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SUBJECT: THE CAPABILITIES AND ACHIEVEMENTS OF FNMOC'S MODERNIZED ANALYSIS OF THE TRENDS AND TENDENCIES OF CLIMATE AND FORENSICS (MATTCAF)

1. Abstract. FNMOC's Modernized Analysis of the Trends and Tendencies of Climate and Forensics (MATTCAF) is introduced as a novel operational climatology tool to create custom climate products in a swift manner to support the Navy and Department of Defense (DoD). MATTCAF is designed to create climatological averages from 6 reanalysis datasets, 59 parameters, 17 types of climatological calculations, 3 types of file output, adjustable image quality, and 5 map projections while saving the outputs with user-defined file naming conventions. MATTCAF's capabilities are discussed, and an example output is included.

2. Introduction. Operational climatology is an increasingly relevant topic for the Information Warfare community in today's changing climate. The melting of the ice caps, the Madden Julian Oscillation, and the El Niño-Southern Oscillation (ENSO) cycle are several examples of major contributors and considerations affecting the climate globally by means of direct interactions and teleconnections. The elite climatology team at Fleet Numerical Meteorology and Oceanography Center (FNMOC) is the Navy's premier atmospheric climatology team, and routinely fulfills requests for climate support by the Navy and the rest of the Department of Defense. An abundance of climatology products and tools are available on FNMOC's portal, however many of the more difficult climate questions require tailored products manually produced by FNMOC's climatology team with reanalysis datasets reaching as close to the current year as possible. As tailored climate requests become more frequent and more complex, the need for a simple yet robust tool was evident.

The Modernized Analysis of the Trends and Tendencies of Climate and Forensics (MATTCAF) was built in-house to reduce the workload for some less-complex requests that would have otherwise required new code to be written. MATTCAF is a self-contained python script capable of creating countless operational climatology products and runs using a text-based question and answer function through a Linux command line. It was written with the intention of operating on linux, but can be run using PuTTY if so desired. Once started, MATTCAF will ask a series of questions for the user to answer through the command line to gather what climate product is required. Once all questions are answered, the operational climate product will be created automatically in a standard and consistent manner. This technical report outlines the capabilities and successes of MATTCAF as it is still used operationally by FNMOC's climatology team.

The source code is maintained in-house at FNMOC as it has been designed, tested, built, and run on FNMOC systems using FNMOC archives. For this reason, it will not be made publically available. This project was conducted independently with no funding from outside sources.

3. Capabilities. MATTCAF is designed to create climatological averages from 6 reanalysis datasets, 59 parameters, 17 types of climatological calculations, 3 types of file output, adjustable image quality, and 5 map projections while saving the outputs with user-defined file naming conventions to produce a climatology product anywhere on the globe. Additionally, MATTCAF is capable of being run through a shell script using the command line inputs for automated product generation or mass production of products. MATTCAF includes a feature ensuring a correct command line input is placed to avoid crashes from typos. A given question will be asked again if one of the possible answer choices is not correctly typed, and a brief description of the problem will be stated. MATTCAF's datasets, corresponding spatial resolutions, and most recent years are listed in table 1.

Reanalysis Dataset	Spatial Resolution	Recent Year
ECMWF Reanalysis V5 (ERA5)	0.25 deg atmosphere / 0.5 deg ocean	Through 2020
Climate Forecast System Reanalysis V2 (CFSRv2)	0.25 deg	Through 2018
NOAA Wave Watch III Reanalysis (WW3)	0.5 deg	Through 2009
International Satellite Cloud Climatology Project (ISCCP)	2.5 deg	Through 2009
Reynolds SST Reanalysis (Reynolds)	1 deg	Through 2006
Simulated Waves Near-Shore (SWAN)	Varies depending on regional model	Varies, but generally through 2020 at least

Table 1. MATTCAF's datasets, corresponding spatial resolutions, and most recent years.

There exists large variability among the spatial resolutions for the included reanalysis models. MATTCAF will automatically adjust the latitudes and longitudes of the user's defined box to match the grid spacing of the chosen reanalysis model for SWAN and ISCCP. This adjustment, if necessary, will always increase the area of the box and never decrease so the original data request will never be cut to a smaller box than requested. For all other reanalysis models, the user must match the latitude and longitude box to the model's resolution. The spatial resolution and latitude/longitude intervals are displayed at the time the first question is asked to identify the desired reanalysis model for ease of use.

There are a total of 59 available parameters between the 6 reanalysis models, and more can be added using the same convention used in the code. These parameters are listed in Tables 2-7.

ERA5
swh (Significant Wave Height and Direction)
T2M (2-m Air Temperature)
mwd (Mean Wave Direction)
mwp (Mean Wave Period and Direction)
CI (Sea Ice Cover)
W10M (10-m Wind speed and Direction)
cbh (Cloud Base Height)
LCC (Low Cloud Cover)
MCC (Medium Cloud Cover)
HCC (High Cloud Cover)
TCC (Total Cloud Cover)

CIE (Sea Ice Extent) Mean and Anomaly Calculations Only

Table 2. ERA5 available parameters. Sea Ice Extent is calculated using the threshold of ice coverage 50% of the time and is output as a contour line.

CFSRv2
T-Surf (Surface Air Temperature)
W10M (10-m Wind speed and Direction)
T-ISO (Isobaric Temperature)
W-ISO (Isobaric Winds)
GEOH (Geopotential Heights)
RH-ISO (Isobaric Relative Humidity)
SH-ISO (Isobaric Specific Humidity)
Cat_FRZ_Rain (Categorical Freezing Rain (6 Hour Average) at Ground or water surface)
Cat_Ice (Categorical Ice Pellets (6 Hour Average) at Ground or water surface)
Cat_Rain (Categorical Rain at Ground or water surface)
Cat_Rain_6 (Categorical Rain (6 Hour Average) at Ground or water surface)
Cat_Snow (Categorical Snow (6 Hour Average) at Ground or water surface)
Heat_Index (Heat Index)
Ice (Surface Ice Cover)
Ice_Th (Surface Ice Thickness)
Precip_Rate (Precipitation rate (6 Hour Average) at Ground or water surface)
MSL_Prs (Pressure reduced to MSL)
Total_Clouds (Total cloud cover (6 Hour Average) at Entire atmosphere layer)
Long_Wave (Upward Long-Wave Radiation Flux (6 Hour Average) at Nominal top of the atmosphere)
Wind_Chill (10-m Wind Chill)
T2M-Max (Maximum 2-m temperature (6 Hour Interval) at Specified height level above ground)
T2M-Min (Minimum 2-m temperature (6 Hour Interval) at Specified height level above ground)
T2M (2-m Air Temperature
Wind_Chill (10-m Wind Chill)
Currents

Table 3. CFSRv2 available parameters. All isobaric-dependent parameters will spawn a new question to define the desired isobaric level. These levels are: 1, 2, 3, 5, 7, 10, 20, 30, 50, 70, 100, 125, 150, 175, 200, 225, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 775, 800, 825, 850, 875, 900, 925, 950, 975, 1000 mb. Similarly, the currents parameter will spawn a depth question. The available depths are 5, 15, 25, 35, 45, 55, 65, 75, 85, 95, 105, 115, 125, 135, 145, 155, 1193 m.

WW3
SWH (Significant Wave Height and Direction)
MWD (Mean Wave Direction)
MWP (Mean Wave Period and Direction)

Table 4. WW3 available parameters.

ISCCP
Mean-Total (Mean Total Cloud Amount)
Mean-Total-High (Mean Cloud Amount of High Clouds)
Mean-Total-Mid (Mean Cloud Amount of Middle Clouds)
Mean-Total-Low (Mean Cloud Amount of Low Clouds)
Cloud-Temp (Total Cloud Temperature)
Cloud-Temp-High (Cloud Temperature of High Clouds)
Cloud-Temp-Mid (Cloud Temperature of Middle Clouds)
Cloud-Temp-Low (Cloud Temperature of Low Clouds)
Cloud-Prs (Total Cloud Pressure)
Cloud-Prs-High (Cloud Pressure of High Clouds)
Cloud-Prs-Mid (Cloud Pressure of Middle Clouds)
Cloud-Prs-Low (Cloud Pressure of Low Clouds)

Table 5. WW3 available parameter.

Reynolds
SST (Sea Surface Temperature)
Ice (Ice Coverage)

Table 6. Reynolds available parameters.

SWAN
mean_wav_dir (mean wave direction)
mean_wav_per (mean wave period and direction)
peak_wav_per (peak wave period and direction)
sig_wav_ht (significant wave height and direction)
swell_ht (swell wave height and direction)

Table 7. SWAN available parameters.

SWAN has differing spatial resolution depending on the SWAN region selected. These spatial resolutions are significantly higher than the other reanalysis datasets and are typically on the order of 1/10 to 1/100 of a degree. MATTCAF can produce products from 57 SWAN regions, but more SWAN regions can easily be added. When new years of SWAN data are added, as long as the file type and naming conventions are consistent with the current set of files, MATTCAF automatically detects the most recent SWAN year and pulls all available files up to that year. When a new SWAN region is downloaded, the area name simply needs to be added to the list of SWAN files for inclusion into the script.

MATTCAF can output 17 types of climatological calculations. These calculations are outlined in Tables 8 and 9. Each entry from Table 8 can be used with any entry from Table 9 with the exception of Traditional Climate Normal (TCN) anomaly which would fully cancel out to 0 if calculated. For this reason, the published number of climatological calculations is 17.

Types of Calculations	Description
Mean	Simple average of all selected years for a given month
Frequency of Occurrence	The frequency at which a parameter exceeds a user-defined threshold during all selected years for a given month.
Anomaly	A comparison between the 30-year average based on the World Meteorological Organization (WMO) standard and a second user-defined set of years for a given month. This difference captures the historical trend of the changing climate.

Table 8. Types of general climatological calculations used by MATTCAF. The 30-year WMO standard changes every 10 years. Due to dataset and storage limitations, MATTCAF chooses a range of years as close to the most recent 30-year average as possible for each given dataset. An in-depth description of these calculations and their uses can be found under the training tab on ACAF 6 (https://portal-alpha.fnmoc.navy.mil/acaf/). SWAN does have one additional calculation option: percentile. When percentile is chosen, an additional question will spawn asking for a specific percentile to calculate. This is only specific to the SWAN model, so it is not included in the general calculation options.

Types of Year Ranges	Description
Super OCN	Super Optimal Climate Normal (OCN): Average of most recent 5 years
OCN	Optimal Climate Normal (OCN): Average of most recent 10 years
TCN	Traditional Climate Normal (TCN): Average of most recent 30 years
Composite	User defined list of years in list format. (i.e. [2000,2001,2002])
El Nino Composite	Average of all El Nino years for a given month: MEI > 0.5
La Nina Composite	Average of all La Nina years for a given month: MEI < 0.5

Table 9. Types of year ranges available for use with the calculation types listed in Table 8. An anomaly product calculated with a TCN range of years will result in 0 everywhere, so TCN should not be selected with an anomaly calculation.

When frequency of occurrence is selected for the calculation, additional questions are spawned to define the threshold. MATTCAF can perform a frequency of occurrence calculation for thresholds greater than a value, less than a value, or between two values. If the between two values threshold is selected, MATTCAF will ask what the high value and low value is. The user will be requested to input numeric values based on the units associated with the selected parameter.

MATTCAF will then ask for the desired month in a two digit format (i.e. 01 for January, 02 for February, etc.). The selected climatological calculations will be run just for the chosen month throughout the applicable range of years. Additionally, MATTCAF can calculate biweekly products for all datasets aside from SWAN and ISCCP. The user can calculate just the first half of a month, second half of a month, or the entire month. The range of days in a given month are displayed in the title of the final product if something other than the entire month is selected.

MATTCAF will ask the user to define the highest latitude, lowest latitude, western-most longitude, and eastern-most longitude to define the desired box. There exists large variability among the spatial resolutions for the included reanalysis models. As mentioned earlier, MATTCAF will automatically adjust the latitudes and longitudes of the user's defined box to match the grid spacing of the chosen reanalysis model for SWAN and ISCCP. This adjustment, if necessary, will always increase the area of the box and never decrease so the original data request will never be cut. For all other reanalysis models, the user must match the latitude and longitude box to the model's resolution. If the input latitudes and longitudes do not match the model resolution, MATTCAF will repeat the question until a matching input is received. The spatial resolution and latitude/longitude intervals are displayed at the time this question is asked for ease of use.

MATTCAF uses a python module called Cartopy to generate figures, and 5 map projections are available for the user. These map projections are listed in Table 10.

Map Projections
plate (PlateCarree)
NPS (North Polar Stereographic)
SPS (South Polar Stereographic)
LC (Lambert Conformal)
R (Robinson)

Table 10. Available map projections.

Once the reanalysis model, parameter, calculations type, latitude and longitude box, month, and map projection are selected, a series of four yes or no questions will be asked for further customization. MATTCAF will always produce a PNG image as the basic output, but additional outputs can be selected.

First, MATTCAF will ask for high or standard image resolution. The standard image resolution is the standard Cartopy output while high resolution is 400 dpi (this value can be easily adjusted in the code itself). High resolution is not recommended when a significant number of products are produced at once as the file size is increased significantly.

Second, MATTCAF will ask if a custom interval should be used in the product's legend. If "No" is selected, MATTCAF will round the highest value in the resulting calculation's data to the highest tenths place and lowest value to the lowest tenths place. Should all values be the same (i.e. frequency of occurrence for extreme parameter values), a standard interval encompassing the selected value will be used. This interval will be dependent on the value. If "Yes" is selected, MATTCAF will spawn more questions to define the minimum and maximum values for the legend. This is recommended if multiple products of the same parameter are used to maintain a standardized contour convention. Regardless of the minimum and maximum values used, the color contours will be split into 20 ranges.

Third, MATTCAF will ask if a CSV is required. If "Yes" is selected, a custom CSV will be generated with the following columns: Latitude, Longitude, Parameter (with units in the title), U component, and V component. For parameters with no directional component (i.e. temperature, pressure, etc.), this will be filled with N/A. Otherwise, the u-component and v-components will be calculated and included.

Fourth, MATTCAF will ask if a NetCDF is required. If "Yes" is selected, a custom NetCDF will be generated including both magnitudes and directions if a direction exists or just magnitudes if no direction exists. Only data for the selected opbox will be included in the NetCDF. This NetCDF has been successfully tested in GrADS and will work with most programs that support NetCDF.

One additional question will spawn after these four questions depending on the box. Due to an artifact inherent in the FNMOC climatology team's version of Cartopy, a custom fix was required when products are generated with a longitude range that crosses the International Date Line. This fix requires an input of longitude line interval in degrees. If this condition is met, an input will be requested to define the interval at which longitude lines should be drawn (i.e. 5 for a longitude line drawn every 5 degrees). This is the most common user error for MATTCAF when this condition is met as the script will crash without this input.

Finally, a question will be asked to define a unique identifier for the product's naming convention. Here, a user can describe the location of the product to differentiate from other similar products if multiple latitude and longitude boxes are required (i.e. the user can add "WPAC" to the front of all produced files to include CSVs and NetCDFs). The user can also add directory paths to save the file in a separate location (i.e. "/home/climatology/products/WPAC").

The outputs of MATTCAF are compatible with several more tools to add further customization and applications to MATTCAF's climatology products. These tools will be discussed in future reports.

4. Example Output. To fully appreciate the utility of MATTCAF, an example input and output is presented below. MATTCAF was run with the following command line inputs:

1. Dataset: "CFSRv2"
2. Parameter: "W-ISO"
3. Level: "500"
4. Calculation: "Mean"
5. Years: "La Nina"
6. Month: "10"
7. Month section: "All"
8. Highest Latitude: "50"
9. Lowest Latitude: "25"
10. Western Longitude: "-126"
11. Eastern Longitude: "-66"
12. Map Projection: "plate"
13. High Resolution: "Yes"
14. Customize Legend Bounds: "Yes"
15. Maximum Legend Bound: "35"
16. Minimum Legend Bound: "0"
17. CSV generation: "No"
18. NetCDF Generation: "No"
19. File Name: "CONUS_"

The resulting plot is shown in in Figure 1 below. Figure 1 depicts the average winds over the Continental United States for the month of October using all years where a La Nina was occurring in October within the CFSRv2 dataset's period or record. This product was made with a custom legend value range of 0-35 knots, and a high-resolution PNG output. The filename of this output is CONUS_10OCT_500mb_Winds_CFSRv2_enso-.png. If CSV or NetCDF was selected as "Yes", MATTCAF would have output an accompanying CSV and NetCDF file with the same names.

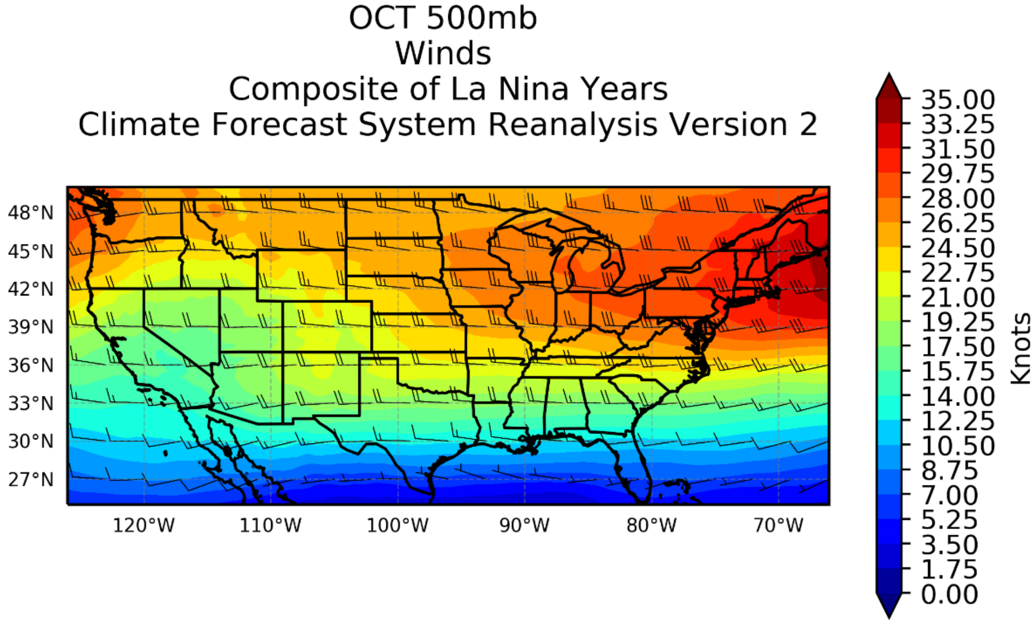

Figure 1. The resulting climatology product depicting 500mb average winds for October during La Niña years over the Continental United States.

5. <u>Successes.</u> MATTCAF proved vital to the success of FNMOC's operational climatology mission through the creation of approximately 56,500 individual products over a 1-year period to include same-day turnaround requests. MATTCAF has been distributed to all climatologists at FNMOC and is consistently used for short-term standard requests to support the Navy and DoD. Additionally, MATTCAF has been used to automate the reproduction of climate atlases using the available updated reanalysis datasets at FNMOC.

6. <u>Conclusion.</u> As the climate continues to undergo change at a significant pace, the operational use of climatology data will likely grow. By understanding the changing physical environment, the information warfare community can maintain an edge in all facets of warfare. MATTCAF provides the ability to swiftly generate decision-making products using a robust number of climate calculation methods. MATTCAF has proven to be a successful and vital tool for FNMOC's climatology team.

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