NOAA MAPP Project Progress Report

Understanding and Quantifying the Predictability of Marine Ecosystem Drivers in the California Current System

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FINAL REPORT

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Introduction: The following provides a summary of what we have accomplished through the third reporting period. We are working as a team on this fundamentally collaborative proposal that involves close collaboration among our institutions and research group members. The results presented here include collaborative work involving Miller, Subramanian, Capotondi, and Di Lorenzo, because we have discussed, instigated and synthesized each others' research activities and results by keeping in close contact via email, video conferences and at various oceanographic conferences during the reporting period and since the funding commenced.

Major Goals and Objectives: Despite the empirical evidence of ENSO influence upon the California Current marine ecosystems, the detailed influence of different ENSO events is unclear, and the degree of predictability of the various ecosystem drivers for specific tropical Pacific conditions has not yet been properly quantified.

The goal of this proposal is to: 1) Use high-resolution ocean reanalysis of the CCS to link the physical drivers of the CCS ecosystem (temperature, upwelling velocity, alongshore & cross-shore transport) to local climate forcing functions (e.g. alongshore winds, wind stress curl, heat fluxes, precipitation and river runoff) at seasonal timescale; 2) Use long reanalysis products (e.g. SODAsi.3, 20CRv2c, CERA-20C) in combination with multiple linear regression and Singular Value Decomposition to objectively link the climate forcing functions variations in the CCS region with conditions (e.g. sea surface temperature, thermocline depth, sea surface height, tropical wind stresses) in the tropical Pacific that can optimally force them at seasonal timescales; and 3) Use Linear Inverse Modeling (LIM) and the North American Multi Model Ensemble (NMME) to determine the predictability and uncertainty of the forcing functions along the CCS region, compare the LIM and NMME forecast skills, and explore possible sources of error in the NMME models.

Approach: We use several approaches to making progress in understanding the predictability of ENSO impacts on the physical and biological system in the California Current System. The first approach is to use a regional eddy-resolving ocean model reanalysis of the CCS to identify and diagnose the precise structures of the atmospheric and oceanic regional forcing functions (RFPs) that drive ecosystem-relevant oceanic processes (SST, upwelling, transport, thermocline depth). The second approach is to use large-scale and long-term reanalysis products to understand how the CCS RFPs are controlled by large-scale dynamics, specifically ENSO, and if these large-scale controls lead to predictability of the ecosystem drivers on seasonal timescales. For example, it is well-known that when El Niño develops in the tropical Pacific during the fall, its teleconnections will impact the CCS in the following winter. However, the precise structures of these teleconnections is strongly dependent on the type/flavor of El Niño, which needs to be assessed. The third approach is to use the North American Multi-Model Ensemble to quantify the predictability and realism of the RFPs associated with ENSO teleconnections. We also use a linear inverse modelling framework to study predictable components and their linear interactions. This will help identify the different temporal and spatial scales that play a role in predictability of variables of interest over the CCS region.

Philosophy: We are also exploring many aspects of predictability that affect the CCS, including those that do not fundamentally involve ENSO timescales. For example, Liu and Di Lorenzo (2018) explain recent progress in the understanding and prediction of pacific decadal variability (PDV). The PDV is now recognized to consist of multiple ocean-atmosphere modes and to be caused by multiple processes. At the leading order, PDV can be viewed as the reddening process of stochastic atmospheric variability on the extratropical ocean. However, PDV is also strongly tied to teleconnection dynamics interacting with the tropics, primarily the interactions between meridional modes in the extra-tropics and ENSO, and between the ENSO teleconnections and the dominant modes of atmospheric variability in the mid-latitude. In the extra-tropics important coupling between the western and eastern boundary are found to be crucial for determining the decadal time scales of the PDV and provide potentially an important source of predictability of PDV.

In the North Pacific, several mechanisms can lead to predictability beyond the El Niño timescales (**Figure 1**). These include:

1) *Tropical/Extra-tropical Coupling (1-2 year predictability)*: The two-way coupling of the ocean-atmosphere system between the North Pacific and the tropics has played a major role in the dramatic marine heatwaves of 2014/15 (Di Lorenzo and Mantua, 2016) and is a key component in the development of anomalous warming along the US West Coast on year-to-year timescales with an inherent predictability that is anticipated to be higher than that associated with canonical El Niño indices (Capotondi et al., 2019a).

2) *W-E Boundary Surface Coupling (2-4 year predictability)*: The surface coupling between the eastern and western boundary systems is associated with the excitation of large oceanic Rossby waves in the central and eastern North Pacific, which then propagate onto the Kuroshio region (Qiu, 2002; Schneider et al., 2002; Ceballos et al. 2009).

3) *W-E Boundary Subsurface Coupling (5-10 year predictability)*: The subsurface coupling from the Kuroshio back to the Gulf of Alaska (GOA) and California Current System (CCS) is linked to the propagation of subsurface anomalies in tracers (e.g. salinity, nutrients, and oxygen) by the mean circulation. These subsurface anomalies have been shown to impact the low-frequency variability of the source waters that feed the upwelling in the CCS and GOA (Pozo Buil and Di Lorenzo, 2015, 2017).

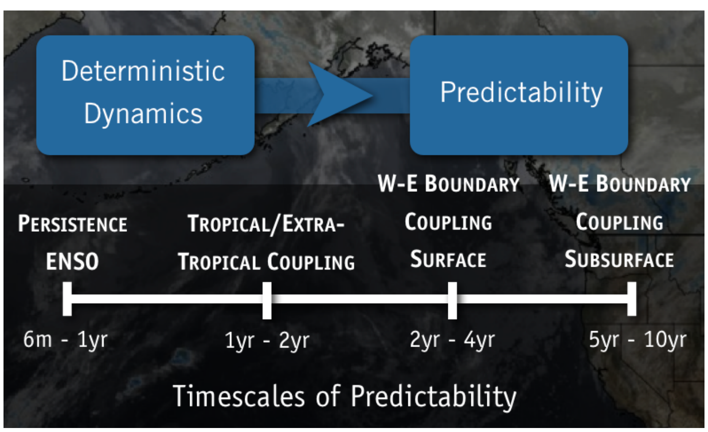

Figure 1: Timescales of physical predictability associated with key mechanisms in the North Pacific.

The dynamics of predictability outlined above are tightly linked to the evolution of the dominant modes of Pacific climate variability (**Figure 2**), which are known to have multiple impacts on ecosystem dynamics of the North Pacific. Given that some of these dynamics and coupling are predicted to become stronger under anthropogenic forcing (e.g. Joh and Di Lorenzo, 2017; Liguori and Di Lorenzo, 2018), better understanding and quantifying the ecosystem predictability that arises from these mechanisms could allow also more accurate climate change predictions.

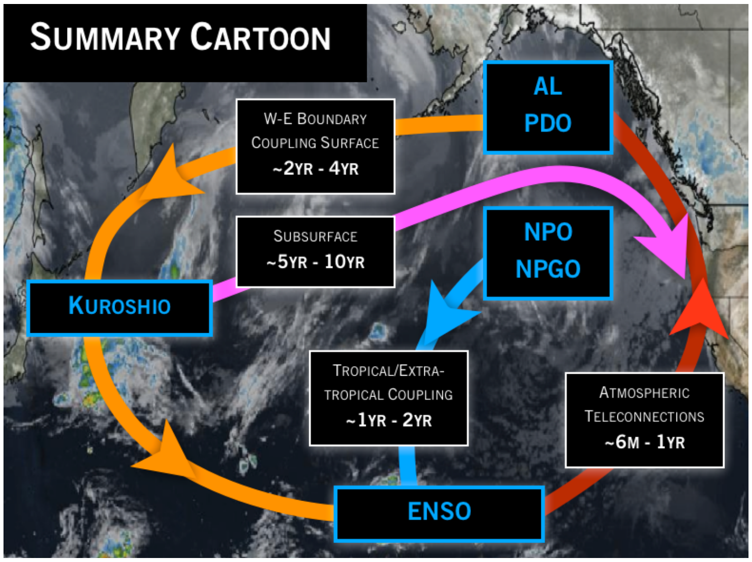

Figure 2: The mechanisms of physical predictability in the North Pacific are linked to the expressions of the dominant modes of Pacific climate variability, as illustrated in this schematic.

Accomplishments in the Third Reporting Period

1) Observational needs for forecasting marine ecosystems: Many coastal areas host rich marine ecosystems and are also centers of economic activities, including fishing, shipping and recreation. Due to the socioeconomic and ecological importance of these areas, predicting relevant indicators of the ecosystem state on sub-seasonal to interannual timescales is gaining increasing attention. Depending on the application, forecasts may be sought for variables and indicators spanning physics (e.g., sea level, temperature, currents), chemistry (e.g., nutrients, oxygen, pH), and biology (from viruses to top predators). Many components of the marine ecosystem are known to be influenced by leading modes of climate variability, which provide a physical basis for predictability. However, prediction capabilities remain limited by the lack of a clear understanding of the physical and biological processes involved, as well as by insufficient observations for forecast initialization and verification. The situation is further complicated by the influence of climate change on ocean conditions along coastal areas, including sea level rise, increased stratification, and shoaling of oxygen minimum zones. Observations are thus vital to all aspects of marine forecasting: statistical and/or dynamical model development, forecast initialization, and forecast validation, each of which has different observational requirements, which may be also specific to the study region. **Capotondi et al. (2019b)** use examples from United States (U.S.) coastal applications to identify and describe the key requirements for an observational network that is needed to facilitate improved process understanding, as well as for sustaining operational ecosystem forecasting. They also describe new holistic observational approaches, e.g., approaches based on acoustics, inspired by Tara Oceans or by landscape ecology, which have the potential to support and expand ecosystem modeling and forecasting activities by bridging global and local observations.

2) Understanding optimal precursors of US West Coast (USWC) warming: Motivated by the extreme warm conditions along the USWC that occurred during 2014/15, **Capotondi et al. (2019a)** completed and published their study of the influence of the tropical Pacific on the USWC. El Nino events are considered a major source of predictability for USWC warming, but not all El Nino events are associated with significant warming along the US West coast. Conversely, the tropical Pacific sea surface temperature (SST) anomalies were generally weak during 2014, when the extreme USWC warming occurred, thus calling into question the role of ENSO in USWC warming. Using a statistical approach, we have identified patterns of tropical SST and sea surface height (SSH) anomalies that USWC SST conditions are most "sensitive" to. These sensitivity patterns do not coincide with SST patterns usually associated with the mature phase of ENSO events, but also include elements associated with ENSO SST precursors and SST anomalies in the central/western equatorial Pacific. These patterns are better precursors of USWC warming than traditionally used ENSO indices. Our study has also shown that the tropical sensitivity patterns are associated with a specific evolution of the atmospheric fields over the North Pacific, which may produce a preconditioning of USWC conditions. Capotondi is now focused on the development of a Linear Inverse Model (LIM) to examine the predictability of the Northeast Pacific SST and SSH. In particular, she is using the LIM to assess the predictability of the 2013-2016 marine heatwave.

3) Seasonal-to-interannual prediction of U.S. coastal marine ecosystems: Marine ecosystem forecasting is an area of active research and rapid development. Promise has been shown for skillful prediction of physical, biogeochemical, and ecological variables on a range of timescales, suggesting potential for forecasts to aid in the management of living marine resources and coastal communities. However, the mechanisms underlying forecast skill in marine ecosystems are often poorly understood, and many forecasts, especially for biological variables, rely on empirical statistical relationships developed from historical observations. **Jacox et al. (2019)** have completed and published their review of statistical and dynamical marine ecosystem forecasting methods and highlight examples of their application along U.S. coastlines for seasonal-to-interannual (1-24 month) prediction of properties ranging from coastal sea level to marine top predator distributions. We then describe known mechanisms governing marine ecosystem predictability in these regions and how they have been used in forecasts to date. These mechanisms include physical atmospheric and oceanic processes, biogeochemical and ecological responses to physical forcing, and intrinsic characteristics of species themselves. In reviewing the state of the knowledge on forecasting techniques and mechanisms underlying predictability in U.S. marine ecosystems, we aim to facilitate forecast development and uptake by (i) identifying methods and processes that can be exploited for development of skillful regional forecasts, (ii) informing priorities for forecast development and validation, and (iii) improving understanding of conditional forecast skill (i.e., a priori knowledge of whether a forecast is likely to be skillful).

4) Drivers of the summer 2019 marine heatwave: In boreal summer 2019, the northeast Pacific Ocean (NEPac) experienced a resurgence of extreme upper ocean temperatures (Fig. 3). The strength and pattern of the sea surface temperature anomalies (SSTAs) earned this event the moniker "Blob 2.0", a reference to the original warm "Blob" that initiated a multi-year marine heatwave (MHW) that devastated regional ecosystems over 2014-2016. In particular, the intraseasonal persistence of the 2019 Blob 2.0 generated similar widespread concern among fishery and wildlife managers for sensitive marine ecosystems along the west coast of North America. Unlike the original Blob, Blob 2.0 peaked in the summer, a season when little is known about the physical drivers of such events. **Amaya et al. (2020a)** show that Blob 2.0 primarily results from a prolonged weakening of the North Pacific High-Pressure System. This reduces surface winds and decreases evaporative cooling and wind-driven upper ocean mixing. Warmer ocean conditions then reduce low-cloud fraction, reinforcing the marine heatwave through a positive low-cloud feedback. Using an atmospheric model forced with observed SSTs, they also find that remote SST forcing from the central equatorial and, surprisingly, the subtropical North Pacific Ocean contribute to the weakened North Pacific High. Their multi-faceted analysis sheds light on the physical drivers governing the intensity and longevity of summertime North Pacific marine heatwaves. This paper was highlighted in numerous media outlets.

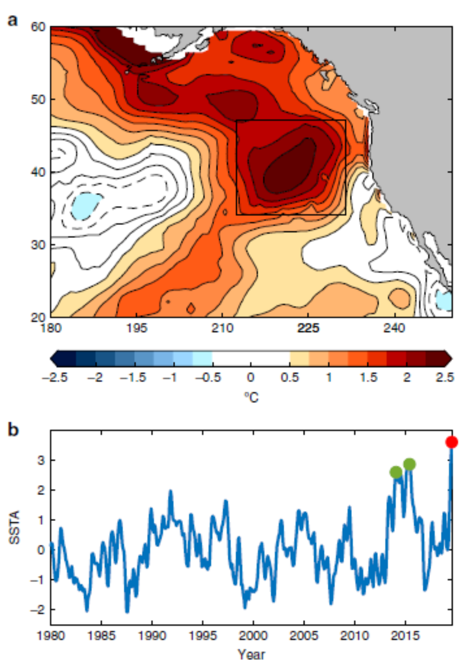

Fig. 3. The Blob 2.0 in an ocean reanalysis product. (a) Five-meter ocean temperature anomalies (°C) averaged for June–August (JJA) 2019 in Global Ocean Data Assimilation System (GODAS). (b) Time series of normalized monthly mean sea surface temperature anomalies areaweighted averaged in black box above, smoothed with a 3-month running mean for the period 1980–2019. Red dot marks JJA 2019. Green dots mark the two peaks of Blob 1.0 averaged in January–March 2014 and May–July 2015, respectively. From Amaya et al. (2020a)

5) Influence of mixed-layer depth on marine heatwaves: Summer 2019 observations show a rapid resurgence of the Blob-like warm sea surface temperature (SST) anomalies that produced devastating marine impacts in the Northeast Pacific during winter 2013/2014. **Amaya et al. (2020b)** investigated the influence of climate change on North Pacific MLD trends, and by extension, the likelihood and intensity of the summer 2019 MHW. They showed that the NE Pacific has likely experienced long-term MLD shoaling since 1980, but significant observational uncertainty regarding the strength of these trends remains. Even so, the 2019 MLD anomalies, which were an important driver of Blob 2.0, were likely exacerbated by these multi-decadal trends. Consequently, the marine ecosystem impacts generated by this MHW were likely similarly intensified.

6) Impact of shifting Subtropical Highs on the California Current: Upwelling in eastern boundary current regions is crucial to bringing nutrient-rich water to the photic zone and supporting the associated ecosystems. This upwelling is a result of the wind-driven ocean circulation and is therefore susceptible to changes in the atmospheric circulation. **Schmidt et al. (2020)** use the Community Earth System Model and observational data to explore the response of upwelling in the California and Canary current systems to shifts in the Northern Hemisphere subtropical high-pressure systems. They find that shifts in the North Pacific subtropical high explain a substantial fraction of both the short-term variability and projected trend in upwelling in the California Current system during boreal summer. By contrast, the Canary Current system is less affected by shifts of the North Atlantic subtropical high, mostly because the strongest wind anomalies associated with shifts of this high-pressure system occur too far north.

7) SST influence on climate prediction over the western U.S.: Seasonal predictions have the potential to improve the management of different sectors of the society by anticipating climate fluctuations and possible weather extremes. Such forecasts must contend with a high level of natural variability as well as challenges posed by climate change. However, they are constrained by limited understanding of local and regional atmospheric predictability. **Dias et al. (2020)** use a canonical correlation analysis (CCA) prediction model of minimum and maximum air temperature anomalies (Tmin and Tmax) over Western North America (WNA) is developed. Remote and local predictors are used: sea surface temperature (SST) across the Pacific and local soil moisture (SM). The evaluation of the skill of predicted air temperature using historical observations indicates that CCA can provide skillful predictions for seasonal anomalies of air temperature over the region. However, skill is found to vary over seasons, location and combination of predictor and predictand variables. SST yields the best predictive skill for Tmax and Tmin during wintertime, but for spring and early-summer its influence is mostly on Tmin. Remote large-scale patterns, in the form of climate indices, are captured by the CCA canonical modes and it is shown that they can be responsible for this predictive ability. On the other hand, the influence of SM is restricted to Tmax and only during the winter, when it is shown that SM has the highest autocorrelation for the region. The results demonstrate the importance of careful analyses that consider season, variable being predicted, and predictors in forming statistical forecast models to be used for decision making.

8) Predictability of marine heat waves: The application of LIM to the study of the recent northeast Pacific Marine heatwaves was examined by **Xu et al. (2020)**.

Impacts:

- Identified optimal forcing drivers of West Coast oceanic conditions due to tropical Pacific SST variations
- Identified time and space scale interactions affecting Pacific SST predictability
- Constructed a composite physical-biological model ENSO in the CCS from a numerical simulation
- The 2019 Northeast Pacific marine heatwave and its impacts were likely amplified by multi-decadal shoaling of the mixed layer, consistent with internal climate variability; anthropogenic forcing was not likely a major factor.
- Capotondi served as Co-Leader of the MAPP Marine Prediction Task Force
- Capotondi served as leader for the preparation of a paper entitled "Observational needs supporting marine ecosystems modeling and forecasting"
- Mentored Ph.D. students Nathali Cordero-Quiros (SIO), Daniela Faggiani Dias (SIO), Dillon Amaya (SIO), Daling Yi (Ocean University of China, Qingdao)

Collaborations Established:

Dr. Laure Zanna (University of Oxford), Dr. Dillon Amaya (CIRES, University of Colorado), Dr. Daniela Faggiani Dias (Colorado State University)

Opportunities for Training, Professional Development, and Mentoring:

Ms. Nathali Cordero-Quiros (Fifth-year Ph. D. student, SIO)
Ms. Daniela Faggiani Dias (defended and awarded Ph. D., 2020, SIO)
Mr. Dillon Amaya (defended and awarded Ph.D., 2019, SIO, and post-doc, SIO)
Ms. Daling Yi (Ph.D. 2018, Ocean University of China, Qingdao)

Other Activities (Professional Dissemination and Community Outreach):

MAPP Marine Prediction Task Force (Capotondi, Leader; Di Lorenzo, Subramanian, Miller, members): Capotondi organizes monthly conference calls to stimulate discussion among the MPTF members and foster collaborative interactions among the funded NOAA projects.

Capotondi led the writing of a published paper entitled "Observational needs supporting marine ecosystems modeling and forecasting", which was encouraged by Ocean Obs'19, and involved a large fraction of the Marine Prediction Task Force members, as well as three other groups external to the Task Force.

Ocean Sciences Meeting, San Diego, CA, February, 2020 (Miller, Di Lorenzo, Capotondi, Subramanian, Cordero-Quiros, Faggiani-Dias, Amaya)

AMS 100th Annual Meeting, Boston, MA, January, 2020 (Miller)

2nd Meridional Modes Workshop, Ohio State University, November, 2019 (Miller, Di Lorenzo, Amaya)

PICES Annual Meeting, October, 2018, Victoria, Canada (Capotondi, Di Lorenzo, Miller)

Eastern Pacific Ocean Conference, Fallen Leaf Lake, CA, September, 2019 (Miller, Cordero-Quiros, Faggiani-Dias, Amaya)

Miller gave lectures at the ICTP-CLIVAR Summer School on Eastern Boundary Upwelling Systems, Trieste, Italy, July, 2019 (Miller, Cordero-Quiros)

Capotondi is Co-Chair and Di Lorenzo is a member of the PICES-CLIVAR working group on "Climate and Ecosystem Predictability". In their roles, they have helped in the organization of a workshop entitled "Toward an Integrated Approach to Understanding Ecosystem Predictability in the North Pacific" in Qingdao, China, June 20-22, 2019. Capotondi presented a talk at the workshop entitled: "Predicting Physical Drivers of North Pacific Marine Ecosystems Using a Linear Inverse Modeling Approach". A workshop report, co-authored by Rikaczewsky and Capotondi, was published in the January issue of the PICES Press.

Subramanian was a member of the Scientific Organzing Committee for the U.S. CLIVAR workshop on "Bridging Sustained Observations and Data Assimilation for TPOS 2020", May 2019, Boulder, CO (Subramanian, Capotondi)

First CICESE-SIO Joint Symposium, Ensenada, Mexico, May, 2019 (Miller, Cordero-Quiros, Amaya)

AMS Annual Meeting, January, 2019, Phoenix, AZ (Capotondi, Miller)

AGU Annual Meeting, December, 2018, Washington, D.C. (Miller)

PICES Annual Meeting, October, 2018, Yokohama, Japan (Capotondi, Di Lorenzo)

Eastern Pacific Ocean Conference, Mt Hood, OR, September, 2018 (Miller, Di Lorenzo, Subramanian, Cordero-Quiros)

PICES 4th International Symposium on "Effects of Climate Change on the World Oceans", June 4-8, 2018, Washington DC (Capotondi)

International Symposium on "Understanding Changes in Transitional Areas of the Pacific", 24-26 April, La Paz, Mexico (Di Lorenzo)

American Meteorological Society Meeting, January 7-11, 2018, Austin, TX (Miller, Capotondi)

AGU Fall Meeting, December 9-15, 2017, New Orleans, LA (Miller)

US CLIVAR Summit. August, 2017, Baltimore, Maryland (Capotondi)

Numerous interviews with TV, radio, and newspapers about climate (Miller)

2018, 2019 Exploring Ocean STEM Careers Night, Birch Aquarium at Scripps (Miller)

Member, *Stay Cool for Grandkids*, climate action group in San Diego (Miller)

Home page (Dr. Art Miller): http://meteora.ucsd.edu/~miller/

Home page (Dr. Aneesh Subramanian): http://www.aneeshcs.com

Home page (Prof. Emanuele Di Lorenzo): http://ocean.eas.gatech.edu/manu/

Plans for the next reporting period: We plan to continue our collaborative research on the various topics relevant to this project, including completing the work needed to publish the numerous submitted manuscripts described previously.

Products: Cumulative publications acknowledging this grant:

Amaya, D. J., Y. Kosaka, W. Zhou, Y. Zhang, S.-P. Xie and **A. J. Miller**, 2019: The North Pacific pacemaker effect on historical ENSO and its mechanisms. *Journal of Climate,* **32**, 7643-7661.

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OMB Number: 0690-0032
Expiration Date: 08/31/2021

DEPARTMENT OF COMMERCE
RESEARCH PERFORMANCE PROGRESS REPORT (RPPR)

For instructions, please visit
http://www.osec.doc.gov/oam/grants_management/policy/documents/RPPR%20Instructions%20and%20Privacy%20Statement.pdf

AWARD INFORMATION	
1. Federal Agency: Department of Commerce / NOAA	2. Federal Award Number: NA17OAR4310107
3. Project Title: Understanding and Quantifying the Predictability of Marine Ecosystem Drivers in the California Current Sys	
4. Award Period of Performance Start Date: 09/01/2017	5. Award Period of Performance End Date: 08/31/2020
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR	
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14. Email: serelia.woods@osp.gatech.edu	15. Phone Number: 404-385-0866
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Signature of Submitting Official: David Walker	
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RECIPIENT ORGANIZATION	
20. Recipient Name: GEORGIA TECH RESEARCH CORPORATION	
21. Recipient Address: 926 DALNEY ST NW, ATLANTA, GA 30332 USA	
22. Recipient DUNS: 097394084	23. Recipient EIN: 580603146

ACCOMPLISHMENTS
24. What were the major goals and objectives of this project? Please see attached PDF file.
25. What was accomplished under these goals? Please see attached PDF file.

Attach a separate document if more space is needed for #6-10, or #24-50.

ACCOMPLISHMENTS *(cont'd)*

26. What opportunities for training and professional development has the project provided?

Please see attached PDF file.

27. How were the results disseminated to communities of interest?

Please see attached PDF file.

Attach a separate document if more space is needed for #6-10, or #24-50.

ACCOMPLISHMENTS *(cont'd)*

28. What do you plan to do during the next reporting period to accomplish the goals and objectives?

This is the final report

PRODUCTS

29. Publications, conference papers, and presentations

Please see attached PDF file.

Attach a separate document if more space is needed for #6-10, or #24-50.

PRODUCTS *(cont'd)*

30. Technologies or techniques

Nothing to Report

31. Inventions, patent applications, and/or licenses

Nothing to Report

Attach a separate document if more space is needed for #6-10, or #24-50.

PRODUCTS *(cont'd)*

32. Other products

Nothing to Report

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

33. What individuals have worked on this project?

Please see attached PDF file.

Attach a separate document if more space is needed for #6-10, or #24-50.

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS *(cont'd)*
34. Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period? Nothing to Report
35. What other organizations have been involved as partners? Please see attached PDF file.

Attach a separate document if more space is needed for #6-10, or #24-50.

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS *(cont'd)*

36. Have other collaborators or contacts been involved?

Nothing to Report

IMPACT

37. What was the impact on the development of the principal discipline(s) of the project?

Please see attached PDF file.

Attach a separate document if more space is needed for #6-10, or #24-50.

IMPACT *(cont'd)*

38. What was the impact on other disciplines?

Please see attached PDF file.

39. What was the impact on the development of human resources?

Please see attached PDF file.

Attach a separate document if more space is needed for #6-10, or #24-50.

IMPACT *(cont'd)*

40. What was the impact on teaching and educational experiences?

Please see attached PDF file.

41. What was the impact on physical, institutional, and information resources that form infrastructure?

Please see attached PDF file.

Attach a separate document if more space is needed for #6-10, or #24-50.

IMPACT ***(cont'd)***

42. What was the impact on technology transfer?

Nothing to Report

43. What was the impact on society beyond science and technology?

Please see attached PDF file.

Attach a separate document if more space is needed for #6-10, or #24-50.

IMPACT *(cont'd)*

44. What percentage of the award's budget was spent in foreign country(ies)?

0 , null

CHANGES/PROBLEMS

45. Changes in approach and reasons for change

Nothing to Report

Attach a separate document if more space is needed for #6-10, or #24-50.

CHANGES/PROBLEMS *(cont'd)*

46. Actual or anticipated problems or delays and actions or plans to resolve them

Nothing to Report

47. Changes that had a significant impact on expenditures

Nothing to Report

Attach a separate document if more space is needed for #6-10, or #24-50.

CHANGES/PROBLEMS *(cont'd)*
48. Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents Nothing to Report
49. Change of primary performance site location from that originally proposed Nothing to Report

Attach a separate document if more space is needed for #6-10, or #24-50.

PROJECT OUTCOMES

50. What were the outcomes of the award?

Please see attached PDF file.

DEMOGRAPHIC INFORMATION FOR SIGNIFICANT CONTRIBUTORS (VOLUNTARY)

Gender:

- ○ Male
- ○ Female
- ○ Do not wish to provide

Ethnicity:

- ○ Hispanic or Latina/o Not
- ○ Hispanic or Latina/o Do not
- ○ wish to provide

Race:

- ○ American Indian or Alaska Native Asian
- ○ Black or African American
- ○ Native Hawaiian or other Pacific Islander
- ○ White
- ○ Do not wish to provide

Disability Status:

- ○ Yes
  - [ ] Deaf or serious difficulty hearing
  - [ ] Blind or serious difficulty seeing even when wearing glasses
  - [ ] Serious difficulty walking or climbing stairs
  - [ ] Other serious disability related to a physical, mental, or emotional condition
- ○ No
- ○ Do not wish to provide

Attach a separate document if more space is needed for #6-10, or #24-50.