR-WPO-2022-2006969	(3) NOAA-OAR-WPO-2022-2006969	(4)	(5)
a. Personnel	$ 79,800.00	$ 143,994.00	$ 148,314.00	$	$ 372,108.00
b. Fringe Benefits	25,376.00	45,790.00	47,164.00		118,330.00
c. Travel	2,894.00	5,788.00	5,788.00		14,470.00
d. Equipment	0.00	0.00	0.00		0.00
e. Supplies	8,000.00	8,000.00	5,000.00		21,000.00
f. Contractual	0.00	0.00	0.00		0.00
g. Construction	0.00	0.00	0.00		0.00
h. Other	3,000.00	3,000.00	3,000.00		9,000.00
i. Total Direct Charges (sum of 6a-6h)	119,070.00	206,572.00	209,266.00		$ 534,908.00
j. Indirect Charges	33,459.00	58,047.00	58,803.00		$ 150,309.00
k. TOTALS (sum of 6i and 6j)	$ 152,529.00	$ 264,619.00	$ 268,069.00	$	$ 685,217.00
7. Program Income	$ 0.00	$ 0.00	$ 0.00	$	$ 0.00

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SECTION C - NON-FEDERAL RESOURCES

(a) Grant Program	(b) Applicant	(c) State	(d) Other Sources	(e)TOTALS
8. NOAA-OAR-WPO-2022-2006969	$ 0.00	$ 0.00	$ 0.00	$ 0.00
9. NOAA-OAR-WPO-2022-2006969	0.00	0.00	0.00	0.00
10. NOAA-OAR-WPO-2022-2006969	0.00	0.00	0.00	0.00
11.				
12. TOTAL (sum of lines 8-11)	$ 0.00	$ 0.00	$ 0.00	$ 0.00

SECTION D - FORECASTED CASH NEEDS

	Total for 1st Year	1st Quarter	2nd Quarter	3rd Quarter	4th Quarter
13. Federal	$ 152,529.00	$ 38,133.00	$ 38,132.00	$ 38,132.00	$ 38,132.00
14. Non-Federal	$ 0.00	0.00	0.00	0.00	0.00
15. TOTAL (sum of lines 13 and 14)	$ 152,529.00	$ 38,133.00	$ 38,132.00	$ 38,132.00	$ 38,132.00

SECTION E - BUDGET ESTIMATES OF FEDERAL FUNDS NEEDED FOR BALANCE OF THE PROJECT

(a) Grant Program	FUTURE FUNDING PERIODS (YEARS)			
	(b)First	(c) Second	(d) Third	(e) Fourth
16. NOAA-OAR-WPO-2022-2006969	$ 0.00	$ 0.00	$ 0.00	$
17. NOAA-OAR-WPO-2022-2006969	0.00	264,619.00	0.00	
18. NOAA-OAR-WPO-2022-2006969	0.00	0.00	268,069.00	
19.				
20. TOTAL (sum of lines 16 - 19)	$ 0.00	$ 264,619.00	$ 268,069.00	$

SECTION F - OTHER BUDGET INFORMATION

21. Direct Charges: $534,908

22. Indirect Charges: $150,309

23. Remarks: Modified Total Direct Costs, Off Campus Adjacent 28.1%
Office of Naval Research, Linda Wood, 703-588-2254

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