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Constructing the Monsoon: Colonial Meteorological Cartography, 1844–1944

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Introduction

During the nineteenth century, the significance of the South Asian monsoon for the expanding the British Empire made it one of the most anticipated, tracked, and studied weather phenomena in the world.[1] Innovations in mapping techniques and scientific instruments, as well as advancements in communication technology, converged with the establishment of colonial rule in South Asia, bringing the monsoon into focus.[2] This paper explores developments in meteorological cartography that highlight constructions of the monsoon during the nineteenth and early twentieth centuries. The early nineteenth century saw a shift in meteorological inquiry towards standardisation, quantification, and synchronisation, which led to the rise of new representational techniques, namely statistical cartography.[3] Weather maps were one of the most remarkable innovations of nineteenth-century meteorology, their emergence an attempt to better understand the invisible forces of the atmosphere.[4] The use of statistical data to create meteorological images made it possible to identify global atmospheric patterns for the first time. Through these new strategies of visualisation, weather patterns were given shape and form, graphically and geographically, thereby enabling weather phenomena to become the object of scientific inquiry.[5] Nineteenth-century statistical cartographies, based on systematic data collection, were a significant advance in scientific knowledge production and played an important role in discovering new meteorological objects of inquiry. The art of

[1] Sunil Amrith, "Risk and the South Asian Monsoon," *Climatic Change* 151, no. 17 (2016): 17-28; Mike Davis, *Late Victorian Holocausts: El Nino Famines and the Making of the Third World* (London and New York: Verso, 2002).

[2] Fiona Williamson and Clive Wilkinson, "Asian Extremes: Experience and Exchange in the Development of Meteorological Knowledge c. 1840–1930," *History of Meteorology* 8 (2017): 159–78; Martin Mahoney and Georgina Endfield, "Climate and Colonialism," *WIREs Climate Change* 9, no. e510 (2018): 1–16.

[3] Vladimir Jankovic, *Reading the Skies: A Cultural History of English Weather, 1650–1820* (Manchester: Manchester University Press, 2000).

[4] Katherine Anderson, *Predicting the Weather: Victorians and the Science of Meteorology* (Chicago and London: University of Chicago Press, 2005).

[5] Birgit Schneider, "Climate Model Simulation Visualization from a Visual Studies Perspective," *WIREs Climate Change* 3, no. 2 (2017): 185–93.

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making pictorial statements in a precise and repeatable form was critical to the advancement of monsoon science and greatly informed colonial constructions of the monsoon.

The monsoon is a complex weather phenomenon that, over time, has become synonymous with South Asia and notions of "tropicality".[6] From the seventeenth century onwards, monsoons became a defining aspect of "the tropics" and a way of emphasising differences between the climates of South Asia and Europe.[7] The region's "unusual weather" and hazardous monsoonal conditions presented obstacles to civil administration and served as a constant reminder to the British of their tenuous position as interlopers.[8] Due to its profound influence on trade, agriculture, communication, and social life across the British Empire, the monsoon presented a meteorological challenge to be mastered.[9] Science offered a potential means for understanding and domesticating monsoonal climates and, as such, meteorology was increasingly recognised as being of fundamental importance to imperial interests.[10] New scientific techniques, enabled by colonial bureaucratic networks, technologies of measurement, and statistical data sets, advanced understandings of the monsoon by making certain aspects of its spatial and temporal dimensions visible. Nevertheless, these cartographic depictions were not neutral; rather, they were an admixture of political, social, and scientific ambitions.[11] Despite their seeming objectivity, monsoonal cartographies emerged from, reflected, and were mobilised in pursuit of colonial agendas.

This paper draws on ideas from post-representational cartography to denaturalise monsoonal maps in order to understand them as social constructions. Post-representational theories of cartography question the notion that maps convey scientific, accurate, and objective representations of reality; instead, they consider them as an agentive set of spatial practices that do work in the world.[12] Maps embed and reflect, as well as create and maintain, social relations and interests, with practical and material implications for the territories and things they depict. As Denis Wood and John Fels point out, maps create, transform, and construct the ideological; they do not mirror nature but produce nature.[13] In other words, maps are ideological constructions that produce the world through the ontologies they advance. From this perspective, cartographic visualisations of the monsoon were not unmediated representations; rather, they mapped the monsoon as colonials perceived and sought to utilise, leverage, and

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[6] David Arnold, "India's Place in the Tropical World, 1770–1930," *The Journal of Imperial and Commonwealth History* 26, no. 1 (1998): 1–21; Felix Driver and Brenda S.A. Yeoh, "Constructing the Tropics: Introduction," *Singapore Journal of Tropical Geography* 21, no. 1 (2000): 1–5.

[7] Arnold, "India's Place in the Tropical World," 2.

[8] Gunnel Cederlöf, *Rule Against Nature: Founding an Empire on India's North-Eastern Frontiers (NMML Occasional Paper, History and Society New Series 20)* (New Delhi: Nehru Memorial Museum and Library, 2013), 5; Robert Markley, "'A Putridness in the Air': Monsoons and Mortality in Seventeenth-Century Bombay," *Journal for Early Modern Cultural Studies* 10, no. 2 (2010): 105–25.

[9] Davis, *Late Victorian Holocausts*, 213 - 238.

[10] Fiona Williamson, "Weathering Empire: Meteorological Research in the Early British Straits Settlements," *British Society for the History of Science* 48, no. 3 (2015): 475–92.

[11] Georgina Endfield and Sam Randalls, "Climate, Empire, and Environment," in *Eco-Cultural Networks and the British Empire: New Views on Environmental History*, eds. James Beattie, Edward Melillo, and Emily O'Gorman (London, UK: Bloomsbury, 2014), 21–43.

[12] Pablo Iván Azócar Fernández and Manfred Ferdinand Buchroithner, "Post-Representational Cartography," in *Paradigms in Cartography: An Epistemological Review of the 20th and 21st Centuries*, eds. Pablo Iván Azócar Fernández and Manfred Ferdinand Buchroithner (Berlin: Springer, 2014), 87–99.

[13] Denis Wood and John Fels, *The Nature of Maps: Cartographic Constructions of the Natural World* (Chicago: University of Chicago Press, 2008), 190; John Pickles, *A History of Spaces: Cartographic Reason, Mapping, and the Geo-Coded World* (London: Routledge, 2004).

control it. This is not to deny the material reality of monsoon winds and rains, but to acknowledge that "the monsoon" is also, in part, a social construction, produced through human ideas, terminology, modes of measurement, and representation. Although the concept of the monsoon refers to material dynamics that exist independently of human imagination and cognition, there are different ways of conceiving of this materiality and, therefore, differing conceptions of the monsoon, dependent on the vantage point of the observer. As meteorological cartographies are practices of apprehending, understanding, and engaging with climatic environments, they provide a way of tracing monsoonal understandings.

This paper analyses meteorological representations of monsoons from 1844 to 1944, which corresponds with the rise of statistical meteorological cartography. The paper is divided into three sections, structured around the representational formats of maritime charts, synoptic charts, and upper-air charts, which broadly reflect dominant socio-political agendas. From 1844 to 1875, increased availability and standardisation of measured data, along with technological advances in global communication and mobile meteorological instruments, produced *Maritime Charts* which solidified and extended previous constructions of the monsoon as periodic and predictable. This section focuses on the work of Matthew Fontaine Maury, whose cartographic constructions added depth and dimension to earlier representations, turning them into "powerful imaginative devices" that improved maritime routes of transportation, trade, and exploitation.[14] A move towards *Synoptic Charts* in 1875 coincided with the establishment of the Indian Meteorological Department (IMD), which initiated the expansion of land-based observatories, formalised entanglements between science and colonialism, and provided an organisational structure for systematic investigations of the monsoon. This section focuses on the work of Henry Blanford, the IMD's first director, and John Eliot, his successor. Blanford put observational structures in place to systematise data collection, which resulted in graphical representations of the monsoon as a forecastable, closed system. Following Blanford, Eliot published a *Climatological Atlas of India*, which positioned the monsoon within a well-defined geographical region, constructing a notion of the "climatological solidarity of the British Empire around the Indian Ocean".[15] From 1904 to the end of British operation of the IMD in 1944, it was realised that atmospheric phenomena could not be considered in geographic isolation, and regionally-defined scientific constructions of the monsoon began to expand their territory of inquiry, including a shift into the upper-atmosphere.[16] The resulting *Upper-Air Charts* produced by the IMD, under the direction of Gilbert Walker, James Hermann Field, and Charles Normand, revealed global teleconnections, moving monsoonal explorations into a planetary frame. In part, these endeavours were linked to ambitions to revitalize the British Empire through aviation.[17] In analysing these successive meteorological cartographies and their modes of production, we attempt to track how Western understandings of the monsoon have been constructed over time—understandings that were inextricably linked with processes of colonisation.

[14] Jason W. Smith, "Matthew Fontaine Maury: Pathfinder," *International Journal of Maritime History* 28, no. 2 (2016): 419.

[15] H.R.M., "Review: Climatological Atlas of India by John Eliot," *The Geographical Journal* 29, no. 3 (1907): 337.

[16] Gisela Kutzbach, "Concepts of Monsoon Physics in Historical Perspective: The Indian Monsoon (Seventeenth to Early Twentieth Century)," in *Monsoons*, eds. Jay S. Fein and Pamela L. Stephens (New York: John Wiley & Sons, 1987), 201.

[17] Gordon Pirie, *Air Empire: British Imperial Civil Aviation, 1919-39* (Manchester: Manchester University Press, 2009).

Winds that Influence Currents: Maritime Charts from 1844–1875

The monsoon first became known to European mariners as a seasonal reversal of winds, associated with the Indian Ocean region. These atmospheric movements fundamentally shaped patterns of trade and exploration, with voyages timed and routes planned in accordance with prevailing winds. Whilst the word "monsoon" first appeared in English usage in the late sixteenth century, the first Western visualisation of monsoon winds was produced by Edmond Halley in 1687 (Fig. 1).[18] Halley's first voyage at sea was facilitated by the East India Company (EIC), placing his work in a lineage of mapped knowledge for imperial purposes. Halley's *Account of the Trade Winds, and Monsoons* was based on his own experiences of living in the "Tropicks" and conversations with navigators "acquainted with all parts of *India*".[19] Arguing that the "variation [of winds] is better expressed in the Mapp [sic] . . . than it can well be in words", his chart outlined the general principles of the winds of the Indian Ocean.[20] Halley understood monsoons to be periodic and predictable, caused by the march of the sun: "half the Year they blow one way, and the other half near upon the opposite points".[21] Such ideas became firmly established in maritime imaginaries and were transmitted through the following centuries.

Subsequent nautical guides continued to draw heavily on Halley's understanding of the predictable monsoon. In their description of typical monthly weather in relation to sailing passages, these guides exaggerated and reinforced a sense of monsoonal regularity, giving an impression of a "clock-work climate".[22] James Capper's *Observations on the Winds and Monsoons*, written in 1801, describes monsoons as shifting winds which "change alternately every six months, according to the sun in the eliptic [sic]".[23] According to Capper, monsoons were a discovery of the "enlightened ages" of the fifteenth and sixteenth centuries when mariners "by help of the compass could venture to extend their voyages beyond sight of land", their "discovery" being intimately associated with oceanic voyages.[24] Monsoons were therefore, first and foremost, associated with oceans and seasonal shipping routes, which shaped initial understandings and depictions.

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[18] Sunil Amrith, *Unruly Waters: How Mountains Rivers and Monsoons Have Shaped South Asia's History* (London: Penguin Books, 2018): 22.

[19] Edmond Halley, "An Historical Account of the Trade Winds, and Monsoons, Observable in the Seas Between and Near the Tropicks, with an Attempt to Assign the Physical Cause of the Said Winds," *Philosophical Transactions of the Royal Society* 16, no. 183 (1687): 153. Emphasis in original.

[20] Ibid., 155.

[21] Ibid., 158.

[22] Christian O'Brien, "A Brief History of the Monsoon," (unpublished manuscript, 2011), typescript, 28.

[23] James Capper, *Observations on the Winds and Monsoons: Illustrated with a Chart, and Accompanied with Notes, Geographical and Meteorological* (London: C. Whittingham, 1801): xx.

[24] Ibid., xxi.

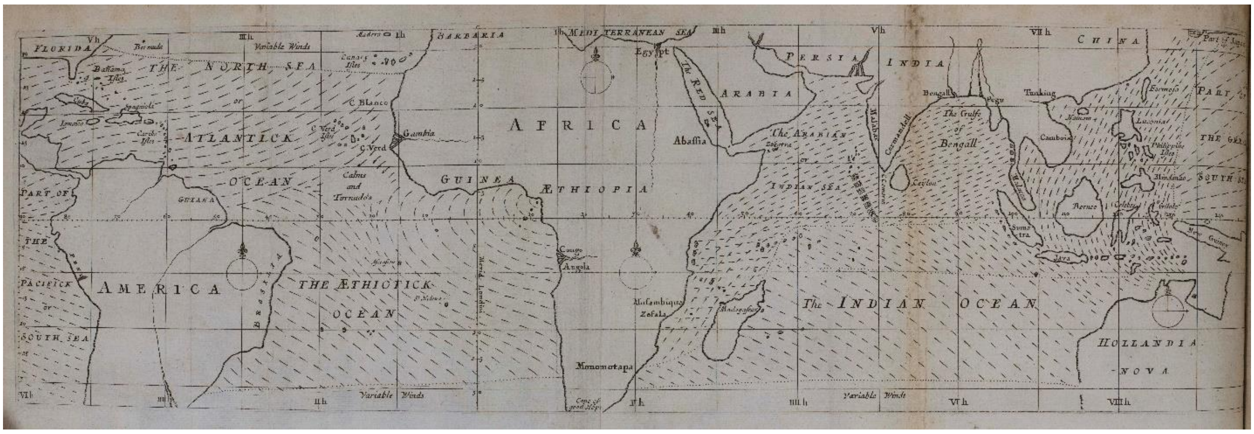

Fig. 1. Map of the trade winds in the Atlantic and Indian Oceans. Source: Halley, "An Historical Account," no page. Image courtesy of Royal Society.

Whilst largely effective in enabling oceanic travel and trade across the region, these early descriptions of the monsoon did little to provide "adequate instructions for utilizing the winds to the best advantage".[25] Although Britain had established the largest merchant fleet in the world by the nineteenth century, voyages were still largely confined to established trading routes and passages were highly weather dependent. For Britain, ensuring profits from foreign lands was dependent on identifying optimal transportation, which made improvements to navigational techniques of the utmost importance.[26] Unsurprisingly, oceans and their winds became the object of intense scientific study, reflecting the geopolitical ambitions of maritime nations. As much of the British fleet consisted of sailing ships, "a science of the winds had an obvious national interest".[27] Between Britain and the US, the scientific study of oceans became a priority in the consolidation of economic and political power.[28] Drawing upon the US Navy's vast collection of ships' logs, the American oceanographer Matthew Fontaine Maury developed a cartographic method of using line weights, line types, and colour that gave depth to geospatial charts and helped "enable the navigator" to "blaze his way" across the ocean, "upon the wings of the wind".[29] Whilst mariners were knowledgeable about specific regional conditions, Maury's charts were the first comprehensive compilation of wind observations on a global scale. Consequently, Maury became known as the "pathfinder of the seas" and produced well-defined navigation routes based on dominant wind patterns, enabling considerably shorter sailing times.[30]

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[25] Norman J.W. Thrower, "Edmond Halley as a Thematic Geo-Cartographer," *Annals of the Association of American Geographers* 59, no. 4 (1969): 659.

[26] Vladimir Jankovic, "Climates as Commodities: Jean Pierre Purry and the Modelling of the Best Climate on Earth," *Studies in History and the Philosophy of Modern Physics* 41, no. 201 (2010): 207.

[27] Anderson, *Predicting the Weather*, 3.

[28] Michael S. Reidy and Helen M. Rozwadowski, "The Spaces in Between: Science, Ocean and Empire," *Isis* 105, no. 2 (2014): 340.

[29] Matthew Fontaine Maury, *The Physical Geography of the Sea* (London: Sampson Low, Son & Co., 1855), 262.

[30] Charles Lee Lewis, *Matthew Fontaine Maury: The Pathfinder of the Seas* (Annapolis: The United States Naval Institute, 1927).

Addressing gaps in the data collection of previous generations, Maury saw mariners as his “corps of observers” and “co-labourers in science”.[31] By 1844 he had created and distributed a systematised logbook for the collection and submission of weather observations. Aided by the invention of more stable and mobile instruments, like the aneroid barometer, these observations included wind and current direction and velocity, ocean temperature, latitude and longitude, and air pressure.

> Each navigator was to enter in his abstract-log every day in the year the temperature of air and water, the direction of the wind, and set of the currents, the height of the barometer, &c. He was also to cast overboard at stated periods bottles tightly corked, containing, on a slip of paper, his latitude and longitude and the day of the month and year. He was to pick up all such bottles found floating, note latitude and longitude of place found, and day of months and year in the abstract-log and forward all to the Observatory.[32]

The millions of observations that these logs produced provided Maury with the material to construct his *Wind and Current Charts*. In gratitude for their contributions, Maury provided his observers with a free copy of the latest edition of his charts. In doing so, he gave his co-producers the means to guide themselves “across the pathless ocean” with charts made not by “theory or conjecture, not the faint glimmering of any one man’s experience, but the entire blaze and full flood of light which the observations of all the navigators that had preceded him could shed”.[33]

Capitalising on the revenue-boosting advantages that ocean and wind currents could provide when seen as a vast and reliable machine, Maury chose to construct his *Wind and Current Charts* of the Indian Ocean in two moments, February and August, representative of the main monsoon seasons. In Maury’s own words, “monsoons, properly speaking, are winds which blow one half of the year from one direction and the other half from an opposite, or nearly opposite direction”.[34] He further elaborates on their timing, writing “monsoons of the Indian Ocean prevail really for about five months each way, viz., from May to September from the southwest . . . and from November to March inclusive from the northeast”.[35] Explaining his intention to represent only the “prevailing direction” of these winds, Maury’s charts continued to construct the monsoon as regular and predictable.[36] In accordance with these ideas, his charts “abstracted and generalized atmospheric patterns”, whilst establishing credibility through increased data collection and enriched forms of representation.[37] Although these processes of simplification created powerful devices, as the written text that appears alongside his chart (Fig. 2) states, “the winds of this Ocean undergo such great, so many, and such regular changes

[31] Matthew Fontaine Maury cited in Smith, “Matthew Fontaine Maury,” 416.

[32] Diana Fontaine Maury Corbin, *A Life of Matthew Fontaine Maury, Author of the Physical Geography of the Sea and Its Meteorology* (London: Sampson Low, Marston, Searle & Rivington, 1888): 57–58.

[33] Maury, *The Physical Geography of the Sea*, vii.

[34] Ibid., 217.

[35] Ibid., 224.

[36] Ibid.

[37] D. Graham Burnett, “Matthew Fontaine Maury’s ‘Sea of Fire’: Hydrography, Biogeography, and Providence in the Tropics,” in *Tropical Visions in an Age of Empire*, eds. Felix Driver and Luciana Martins (London and Chicago: University of Chicago Press, 2005), 125.

according to the seasons, that it has been found very difficult to map them", hinting at a more complex reality.[38]

Nevertheless, in charts such as Fig. 2, the seas emerged in quadrants of quantification, or measured units of space in which data could be plotted or read. Such charts allowed mariners to access layers of historical information on wind speed and direction for different seasons of the year at a glance. Like Halley, Maury placed great confidence in the value of cartography to express "what volumes of written directions could but imperfectly describe".[39] He took great care to make sure each subsequent production of the *Wind and Current Chart* helped the mariner to visualise the winds, currents, ocean temperatures and meteorology "that he could rarely discern with his own eye".[40] Showing the typical wind patterns for the month of February during the Northwest Monsoon on the left, and the typical wind patterns for the month of August during the Southeast Monsoon on the right, Fig. 2 simplifies the complicated arrow arrangement of Halley's 1686 construction of the same phenomena. Like Halley, Maury uses short strokes to illustrate wind direction as it registers against the movement of a ship; however, differentiated arrows or strokes express variegated wind types. Seen in Fig. 3, these distinctions add depth, dimension, and credibility through the graphic construction of detail.

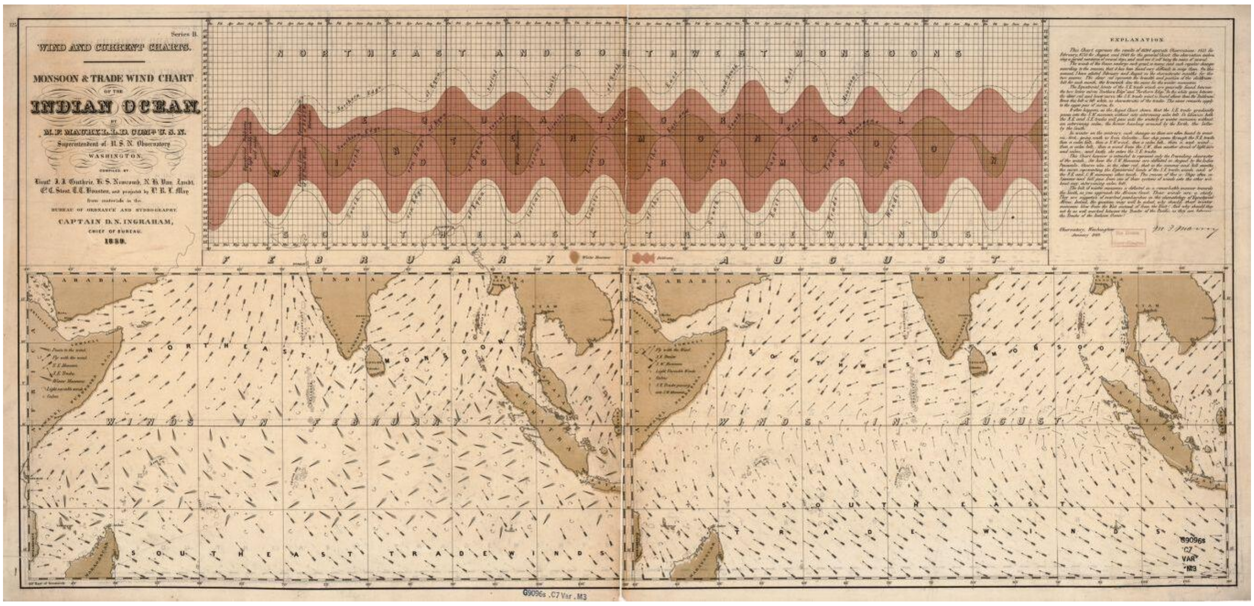

Fig. 2. Monsoon & trade wind chart of the Indian Ocean. Source: Maury et al. *Monsoon & trade wind chart of the Indian Ocean*, Series B. Image courtesy of Library of Congress. The image shows wind data in relation to the navigation of ships.

[38] Matthew Fontaine Maury, John Julien Guthrie, R.L. May, United States Bureau of Ordnance and Hydrography, United States Hydrographic Office, and the United States Naval Observatory, *Monsoon & Trade Wind Chart of the Indian Ocean* (Washington, DC: United States Hydrographical Office, 1859). Retrieved from the Library of Congress, <https://loc.gov/item/2009575919>, on 31 January 2018.

[39] Matthew Fontaine Maury, "Blank Charts on Board Public Cruisers," *Southern Literary Messenger* 9, no. 8 (1843): 459.

[40] Smith, "Matthew Fontaine Maury," 417.

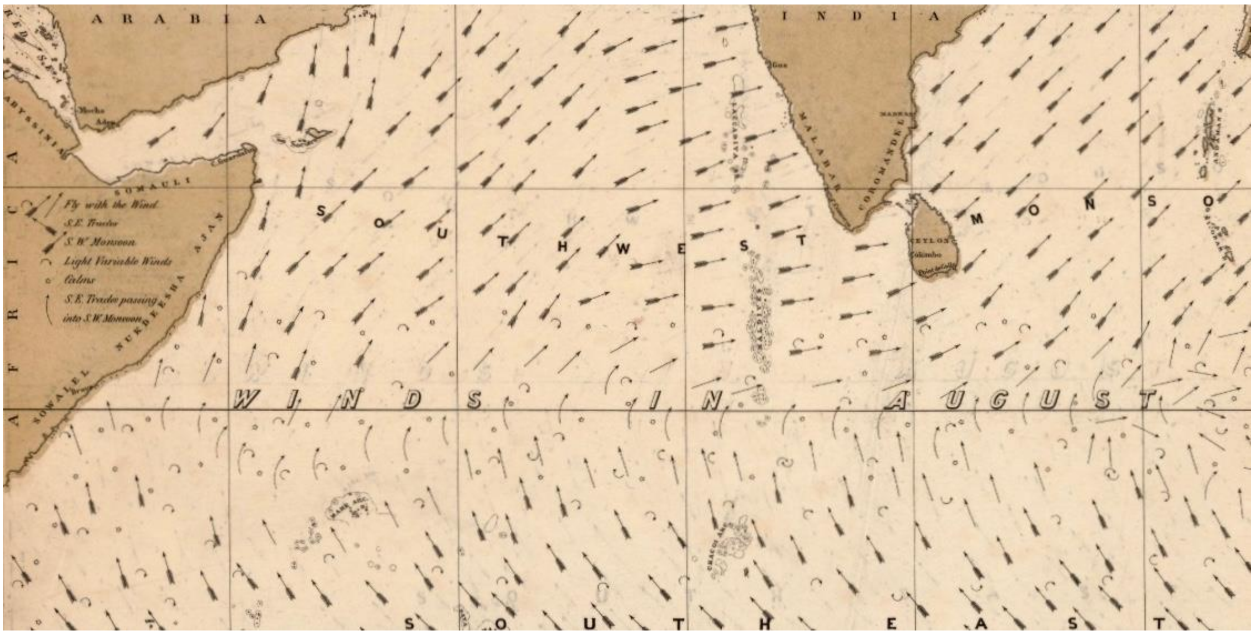

Fig. 3. Monsoon & trade wind chart of the Indian Ocean. Source: Maury et al., *Monsoon & trade wind chart of the Indian Ocean*, Series B. Image courtesy of Library of Congress. The image shows the detailed strokes and symbols used to express wind variations.

Navigators came to trust the solidity of these cartographic practices, to the extent that some mariners would stick to Maury's routes even when they encountered contrary winds and currents. "Maury's paths were powerful imaginative devices . . . so as to convince mariners that winds and currents were always predictable and systematic when, in fact, they were not", demonstrating the capability of such visualisations to "transform mariners' ideas about the sea . . . its order, its laws and its design".[41] In 1858, Maury published another version titled *Winds and Routes* (Fig. 4) that explicitly depicted ship routes through wind regions by not conflating the two into simplified line types. Winds are represented as patterns filling the ocean, with routes of transporting or obstructing winds layered onto these regions almost as an infrastructure. The process of communicating existing knowledge and experience through the cartographic image activated powerful "neural assemblages" that created new knowledge and pathways.[42] The inclusion of data points in the construction of these maps, demonstrated by the explicit appearance of charted tracks of prior routes, denaturalises constructions of meteorological and oceanic systems, whilst making the social construction of cartographic knowledge explicit.[43] The result was a visualised set of mapping practices, institutionalised across time and space, that lent a sense of security and validity to the object of the map and the winds depicted.[44]

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[41] Ibid., 419.

[42] Rob Kitchin, Chris Perkins, and Martin Dodge, "Thinking About Maps," in *Rethinking Maps: New Frontiers in Cartographic Theory*, eds. Rob Kitchin, Chris Perkins, and Martin Dodge (London and New York: Routledge, 2009), 14.

[43] Pickles, *A History of Spaces*, 66.

[44] Rob Kitchin and Martin Dodge, "Rethinking Maps," *Progress in Human Geography* 31, no. 3 (2007): 331–44.

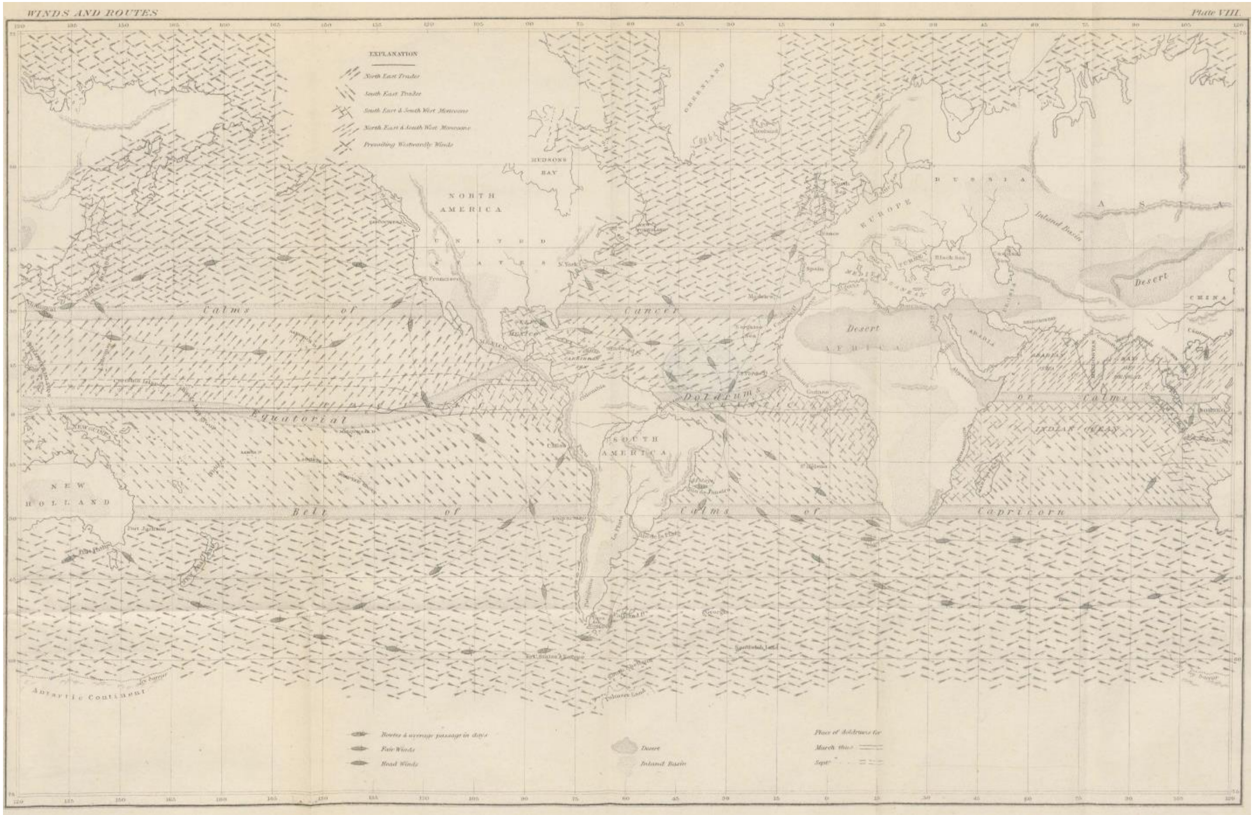

Fig. 4. Winds and routes. Source: Matthew Fontaine Maury, *The Physical Geography of the Sea* (London: Sampson Low, Son & Co, 1855), Plate VIII. Image courtesy of British Library. The image shows the direction and force of wind, registered against the movement of ships.

Maury's expansion of data collection networks and improvements to standardised data collation, together with the first transatlantic telegram and the widespread distribution of meteorological instruments, provided a solid foundation for an expanded and systematic approach to marine meteorology. The 1853 Brussels Convention—convened at Maury's instigation—led to the founding of the International Meteorological Organisation (IMO).[45] One of its first acts was to create "an international standard meteorological logbook for ships at sea".[46] The president of the British Association of Science recommended that this system be extended to the Indian Ocean on speculation that reducing the length of ocean voyages would result in substantial annual savings. George Buist, president of the Geographical Society of Bombay, was meant to coordinate the project, but was unable to do so due to his obligations to the East India Company. Nevertheless, he later sent Maury six "skeletal charts" containing observations from over a hundred ships, which perhaps contributed to Maury's 1859 *Monsoon & Trade Wind Chart of the Indian Ocean*.[47]

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[45] Stephen J. Dick, *Sky and Ocean Joined: The US Naval Observatory 1830–2000* (Cambridge: Cambridge University Press, 2003).

[46] Paul N. Edwards, *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming* (Cambridge, MA: The MIT Press, 2012), 24.

[47] Kutzbach, "Concepts of Monsoon Physics," 166.

As well as visualising the monsoon, such weather charts "followed the paths of British ships and traced a geography . . . that conformed to the contours of Britain's imperial interests".[48] Following the IMO's formation, the Board of Trade's Meteorological Department was established in London in 1854. Under the leadership of Captain Robert Fitzroy, this newly established department "tasked with providing information on marine meteorology" became a centre for industrial and governmental command.[49] As Britain's Empirical reach grew, so did concerns over how order could be brought to unruly climatological phenomena that continued to evade representation and challenge imperial control.[50] In response, the Meteorological Department sought to address these concerns at an increasingly global scale.

Winds that Bring Rains: Synoptic Charts from 1875–1904

Western explorations of the monsoon, initially pertaining to the oceans, gradually extended to land with the expansion of the British Empire. The East India Company undertook substantial meteorological monitoring and observation programmes, primarily aimed at maximising revenue generation and resource extraction from a rain-fed terrain, driven by knowledge that "an appreciation of monsoon patterns would reduce the impact of periodic revenue-depleting droughts".[51] Observatories were established in Madras (1792), Calcutta (1825), Lucknow (1832), Trivandrum (1837), and Poona (1842), often as private undertakings.[52] However, early monitoring was piecemeal, limited by faulty instruments and a lack of standardisation. Following the Indian Rebellion of 1857, the East India Company was transferred to the Crown. Territorial acquisition and the need for sustained governance saw British involvement in India transition from mercantile enterprise to bureaucratic administration.[53] Concerns about India's improvement and natural disaster mitigation, including droughts brought on by monsoon failure, became increasingly important in the justification of imperial governance, as reflected by an intensification of meteorological observation.[54] As land-based observatories and agendas became more established, visual depictions of the monsoon shifted towards synoptic forecasting techniques and focused on understanding the monsoon in relation to rainfall. Maritime understandings of monsoons as seasonally reversing winds become significantly more complex when extended to explorations of precipitation over land. Endeavours to predict monsoon rainfall resulted in a more systematic approach to meteorology and an expanded understanding of monsoonal dynamics.

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[48] Simon Naylor, "Log Books and the Law of Storms: Maritime Meteorology and the British Admiralty in the Nineteenth Century," *Isis* 106, no. 4 (2015): 782.

[49] Simon Naylor, "Nationalizing Provincial Weather: Meteorology in Nineteenth-Century Cornwall," *British Journal for the History of Science* 39, no. 3 (2006): 414.

[50] Siobhan Carroll, *An Empire of Air and Water: Uncolonizable Space in the British Imagination, 1750–1850* (Philadelphia: University of Pennsylvania Press, 2015).

[51] George Adamson, "The Discovery of ENSO," in *El Nino in World History*, eds. Richard Grove and George Adamson (London: Palgrave Macmillan, 2018), 109.

[52] S.M. Razaullah Ansari, "On Indian Observatories in the Nineteenth Century," *Proceedings of the Indian History Congress* 36 (1975): 523.

[53] Kapil Raj, "From Merchants to Imperial Bureaucrats? Territorial Administration and the East India Company, Seventeenth–Nineteenth centuries," in *Serve the Power(s), Serve the State: America and Eurasia*, eds. Juan Carlos Garavaglia, Michael J. Braddick, and Christian Lamouroux (Newcastle upon Tyne: Cambridge Scholars Publishing, 2016), 244–74.

[54] Adamson, "The Discovery of ENSO," 110.

With the establishment of the Indian Meteorological Department (IMD) in 1875, India's first centralised system for meteorological observations was put into place, providing "the organisational structure for systematic investigations of the monsoon and the first attempts at seasonal forecasts".[55] The appointment of Henry Blanford as Imperial Meteorological Reporter to the Government of India (GOI), followed by John Eliot from 1886 to 1904, set the agenda for the IMD's first thirty years. Less than a year into the job, Blanford's first report to the GOI "practically laid the foundation of the pursuit of scientific meteorology in India", establishing key steps for the centralisation of Indian meteorology.[56] Blanford, already resident in Calcutta, requested a central observatory that would enable "the systematic study of the climate and India as a whole" and the "adoption of uniform methods of observation" to "secure a basis of accurate data".[57] His initial proposal included a call to expand the number of observatories, ensure their distribution across the provinces, and establish additional observatories in Burma, Rajputana, Central India, and the Bombay Presidency. These were to be networked with those of "neighbouring countries and Europe" to gain a better sense of the state of weather across the subcontinent.[58] Approved in full by the GOI, the quick expansion of land-based observatories allowed this newly established arm of the imperial government to take significant strides in defining the monsoon as scientific object.

Immediately following the IMD's formation, severe drought and subsequent famine occurred in 1876 and 1877, setting a clear priority for monsoon forecasting. Even with the assistance of an expanded network of observatories and standardised instruments—in particular, the thermometer, rain gauge, anemometer, and barometer—Blanford commented, "we are in the position of a commander on a vast battle-field who can find no eminence from which he may gain a bird's eye view of the combat".[59] Determined to find causes and patterns that would enable the forecasting of future deficits and excesses, Blanford limited his scope of inquiry to the distribution of air pressure and winds that carried rains across the landmass of the Indian subcontinent. Reflective of this detailed and mathematical study of the atmosphere, meteorological cartography shifted towards synoptic charts. These charts, which summarised atmospheric conditions over a wide area by displaying information on temperature, pressure, precipitation, wind speed, and direction, became the basis for action for the first thirty years of the IMD's investigative practice.

Blanford's approach appears to have been influenced by Balfour Stewart, director of Kew Observatory in England, who championed splitting meteorology into two branches of inquiry: climatic and physical. In an influential article in *Nature*, he wrote, "we are so mixed up with the earth and its atmosphere, and the motions of the latter are on so large a scale, that we find the greatest possible difficulty in grasping their true import".[60] Calling for "a bird's eye view of the atmosphere", Stewart described the need to distance the measurer from that

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[55] Kutzbach, "Concepts of Monsoon Physics," 205.

[56] D.R. Sikka, "The Role of the India Meteorological Department, 1875–1947," in *History of Science, Philosophy and Culture in Indian Civilization, Volume XV, Part 4, Science and Modern India: An Institutional History, c.1784–1947*, ed. Debi Prasad Chattopadhyaya (New Delhi: Pearson Longman, 1999), 388.

[57] John Eliot, *Climatological Atlas of India, published by the authority of the Government of India under the direction of Sir John Eliot; Issued by the Indian Meteorological Department* (Edinburgh: J. Bartholomew & Co., 1906), xi.

[58] Sikka, "The Role of the India Meteorological Department," 388.

[59] Henry F. Blanford, *The Indian Meteorologist's Vade-mecum* (Calcutta: Office of the Superintendent of Government Printing, 1877), 99.

[60] Balfour Stewart, "Physical Meteorology I: Its Present Condition", *Nature* 1, (1869): 102.

being measured in order to gain a “general plan of the whole”.[61] Blanford recognised the capacity of the synoptic chart to construct this view, enabling observers to advance their “knowledge of the laws that regulate the internal movements of the atmosphere”.[62] Referring to Stewart, he outlined the potential for these techniques to put sections of the atmosphere “under a meteorological blockade”, believing that “a few years would suffice to place our knowledge of meteorological laws on a very advanced footing”.[63] As central concerns of the British Empire, the Indian subcontinent and its weather were placed at the forefront of meteorological inquiry.

Tropical settings were understood as natural laboratories, where natural laws could be traced.[64] The notion that “atmospheric change” in the tropics could be “reduced to its essentials”, presenting “meteorologists with fewer fluctuations to unravel”, underwrote early synoptic constructions of the monsoon and related cartographic experiments.[65] In the early years of his tenure at the IMD, Blanford wrote, “order and regularity are as prominent characteristics of our [India’s] atmospheric phenomena as are caprice and uncertainty to those of their European counterparts”.[66] As such, monsoonal dynamics continued to contribute to constructions of a tropical region defined by regularity. These notions informed the conceptual invention of distinctions between the temperate and the tropical, “one of the most enduring themes in the history of global imagining”.[67] Conceptions of a simplified atmosphere greatly informed the IMD’s early work as it began to impose Western scientific ideas on India’s weather and climate, an effort to reconcile imperial governance with a monsoonal climate.[68]

In *A Practical Guide to the Climates and Weather of India, Ceylon and Burmah*, Blanford describes the process of making synoptic charts, “to render the facts of pressure distribution evident at a glance”, describing the resulting lines as representing “differences of pressure in the same way that the contour lines of a map show differences of elevation and the slope of the ground, enabling one to gather notions of the form of its surface”.[69] The enumerated monsoon emerged through a process of culling and averaging data, and the general trajectory of the monsoon was revealed through “the course and position of the isobars”.[70] For the first time, synoptic weather maps made it “possible to ‘watch’ storms and other phenomena develop and move” through dramatic God’s-eye views.[71] Whilst Blanford and the IMD were not the first to use this method of representation, synoptic charts provided a new perspective for meteorological investigations of the monsoon, as previous charts presented “only idealised models”.[72] Through synoptic depictions, the monsoon emerged as an identifiable, trackable entity, profoundly transforming representations of, and relations with, atmosphere and

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[61] Ibid.

[62] Blanford, *The Indian Meteorologist’s Vade-mecum*, 99.

[63] Ibid.

[64] Anderson, *Predicting the Weather*, 250.

[65] Ibid., 261.

[66] Blanford, *The Indian Meteorologist’s Vade-mecum*, 48.

[67] Felix Driver and Luciana Martins, eds., *Tropical Visions in an Age of Empire* (Chicago: University of Chicago Press, 2005), 3.

[68] Mahoney and Endfield, “Climate and Colonialism,” 5.

[69] Blanford, *A Practical Guide to the Climates and Weather of India*, 24.

[70] Ibid., 27.

[71] Paul N. Edwards, “Meteorology as Infrastructural Globalism,” *Osiris* 21, no. 1 (2006): 231.

[72] Martin Mahoney, “The ‘Genie of the Storm’: Cyclonic Reasoning and the Spaces of Weather Observation in the Southern Indian Ocean, 1851–1925,” *British Journal for the History of Science* 51, no. 4 (2018): 618.

weather.[73] Such charts (Fig. 5) gave a general picture of the atmospheric pressure that structured seasonal monsoon cycles; however, in their "use of means, without standard deviations" such constructions concealed variation and variability, and so continued to distort monsoonal dynamics.[74]

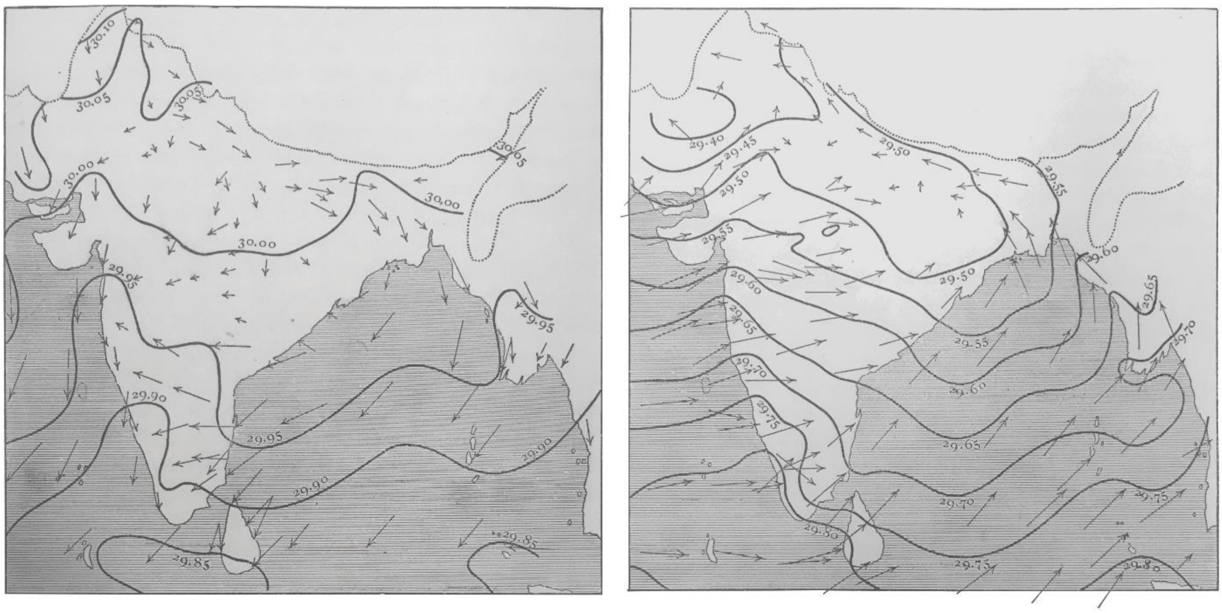

Fig. 5. Average barometric and wind chart for January (left) and July (right). Source: Blanford, *A Practical Guide to the Weather and Climates of India*, 25–26. Image courtesy of British Library.

In Fig. 5, the weight, or thickness, of the isobaric contour line is the dominant feature within the frame, drawing the atmosphere into conversation with land—a departure from previous constructions of ocean and wind currents as correlational and defined by the seas. The limited field of data collection, then excluding the Indian Ocean, restricts the map to the Indian subcontinent and the immediate coasts of the British Empire surrounding the Bay of Bengal. Two types of lines express large- and small-scale barometric changes that occur over the subcontinent, demonstrating a distinctive pattern of exchange between "January and July, when the two monsoons [summer and winter] are respectively at their height".[75] Winds are shown by strokes of variable length that "exhibit the average wind directions" and "the relative steadiness of the wind is indicated by the lengths of the arrows", while the air surface is defined by continuous, solid lines marking isobaric contours of atmospheric pressure.[76] In January (Fig. 5, left) the "seat of the highest pressure is in the north-western corner of India" and as it "decreases steadily southwards" to Ceylon and Sumatra, the isobar in the lower right-hand corner is shown as "incomplete".[77] In July (Fig. 5, right) the northwestern seat of high pressure

[73] Fabian Locher, "Atmosphere of Globalisation: Depressions, the Astronomer and the Telegraph," *Revue d'histoire moderne et contemporaine* 56, no. 4 (2009): 77–103.

[74] Chris O'Brien, "Imported Understandings: Calendars, Weather, and Climate in Tropical Australia, 1870s–1940s," in *Climate, Science and Colonization: Histories from Australia and New Zealand*, eds. James Beattie, Emily O'Gorman, and Matthew Henry (New York: Palgrave Macmillan, 2014), 206.

[75] Blanford, *A Practical Guide to the Climates and Weather of India*, 37.

[76] Ibid.

[77] Ibid., 27.

is replaced by low pressure centres with high pressures occupying the equatorial seas. In all instances, the isobaric lines meet an abrupt end at the Indian State's northern and eastern boundaries. As Blanford and the IMD's first synoptic construction of the monsoon, these charts reflect political realities and climatic imaginations. The northern Indian border is treated as a hard stop and the southern edge of the map is questioned with several "strokes" of wind extending beyond the frame.

John Eliot succeeded Blanford in 1886 and published the *Climatological Atlas of India* in 1906. Drawing upon data collected between 1875 and 1900, the GOI ordered the preparation of the *Atlas* to illustrate "all the important features of the climatology of that tropical area as determined from the results of the observations".[78] According to the GOI, observations from this period, as "imperial and directed from a central office", had "reached such a level of uniformity and accuracy as could warrant the detailed treatment necessary to turn them to account in establishing the climatology of India".[79] Constructed through careful review of Blanford's data, the *Atlas* is a manifestation of Blanford's enumerated monsoon, only hinting at Eliot's own ideas of a far more complex monsoon system inclusive of vertical and horizontal dynamical structures reaching well outside of India and the Bay of Bengal. Reminiscent of Blanford's earlier work, Eliot's *Atlas* includes two double-page charts of the Indian Ocean (Figs. 6 & 7) illustrating "two seasons of nearly equal period, one being characterized by the prevalence of dry land winds (Fig. 6), and the other (Fig. 7) by the prevalence of sea winds of great volume and intensity".[80] These seasons, otherwise known as the North-east Monsoon and the South-west Monsoon, continued to be considered India's two defining climatic conditions.

In 1893, Eliot organised an expedition "to collect all available ship-weather data from the Indian Ocean".[81] This initiative was perhaps prompted by Blanford's view that meteorological knowledge of India would remain incomplete until "some system of taking observation over the middle and northern portion of the India Ocean has been devised and brought into operation".[82] Blanford hypothesized that the "distribution of pressure over the land and sea areas" was the primary driving force behind rainfall "irregularities" over land.[83] Following this lead, Eliot's collation of ship data helped to contextualise the wind strokes and incomplete isobars from Fig. 5 within the larger framework of data in Figs. 6 & 7. Eliot's research provided a "dynamical explanation of the structure of monsoon depressions" as a set of interconnected forces defined by the horizontal convergence and uplift of air currents over extended periods of time.[84] Reflecting this knowledge in Figs. 6 & 7, the use of colour within the isobaric contours implies a weighted surface of air oscillating between different locations over the course of the year. The distinction between highs, depicted in orange to yellow tones, and lows, depicted in green to blue tones, expresses conditions of hot and dry to cool and wet, showing "the chief conditions" of "the monsoon alterations of climate and weather in India".[85] These binary representations of two opposing climatic conditions were constructions not only

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[78] Eliot, *Climatological Atlas of India*, preface.

[79] H.R.M., "Review: Climatological Atlas of India," 336.

[80] John Eliot, "On the Origin of Cold Weather Storms of the Year 1893 in India," *Quarterly Journal of the Royal Meteorological Society* 22, no. 97 (1896): 1.

[81] Sikka, "The Role of the India Meteorological Department," 395.

[82] Blanford cited in Ibid., 388-89.

[83] Ibid.

[84] Ibid., 395.

[85] Eliot, *Climatological Atlas of India*, xxiv.

of the monsoon, but of the British Empire surrounding the Indian Ocean and Bay of Bengal. In depicting a cohesive, bounded atmospheric territory the charts were an attempt to naturalise colonial state space whilst creating a soothing picture of the chaotic weather events that presented such obstacles to colonial control.[86]

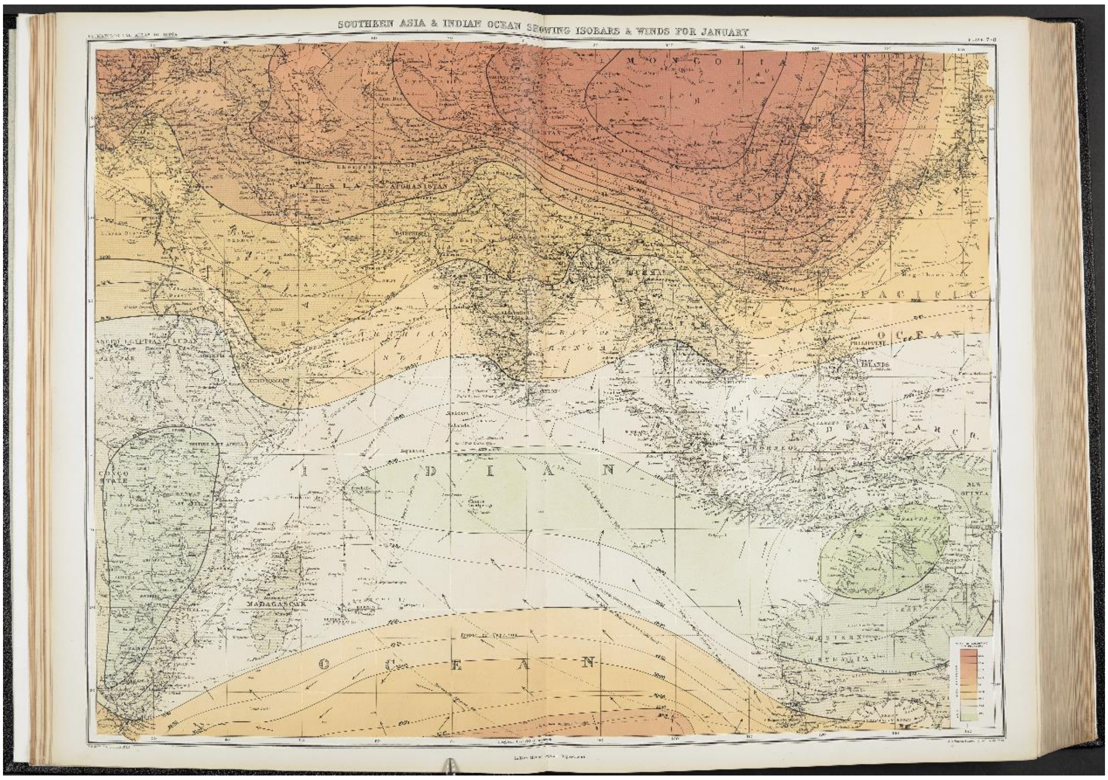

Fig. 6. Southern Asia and Indian Ocean showing isobars and winds for January. Source: Eliot, *Climatological Atlas of India*, plate 7–8. Image courtesy of British Library.

Reflective of prevailing climatic understandings and their relation to Empire, the *Climatological Atlas of India* is not, however, representative of the IMD's efforts at forecasting. Whilst such cartographic representations were useful for informing short-term prediction, they were less informative for long-range prediction. For both Blanford and Eliot, the project of long-range monsoon forecasting was a matter of great importance, due to the urgent need to foresee drought and flood events that could harm India's economy. The distinctly different frames, presented by Blanford's 1889 study of isobaric changes over India and the Bay of Bengal and Eliot's inclusion of the Indian Ocean in the 1906 *Atlas*, convey Eliot's instinct to look towards the sea for the origins of monsoon winds. From 1893 attention turned to understanding the monsoon's origins and driving forces through the routine generation of daily charts using observations extracted from logs of ocean-going ships, an activity that continued until 1904.[87]

[86] Manu Goswami, *Producing India: From Colonial Economy to National Space* (Chicago: University of Chicago Press, 2004).

[87] Indian Meteorological Department, *Administration Report of the India Meteorological Department for the Year 1924–25 and A History of the Department During the Half Century 1875–1924* (Simla: Government of India Press, 1925), 10.

Fig. 7. Southern Asia and Indian Ocean showing isobars and winds for July. Source: Eliot, *Climatological Atlas of India*, plate 9–10. Image courtesy of British Library.

Known as the *Indian Monsoon Area Charts*, these visualisations outlined the prevailing characteristics of the Indian monsoon region.[88] Comparing two such synoptic charts—Fig. 8, 2 May 1893, and Fig. 9, 21 June 1893—covering the subcontinent including both the Bay of Bengal and Indian Ocean, Eliot addresses the development of the southwest monsoon relative to its expected onset. For Eliot, these charts "throw a considerable amount of light" on air movements and oceanic currents as the monsoon advances and retreats.[89] Whilst failing to garner consensus among meteorologists as to the causes of such meteorological movements, these studies worked towards defining measurable indicators of monsoon onset.[90] Eliot deduced that shifts in isobaric distribution were not produced by thermal conditions; rather, they indicated "the transition from the hot weather to the rainy season", or the "burst of the monsoon".[91] According to Eliot, erroneous meteorological descriptions of its arrival served only to produce confusion, as well as suggesting false origins for the monsoon, with implications for an informed understanding of India's wet season. As a "subject of the greatest

[88] Eliot, "On the Origin of Cold Weather Storms," 1.

[89] Ibid., 7.

[90] Ibid.

[91] Ibid., 7.

importance from an economic standpoint", Eliot focused on understanding the arrival, departure, source, and logic of the moisture-laden winds that fed this corner of the Empire.[92]

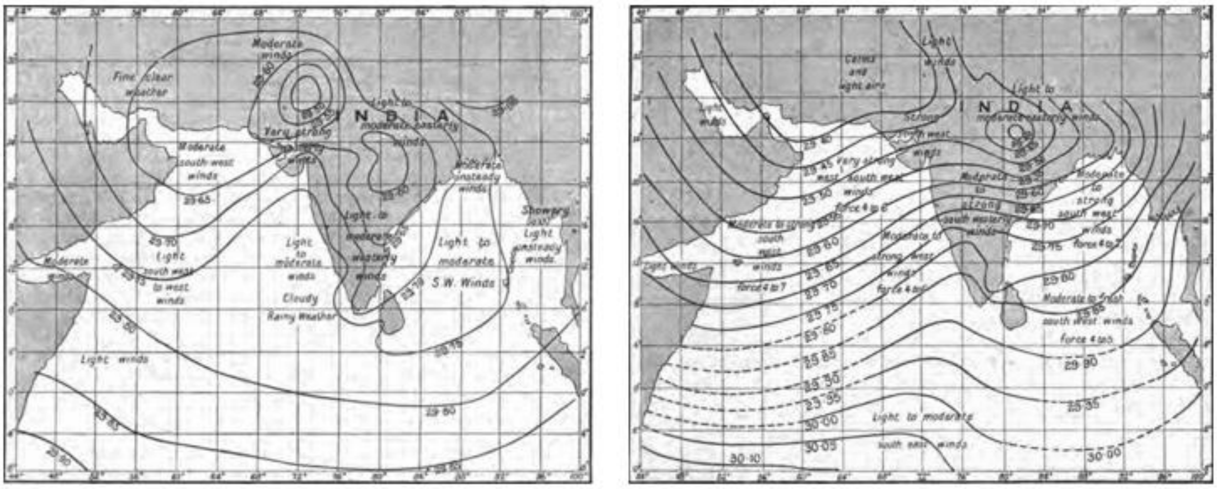

Fig. 8. Chart of the Indian Monsoon Area, 2 May 1893 (left) and 21 June 1893 (right). Source: Eliot, "On the Origin of Cold Weather Storms," 24. Image courtesy of John Wiley and Sons.

Blanford and Eliot's production and analysis of daily weather observations constructed a more nuanced understanding of the monsoon's development than earlier maritime representations, particularly its behaviour over the course of its season and the weather patterns that accompanied its departure. Daily weather reports graphically charted the course of weather throughout the year, drawing a better understanding of connections between local and regional patterns in monsoonal development. The production of daily weather charts was instrumental to Eliot's notion that the "two seasons" that divide India's year and climate "may be subdivided into two subordinate seasons or periods".[93] However, for purposes of short-term forecasting, daily weather charts often proved insufficient. Following "unsatisfactory seasons and the partial failure of crops in 1892 and 1893 in the Madras Presidency", both authorities and the public requested improved daily reports.[94] In 1904 it was decided that the recorded area should be extended to "include the far southern pressure region where monsoon winds might originate".[95] Despite expanded data collection, and introduction of weekly and monthly means rather than daily observations, efforts to predict monsoon behaviour continued to prove inadequate and the work was relinquished.

Winds that Bring Winds: Upper-Air Charts from 1904 to 1944

In 1904, Gilbert Walker—physicist and mathematician—was appointed to lead the IMD following three drought-incurred famines in 1896, 1899, and 1902. Leading to reduced revenue and a depleted Indian population, these events brought meteorological concerns to the fore. In the first year of Walker's service, the monsoon had failed again with a repeated failure

[92] Ibid., 36.

[93] Eliot, *Climatological Atlas of India,* xxxi.

[94] Indian Meteorological Department, *Administration Report,* 8.

[95] Ibid., 10.

in 1905, producing what appeared to be a statistical anomaly.[96] Within a decade, five years of monsoon failure had eluded all attempts at long-range prediction. A preoccupation with synoptic charts had restricted the spatial and temporal scope of geographic and seasonal inquiries. Towards the end of the nineteenth century meteorologists began to accept that "atmospheric phenomena could not be considered in isolation".[97] Walker was certain that the subcontinental dimensions of the monsoon must have some relation to other features of the global land-ocean-atmosphere system; putting his mathematical training to use he adopted a more quantitative approach to tackling the problem of long-range forecasting.[98] With the global reach of the British Empire and the early work of the IMO, Walker had access to meteorological records from across the globe; under his direction, the IMD pioneered statistical forecasting.[99] Although cartographic methods had allowed previous generations of meteorologists to use graphics as a way of drawing-out and establishing hypotheses regarding interrelating factors of meteorological concern, Walker moved away from geographic limitations and maps, instead examining the monsoon as a pan-oceanic, planetary system through carefully plotted tables, charts, and line graphs of numerical data.[100]

Walker's quantitative approach to monsoon science differed from previous attempts. While Eliot's methods for monsoon forecasting had grown more complex by considering possible extra-Indian factors, Blanford and Eliot's work still depended very much on intuition when it came to interpreting tables and charts.[101] In contrast, Walker's approach was "resolutely empirical". [102] Reliant on numerical methods such as correlation-coefficients and multiple-regression equations, he attempted to eliminate "the personal factor" from the seasonal forecasting formula.[103] With the vast global resources available to him, Walker's range of inquiry expanded geographically and considered atmospheric relationships between the Indian monsoon and inter-seasonal weather in distant parts of the globe. His hypotheses were informed by previous findings including: Blandford's discovery of an isobaric opposition between Siberia and the Indo-Malay region in 1800; and Hoffmeyer's discovery of associative isobaric relationships between North Atlantic and European weather systems in 1878.[104] Through the lens of the monsoon, Walker's studies of the atmosphere established foundational "knowledge of the connections between weather in distant parts of the earth".[105] Skeptical of graphic representation and the intuitive biases that it might induce, Walker focused instead on collecting and analysing quantitative information that revealed relationships which could inform forecasting. This "made the study of conditions over a very wide area unavoidable" and demanded calculations based on "seasonal, not annual, value" to account for time-based variability.[106] Walker agreed with Eliot's division of four separate seasons in India and further asserted that "there was no hope of unravelling the tangled threads of causes and effects" unless

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[96] Sikka, "The Role of the India Meteorological Department," 399–400.

[97] Kutzbach, "Concepts of Monsoon Physics," 201.

[98] Sikka, "The Role of the India Meteorological Department, 400.

[99] Amrith, *Unruly Waters*, 138-139.

[100] Ibid., 139.

[101] Baini Prashad, ed., *The Progress of Science in India During the Past Twenty-Five Years* (Calcutta: Indian Science Congress Association, 1939), 732.

[102] Amrith, *Unruly Waters*, 138.

[103] Prashad, *The Progress of Science*, 733.

[104] Gilbert Walker, "World Weather," *Quarterly Journal of the Royal Meteorological Society* 54, no. 226 (1928): 79.

[105] Ibid.

[106] Ibid.

relationships between one or two factors could be proven to have occurred "one or two seasons before those of the other", providing some statistical significance.[107] This meant that Walker's equations worked across seasons to determine the causes of seasonal rotation, rather than between adjacent periods.

The sheer quantity of data at Walker's disposal gave multiple dimensions to "empirical methods"; yet, he writes that graphic representations "are open to some objection", particularly when "the disturbing factors are numerous or the connection sought is slight", as the graphs may be interpreted differently by each observer.[108] Walker did recognize that the "purely graphic" methods used in the discovery of the isobaric "see-saw" between Argentina and India or Australia had "produced the first map showing the distribution of the world-wide surge".[109] However, referencing a similar study by Bigelow that had included a more complex set of values, Walker continued to point to graphic failings stating that the work had been "lessened by excessive and rather arbitrary smoothing" of data.[110] Subsequently, when assessing scientific methods applied to studies of the Indian monsoon and forecasting models, he stressed the importance of "not mere visual *impressions* from plotted curves", but statistically-proven relationships.[111] With the Empire's social and economic health dependent on monsoon rainfall and facing the same challenge as his predecessors, Walker chartered a new territory for monsoon forecasting based on "twenty-eight factors" which he used to "systematically examine" interrelations between the Indian monsoon and global circulation patterns.[112] For Walker, thirty years of weather data and comparative numerical analysis revealed clues about global meteorological affairs through tables and line graphs rather than cartographic depictions.

Through his examinations of global weather data, Walker continued to tweak calculation methods for monsoon rainfall forecasts. By 1908, he had made significant changes to the IMD's mathematical formulas using correlation analysis and multiple regression equations.[113] From this work, Walker determined that his forecasting model required the "calculated departure" to be "relatively large" for reliable rainfall prediction.[114] Significantly, Walker's expanded field of study and methods of calculation (Fig. 10) shed light on a "see-saw" relationship between two atmospheric "centres of action", one in the Indian Ocean and the other in the southeast Pacific Ocean.[115] Known as the "Walker Circulation", this discovery was an important milestone towards understanding dynamic atmosphere-ocean couplings and is still thought to account for rainfall variations across the tropics.[116] While Walker's observations helped to put monsoon failures and consequent droughts into wider perspective,

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[107] Ibid., 79–80.

[108] Gilbert Walker, "Correlation in Seasonal Variation of Climate," in *Memoirs of the Indian Meteorological Department, Vol. XX, Part 6* (Simla: Government Central Branch Press, 1909), 117.

[109] Walker, "World Weather," 79.

[110] Ibid.

[111] Ibid. Italics not original.

[112] D.A. Mooley and B. Parthasarathy, "Indian Summer Monsoon and the East Equatorial Pacific Sea Surface Temperature," *Atmosphere-Ocean* 22, no. 1 (1984): 24.

[113] Richard W. Katz, "Sir Gilbert Walker and a Connection Between El Nino and Statistics," *Statistical Science* 17, no. 1 (2002): 97–112.

[114] Kutzbach, "Concepts of Monsoon Physics," 203.

[115] Katz, "Sir Gilbert Walker," 97.

[116] Mooley and Parthasarathy, "Indian Summer Monsoon," 24.

his work offered "more promise for prediction of events in other regions" than for India.[117] Through studying the monsoon, Walker constructed "a productive starting point for a theory of global teleconnections".[118] Like his predecessors, Walker's long-range forecasting models were unsuccessful; however, he remained confident that physical relationships with "commercial value" were not a "mathematical figment". [119] If Blanford and Eliot had attempted to define the origins of the Indian monsoon through regional borders, Walker, who believed that "knowledge of the connections between weather in distant parts of the earth" had to be won step by step, had worked to define them by limitless inquiry.[120]

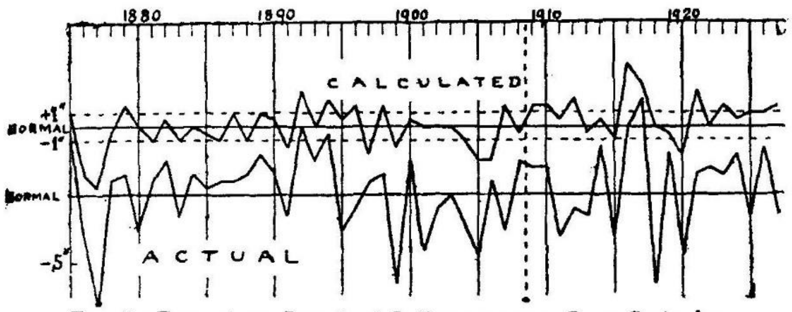

FIG. 6.—Forecast on June 1 of Indian monsoon, June—September. (1908 Formula, R=0.58).

Fig. 9. Line graph showing the calculated prediction for monsoon rainfall, from June to September, versus actual rainfall measurements taken from 1880 to 1920. Source: Walker, *World Weather*, 86. Image courtesy of John Wiley & Sons.

Walker's focus on atmospheric dynamics precipitated a shift towards the vertical expansion of meteorological exploration. Although both Blanford and Eliot contributed to expanding observation stations across India, especially at higher altitudes, India's membership in the International Meteorological Commission (IMC) after 1891 secured further expansion.[121] By 1900–1901, India's network of surface observatories had grown to 230 stations.[122] In 1912, with support from the Royal Society of London, Walker persuaded the English Secretary of State to fund an upper air observatory in Agra "to systematically undertake upper-air experiments for a period of ten years".[123] Under Walker's direction, James Hermann Field designed and led the Agra Observatory. Previously based in Simla, Field had made early upper-air observations using balloons and kites across India "with the object of investigating upper-air conditions during the south-west monsoon".[124] Field charted the position of his kites in daily weather reports (Fig. 10), locating them in relation to air pressure, wind, and rainfall

[117] Charles Normand, "Monsoon Seasonal Forecasting," *Quarterly Journal of the Royal Meteorological Society* 79, no. 342 (1953): 469.

[118] Kutzbach, "Concepts of Monsoon Physics," 205.

[119] Gilbert Walker, "Seasonal Weather and Its Prediction," *Nature* 132 (1933): 807.

[120] Walker, "World Weather," 79.

[121] Edwards, *A Vast Machine*, 53.

[122] Sikka, "The Role of the India Meteorological Department," 396.

[123] Ibid., 397.

[124] G.C. Simpson, "Obituary: James Hermann Field, C.S.I.," *The Meteorological Magazine* 72, no. 857 (1937): 119.

data. Located in India's northern plains, "near the boundary of the two main monsoon currents", Agra was ideally positioned as a launch pad for investigating the upper air dynamics of the monsoon—charting a future path for the IMD.[125]

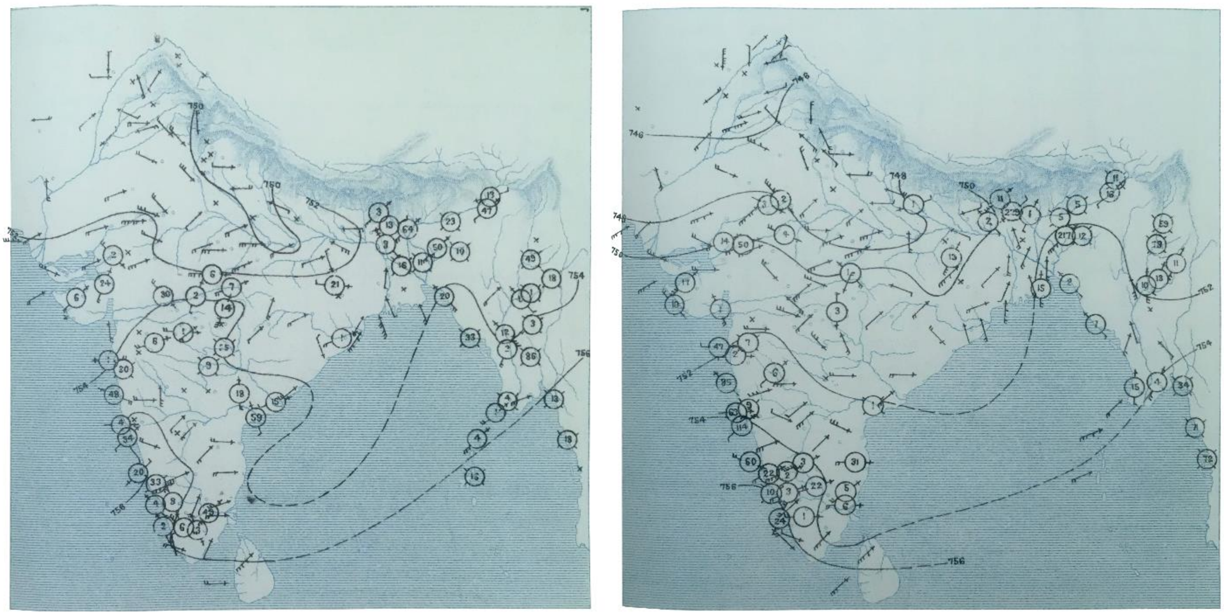

Fig. 10. Pressure in millimetres (mm.) and winds at 8:00 on 14 July 1907 with rainfall in the mm. of ensuing 24 hours (left). Pressure in mm. and winds at 8:00 on 17 July 1907 with rainfall in the mm. of ensuing 24 hours (right). Source: James Hermann Field, *Kite flights in India and over the neighbouring sea areas during 1907, Memoirs of the Indian Meteorological Department, Vol. XX, Part 7* (Simla: Government Central Branch Press, 1908), 141. Image courtesy of British Library.

Field succeeded Walker as director of the IMD in 1924. Whilst in Agra, he had pioneered investigations of the "free atmosphere", and importantly his early analysis of upper-air temperature over India uncovered discrepancies between air temperatures at different altitudes within the stratosphere. [126,] His discoveries included a "fall in temperature over India . . . marked by strong temperature inversion", which differed from Europe and the USA.[127] These were significant findings for long-range forecasting models and indicated a new exploratory plan for monsoon science. By the end of the nineteenth century, meteorologists had gained a basic knowledge of global atmospheric flows, but establishing a scientific basis for seasonal prediction would require "observations at different altitudes".[128] This indicated a

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125 India Meteorological Department, *Report on the Administration of the Meteorological Department of the Government of India in 1938–39* (New Delhi: Government of India Press, 1939), 2.

126 James Hermann Field, "The Meteorology of India," *Journal of the Royal Society of Arts* 82, no. 4256 (1934): 787.

127 Sikka, "The Role of the India Meteorological Department," 397.

128 Normand, "Monsoon Seasonal Forecasting," 468.

shift in perspective with an emphasis on vertical analysis as a way of seeing, ordering, and understanding atmospheric circulations.[129]

This shift ushered in a new era of exploratory mapping. The number of observatories producing upper-air data significantly increased, enabling "an understanding of the whole body of air up to the greatest accessible heights".[130] By 1928, in addition to daily weather charts, trajectories of kite and balloon missions were granted graphic representation (Fig. 11); their flight patterns indicated wind force and direction at different altitudes and began to draw a more complex image of the atmosphere. These visualisations improved aviation safety and advanced understandings of meteorological dangers within India's air space; these included "sudden dust storms which may blot out invisibility, rainfall that loses all control of itself, drifting cloud so low that a landing ground may be lost, and now and again a tornado".[131] Much like earlier nineteenth-century cartographies of shipping routes, these maps progressed knowledge about atmospheric phenomena that could be utilised for new, more efficient transportation routes. Whereas colonial activities on land and sea had relied on surface knowledge of winds and rain, aviation required knowledge of the upper-airs to extend the imperial reach vertically.

Reflecting preoccupations with aviation, upper-atmospheric meteorological explorations constructed the atmosphere as a traversable space.[132] As James Hermann Field wrote, "a great revolution in weather requirements has had to be met in India as the flying services have developed eastwards", describing advances between 1924 and 1934 as "little short of magical".[133] By 1934, the IMD's daily meteorological maps included "a complete and connected bird's eye view of the winds sheets over India at seven levels" and improved the accuracy of daily forecasts.[134] Through these efforts, meteorologists achieved the vantage point Blanford had envisioned in 1877, enabling them to depict atmospheric territories and geophysical dynamics. Meteorological measurements taken from Agra's upper-air exploratory surveys revealed that the height of the tropopause—the atmospheric limit of the troposphere—is higher over the tropics and shifts with the summer monsoon (Fig. 12).[135] Building on these findings, recent meteorological studies exploring "folds" in the tropopause surface have shown relationality with "monsoon intensity".[136] Such studies continue to indicate the monsoon's importance for knowledge construction.

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[129] Michael S. Reidy, "The Most Recent Orogeny: Verticality and Why Mountains Matter," *Historical Studies in the Natural Sciences* 47 (2017): 578–87.

[130] Field, "The Meteorology of India," 787.

[131] Ibid., 790.

[132] Roger Turner, "Weathering Heights: The Emergence of Aeronautical Meteorology as an Infrastructural Science" (PhD diss., University of Pennsylvania, 2010).

[133] Field, "The Meteorology of India," 788.

[134] Ibid.

[135] Ibid., 798.

[136] Yutian Wu, Gang Chen, Lindsey Taylor, and Pengfei Zhang, "On the Linkage Between the Asian Summer Monsoon and Tropopause Folds," *Journal of Geophysical Research: Atmospheres* 123, no 4 (2018): 2037–49.

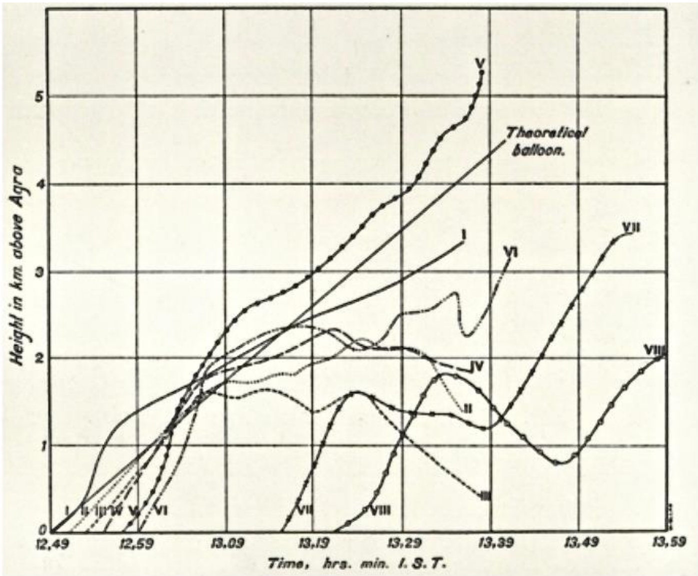

Fig. 11. Height-time curves of eight special pilot balloon ascents at Agra on 30 March 1928. Source: Field, *The Meteorology of India*, 795. Image courtesy of Royal Society of Arts (RSA) London.

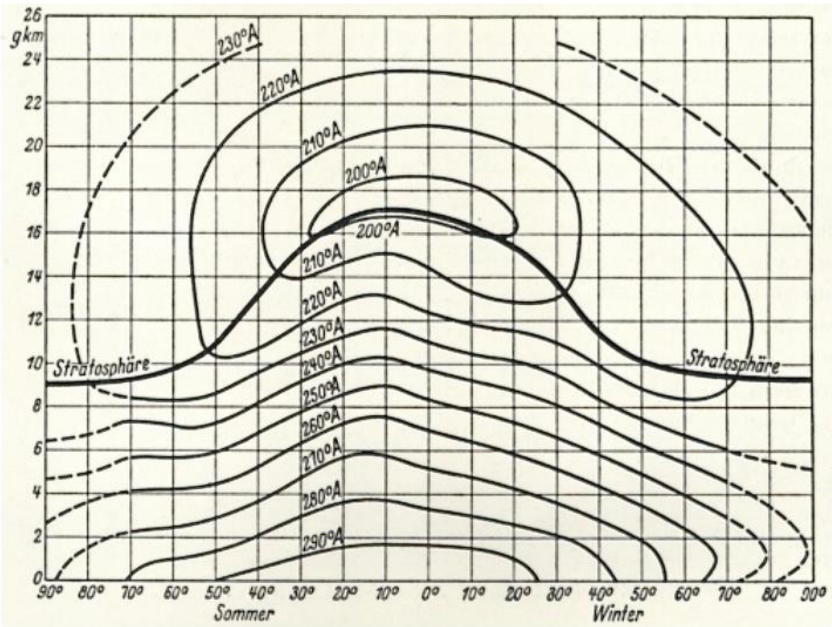

Fig. 12. Temperatures (absolute) in the upper air and stratosphere, from Equator to North Pole: Summer and Winter half-years. Source: Field, *The Meteorology of India*, 798. Image courtesy of Royal Society of Arts (RSA) London.

Between 1928 and 1944, Charles Normand served as the IMD's last British director. Still under pressure to develop better seasonal forecasting models, he introduced the "Performance Test", furthering Walker's commitments to quantitative monsoon science.[137] Whereas Walker had relied on regression equations for eliminating personal bias from forecasting, Normand's test provided a new method for determining significant and insignificant factors.[138] Although his meteorological predecessors had long understood the monsoon to be "pulsatory in character and not characterized by steady conditions", Normand continued to advance understandings of its dynamic behaviour.[139] In *The Weather of India*, Normand describes monsoon conditions over the subcontinent and the location of the monsoon trough as "not stationary" but moving North and South affecting "rainfall distribution as it moves", indicating ongoing concerns with variations in monsoon rainfall over India.[140]

Significantly, the World Wars brought meteorologists from around the world into discussion about atmospheric dynamics. Norway's Bergen School developed models to examine "frontal surfaces and instabilities" in the "mid-latitude extra-tropical cyclones" which were found to be controlled by "atmospheric waves in the upper air".[141] Bjerknes's model for frontal analysis provided a "powerful method" to aid in forecasting "weather that is caused by interaction between different types of air masses".[142] As a result, concepts based on air-mass interactions became so important in India between the 1930s and 1950s that investigations focused heavily on examining the interplay between them and "the formation of the monsoon".[143] Conjunctly, Normand's studies of the monsoon's atmospheric dynamics led him to insist that the monsoon is "an active, not a passive feature in world weather", whose behaviour advanced understandings of world-wide weather.[144] From the late nineteenth century onwards, meteorologists had worked to uncover the "vertical structure of the monsoon" and "the three-dimensional nature of atmospheric processes".[145] Building on these developments, the winds of the upper atmosphere, or the "winds that bring winds", a piece of the monsoon puzzle that had been inaccessible to earlier surface investigations, finally found cartographic expression in the *Meteorological Atlas of the International Indian Ocean Expedition* in 1972 (Fig. 13). Combining Maury's oceanic winds, Blanford and Eliot's regional winds, and Walker, Field, and Normand's atmospheric winds, the 1972 *Meteorological Atlas* constructs a monsoon of all three.

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137 S.R. Savur, "Application of the Performance Test to Seasonal Forecasting of Rainfall in India," *Sankhyā: The Indian Journal of Statistics* 2, no. 1 (1935): 2.

138 Prashad, *The Progress of Science*, 733; Savur, "Application of the Performance Test to Seasonal Forecasting", 2.

139 E.V. Chelham, "Synoptic Aspects of the Monsoon Circulation and Rainfall Over Indo-Pakistan," *Geology and Geophysics* 4, no. 3 (1953): 264.

140 Ibid., citing Normand.

141 Sikka, "The Role of the India Meteorological Department," 407.

142 Prashad, *The Progress of Science*, 734.

143 Sikka, "The Role of the India Meteorological Department," 408.

144 Charles Normand, "Monsoon Seasonal Forecasting," *Quarterly Journal of the Royal Meteorological Society* 79, no. 342 (1953): 468.

145 Kutzbach, "Concepts of Monsoon Physics," 184.

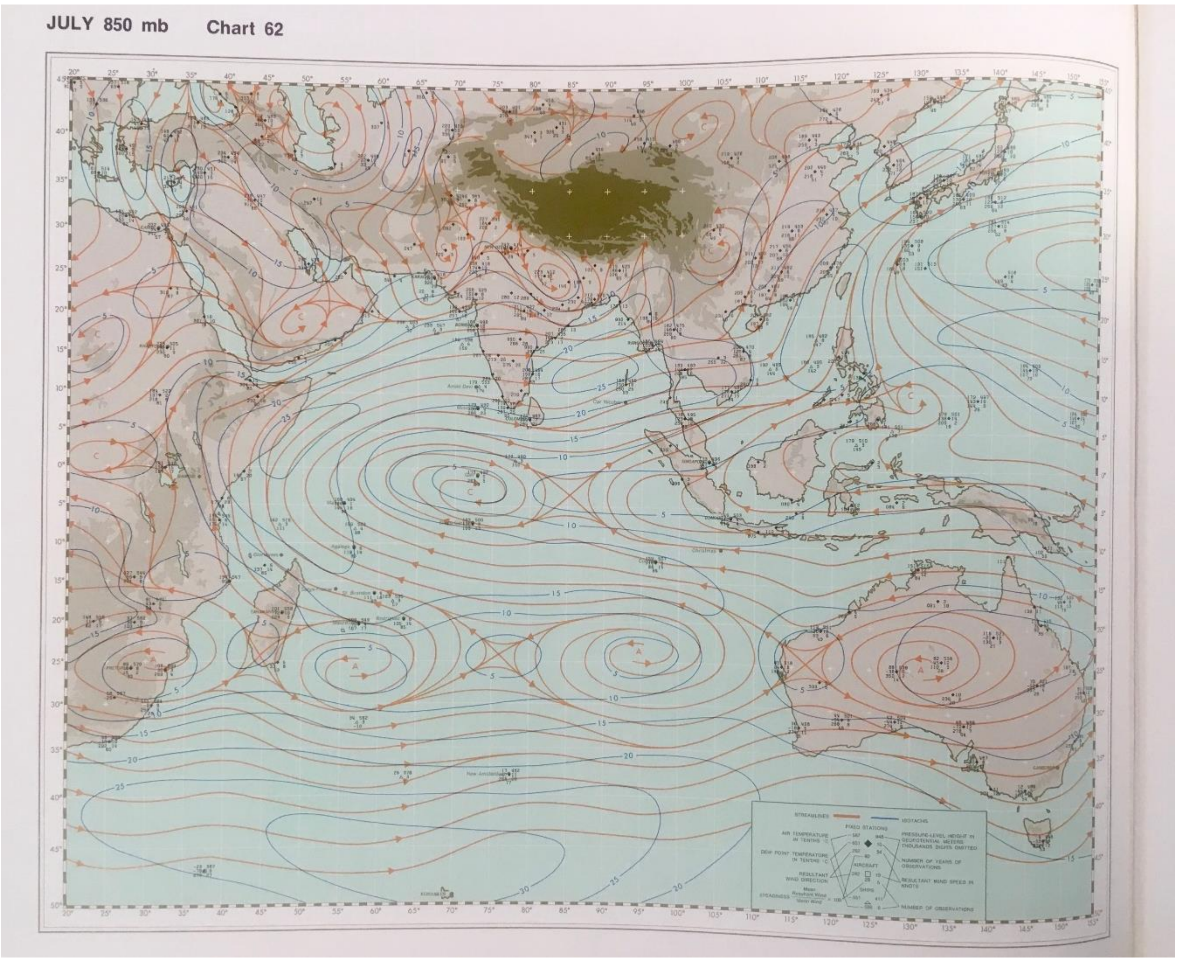

Fig. 13. Upper air chart showing mean wind flow for July at 850 millibars (mb). Source: International Indian Ocean Expedition, *Meteorological Atlas of the International Indian Ocean Expedition* (Washington, DC: US Government Publishing Office, 1972), chart 62. Image courtesy of British Library.

Conclusion

From 1844 to 1944, various meteorological constructions saw the monsoon transition from a predictable and seasonally reversing wind at sea, to an unpredictable travelling rain cloud over land, to a tele-connected planetary phenomenon extending into the upper reaches of the atmosphere. As part of ongoing, nonlinear progressions of monsoonal understandings, these perspectives were intimately tied to processes of imperial expansion: each phase of cartographic construction reflected advancing colonial agendas, from oceanic trade and exploration, to land-based revenue extraction and exploitation, to aerial transportation and atmospheric globalisation. Tracing the histories of monsoonal cartography reveals the intimate relations between colonial rule and meteorological science and their contributions to modern understandings of weather and climate. As an entanglement of material realities and human concerns, the monsoon has always been as much an ideological construction as a material entity; a meteorological assemblage that has variously catalysed, sustained and thwarted human ambitions.[146]

Nineteenth-century understandings of the monsoon were predominantly formed through measurement and quantification, largely directed by British attempts to master India's weather and climate. Towards the end of the period, the graphic techniques that initially brought shape and form to the monsoon were superseded by mathematical equations which sought to eliminate personal bias and human intuition. In part, such quantitative explorations were an attempt to escape the subjectivity of the observer. Through such endeavours, the monsoon became an abstraction, purified and naturalised through science.[147] In the minds of imperial meteorologists, such techniques of order and measurement would reveal the "laws" of natural entities, establishing knowledge that could be utilised in the productive control of nature, the pursuit of governance, and the improvement of colonial territories. Despite these ambitions and the huge leaps in understanding brought about by constellations of technologies, instruments, data, and representational techniques, the monsoon continued to defy definition and prediction.

The various historic constructions of the monsoon that emerge, converge, and diverge throughout the period considered here describe the monsoon's different aspects in their manifest complexity. Like the Indian proverb of blind men touching different parts of an elephant and giving different accounts of its form, each cartographic construction depicts a different part of the monsoon system. As a result, the monsoon remains elusive, moving in and out of focus as successive generations seek to understand, predict, leverage, and control it. Whilst contemporary meteorology now identifies the monsoon as a "fully coupled ocean-land-atmospheric system", it is widely acknowledged that many of its mechanisms, including the coupled feedbacks, are "yet to be fully explored".[148] As a result, there is still no common consensus about the monsoon and its dynamics, and no unified scientific definition.[149] This ambiguity demonstrates that human encounters with the monsoon are always inherently partial, regardless of the methods of observation and associated modes of representation.

Acknowledgements

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[146] Endfield and Randalls, "Climate and Empire."

[147] Bruno Latour, *We Have Never Been Modern* (New York, London: Harvester Wheatsheaf, 1993).

[148] Andrew G. Turner and H. Annamalai, "Climate Change and the South Asian Summer Monsoon," *Nature Climate Change,* vol. 2, (2012): 587.

[149] Matthew Alexander Stiller-Reeve, Md. Abu Syed, Thomas Spengler, Jennifer A. Spinney, and Rumana Hossain, "Complementing Scientific Monsoon Definitions with Social Perception in Bangladesh," *Bulletin of the American Meteorological Society* 96, no 1 (2015): 49–57.