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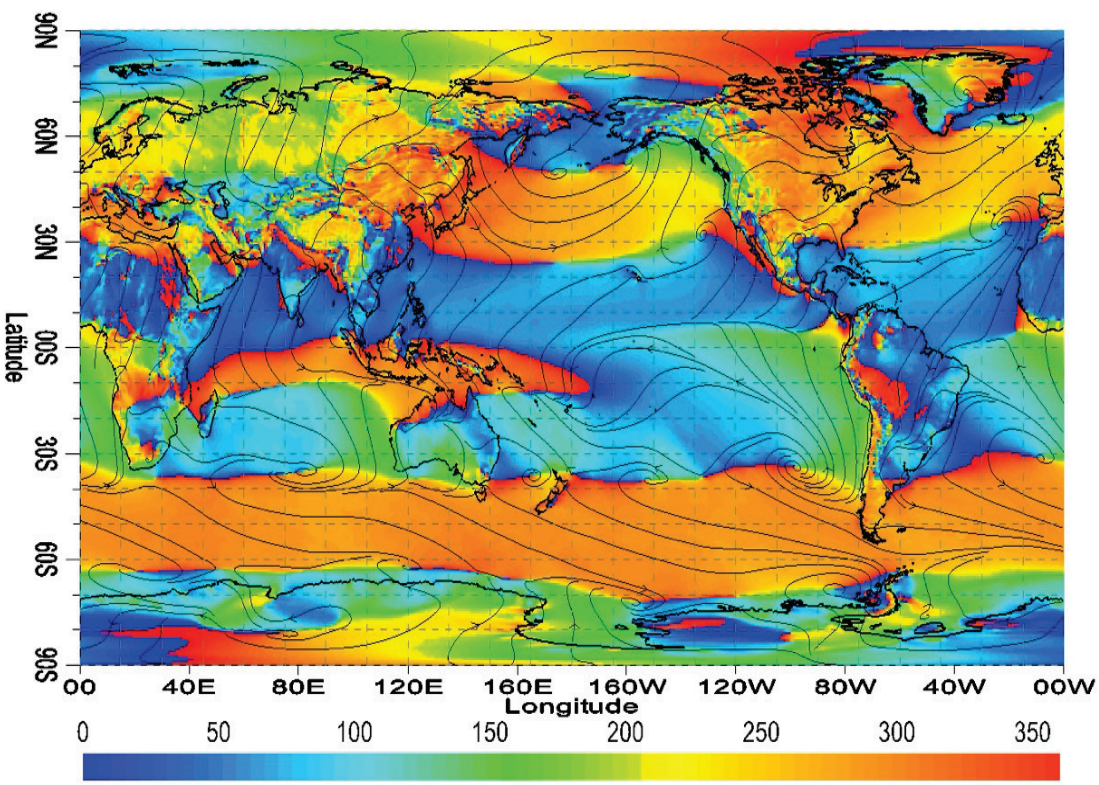
Geospatial Data Manipulation

A 10-Year Monthly Climatology of Wind Direction

Case-Study Assessment

Brendon Hoch and Samantha N. Cook

April 2023



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A 10-Year Monthly Climatology of Wind Direction

Case-Study Assessment

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Abstract

A 10-year monthly climatology of wind direction in compass degrees is developed utilizing datasets from the National Oceanic Atmospheric Administration, Climate Forecast System. Data retrieval methodologies, numerical techniques, and scientific analysis packages to develop the climatology are explored. The report describes the transformation of input data in Gridded Binary format to the Geographic Tagged Image File Format to support geospatial analyses. The specific data sources, software tools, and data-verification techniques are outlined.

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Preface

The work was performed for the US Air Force by the Terrestrial and Cryospheric Sciences Branch of the Research and Engineering Division, US Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL), under MIPR F2BDAN1239G003. At the time of publication of this report, Dr. John Weatherly was chief of the Terrestrial and Cryospheric Sciences Branch, and Dr. Caitlin A. Callaghan was chief of the Research and Engineering Division. The deputy director of ERDC-CRREL was Dr. Ivan P. Beckman, and Dr. Joseph L. Corriveau was the director.

The Information Generation and Management Branch of the Geospatial Research Division, ERDC Geospatial Research Laboratory (GRL), also performed this work. At the time of publication of this report, Mr. Michael F. Mailloux was branch chief, and Mr. Jeffrey B. Murphy was division chief. The deputy director of the ERDC-GRL was Ms. Valerie L. Carney, and the director was Mr. David R. Hibner.

COL Christian Patterson was commander of ERDC, and the director was Dr. David W. Pittman.

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1 Introduction

1.1 Background

The American Meteorological Society defines *climate* as the slowly varying aspects of the atmosphere-hydrosphere-land surface system. More commonly, climate is the expected weather at a specific location over a given period of time. Planners can leverage climatological data for guidance when making decisions about future natural resource management and infrastructure investments, particularly for military, transportation, and agricultural sectors (e.g., AMS 2021; Eylander et al. 2019; Guerrero et al. 2021; Hudda et al. 2018).

Climatological wind-flow directions are a critical consideration for applications related to the establishment of infrastructure for transportation and agricultural sectors. Oktal and Yidirim (2016) discuss how wind direction may affect the optimization of runway orientations. Scorah et al. (2012) discuss how wind-flow direction may affect renewable energy infrastructure such as wind farms. Wind-direction patterns also affect several aspects of Army operations, including ground and air maneuver (HQ, Dept. of the Army 2020), fires (HQ, Dept. of the Army 2012), flight operations (HQ, Dept. of the Army 2021), and biohazard or air quality management (HQ, Dept. of the Army 2013). However, wind-direction climatology datasets with global coverage expressed as a direction in compass degrees (0° to 360°) are often missing from commonly used environmental planning tools. To fill this gap, we developed a collection of monthly wind-direction climatology data layers with global coverage in Geographic Tagged Image File Format (GeoTIFF) (OGC 2019) to enhance existing geospatial decision support capabilities used by the Army.

1.2 Objectives

This report documents procedures used for developing a 10 yr* monthly wind direction climatology data layer with global coverage.

Our objectives are as follows:

- To describe the input data and our data acquisition process.
- To document the wind direction climatology development procedure
- To provide an overview of the resultant wind direction climatology output

1.3 Approach

We created a 0.5°-resolution wind-direction climatology monthly dataset by using 10 yr of monthly Climate Forecast System (CFS) forecasts from January 2011 to December 2020. We specifically chose this dataset following guidance from the US Air Force (USAF) 14th Weather Squadron, which supports the applied climatology mission for USAF and Army. Section 2 elaborates on the characteristics and availability of the CFS model datasets and the acquisition source. In Section 3, we describe calculations and formatting steps used to create a wind-direction climatology in GeoTIFF format, and Section 4 describes features of the resulting dataset. Finally, Section 5 contains conclusions and recommendations for future work.

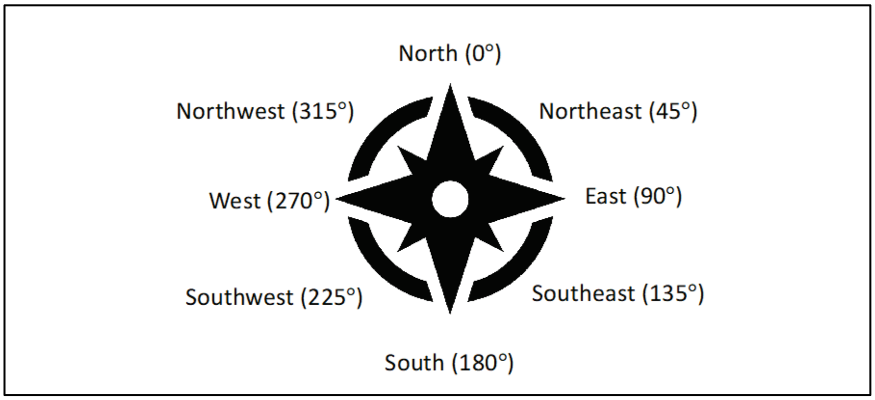
* For a full list of the spelled-out forms of the units of measure and unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248–52 and 345–7, respectively. *https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf*.

2 Input Data

2.1 Primer on wind direction conventions

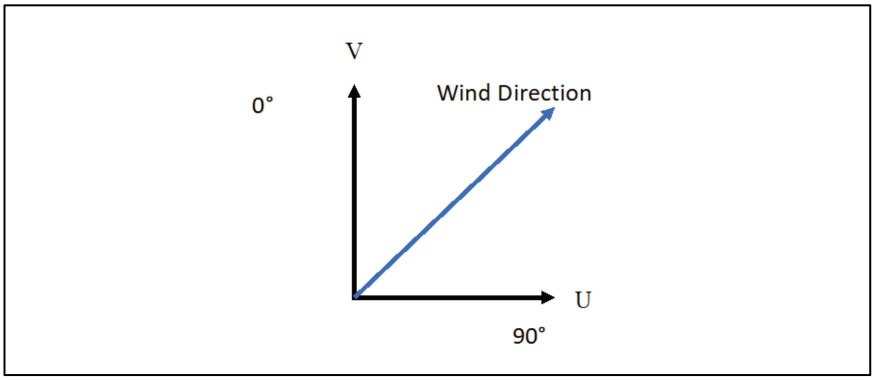
Meteorological convention for surface wind direction can be expressed in several ways. Traditionally, winds are named for the cardinal direction from which they originate. These wind directions are also expressed as compass degrees, beginning with 0° to the north and degrees increasing clockwise through 360° (Stull 2017). Figure 1 presents a compass rose indicating both wind direction in degrees (0°–360°) and in terms of cardinal directions.

Figure 1. Compass rose with wind direction expressed in cardinal directions and corresponding compass degrees.



In numerical weather prediction (NWP) models, the equations governing the dynamics and thermodynamics of the atmosphere express the horizontal wind in terms of their U (west–east) and V (south–north) component vectors (e.g., Figure 2).

Figure 2. Cartesian coordinates and U and V wind velocity components. Positive values correspond to east and north directions, respectively.



Since we obtained our input data to build our climatology from NWP model output, we refer to wind data in terms of their U and V components in our data acquisition overview (Section 2.3). Later, in Section 3.2, we demonstrate our procedure for converting U and V to compass wind directions.

2.2 Climate Forecast System (CFS)

To develop the wind climatology, we used data from the National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS), National Centers for Environmental Prediction (NCEP), CFS, NWP model version 2 (Saha 2014). CFS simulates the interactions between the atmosphere and surface (land or oceans) on a global scale in three dimensions.

The current version of CFS (CFS v2) was implemented by NCEP in January 2011. CFS combines elements of an atmospheric model, an ocean-circulation model, and a land-surface model. By linking these normally disparate models together, CFS serves as a fully coupled atmosphere-ocean-land model used primarily for operational real-time seasonal prediction. The system features global ocean-data assimilation, an interactive four-level soil model, and an interactive three-layer sea-ice model. CFS incorporates observations from a variety of data sources, including surface weather stations, radiosondes, and satellite imagery. NCEP runs the CFS four times daily, providing datasets as full monthly means in horizontal resolutions ranging from 0.3° to 2.5°.

2.3 CFS wind data acquisition

The CFS data were obtained from the National Center for Atmospheric Research (NCAR) Computational and Information Systems Lab (CISL) Research Data Archive (RDA) at Boulder, Colorado, USA (Saha et al. 2012). The RDA contains a diverse collection of meteorological and oceanographic observations, operational and reanalysis model outputs, and remote sensing datasets to support atmospheric and geosciences research.

RDA provides the CFS data as originally published in Gridded Binary (GRIB) formatted file version 2 (GRIB2). GRIB2 is a concise data format commonly used in meteorology to store operational forecast weather data from NWP models from operational forecasting agencies worldwide.

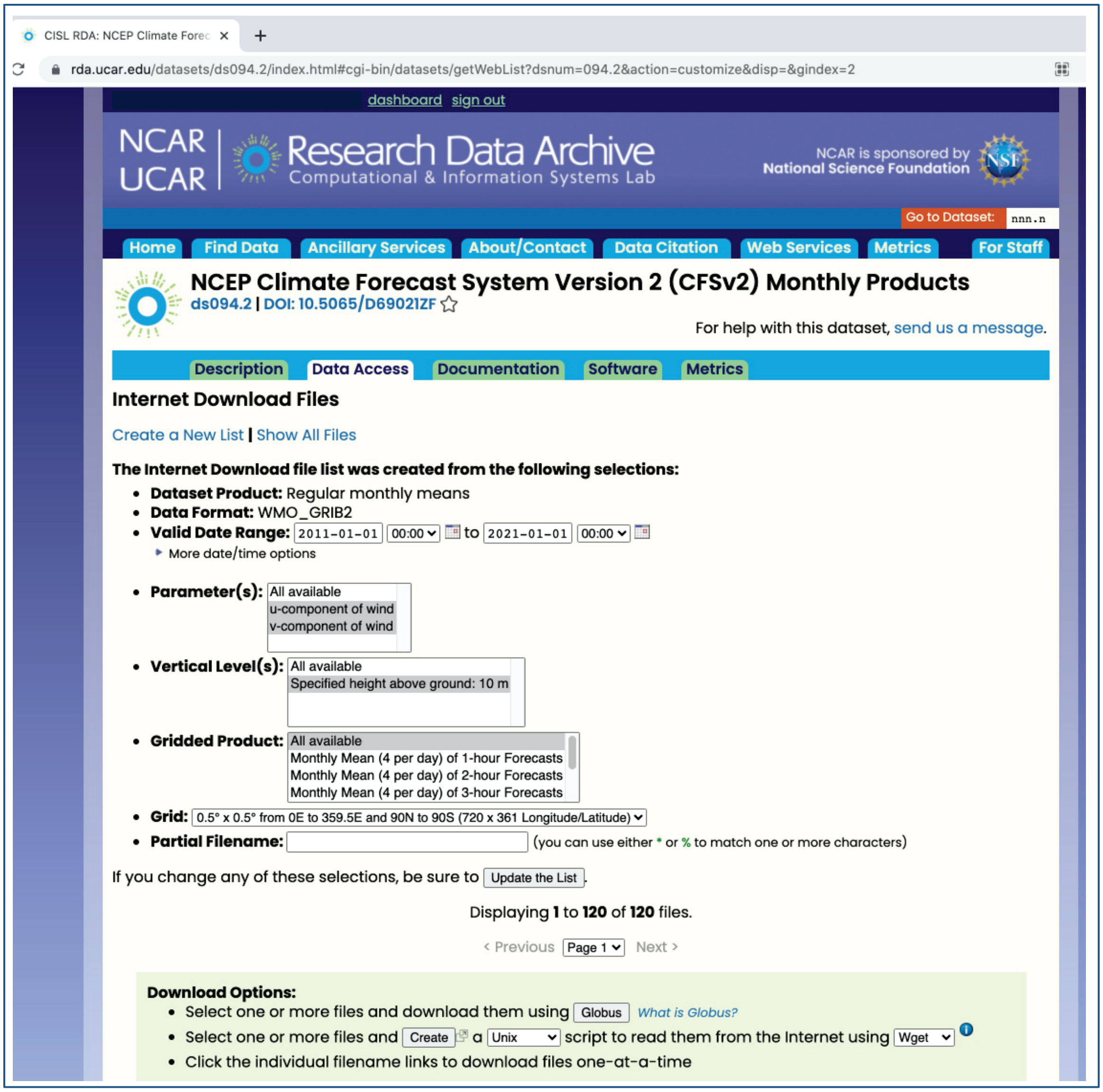
Created with specifications provided by the World Meteorological Organization, GRIB2 files rely on external tables to provide the necessary metadata required to use the data with other software or NWP applications; this allows each file to be reduced in size compared to other commonly used geospatial file formats (WMO 2003).

The RDA provides three different CFS version 2 data products, with each product featuring a reference number: Selected Hourly Time Series Products (ds094.0), 6-Hourly Products (ds094.1), and Monthly Products (ds094.2). For our climatology method, we selected the Monthly Products (ds094.2), which provide monthly means of each weather parameter. From there, the data request was further narrowed to data files with 0.5° horizontal resolution data (approximately 56 km grid spacing near the equator). Data files containing near-surface atmospheric parameters, including the *U* and *V* components of the wind at 10 m elevation above ground level, were selected to narrow the request further. Ten years of monthly data were selected to develop the climatology, from January 2011 to December 2020.

In addition to providing access to the NCEP CFS datasets, RDA also provides all of the resources and program scripts necessary to download data files in bulk through their graphical user interface (GUI) website. Figure 3 contains a screen capture of the RDA and the criteria we selected for our data download.

To more easily calculate monthly wind direction averages for the 10 yr duration, we converted the GRIB2 files downloaded from the RDA to Network Common Data Form (commonly known as netCDF) format. The netCDF file format is developed and maintained by the Unidata Program at the University Corporation for Atmospheric Research, Boulder Colorado. As of the writing of this report, NetCDF is currently on software version 4.8.0 (UCAR Community Programs 2023a).

Figure 3. Web browser view of the National Center for Atmospheric Research (NCAR), Computational and Information Systems Lab (CISL), Research Data Archive (RDA), website with Climate Forecast System (CFS) data selections.



To complete the conversion of the data files from GRIB2 to netCDF, we employed the wgrib2 (version 3.0.2) software utility. Wgrib2 is a product of the NOAA/NWS/NCEP Climate Prediction Center (NOAA 2020). The software provides relatively quick and easy command line options for reading, subsetting, and writing files to other formats, including netCDF. The software is freely available from NOAA; the source code is either public domain or available through GNU's Not Unix (GNU) licensing.

Using our download criteria, the original CFS data files provided by the RDA consisted of 735 MB tar bundles of GRIB2 files for each month between January 2011 and December 2020, resulting in approximately 22 GB of data. While the RDA GUI assists the user in narrowing which files contain their desired parameters, it does not actually modify the original GRIB2 files to filter out the undesired parameters. The interface provides the GRIB2 files as originally produced by the CFS. In addition to the requisite surface wind-velocity data contained within U and V wind components, the GRIB2 files that we downloaded also included numerous meteorological variables that were unnecessary for building the wind direction climatology. Thus, we extracted the U and V wind-velocity components from the CFS GRIB files and subsequently converted them to netCDF format utilizing wgrib2. This alteration substantially reduced the size of the data files, making them more efficient to work with and transfer between systems.

These processing steps generated 10 years' worth of monthly wind velocity data in netCDF format (120 data files).

3 Wind Climatology Development

3.1 Averaging the data

The next task was to create an average of the monthly mean data for each month by using command line tools. Climate Data Operators (CDO) is a collection of command line operators designed to manipulate and analyze NWP data that include support for netCDF files (Schulzweida 2019). The open-source software package is provided by the Max Planck Institute for Meteorology and is freely available through the GNU General Public License (GPL). We used CDO version 1.9.10 for this project, which includes functions to average data from multiple annual netCDF files via the ensmean command into 12 monthly files.

3.2 Computing wind direction from component vectors

As previously discussed in Section 2.1, wind-velocity components can be translated to wind-direction origin in terms of compass direction (0°–360° degrees; 0° at due north). To provide the data in this format, the U and V data require an additional transformation with the following programmatic equation:

$$D = 180° + \frac{180°}{\pi} arctan(U, V). \tag{1}$$

In Equation (1), D represents the meteorological wind angle (direction) in compass degrees, U represents the magnitude of the west-east wind direction (negative for winds flowing towards the west), and V represents the magnitude of the south-north wind direction (negative for winds flowing towards the south). *atan2* serves as a computer function that calculates the arc-tangent of U/V (Zender 2023).

Throughout the following results and discussion, the wind-origin direction D is described using the meteorological usage of northerly (from the north), southerly (from the south), easterly (from the east), and westerly (from the west).

To apply this transformation to the CFS data, we used a command line utility package known as netCDF Operators (NCO). Specifically, we used the netCDF arithmetic processor (ncap2) from the NCO utility library, version 4.6.8. The NCO software is available from NCAR and is freely available through open-source licensing.

3.3 Data format conversion

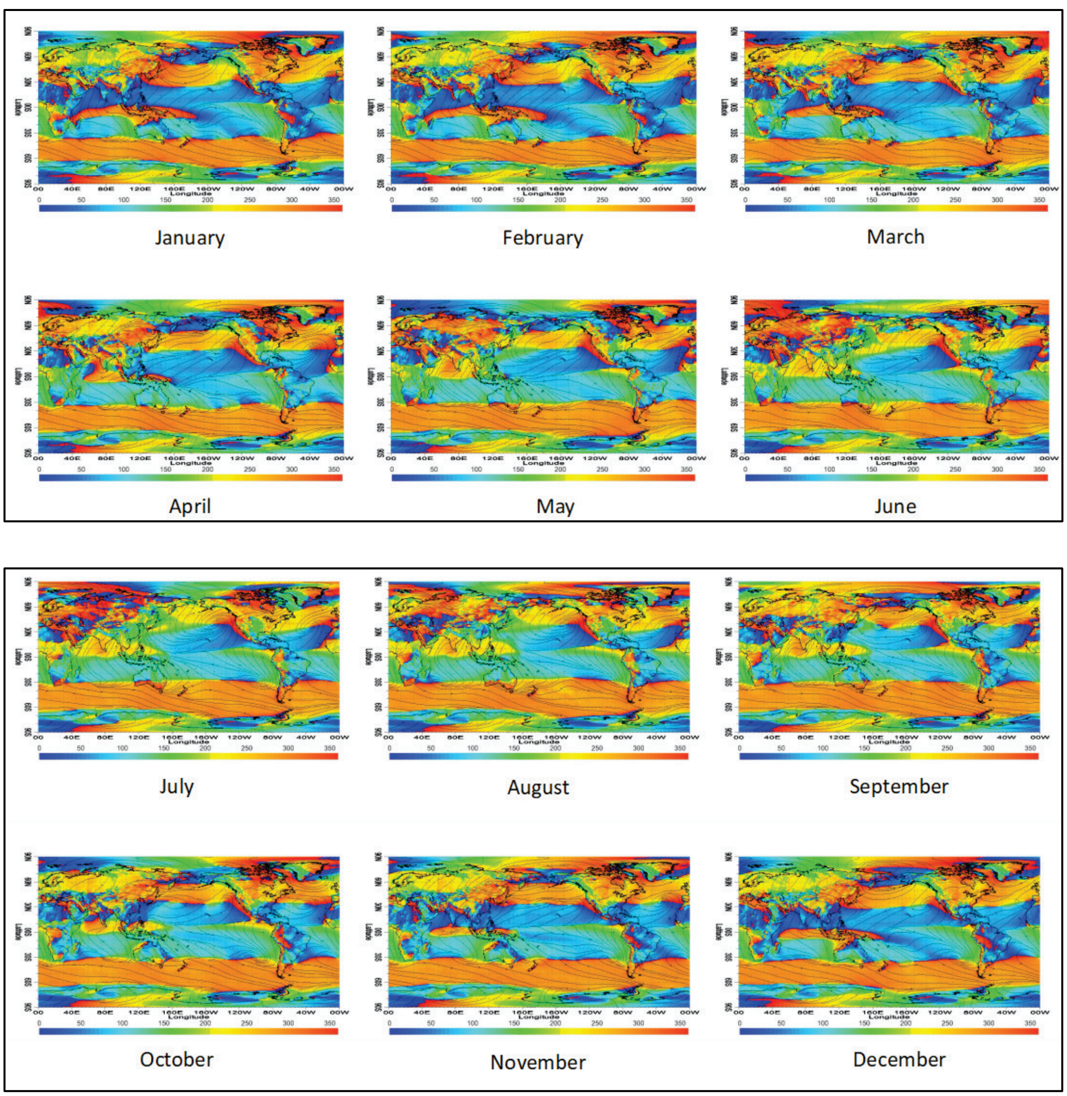
To facilitate incorporation of the wind-direction climatology data into Geographic Information System (GIS)–based analyses, we converted the derived wind direction climatology netCDF files to GeoTIFF using QGIS version 3.16.5-Hannover, a GIS GUI software package available for multiple operating systems including MacOS, Microsoft Windows, and Linux. QGIS supports the import and export of multiple file formats including netCDF and GeoTIFF. The software is freely available under GNU GPL. We used QGIS to open each of the netCDF files and convert to GeoTIFF format by using the export functionality embedded within the software.

4 Results

4.1 Overview

As an initial means of quality control, the wind-direction climatology data were visualized and compared to known empirical global climatological wind patterns. Figure 4 shows the resultant monthly climatology datasets, with color shading keyed to compass-based wind-origin direction. Black streamlines in the figure highlight wind flow patterns. However, it is important to remember that these streamlines are indicative only of wind direction and that neither the length nor spacing of the streamlines has any relationship to wind speed.

Figure 4. Monthly 2011–2020 global wind direction climatology in compass degrees; *black* streamlines indicate general wind-direction patterns.

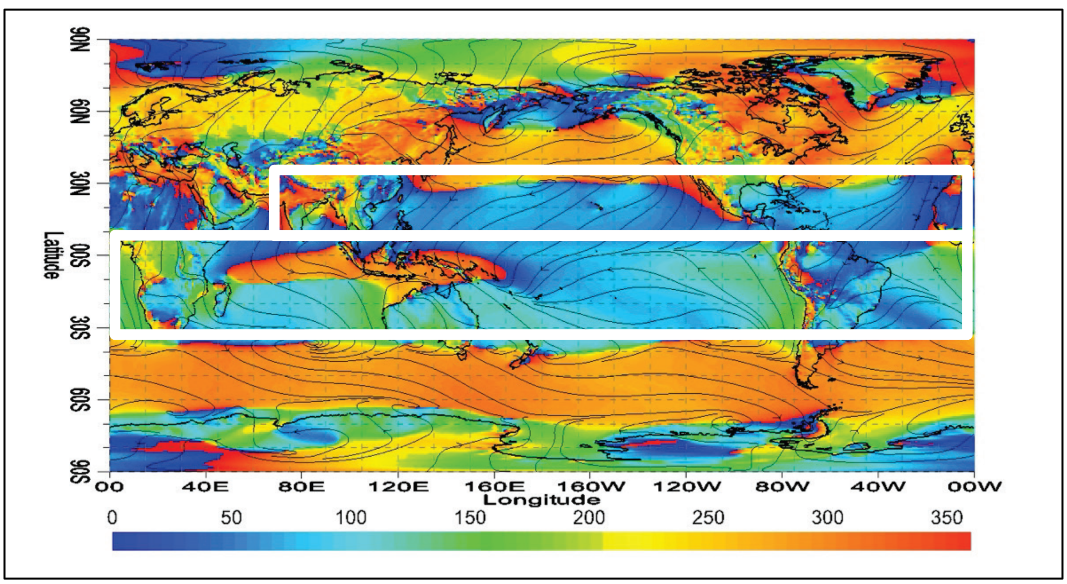


Climatological global wind circulation (CGWC) varies over the earth's surface due to such factors as pressure gradient forces, sun angle, the Coriolis Effect, and surface-roughness variations and differential heating between land masses and ocean areas (Lydolph 1985). It is beyond the scope of this report to fully explain the physical reasoning behind CGWC patterns, the reader is referred to meteorological textbooks such as Stull (2017) for additional information. The remaining subsections highlight key wind direction features present in the climatology output.

4.2 Northeast and southeast trade winds

As part of CGWC patterns, air flow in the vicinity of the equatorial region is characterized with winds converging towards a boundary commonly known as the Intertropical Convergence Zone. Between 30° north latitude and the equator, these winds typically flow from the northeast, while between 30° south and the equator, the winds typically originate from the southeast. These winds are commonly known as *trade winds*, named such as they provided sailing ships with an ocean route to the New World in the preindustrial age. As can be seen in Figure 5, the climatological dataset adequately represents the Trade Winds, especially over the Atlantic and Pacific Oceans areas.

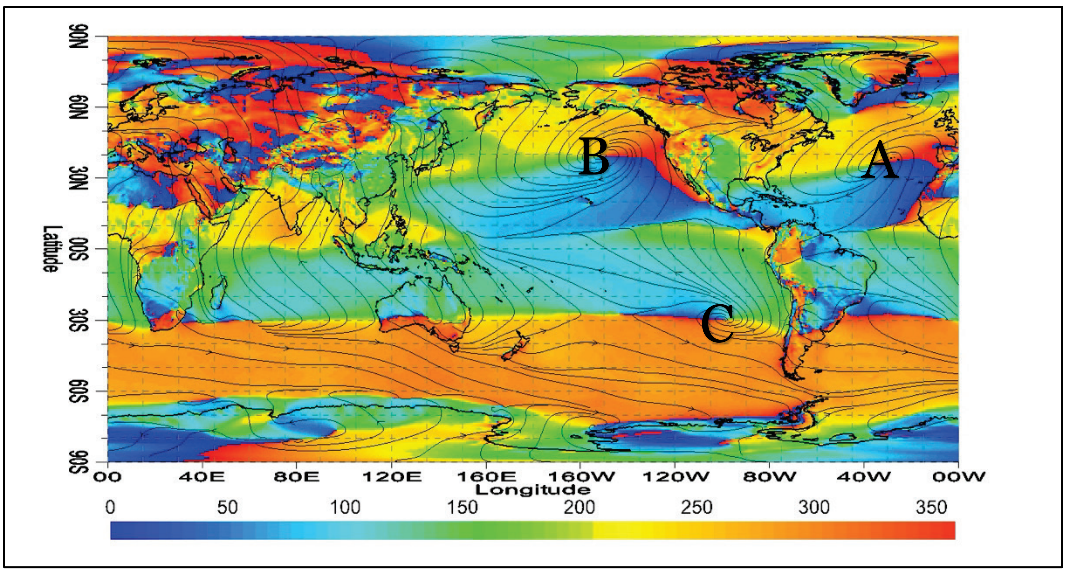
Figure 5. March 2011–2020 global wind direction climatology in compass degrees; *white boxes* highlight data commonalities with climatological global wind circulation (CGWC) trade wind patterns.



4.3 Subtropical highs

Figure 6 annotates three areas of the wind-direction climatology that illustrate the subtropical high-pressure areas, which feature clockwise rotation in the Northern Hemisphere and counterclockwise rotation in the Southern Hemisphere, and all are considered to be semipermanent atmospheric phenomena. Figure 6 (point *A*) is in the vicinity of what is commonly referred to as the *Bermuda High*, which is situated over the northeastern Atlantic Ocean at approximately 40° north latitude, 40° west longitude. The system is named due to its proximity to the islands of Bermuda. Figure 6 (point *B*) is in the vicinity of the 40° north latitude 150° longitude in an area of high pressure typically known as the *Pacific High*, located northeast of the Hawaiian Islands. Figure 6 (point *C*) annotates a semipermanent area of high pressure west of the central Chilean coast, known as the *South Pacific High*.

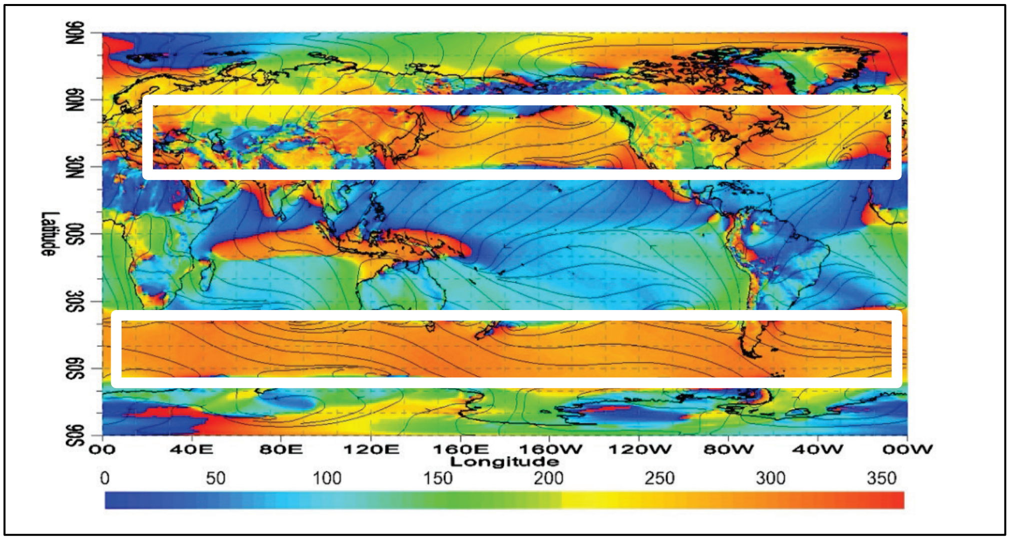
Figure 6. July 2011–2020 global wind direction climatology in compass degrees: (*A*) Bermuda High, (*B*) Pacific High, and (*C*) South Pacific High.



4.4 Midlatitude westerly winds

In the middle latitudes (between 30° and 60° north and south), CGWC wind patterns are typically represented by westerly winds. Figure 7 clearly shows this midlatitude westerly pattern. The data show the consistent coherent wind pattern in the southern hemisphere, a result of less continental land surface area interfering with wind flow.

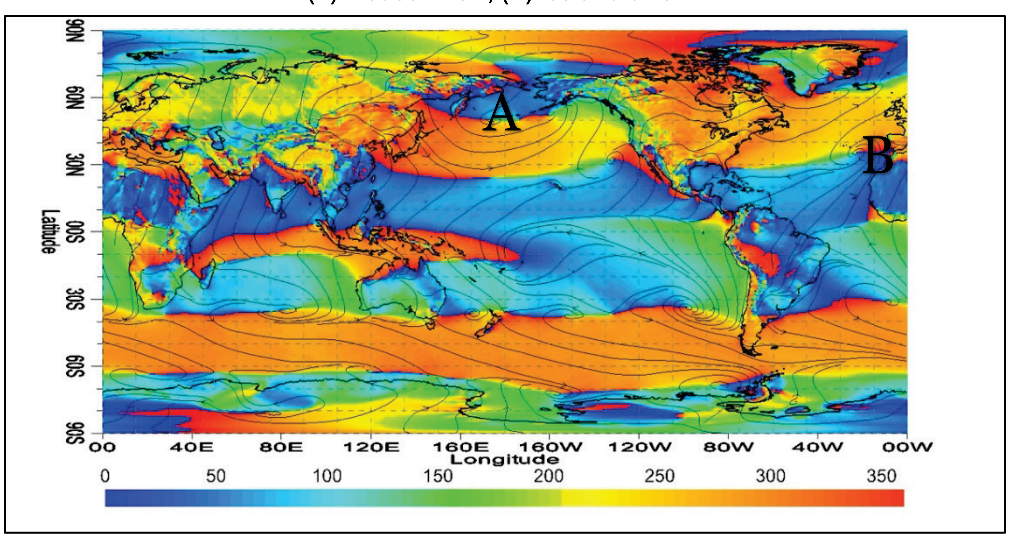
Figure 7. March 2011–2020 global wind direction climatology in compass degrees; *white boxes* highlight data commonalities with CGWC trade midlatitude westerly wind patterns.



4.5 Subpolar lows

Figure 8 (point *A*) annotates the climatology correspondence with a center of low pressure commonly known as the *Aleutian Low*. Located off the southwest coast of Alaska, the system is a known CGWC pattern that generally brings strong onshore flow toward the west coast of North America. Figure 8 (point *B*) marks an area of low pressure situated between Iceland and Greenland. Commonly known as the *Icelandic Low,* this circulation typically steers midlatitude cyclones towards Great Britain and Europe.

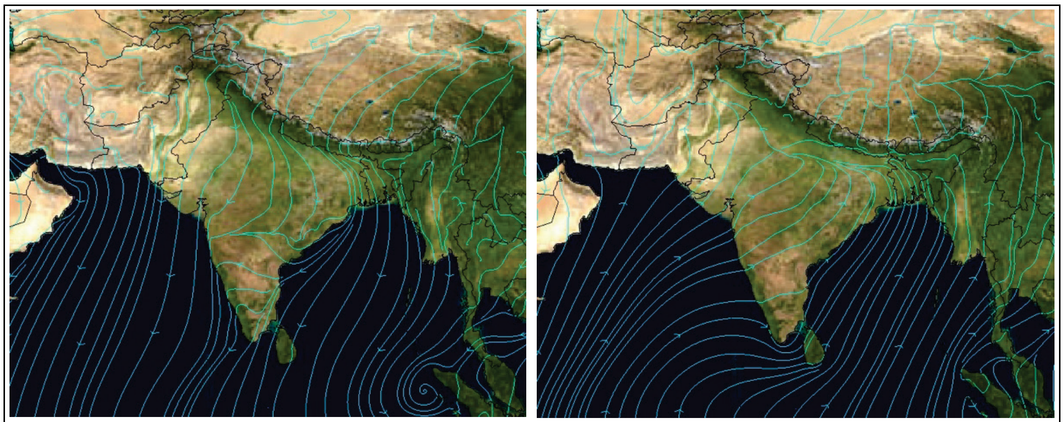
Figure 8. January 2011–2020 global wind direction climatology in compass degrees; (*A*) Aleutian Low; (*B*) Icelandic Low.



4.6 Monsoon winds

Seasonal reversal of winds is commonly referred to as *monsoon winds*. These types of winds are found in many areas and are particularly well defined in Southeast Asia (Lydolph 1985) During the summer months, low pressure typically develops over the Indian subcontinent near the surface of the earth. This results in seasonal on-shore winds from the Bay of Bengal and the Arabian Sea. The pattern reverses itself in winter. High pressure forms over land and causes surface winds to diverge, resulting in winds flowing from land areas to the coast. Figure 9*a* and Figure 9*b* visualize the airflow from the generated climatology for January and July, respectively.

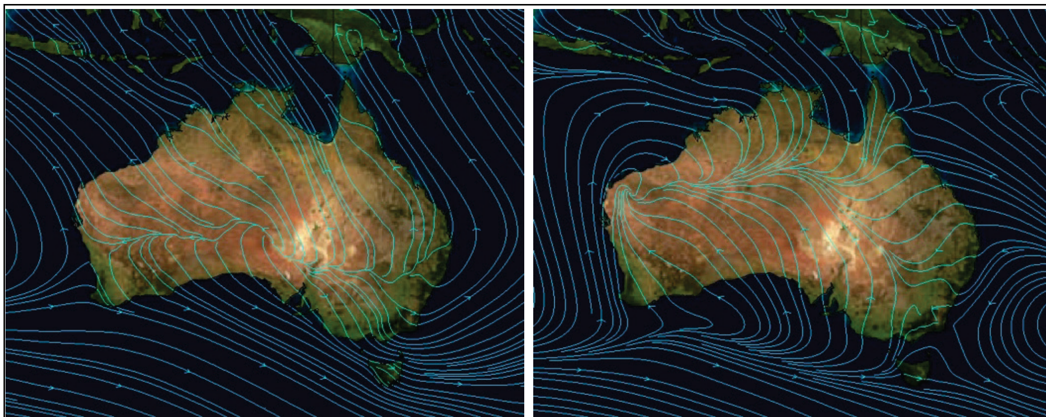
Figure 9. (*a*) January 2011–2020 global wind direction climatology wind flow; (*b*) July 2011–2020 global wind-direction climatology wind flow.



(a) (b)

Another area with a similar wind pattern is in Australia. Similar to India, surface winds typically flow on-shore from summer and reverse direction during winter months. Figure 10*a* and Figure 10*b* visualize the airflow from the generated climatology over Australia for January and July, respectively.

Figure 10. (*a*) January 2011–2020 global wind direction climatology wind flow; (*b*) July 2011–2020 global wind-direction climatology wind flow.



(a) (b)

The climatology we developed also reflected seasonal shifts in wind directions in other areas of the world, such as Western Africa and the southwestern United States (Lydolph 1985).

5 Conclusions and Recommendations

This report outlined the steps taken to develop a global climatology of wind direction in a commonly accessible GeoTIFF format. Ten years of 0.5° resolution data were acquired from the NCEP CFS model version 2 through the NCAR CISL RDA. Once obtained, surface (10 m above ground level) *U* and *V* wind components were extracted and converted to the netCDF format using Wgrib2 software. Additional software tools such as CDO and NCO were utilized to average the data and convert *U* and *V* wind components to wind direction in compass degrees. Finally, the climatology data were exported to GeoTIFF format so that they could be easily accessed for a variety of geospatial applications. By aggregating the requisite datasets in their native data format, averaging them into a climatological mean, and storing the data in a commonly used format, the dataset is more accessible to the user community.

The process by which the wind-direction climatology was developed from model-gridded data could also be applied to other meteorological parameters. Other parameters could be developed into similar climatological datasets that may be used by the military, government, public, and private sectors for planning purposes and or to conduct additional research. Data provided in netCDF and GeoTIFF formats ensure a wide range of disciplines would benefit from the data.

While the process to develop the wind-direction climatology was manually performed for this task, additional work could be implemented to automate the process. Once a system is developed, the climatology may be updated at regular intervals and provided to customers in need of a simplified climatological dataset. Additionally, the CFS data from the RDA are available through a Thematic Real-time Environmental Distributed Data Services data server at NCAR (UCAR Community Programs 2023b). The process to create the climatology could potentially be streamlined by developing a series of programs designed to interact with the data remotely (using client-server technology), thereby minimizing the need to download and physically store the data on local disk.

The climatology produced for this effort was for a global domain. Future efforts could potentially build on this work to produce regional datasets using similar methods with higher-resolution input data sources. For example, NWP models such as the NCEP North American Model could be used to generate wind-direction climatology data for North America with 12 km horizontal resolution.

The resulting wind-direction climatology dataset produced for this work was qualitatively described. It would be interesting to compare this dataset produced using CFS v2.0 forecasts to wind direction climatologies derived from other climatological models. Additionally, for users interested in historical weather trends, performing a decadal temporal comparison of wind or other atmospheric climatological data would also provide users with a trend as to how conditions may be changing or evolving in a particular area.

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Abbreviations

AMS	American Meteorological Society
CDO	Climate Data Operators
CFS	Climate Forecast System
CGWC	Climatological global wind circulation
CISL	Computational and Information Systems Lab
GeoTIFF	Geographic Tagged Image File Format
GIS	Geographic Information System
GNU	GNU's Not Unix
GPL	General Public License
GRIB	Gridded Binary
GRIB2	Gridded binary format (version 2)
GUI	Graphical user interface
HQ	Headquarters
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCO	netCDF Operators
netCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
NWS	National Weather Service
QGIS	Quantum Geographic Information System
RDA	Research Data Archive
UCAR	University Corporation for Atmospheric Research
USAF	US Air Force

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A 10-year monthly climatology of wind direction in compass degrees is developed utilizing datasets from the National Oceanic Atmospheric Administration, Climate Forecast System. Data retrieval methodologies, numerical techniques, and scientific analysis packages to develop the climatology are explored. The report describes the transformation of input data in Gridded Binary format to the Geographic Tagged Image File Format to support geospatial analyses. The specific data sources, software tools, and data-verification techniques are outlined.

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