Received: 27 February 2018 | Revised: 12 June 2018 | Accepted: 13 June 2018

DOI: 10.1002/wcc.544

WILEY WIREs CLIMATE CHANGE

ADVANCED REVIEW

Understanding weather and climate of the last 300 years from ships' logbooks

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Funding information
Ministerio de Economía y Competitividad, Grant/Award Numbers: CGL2015-72164-EXP/AEI, CGL2014-51721-REDT, CGL2015-69699-R, CGL2013-44530-P

Edited by Matilde Rusticucci, Domain Editor, and Mike Hulme, Editor-in-Chief

Ships' logbooks have been preserved in archives of different European countries. This paper reviews how their records provide reliable information relevant to meteorology and climatology, extending the observational record back to at least the early 18th century. This allows describing weather during historical events, improving the knowledge on hurricanes or unveiling multidecadal variability previously unsuspected, such as the steady enhancement of the Australian monsoon, the high variability of the atmospheric circulation over the Euro-Atlantic region during the Late Maunder Minimum or the relationship between the Western North Pacific Summer Monsoon and the El Niño—Southern Oscillation. Observations from ships can feed long-term reanalysis projects and contribute to reduce their uncertainties over the oceans. The extended record of observations also aids the search of analogues before the human fingerprint, thus improving the detection and attribution of climate change. The integration with paleoclimate proxies is a complex task that requires merging heterogeneous records with a wide range of time resolutions, spatial density, and responses to the climate system. However, recent international efforts open the field to new opportunities. Summing up, logbooks are a consistent, but underexploited, source of relevant climatic data that will widen our knowledge of the past climate. This in turn provides a way to better understand present climatic variations and predict future changes.

This article is categorized under:
Paleoclimates and Current Trends > Modern Climate Change

KEYWORDS
climate variability in the last millennium, climatology, documentary sources, ships' logbooks

1 | INTRODUCTION

Currently, the Earth system, that is, the land, oceans, atmosphere, and poles, is monitored by a complex array of instruments that are mostly connected in real time. These include surface observations from meteorological and climatological stations; upper-air observations from radiosondes and devices such as lidars and sodars; marine observations from ships, moored and drifting buoys; aircraft-based observations; satellite observations from geostationary and polar platforms or weather radar observations. All these data are ingested in supercomputers through communication systems and lead to global and local weather forecasts, as well as to sophisticated climate products such as reanalyses. These gridded datasets provide a dynamically-consistent estimate of the climate state through a data assimilation scheme and a model that incorporates all available observations (~7–9 million) every 6–12 hr over the period of analysis (e.g., Kalnay et al., 1996; Kobayashi et al., 2015; Uppala et al., 2005; https://climatedataguide.ucar.edu/climate-data/atmospheric-reanalysis-overview-comparison-tables). In

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this highly technological environment, why should we pay attention to old ships' logbooks of the sailing era? Why should climatologists invest time and effort in these old records that have been preserved since the end of the 17th century in different archives? (García-Herrera, Wilkinson, et al., 2005, Wheeler, 2014). This paper tries to answer these questions and show the value of the meteorological observations kept in these documents. After a historical overview, the meteorological applications will be described, with emphasis on hurricanes and weather descriptions during historical events. Next, we will show also how historical records can be combined with modern instrumental observations to reveal low-frequency features of certain circulation systems. Some conclusions and outlook will be drawn in the last section.

2 | HISTORICAL OVERVIEW

From the 15th century, European powers, initially Portugal and Spain but soon followed by France, the Netherlands, and England, established overseas empires that demanded regular and reliable lines of marine communication. This, in turn, required new methods of navigation. Previously, coastal sailing could be conducted merely by sighting onto known land features (Taylor, 1956). In “blue water” navigation across the Atlantic, Indian, and Pacific Oceans this was impossible. The challenge was to determine the ship's daily latitude and longitude. Both required a degree of calculation and estimation—the former less so but the latter decidedly more so—(Robertson, 1785; Norie, 1889). The necessary observations were from earliest times dutifully noted and recorded and, so, the ships' logbook or journal was born by dint of navigational necessity. In fact, as early as 1575, Phillip II of Spain made mandatory through a Royal Order the completion of diaries for all Spanish ships sailing through the Atlantic (García-Herrera et al., 2003). Assuredly, as time went by, these documents became more formalized and included much more detail on the day-to-day management of the vessels. Shipboard incidents such as the recording of storm damage, mortality, and matters of discipline, all went to produce an account to fulfill regulatory requirements, accountability to ship owners and, in the case of naval services, to establish a legal record that could be produced at a Court of Enquiry. It must be noted therefore that logbooks were kept also for such administrative or legal purposes (Wheeler & García-Herrera, 2008). Such bureaucratic considerations notwithstanding, the survival of the ship and crew depended on their ability to observe accurately the weather and sea conditions, and, consequently, there is a prima facie case to argue that those observations are highly reliable. The millions of pages of such records that are preserved in different archives (García-Herrera, 2006; Koek & Können, 2005; Prieto, Gallego, García-Herrera, & Calvo, 2005; Wheeler, 2014) today represent a valuable resource and provide unique information for an area of the globe poorly covered (the oceans) and for a period (c. 1680–1900) when weather observation procedures were yet at an early stage and, additionally, climate was mostly driven by internal variability and natural forcings.

Once the ship's voyage was completed, the logbook was usually delivered to a royal or company officer, depending on the ownership of the vessel. In the early times, these logbooks acted also as the basis for the training of captains and pilots. Once the various sailing routes were established, the logbooks were either stored, as was mostly the case in Britain, or, as happened in some cases in Spain, destroyed to avoid the valuable information they contained falling into the hands of rival powers. By the mid-18th century, the logbook content was becoming more homogeneous irrespective of the country of origin and it came to include daily (sometimes even hourly) observations, information on the midday position, wind force and direction, and a description of sea and weather state (García-Herrera, Wilkinson, et al., 2005). Figure 1a shows two pages of the logbook from the Spanish brig S Francisco Javier (La Suerte) during a trip from Cádiz (Spain) to Cartagena de Indias in Colombia. The page layout is typical, with the bi-hourly observations of ship's course, wind direction and leeway that is, is the degree to which the prevailing wind and currents deviates the ship from its steered or compass course, (columns 3–5). In other cases, the records were taken hourly and the observations again included wind force. The dates are recorded in the second column from the right. The main text is devoted to a narrative account for changes in weather conditions, or relevant issues of daily life onboard, while the computations of latitude and position are included in the final rows. Similar layout can be seen in Figure 1b, corresponding to April 3–4, 1827 of the East India Company vessel Farquharson during a trip between the Canary Islands and Cape Verde.

Latitude, from the earliest days, was relatively easy to estimate by sighting the “altitude” of the midday Sun. Longitude was a more challenging and controversial matter (Sobel, 1996). Before the invention of the marine chronometer in the late 18th century, it could only be determined by close attention to the ship's apparent course (using the compass), its speed through the water (using the log line) and the prevailing wind directions and strengths (made by the compass and visual observations). It is for this latter reason that ships' logbooks are, as noted above, an abundant source of reliable data for wind direction and force. Even following the introduction of the marine chronometer in the 19th century, the convention of recording wind direction and wind force data persisted, as it does to the present day. Some of these marine observations are from as early as the late 17th century, and among the earliest instrumental marine observations are those made by Halley (1686) and Hadley (1735), it was not until the 1780s and 1790s that regular air pressures and temperatures are found in some of the logbooks of the English East India Company (Dalrymple, 1778; May, 1974). The widespread use of the marine barometer as a weather

(a)

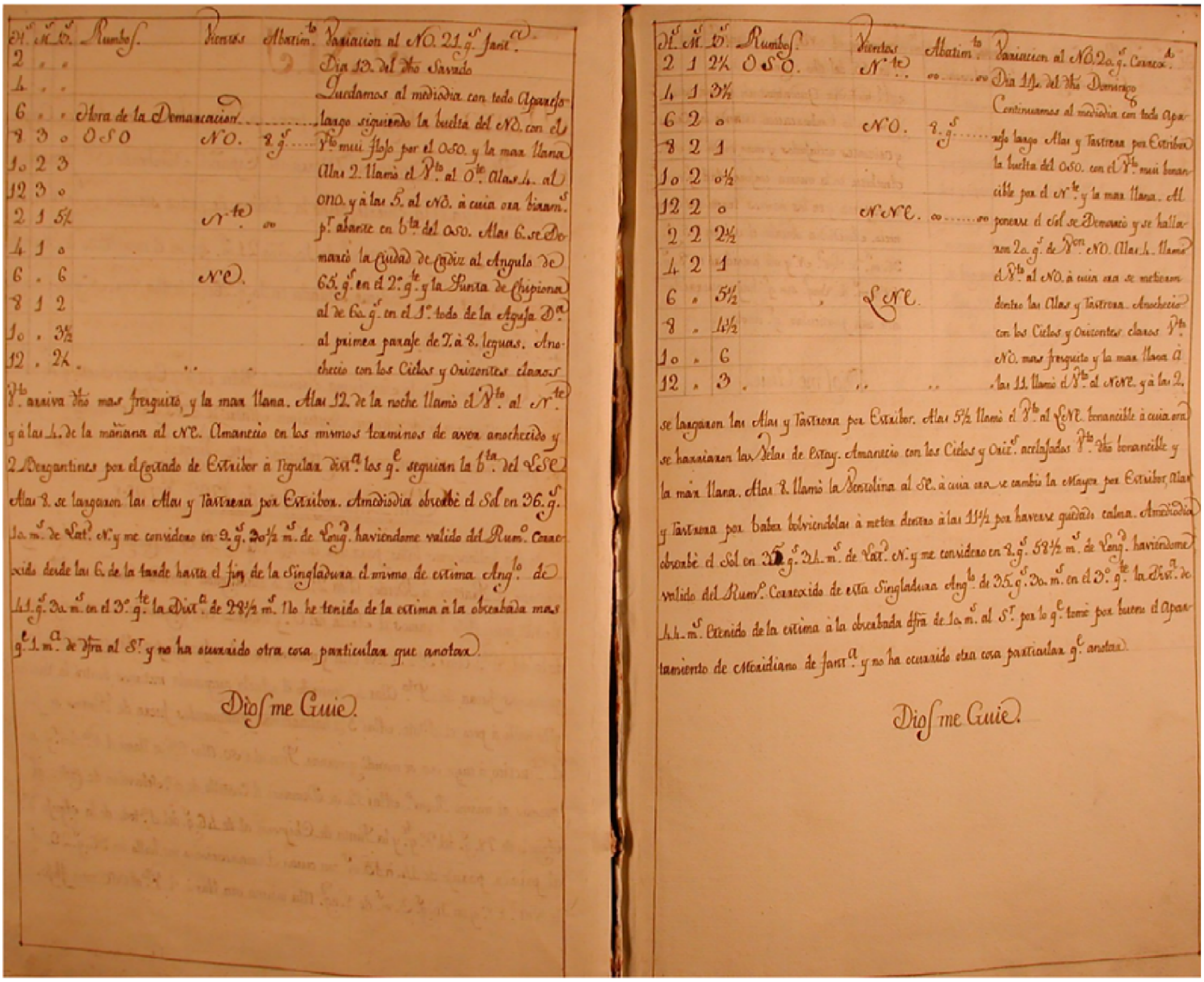

FIGURE 1 (a) Pages of the Spanish brig S Francisco Javier (La Suerte). See the text for details. With permission from the Archivo del Museo Naval in Madrid (Ms 241) (b) Pages HEICS (Honourable East India Company Ship) Farquharson, 3–4 April, 1827. The vessel is between the Canary Islands and Cape Verde islands, bound for St. Helena and then Whampoa. Ref. British Library: L/MAR/B/40/D

prognosticator—rather than a recording device—was largely achieved by the 1840s. The appearance in logbooks of instrumental data sensu stricto, that is, barometer and thermometer readings, began, albeit falteringly, in the 17th century but only became formalized in the mid-19th century following the 1853 Brussels Conference organized by the American Hydrographer Matthew Maury (Maury, 1854).

It was soon recognized that these daily observations had scientific applications to hydrography, cartography, and the development of sailing directions, with direct application to exploration or commerce. Moreover, as time passed, and a sense of scientific enquiry became more widespread, some ships' logbooks came to be more specifically concerned with scientific data gathering. These were often associated with ships of exploration, research vessels, and some commercial and naval vessels with dedicated meteorological logbooks for submission to an established meteorological service or institution. The English East India Company (Sutton, 1981), whose principal, but not only activities, were mercantile and were quick to exploit the potential of logbooks for the purposes of optimizing sailing routes and saving voyage time by taking advantage of seasonal wind patterns and ocean currents as divined from the growing volume of observations. Leading the way in the late 18th and early 19th century were one of the Company's hydrographers (the fact that they employed such a person is indicative of the importance attached to gathering climatological data for economic advantage) and his near-contemporaries Major James Rennell and James Horsburgh. The latter's work (Rennell, 1832) on ocean currents remains a seminal text while Horsburgh's Sailing Directions (Horsburgh, 1841) remained for many years the standard navigational guide for sailing vessels en route to India and the Far East. See Wheeler (2014) and Wheeler and García-Herrera (2008), for further descriptions of these early applications.

(b)

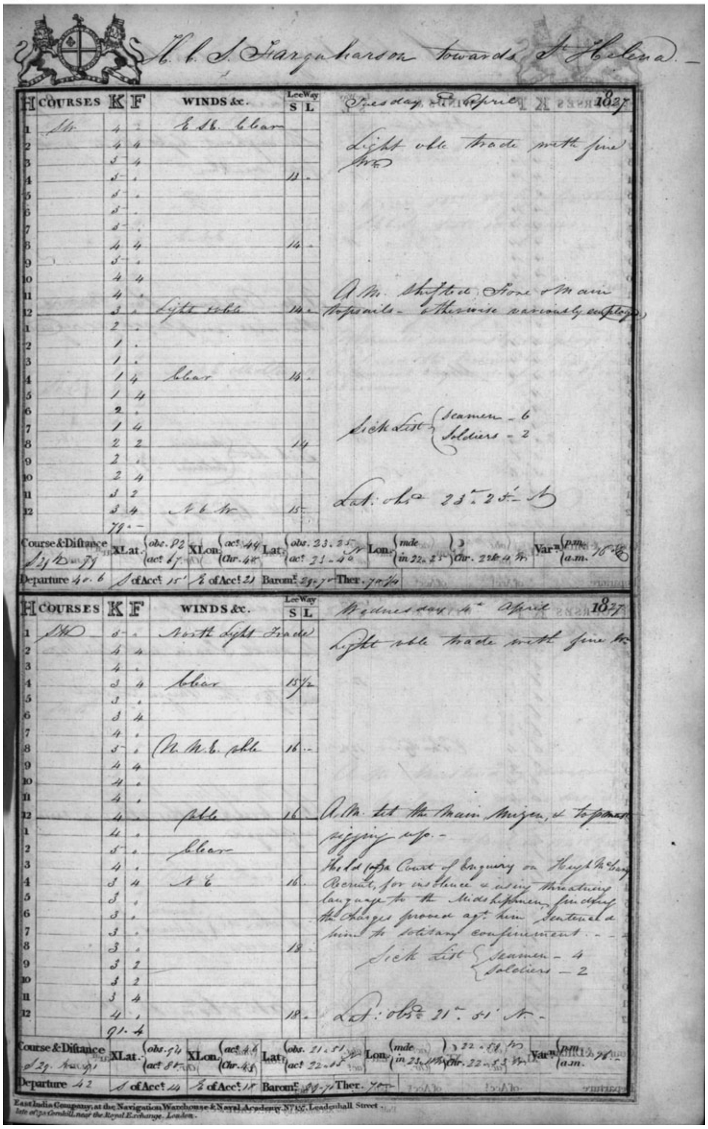

FIGURE 1 Continued

H.H. Lamb (1982) appropriately described logbooks as "a vast treasure trove [of meteorological data] waiting to be used" (see Wheeler, 2014 and Wheeler & García-Herrera, 2008 for details). However, their exploitation was, for purely scientific purposes, sporadic until the end of the 20th century due to a number of reasons. Wind was the only variable consistently recorded from the earliest days of "blue water" navigation, but was done so using a literal and non-numerical scale for wind force. This made difficult its conversion to their ready-to-use numerical equivalents (García-Herrera, Wilkinson, et al., 2005; Gallego, García-Herrera, Calvo, & Ribera, 2007). The lack of a standard zero meridian until 1884 and the problems in the longitude determination are sources of further uncertainty that must be corrected. Wind direction records, too, need to be treated

BOX 1

DATA DIGITIZATION AND ABSTRACTION

Logbooks abstraction, management, and dissemination are not easy tasks. Not least among the challenges is the purely mechanical one of securing hand-written data in digital form. Optical Character Recognition (OCR) is not yet a possibility and manual transcription is unavoidable although future developments in OCR technology may yet liberate researchers from this limitation. Other avenues are, however, open, one of the most productive of which is "crowd sourcing." The Old Weather project (https://www.oldweather.org) has enjoyed notable success in securing high-quality logbook data and has been followed by other undertakings such as the Australian Weather Detective and U.S.-based Weather Wizards (http://weatherwizards.org) projects.

with caution as they are based on the magnetic compass and require correction to "true" north bearings in order to be of climatological value (Box 1).

All such enterprises as those noted above will continue to face challenges in terms of expressing archaic data, in different languages, in a form that can be used in current research. Fortunately, as will be shown later, many of these challenges have been confronted and solved, thanks to projects such as CLIWOC (García-Herrera, Können, et al., 2005) or RECLAIM (Wilkinson et al., 2011). Most of the data collected through these projects are now in the International Comprehensive Ocean–Atmosphere Data Set (ICOADS, http://icoads.noaa.gov/), which includes meteorological observations over the oceans mostly based on ships' records. From the mid-20th century onwards, ICOADS also incorporates data from observation platforms other than ships (e.g., buoys, oceanographic stations, etc.). In its most recent release (3.0) ICOADS (Freeman et al., 2017) holds over 456 million individual marine reports, covering the period 1662–2014, although data from 1662 through the early 1800s are based on scattered ship voyages and they are, as a result, rather sparse. Consequently, ICOADS observations only provide continuous series since the first half of the 19th century for some regions of the globe. The abstraction of ships' logbooks not included in ICOADS can extend these records back in time for those areas where abundant logbook information has been preserved.

3 | METEOROLOGICAL APPLICATIONS

We will now respond to some of the questions that have been most frequently addressed using ships' logbooks from a meteorological perspective: how was the weather like during a given historical event? What was the trajectory of a certain hurricane?

3.1 | Weather during naval battles

These were some of the earliest applications of logbooks probably because they allowed a targeted search of dates and/or regions in the archives. They also showed the consistency and reliability of the logbooks records at these time scales and paved the way to the more climatological analysis, which require more ambitious and larger-scale data abstraction allied to more complex methods to check the homogeneity of the resulting databases.

In the early days of such work Douglas, Lamb, and Loader (1978) and Douglas and Lamb (1979) analyzed weather conditions behind the disaster of the Spanish Armada from July to October 1588. They did not use formal logbooks, but reports from the Spanish ships jointly with English sources, and observations reported by Tycho Brahe in Denmark. After drawing synoptic charts, they were able to identify the succession of anticyclones (probably associated to blocking over the British Isles and northern Europe) and cyclones that helped to explain the course of the campaign.

Wheeler (1985) used the information from 10 vessels involved in the Battle of Trafalgar (October 21, 1805) combined with observations from a number of land stations in England in order to embrace a wider geographic range. This dataset allowed him to reconstruct the main meteorological features dominating southern Iberia during October 1805. According to him, anticyclonic conditions prevailed over the area, with a low-pressure center north-west of the Biscay Gulf. However, the weather changed on the eve of the battle with the passage of a storm over the Bay of Cadiz area. His main hypothesis is that this weather disturbance could be interpreted as a cut-off-low, which is in agreement with the climatology of the region, it being one the areas of the globe where these systems occur most frequently (Nieto et al., 2005). As an additional feature, it was one of the first studies comparing data from different ships sailing within the same close area. It showed that when the narrative descriptors previous to the widespread adoption of the Beaufort scale were used, the observations from the different ships were consistent, even in such difficult circumstances as a naval battle. This added confidence to any later use of data from ships' logbooks. More weather descriptions from naval campaigns and battles can be found in Wheeler (1987, 1991, 1993, 1995).

3.2 | Tracking hurricanes

Hurricanes were known to Europeans since the first Columbus voyages and they soon became aware of their devastating effects. Consequently, ship routes and timing were designed to avoid the peak of the hurricane season in the Caribbean. Something similar happened in the Pacific with the Manila Galleon, the route connecting the Philippines and Mexico for almost three centuries (García et al., 2001). Of course, when a ship was subject directly to the effects of a hurricane, shipwrecks often resulted and no records survived. However, as the Mexican Gulf was frequently navigated, records from ships marginally affected by hurricanes and tropical storms have survived and this has allowed for either identification of the occurrence, or to refine the track of, a significant number of such cyclones.

Recent descriptions of hurricanes can be found in Chenoweth and Mock (2013) or Vaquero, García-Herrera, Wheeler, Chenoweth, and Mock (2008). This type of work has usually been accomplished by assembling different contemporary sources. For example, Mock, Chenoweth, Altamirano, Rodgers, and García-Herrera (2010) combined ships logbooks, newspapers, diaries, ships protests, and other documentary sources from the United States, Britain, and Spain to reconstruct the path, intensity, and societal impacts of a major hurricane in 1812. It was the closest known storm to pass New Orleans at that time, and while its force could have been higher than Katrina, its impact was lower than it would have been today due to the less vulnerable urban environment at that time.

The abundance of ships logbooks and other documentary sources has allowed the production not only of meteorological analyses, but also of extended series to analyze long-term variability. Thus, Chenoweth (2006) reassessed the historical Atlantic basin tropical cyclone activity reported by Poey (1855). The new chronology includes 383 identifiable storms for the period 1700–1855. Later, Chenoweth and Divine (2008, 2012) compiled a database of tropical cyclones in the Lesser Antilles for the years 1690–2007. Newspaper accounts, ships' logbooks, meteorological journals, and other document sources were used to create this dataset, and a new methodology was applied for classifying historical tropical cyclone intensity. The resulting frequency of tropical cyclones shows, interestingly, no significant trends although the time span 1968–1977 was identified as probably the most inactive period since the island's settlement in the 1620s and 1630s. They also found a pronounced ~50–70-year variability in the "accumulated cyclone energy" from 18° to 25°N, most likely associated with multidecadal variations in the North Atlantic sea surface temperature. Energy variations at the shorter time scales of ~3–8 years are coherent with correspondent fluctuations in El Niño Southern Oscillation (ENSO).

4 | CLIMATOLOGICAL APPLICATIONS

A good early modern climatological application of ships' records was undertaken using the logbooks of the Hudson Bay Company (Catchpole & Faurer, 1983; Catchpole & Halpin, 1987; Catchpole & Hanuta, 1989; Moodie & Catchpole, 1975). They allowed for the analysis of the summer sea ice variability from the beginning of the 18th century to the end of the 19th century. Content analysis was applied to the sea ice literal descriptions to generate the corresponding series, but the records of the purely meteorological variables were not exploited. This, however, has been recently completed by Ward and Wheeler (2012). Databases with the marine temperature instrumental data from ships' logbooks have also been assembled (Chenoweth, 1996, 2000) and they have allowed, for instance, for the identification of two major cooling episodes associated to the volcanic eruptions of the Tambora (1815) and an unidentified volcano in 1809 (Chenoweth, 2001).

Most climatological applications have used the wind information derived from ships. Historical wind force observations before the introduction of the Beaufort scale in the late 19th century were not instrumental but estimated and codified as "wind descriptors" in the logbooks. As a consequence, they are subject to changes in the wind terminology and interpretation of the terms used to describe the wind strength prior to its numerical conversion (Prieto et al., 2005). On the other hand, wind direction observations do not suffer from such limitation. They are measured with a compass and hence can be considered a truly instrumental observation that only needs to be adjusted to true north. This has fostered the construction of long-term and continuous series based on daily wind direction observations from key climatic regions (e.g., Barriopedro et al., 2014; Gallego, García-Herrera, Peña-Ortiz, & Ribera, 2017; Gallego, Ordóñez, Ribera, Peña-Ortiz, & García-Herrera, 2015; Mellado-Cano, Barriopedro, García-Herrera, Trigo & Álvarez-Castro, 2018; Ordoñez, Gallego, Ribera, Peña-Ortiz, & García-Herrera, 2016; Vega et al., 2018). The common strategy is to compute the monthly frequency of the wind direction from a given sector based on the daily records as ns/n, where ns stands for the days in a month with wind blowing for the predefined sector and n for the number of days when the observations are available. This has allowed the generation of centennial series over specific regions that provide detailed insights into circulation patterns and their long-term variability. Some of the questions addressed are: how has the atmospheric circulation varied over the Atlantic? How has the monsoon system evolved over the last two centuries?

4.1 | Atmospheric circulation indices

Atmospheric circulation is crucial to the quantification of the degree of internal as opposed to the forced variability of the climate system and to explain anomalous conditions at the surface. In this sense, logbooks have demonstrated their great value as a source of high-resolution information about the atmospheric circulation (e.g., Küttel et al., 2010). Early efforts were made to build circulation indices based solely on ships' logbooks records for specific periods without systematic observations (e.g., Wheeler, Garcia-Herrera, Wilkinson, & Ward, 2009). In order to derive long series extending to present day, more recent developments have combined these historical logbook records with other marine observations, such as those from ICOADS. Connecting logbooks with ICOADS is justified because most of the information contained in ICOADS comes from ships, including logbooks records recovered in key projects such as CLIWOC for 1750–1850. The indices described in this

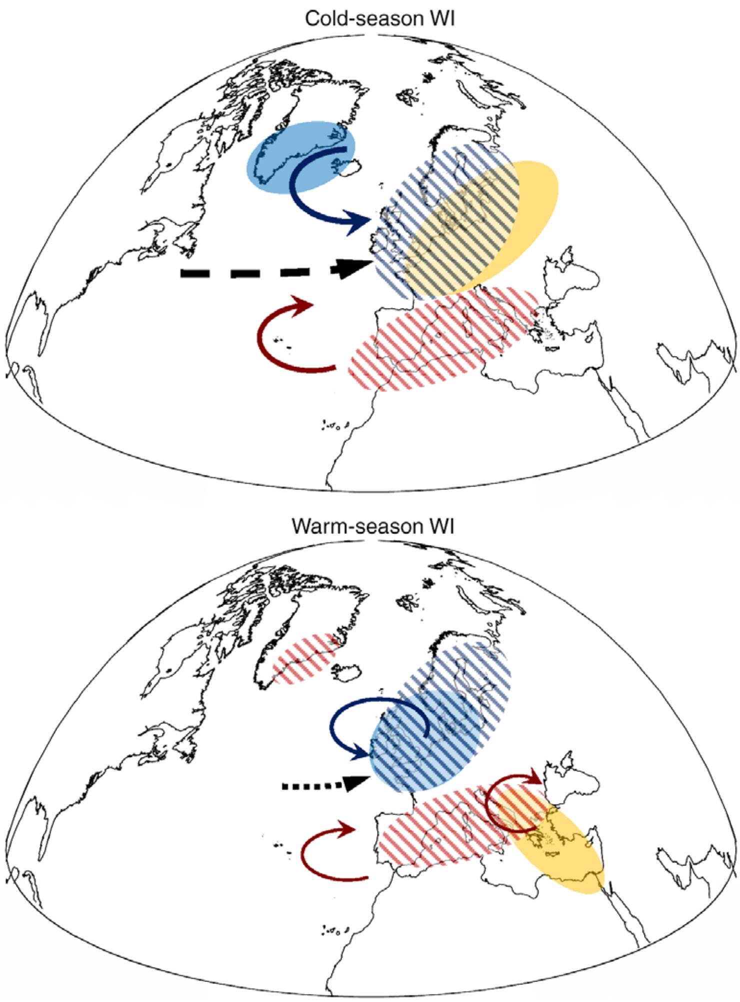

FIGURE 2 Schematic displaying the main signatures in atmospheric circulation (arrows), precipitation (hatching) and temperature (filled shading) associated with enhanced westerlies (positive phases of the standardized WI anomalies) in: top) cold seasons (herein referred to all seasons, with the exception of summer); bottom) warm season (June-to-August). Solid arrows denote enhanced cyclonic (in blue) and anticyclonic (in red) circulation, with dashed arrows indicating the intensity of the westerlies. Orange/blue shading denotes anomalously warm / cold temperatures. Red/blue hatching indicates regions with reduced/increased precipitation

section will show how ships' reports not included in ICOADS can be used to extend its record back in time over regions with abundant logbook information.

4.1.1 | The Westerly Index as indicator of the European and East Atlantic climate

The English Channel was an active maritime route of the British Royal Navy and the Dutch and French fleets, providing strategic lines of communication between the Atlantic and north-western Europe. This region is located at the exit of the Atlantic jet stream, capturing flow anomalies that govern much of the climatic variations in Europe. Wheeler, García-Herrera, Wilkinson and Ward (2009), inspired by the weather regimes of Lamb (1972), were the first to introduce the directional indices (DIs), defined as the monthly frequency of the wind direction in the four (N, S, E, and W) quarters. These authors provided the historical climatology of the DIs for the English Channel between 1685 and 1750 based on ships' logbooks. More recently, Barriopedro et al. (2014) extended the record of the westerly DI (the so-called Westerly Index, henceforth WI) to the present by merging historical ships' logbooks records (1685–1850) with wind direction observations from ICOADS (1851-present) over the English Channel.

The WI is a valuable tool with which to characterize past atmospheric circulation and its climatic implications. For example, the WI exhibits significant robust signals in European temperature and precipitation during the whole year. Figure 2 shows a schematic of the precipitation (colored hatching) and temperature (filled shading) responses to above normal WI values during the cold (Figure 2, top) and warm (Figure 2, bottom) seasons. A higher than average persistence of westerlies leads to enhanced moisture transport toward north and central Europe, thus causing precipitation increases therein (blue hatching, Figure 2) as well as drier conditions in the Mediterranean (red hatching, Figure 2). Persistent westerlies also lead to seasonally-varying temperature anomalies over the British Isles and central Europe, characterized by warmer conditions in cold seasons due to enhanced warm advection (orange shading, Figure 2 top), and colder conditions in summer due to radiative processes (blue shading, Figure 2 bottom).

Regarding the atmospheric circulation (solid arrows, Figure 2), the WI is able to capture the seasonally-varying signatures of the North Atlantic Oscillation (NAO) and hence it provides insight into past atmospheric fluctuations over the North Atlantic-European region from the 17th century. However, the WI and NAO should be viewed as complementary rather than "identical" climatic indicators due to fundamental differences in their nature and construction (Barriopedro et al., 2014). Thus, while the WI is based on the persistence of the real (ageostrophic) wind direction, the NAO and other zonal indices rather measure the strength of the geostrophic zonal wind speed. Directional (zonal) indices tend to be better indicators of north-central European precipitation (temperature), whose fluctuations are largely determined by the storm-track pathways (temperature advection). Therefore, their combined information can be exploited to understand better the past climatic conditions. As an example, Vicente-Serrano et al. (2015) found that the 20th century drought variability over northern (southern) Europe is well explained by the WI (NAO) so that the WI signal in drought complements that of the NAO better than any other circulation index. Accordingly, when used together, they can explain drought severity across most of Europe, making it possible to infer European drought conditions since at least 1821 by using purely instrumental observations. In agreement with this complementarity of the frequency and intensity of the zonal flow, Barriopedro et al. (2014) reported recurrent multidecadal periods of weakened correlations between the WI and NAO for the last three centuries. These decoupling periods were related to departures from zonality in the spatial configuration of the NAO pressure dipole (i.e., a "low-zonal" NAO pattern). On the contrary, periods of strong correlation between the NAO and WI were dominated by the more canonical "high-zonal" NAO spatial pattern.

4.1.2 | Multiple DIs

The westerlies characterize the dominant wind regime over the eastern Atlantic, but they do not capture all the features of the atmospheric circulation in that region. Obviously, an anomalous frequency in the persistence of the westerlies must be accompanied by a corresponding change in the other three cardinal directions. However, the atmospheric circulation will be quite different depending on the wind direction that compensates the WI anomaly. Thus, the WI can be supplemented by computing the DIs from the other cardinal sectors, which represents a significant step forward in the characterization of the atmospheric circulation. Thus, the WI rationale has recently been extended to the other three cardinal directions (the DIs), and even to 8-point wind roses (Mellado-Cano et al., 2018), thus getting a finer picture of the wind direction persistence over the eastern Atlantic since 1685 to present. These indices were derived from daily wind direction observations of ships' logbooks (1685–1850) and ships' observations contained in ICOADS (1851-present) over the English Channel. Importantly, they stand out as the longest instrumental climatic indices ever developed, covering key periods such as the last part of the Little Ice Age (LIA) and the Late Maunder Minimum (LMM). These DIs have provided a deeper insight into the understanding of the past climate and the associated circulation patterns, as they describe simultaneously the variability of the wind frequency from every directional quarter, yielding a better dynamical characterization. Thus, the combined use of the DIs provided a new catalogue of LMM winters according to the prevalent atmospheric circulation, showing that the LMM was more heterogeneous than previously thought (Mellado-Cano et al., 2018). These authors reported substantial decadal variability within the LMM, including a considerable number of mild winters. Overall, the LMM was characterized by "high-zonal" NAO patterns and extremely cold winters in its early stages, and by "low-zonal" NAO patterns and milder winters during the second half.

DIs are also very useful in capturing anomalous periods in Europe throughout the last three centuries from annual to sub-monthly time scales. For example, the extremely cold February 1688 in the Central England Temperature (CET) was associated to persistent and strong easterly flows. At seasonal scales, the warm summer of 1706 (Casty, Wanner, Luterbacher, Esper, & Bohm, 2005; Lamb, 1977) displayed warm air advection from lower latitudes by enhanced southerlies. On the other hand, 1740, the coldest year in the CET, is clearly seen in the DIs record by a significant decrease in the westerlies throughout most of the year, which was accompanied by an increase of easterlies (northerlies) during the first (last) part of the year. The daily nature of the records allows a more finely-resolved temporal picture than that from the aggregated and "smoothed" monthly series. For example, the westerliness of late November and early December 1703 that preceded the "Great Storm" (Wheeler, 2003) appears clearly in the daily records. The same occurs for the intense storm activity across western Europe in the winter of 1738 (Pfister et al., 1999), or the swing of "Popish winds" and "Protestant winds" in October 1688 that determined the sailing of the aspiring William of Orange from the Dutch ports to England to claim the throne of James II (Wheeler et al., 2009).

An additional example is shown herein to illustrate the added value of the DIs. Figure 3 (top and middle panels) shows the composited anomaly of geopotential height at 500 hPa (Z500) and near-surface temperature computed from data of the Twentieth Century Reanalysis (Compo et al., 2011) for four groups of winters of the 1901–2014 period. They are identified from a

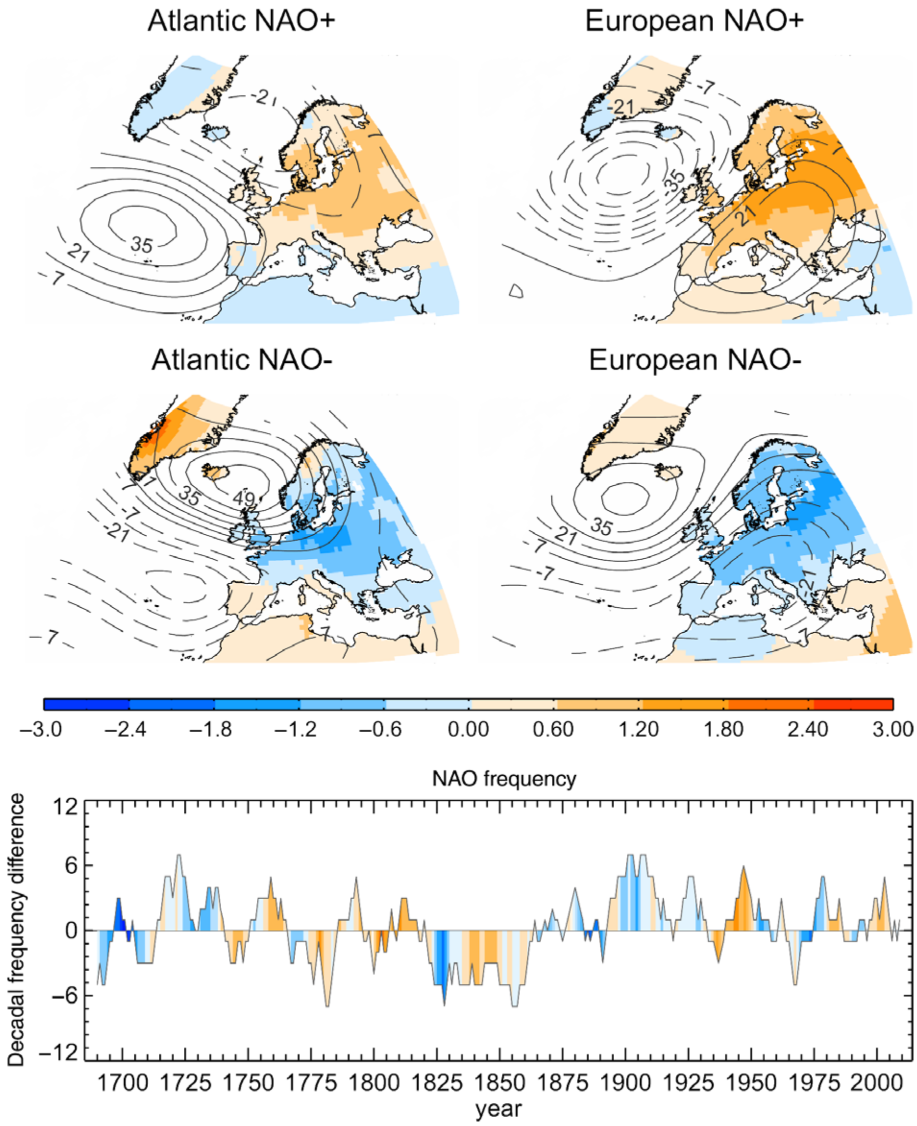

FIGURE 3 Composites of Z500 (contours, in m) and near-surface temperature (color shading, °C) anomalies for two types of negative (top panels) and positive (bottom) NAO winters of the 1901–2014 period, as derived from a k-means cluster analysis of the DIs (see text for details). The Z500 and temperature data come from the Twentieth Century Reanalysis (Compo et al., 2011). The bottom panel shows the time series with the running decadal frequency of positive minus negative NAO winters from 1685 to 2014. Shading indicates the decadal frequency of Atlantic minus European NAO-like patterns, with orangish (bluish) indicating predominance of Atlantic (European) NAO patterns

k-means clustering, which is a common approach to partition the sample into a predefined number of k clusters according to a metric, often the Euclidean distance (Wilks, 2006). In this case, the k-means clustering is applied to the winter DIs series of 1901–2014, so that the DI values display minimum differences for winters of the same group and maximum differences between groups. Each winter is assigned to its closest cluster, which in turn is characterized by the centroid (the mean DIs of all winters belonging to that cluster). This arrangement of winters based on the DIs captures positive (top panels, Figure 3) and negative (bottom panels, Figure 3) NAO patterns, but also discriminates between "Atlantic" (left panels, Figure 3) and "European" (right panels, Figure 3) NAO-like patterns. The former (latter) reflects a SW–NE (NW–SE) tilted dipole with the Azores high shifted toward the Atlantic (European) region. The associated temperature anomalies differ substantially between the two "modes" of a given NAO phase. On the other hand, the cluster centroids derived from the DIs series of the 20th century can be used to infer the dominant NAO mode in the past, by simply assigning each winter of the last three centuries to the closest DI centroid. The bottom panel of Figure 3 (black line) shows the resulting running decadal frequency of positive minus negative NAO patterns. This series is significantly correlated ($r = .56$, $p < .05$) with the NAO index of Jones, Jonsson, and Wheeler (1997) for the period 1901–2014. It indicates preferred negative NAO phases during the LMM and the first half of the 19th century, as well as the well-known dominance of positive NAO phases for the early 20th century. However, the DIs also unveil a nonstationary behavior of the NAO pattern during the last three centuries, with recurrent multidecadal periods of Atlantic and European NAO-like patterns (shading in the bottom panel of Figure 3). This calls for caution regarding

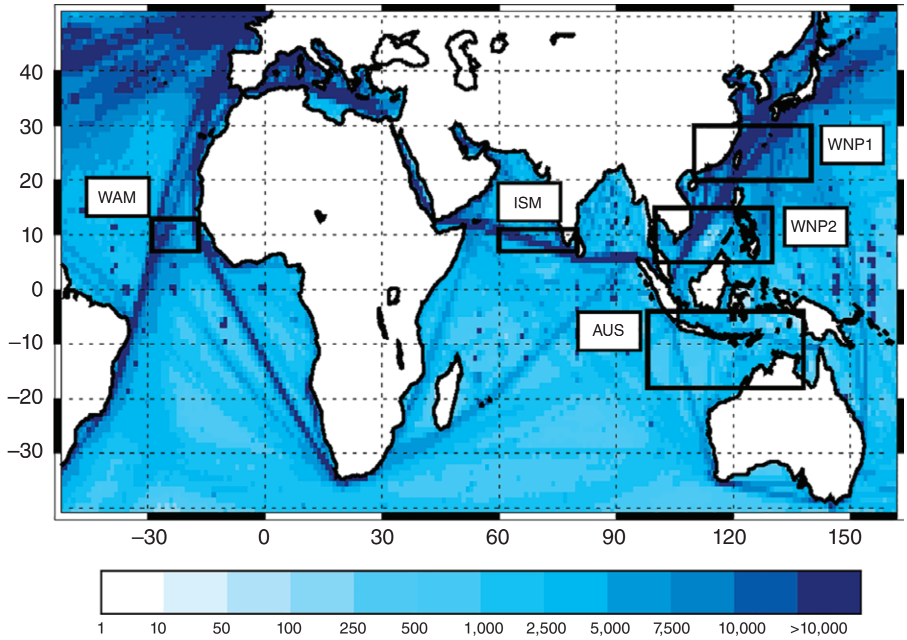

FIGURE 4 Number of wind direction observations in a 1 × 1 grid for the 1800–2014 period available in ICOADS 3.0. Black rectangles (labeled by white boxes) indicate the areas selected to compute monsoonal DIs (see text for details)

proxy-based NAO reconstructions, which assume a time invariant NAO pattern and stationary relationships with local climate. All these results emphasize the contribution that logbooks can make to historical climatic studies (often lacking data from the ocean) and give grounds for their reliability to improve climate reconstructions.

4.2 | The monsoons system

Rainfall associated with the monsoon has an extraordinary social impact. It is estimated that over 40% of the Earth's population is directly affected by monsoonal regimes (Carvalho, 2016). This has resulted in numerous studies proposing indices to estimate the strength or onset date of the monsoons (Carvalho & Jones, 2016). Traditional indices often rely on monthly precipitation series because they are the longest instrumental observations available for most monsoonal areas (Dai et al., 2004; Parthasarathy, Kumar, & Kothawale, 1992). However, it is usually recognized that the large-scale variability of a monsoon can be more precisely quantified by dynamical indices based on wind averaged over the monsoon's moisture source (Goswami, Krishnamurthy, & Annamalai, 1999; Wang et al., 2014; Zhou, Brönnimann, Griesser, Fischer, & Zou, 2010), which typically cover a vast oceanic area (Gimeno et al., 2012). As a consequence, wind-based series representative of the broad monsoon structure are limited to the second half of the 20th century (Hung & Yanai, 2004; Li & Zeng, 2002; Wang & Ding, 2008; Wang & Fan, 1999; Webster & Yang, 1992).

Due to the dramatic seasonal change in wind direction, this variable can be used to characterize the regional monsoons. As shown in Figure 4, a large part of the ships' routes connecting Europe with America and Asia crossed monsoonal regions. Until the opening of the Suez Canal in 1869, the communication between Europe and Asia was forced to circumnavigate Africa crossing the area under the direct influence of the West African Monsoon (WAM area in Figure 4), and even after this year, this area was frequently navigated by ships sailing to South Africa or South America. After the opening of the Suez Canal, the subsequent increase in the European-Asian route resulted in abundant wind reports for the region of the North Indian Ocean, directly affected by the Indian Summer Monsoon (ISM area in Figure 4). Commercial and fishing routes with the Far East, especially the South China Sea and the East China Sea were also active from the second half of the 19th century. Incidentally, these are the two centers of action of the Western North Pacific Southern Monsoon (WNP1 and WNP2 areas in Figure 4). In the Southern Hemisphere, the number of historical wind observations is comparatively low. However, in the case of the Australian Summer Monsoon, the region displaying a coherent seasonal wind reversal associated with the monsoon is so vast (AUS area in Figure 4) that the cumulative number of observations along the routes connecting Australia with east and south-east Asia, Indonesia and the Philippines are enough to produce a reliable index since the European settlement in this continent in the late 18th century.

Between the years 2014 and 2017, in the framework of the INCITE project ("INstrumental Climatic Indexes. Application to the study of the monsoon-Mediterranean Teleconnection") new quantitative indices for the WAM (Gallego et al., 2015), the Australian Summer Monsoon (Gallego, García-Herrera, Peña-Ortiz, & Ribera, 2017), the Western North Pacific Summer

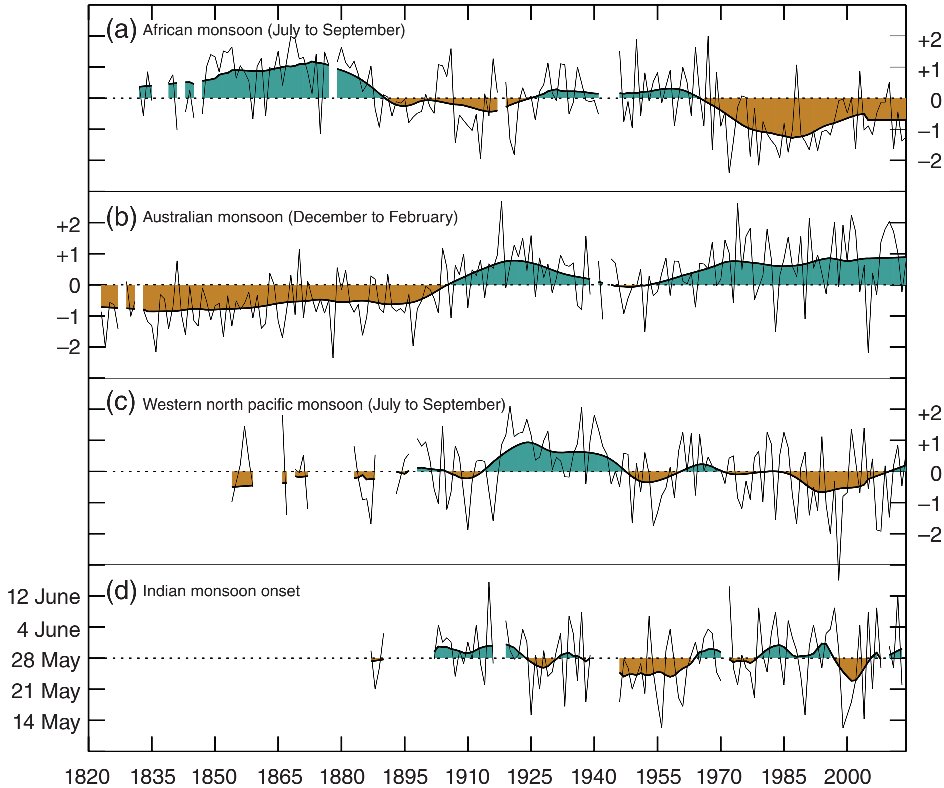

FIGURE 5 Directional indices constructed from ICOADS 3.0 raw data for (a) the African Sumer Monsoon, (b) The Australian Summer Monsoon, (c) the Western North Pacific Summer Monsoon and, (d) date of the Indian Summer Monsoon onset. Shaded smoothed curves are computed as a robust locally weighted regression with a 21-year window width (Cleveland, 1979). Note that values of DIs in (a), (b), and (c) are standardized anomalies with respect the period 1820–2014

Monsoon (Vega et al., 2018), and the ISM onset (Ordoñez, Gallego, Ribera, Peña-Ortiz, & García-Herrera, 2016) were developed using exclusively the wind direction observations contained in ICOADS. It must be stressed that ships' observations represent more than 90% of all records included in ICOADS. The resulting series have extended the known record of these monsoons well into the 19th century and they reveal large interdecadal changes affecting all monsoonal systems.

4.2.1 | The West African Monsoon

Monsoonal winds in West Africa are crucial for the precipitation of the Sahel, which has experienced a strong and persistent drought since the 1970s (Dai et al., 2004*)*. Indices based on instrumental precipitation are only available since 1900 (Nicholson, Dezfuli, & Klotter, 2012), so it is difficult to judge the severity of this mega-drought from a long-term perspective. By computing the monthly percentage of days with prevailing south-westerly winds in the WAM area, it was possible to build an index quantifying the strength of this monsoon since 1839 (Figure 5a, Gallego et al., 2015). The WAM index is significantly correlated with the monthly precipitation in the Sahel for their concurrent 1900–2013 period ($r = +.57$, $r = +.66$, and $r = +.53$ for July, August, and September, respectively, $p < .01$ in all cases). It also captures the drought in the Sahel as a period of persistent weak monsoons starting in the late 1960s. Interestingly, this series demonstrated that the period 1839–1890 was characterized by a stronger than average monsoon, indicative of wet conditions not recorded in recent times and showing that the recent drought is unprecedented over at least the last 170 years.

4.2.2 | The Australian Summer Monsoon

Northern Australia experiences a strong monsoonal cycle. Beginning in October, the austral winter wind regime then starts to decline and by December and up to March, a strong westerly regime is established resulting in the monsoonal rainfalls. The strength of this monsoon can be quantified by the percentage of days in a month between December and February with wind flowing from the west in AUS region. Historical wind data have allowed the extension of this index back to 1816 (Gallego et al., 2017). Figure 5b shows that the Australian monsoon strength has increased noticeably since the 1950s. Evidences of this recent intensification have been reported in northern Australia and include a positive trend in precipitation (Zhang & Zhou, 2011), an increase of cloud cover (Jovanovic, Collins, Braganza, Jakob, & Jones, 2011) or the extension of the monsoon rainforest (Bowman, Murphy, & Banfai, 2010). However, the history of the Australian Monsoon prior to 1900 was largely unknown. The new index revealed that the Australian monsoon prior to 1900 was noticeably weaker than today and that the recent observed increase in the northern Australian precipitation is a manifestation of a much longer trend related to a persistent strengthening of the monsoon that has been occurring since the beginning of the 19th century.

4.2.3 | The Western North Pacific Summer Monsoon

The Western North Pacific Summer Monsoon has a profound impact on the precipitation of highly-populated regions but was not considered as an independent monsoon until relatively recent times (Tao & Chen, 1987), possibly due to a small imprint in the wind field over land. However, it possesses a distinctive wind pattern in open seas characterized by south-westerly winds over the South China Sea (area WNP2 in Figure 4) and an easterly flow over the East China Sea (area WNP1 in Figure 4). The oceanic character of this dipole-like structure has troubled the development of dynamical indices prior to the mid-20th century. Research based on reanalysis data suggested that this monsoon is variable at subdecadal scales (Wang, Gong, & Zhu, 2001), with a noticeable biannual signal in which an anomalously strong monsoon is typically followed by a weak one and vice versa. With the current ICOADS coverage, an index based on the simultaneous persistence of easterly/westerly winds at the WNP1/WNP2 areas (Vega et al., 2018) allowed for the quantification of this monsoon since 1898 (Figure 5c). This series revealed that, superposed to high-frequency variability, the Western North Pacific Monsoon has important multidecadal variability, with long periods (as it was 1918–1948) of lower interannual variability and stronger than average monsoons. In fact, the two strongest monsoon episodes of the 20th century occurred in this period (1920 and 1937). The Western North Pacific Summer Monsoon is strongly related to the ENSO cycle. Previous studies (Lee, Ha, & Jhun, 2014; Weng, Ashok, Behera, Rao, & Yamagata, 2007; Weng, Wu, Liu, Behera, & Yamagata, 2011) reported that this monsoon tends to be stronger (weaker) during a developing phase of El Niño (La Niña). The index based on ICOADS shows the same behavior for the second part of the 20th century. However, it also reveals that this relationship has not been stable in time, providing the first evidence of an opposite behavior prior to the 1950s (Vega et al., 2018).

4.2.4 | The Indian Summer Monsoon

The Indian Monsoon is characterized by very stable south-westerly winds over the Arabian Sea (ISM area in Figure 4). Unfortunately, the reduced variability in the direction of these winds during the monsoonal season makes it difficult to characterize the monsoon strength (Ordoñez et al., 2016). However, it is possible to compute the monsoon onset by tracking the date in which winds over the ISM area quickly change to persistent westerlies–southwesterlies. The date of the ISM onset is one of the most important meteorological events of the world, affecting the lives of hundreds of millions of people (Wang & Ding, 2008). The Indian Meteorological Department developed a long onset series starting in 1901 (Joseph, Eischeid, & Pyle, 1994). However, the methodology used was subjective and it was updated in 2006 to include satellite-derived data, thus impeding the generation of an objective onset series before the 1970s (Pai & Rajeevan, 2009). The use of historical wind direction measurements (Ordoñez et al., 2016) allowed for the definition of an objective series of the Indian monsoon onset for the entire 20th century (Figure 5d). The new approach captures the rapid precipitation increase associated with the onset and it is robustness against false detections, usually referred as “bogus onsets.” Results indicated that throughout the 20th century, the onset date was variable, ranging between May 11, 1956 and June 15, 1915. There is no significant long-term trend in the onset, but a noticeable interdecadal variability, with a tendency to later than average onsets during the 1900–1925 and 1970–1990 periods and earlier than average onsets between 1940 and 1965. The analysis of this series also revealed a relatively stable relationship between the ENSO and the onset date; however, this link tends to be weaker during decades characterized by prevalent La Niña conditions (Ordoñez et al., 2016).

5 | CONCLUSION AND OUTLOOK

This perspective paper shows the added value of historical ships' logbooks as a source of reliable information relevant to meteorology and climatology since the preinstrumental era. Ships' logbooks extend back the instrumental record, thus reducing the limitations derived from the shortness of current records. They inform on weather during historical and high-impact events, and the climatology of sea ice or marine temperature in certain periods. They also allow for building series that are able to capture low-frequency variability of dynamical systems for the last centuries over key climatic areas, such as eastern North Atlantic and the monsoonal regions. Consequently, after several decades of active research, ships' logbooks can be considered a consolidated source of climate data. The experience learnt can be summarized as follows:

- Data abstraction will continue to be an issue. Apart from the arduous digitizing process, the determination of the ships' position in longitude can be problematic, as it must be estimated for logbooks dating before the introduction of a universal reference meridian in 1884. In fact, the CLIWOC project (García-Herrera, Können, et al., 2005) showed that in the period

1750–1854, European ships had used more than 300 references for longitude. Consequently, a preliminary processing is required to assign a proper longitude to a given observation. This is a highly time-consuming task that requires a certain level of expertise and cannot be automatized.

- Investment on dedicated collections. Since massive abstraction should require intensive use of skilled manpower, dedicated data rescue projects are more likely to be envisaged. For example, the recent analysis of the Arctic logbooks collection (Ayre, Nicholls, Ward, & Wheeler, 2015) identifies the relevant logbooks and provides the methods for their full scientific exploitation. Similarly, Hannaford, Jones, and Bigg (2015) pointed out that the reconstructed series of summer and winter precipitation in Southern Africa from 1796 to 1854 could be enlarged if the English East India Company collection is fully digitized. Following the previous experience from CLIWOC or RECLAIM, this type of project should also contribute to support ICOADS, which provides most of the marine weather observations over the globe through regularly updated and freely available versions.
- Search of logbooks for target regions. In these cases, the search can be simplified by the existence of Fleet lists; these are usually in the form of contemporary naval documents that arrange ships geographically and by month so that ships in any given area at any given time can be readily identified among the great number of vessels. The targeted region should be frequently sailed by ships to guarantee sufficient data coverage and the creation of a continuous series of observations, but at the same time, small enough to avoid intraregional changes in observations. During the search of ships, priority must be given to: (a) unanchored ships in the open sea to avoid boundary layer and land/sea breeze effects that would otherwise distort the measurements; (b) the midday (principal) observation of each day, since this is most frequent one. However, observations at other times of day these can be valuable to understand diurnally-varying observation biases.
- The reliability of ships' logbooks records varies with the abstracted meteorological variable. Historical observations of wind must be handled with care, especially when translating wind forces near land. The seasonal march of the wind speed computed from ships' logbooks observations is usually well captured, even at the coast (Gallego et al., 2007) and this has allowed for reconstructing sea level pressure (SLP) fields in the North Atlantic based on wind speed anomalies for the 18th and the 19th centuries (Gallego, García-Herrera, Ribera, & Jones, 2005; Jones & Salmon, 2005). However, the direct use of translated wind speeds in long series could introduce nonclimatic biases (Gallego et al., 2007). In the open sea, this bias should be significantly lower (Küttel et al., 2010). Fortunately, however, ships' logbooks have high degree of homogeneity in observational and recording procedures of the wind direction, differing little from modern standards. As wind direction was always measured with a compass, each record just needs to be re-expressed with reference to the true north by correcting for the magnetic declination.
- Combination of ships' logbooks with other marine records (ICOADS). Inhomogeneity issues may arise from different factors. To avoid effects from changes in the observing system, it is convenient to retain only ICOADS observations taken by ships in the open sea and at midday if they are to be merged with ships' logbooks records (Mellado-Cano et al., 2018). These observations can entail different levels of precision. For instance, wind direction depends on whether it was measured with a compass of 8, 16, or 32 points, and it is therefore useful to degrade them to the lowest common precision available. In spite of this, the resulting series often display large differences in data coverage density through the full period. This issue can be tackled by devising techniques aimed to maximize the correlation of the derived series with those that may result from a single observation. Different tests of homogeneity can also be applied to confirm the lack of significant discontinuities (e.g., Barriopedro et al., 2014).

The work ahead can follow different directions. Due to the amount of data already recovered, perhaps the most obvious one is their integration with other contemporary documentary sources. The extremely high resolution of the data provided by logbooks (up to subdaily) makes it specially well adapted for the study of extremes. Additional evidence to that shown above is provided by Degroot (2014), who analyzed the climatic conditions in the North Sea region during the LIA by combining ships' logbooks, diaries, and other documentary evidence. The results suggested that a rise in the frequency of easterly winds accompanied the coldest phases of the LIA, and these decadal trends had consequences on the Anglo-Dutch wars (1652–1674). In the first war, persistent westerly winds and a warmer climate frequently favored the English warships. However, during the second and third wars, more frequent easterlies and a cooler climate granted critical advantages to the Dutch. They can also be used to assess the societal impact of certain extremes. In this context, Pfister et al. (2010) analyzed three violent storms that affected the North Sea, western central Europe and Portugal during the 18th century combining chronicles, poems, institutional inventories, and logbooks. According to those sources, the impact of the three storms can be considered as “war-like” on the corresponding societies. As shown in Wheeler (2014) for the English Channel, centennial series of storminess can be built from ships' logbooks and this should contribute to characterize the natural variability of a phenomenon with serious impact over Western Europe (http://www.europeanwindstorms.org/).

The integration of the wind ships' observations with paleoclimate proxies is a more complex task, because it requires merging heterogeneous records with a wide range of time resolutions, spatial density, and responses to the climate system. However, Küttel et al. (2010) demonstrated that it is possible to combine early instrumental records, natural and documentary proxies, and ships' logbooks records to reconstruct monthly SLP fields in the Euro-Atlantic region. In fact, the inclusion of wind data from ships in certain Atlantic areas improved dramatically the performance of the reconstruction. Barrett, Jones, and Bigg (2017a) and Barrett, Jones, and Bigg (2017b) combined ships' logbook records to produce an ENSO index for the period 1815–1854 through the application of different statistical techniques. The logbook-based reconstruction captured El Niño events better than La Niña events, and East Pacific El Niño events better than Central Pacific El Niño events, thus suggesting a potential bias in the historical reconstructions. Recent international efforts open the field to new opportunities: the recent developments of the PAGES 2K initiative (http://www.pages-igbp.org/ini/wg/2k-network/intro) compiling new proxy data, the increased availability of high-resolution global modeling for the past centuries in exercises such a PMIP4 (Paleoclimate Modelling Intercomparison Project; https://pmip4.lsce.ipsl.fr/) and the possibility of applying statistical techniques such as Boolean approaches (Tingley & Huybers, 2010) or softcomputing algorithms (Troncoso, Ribera, Asencio-Cortés, Vega, & Gallego, 2017) have been scarcely applied in the field so far.

The combination of historical and modern records is still a challenge. The work undertaken so far for the English Channel and the monsoon systems show that problems associated with the different data density or the lack of homogeneity of the sources can be overcome to produce centennial or multicentennial records able to uncover low-frequency variability features previously unknown. But there are other examples. The recent work by Edinburgh and Day (2016) comparing ships' logbooks from 1897 to 1917 with satellite records from 1989 to 2014 has made it possible to show that the summer sea ice limit was at that time more than 1° north of its current location in the Weddel Sea, but comparable to present day in other areas of Antarctica. An active field of debate deals with the uncertainties in the trend of North Atlantic tropical cyclone frequency, which complicates the evaluation of the anthropogenic impact. Chenoweth and Divine (2014) were able to reanalyze eastern Atlantic tropical cyclones from 1851 to 1898. The results suggest that the frequency at that time was comparable to that during the entire satellite era (1965–2012). In any case, the ability to compare historical and modern records and produce centennial series of tropical cyclones is still far from realized.

Apart from extreme events, ships' logbook data can contribute to improve centennial reanalyses (Compo et al., 2011; Poli et al., 2016). Different from the other reanalysis projects, these are based solely on surface observations. When combined with outputs from numerical weather prediction (NWP) models, they provide physically consistent information of the state of the atmosphere on regular longitude/latitude grids and different pressure levels. The currently available centennial reanalyses extend back to the mid-19th century. As we move backwards in time the density of observations is reduced and this leads to some limitations in their quality and applicability (Bengtsson, Hagemann, & Hodges, 2004). Increased availability of ships logbooks should improve the current products, by detecting errors in the current versions, helping to produce new versions with higher data density over the oceans and extending backwards the reanalyses until the early 19th century. This should require a continued and coordinated effort as is being done through the ACRE initiative (http://www.met-acre.org/) (Box 2).

BOX 2

SHIPS LOGBOOK DATA AND CONTEMPORARY HISTORICAL RECORDS

The benefits derived from these integration of ships logbooks and data from contemporary sources would be huge. The improved characterization of atmospheric dynamics during the historical period will potentially contribute, among others, to a better separation of internal and forced variability, identify the responses to natural forcings, improve detection/attribution exercises, and even reduce uncertainties in future climate projections. Thus, for example, in the context of climate change, the hurricane Vince (October 2005) was claimed to be the first one to hit the Iberian Peninsula after becoming a tropical depression, but logbooks and documentary sources reported an analogue in 1842 (Vaquero et al., 2008). In fact, the extended record of observations provided by logbooks can help to search for analogues (systems with similar dynamical behavior) before the human fingerprint, thus improving the detection and attribution of climate change.

More opportunities could be explored if the number of abstracted logbooks is increased. According to Wheeler (2014) around 100.000 Royal Navy logbooks for the pre-1850 period remain unexplored in the British Archives (and a similar amount for more recent periods). Other collections can also be found in the Netherlands, United States, and France, while in Spain most of the preserved logbooks were digitized under CLIWOC. The situation in other countries is unclear, but it deserves to be explored on the light of the outstanding advances derived from the exploitation of ships' logbooks in our understanding of the climate system.

ACKNOWLEDGMENTS

This research was funded by the Spanish Ministerio de Economía y Competitividad through the projects CGL2013-44530-P, CGL2014-51721-REDT, CGL2015-69699-R, and CGL2015-72164-EXP/AEI. NCEP Reanalysis Derived data, CMAP Precipitation data, and GPCC Precipitation data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/. ICOADS data provided by the NCAR/UCAR Research Data Archive, from their Web site at https://rda.ucar.edu/datasets/ds548.0/. Two anonymous reviewers helped to improve the original manuscript.

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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How to cite this article: García-Herrera R, Barriopedro D, Gallego D, Mellado-Cano J, Wheeler D, Wilkinson C. Understanding weather and climate of the last 300 years from ships' logbooks. *WIREs Clim Change*. 2018;9:e544. https://doi.org/10.1002/wcc.544

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