Charles Darwin's Meteorological Observations aboard the H.M.S. *Beagle*

BY RANDALL S. CERVENY

On his milestone voyage, the founder of modern evolution theory often wrote perceptively about weather and climate, including the first discussion of the global teleconnective nature of El Niño/Southern Oscillation.

Famed naturalist Charles Darwin's epic journey to South America on board the H.M.S. *Beagle* is best known for his observations leading to his theory of evolution. However, as a naturalist, Darwin was interested in, and hired for, his expertise in all areas of natural science. This is particularly true of meteorology given that the captain of the *Beagle,* and Darwin's employer, was Robert FitzRoy, who later became the head of the Meteorological Department of the British Board of Trade and developer of the first weather-warning service in 1859 (Botley 1938; Humphreys 1947; Talman 1931). Indeed, Darwin noted in his diary prior to his voyage

> I am often afraid I shall be quite overwhelmed with the number of subjects which I ought to take into hand. It is difficult to mark out any plan & without method on shipboard I am sure little will be done. The principal objects are 1st, collecting, observing & reading in all branches of Natural History that I possibly can manage. Observations in Meteorology, French & Spanish, Mathematics, & a little Classics, perhaps not more than Greek Testament on Sundays. (Darwin 1933, p. 14)

AFFILIATIONS: CERVENY—Department of Geography, Arizona State University, Tempe, Arizona
CORRESPONDING AUTHOR: Randall S. Cerveny, Dept. of Geography, Arizona State University, Tempe, AZ 85287-0104
E-mail: cerveny@asu.edu
DOI:10.1175/BAMS-86-9-1295

In final form 12 March 2005

Yet Darwin's insightful meteorological observations have been relegated to brief mentions in older textbooks (e.g., Hartwig 1887; Talman 1931; Tomlinson 1860). This article relates Darwin's notes on important meteorological and climatological topics such as lightning, drought, floods, wind transport, and the implications of his observations in relation to the El Niño–Southern Oscillation (ENSO) phenomenon.

LIGHTNING. As Darwin waited for the loading and final debarkation of the *Beagle,* he attended with Captain FitzRoy a scientific lecture at the Athenaeum that was of critical importance to both him and the expedition:

> Monday, November 21st: In the evening went to the Athenaeum & heard a popular lecture from Mr. [later Sir William Snow] Harris on his lightning conductors. By means of making an Electric machine a thunder cloud; a tub of water the sea; & a toy for

a line of battle ship, he showed the whole process of it being struck by lightning & most satisfactorily proved how completely his plan protects the vessel from any bad consequences. This plan consists in having plates of Copper folding over each other, let in the masts & yards & so connected to the water beneath. The principle from which these advantages are derived, owes its utility to the fact that the Electric fluid is weakened by being transmitted over a large surface to such an extent that no effects are perceived, even when the mast is struck by the lightning. The *Beagle* is fitted with conductors of this plan; it is very probable we shall be the means of trying & I hope proving the utility of its effects]. (Darwin 1933, 8–9)

Following that lecture and, in part, because of the success of the *Beagle*'s voyage, Harris continued his studies of maritime lightning protection and in 1847 published a government report detailing the damages to 250 naval vessels struck by lightning. The British Navy eventually adopted Harris's basic safety recommendation (as described by Darwin above) that the ship mast itself be made into a conductor by having a copper band nailed along its whole length, and connecting the band to copper plates on the keel and hull. This solution significantly reduced the losses at sea due to lightning. Indeed, throughout its around-the-world voyage (see Fig. 1), the *Beagle* suffered many lightning storms (FitzRoy observed the lightning destruction of the H.M.S. *Thetis*'s mast while in Argentina), but the most significant electric phenomenon to the *Beagle* was only the occurrence of St. Elmo's fire:

Sunday, July 22nd. We are about 50 miles from Cape St. Mary's. I have just been on deck;—the night presents a most extraordinary spectacle;—the darkness of the sky is interrupted by the most vivid lightning. The tops of our masts & higher yard ends shone with the Electric fluid [Darwin annotates in a footnote: "St. Elmo's fire"] playing about them; the form of the vane might also be traced as if it had been rubbed with phosphorous (Darwin 1933, p. 80);

and later:

Sunday, April 21st: At noon 300 miles from Maldonado, with a foul wind. Our usual alternation of a gale of wind & a fine day. We are off the mouth of the Plata. At night there was a great deal of lightning; if a hurricane had been coming, the sky could not have looked much more angry. Probably we shall hear there has been at M. Video a tremendous Pampero. Our Royal mast head shone with St. Elmo's fire & therefore, according to all good sailors, no ill luck followed. (Darwin 1933, p. 144)

Darwin personally witnessed the localized damages of a lightning strike on the British Consul General's house in Mercedes:

I called one day on Mr Hood, the Consul General, in order to see his house which had been a short time previously struck by lightning. The effects were curious: the bell wires were melted & the red hot globules dropping on the furniture drilled small holes in a line beneath them; when falling on glass vessels, they melted & adhered to them. Yet the room was at least 15 feet high & the wire close to the ceiling. In one of the walls the electric exploded like gunpowder, & shot fragments of bricks with such force as to dent the wall on the opposite side. Where the bell wire ran, the paper was blackened by the oxide of the metal for nearly a foot on each side; in a like manner the frame of a looking glass was blackened; the gilding must have been volatized, for a smelling bottom which stood near, was firmly coated with some of it. The windows were all broken & everything handing up fell down by the Jar. It happened very early in the morning. When I was at B. Ayres a short time previous to this, the church was much shattered, & a vessel lost his main-mast. (Darwin 1933, 199–200)

Additionally, Darwin discovered and identified a group of lightning tubes, or fulgurites, in a broad band of sand hillocks near Maldonado, at the mouth of the La Plata River. Although fulgurites had been first been discovered in 1711 in Silesia, Poland (Brocklesby 1851), and conclusively linked to lightning by Priestley in 1790, Darwin's fulgurites in 1832 were the first such specimens discovered in the Western Hemisphere. He initially noted fulgurite fragments at the surface and further inspection indicated that they continued to greater depths. Subsequently, Darwin found four sets entering the sand perpendicularly and traced (by digging) one of them to a depth of two feet (Darwin 1897, 59–62). Other fragments, evidently belonging to the same tube, created a fulgurite of greater than five feet three inches in total length.

AERIAL TRANSPORT. Not surprisingly, given his later work on evolution, Darwin was intrigued with the dispersion of materials and organisms. He first noted (and later published work on) the aerial transport of dust from North Africa into the Atlantic Ocean. He described the atmospheric situation on board the *Beagle* while in the Verde Islands in 1832:

> Generally the atmosphere is hazy; and this is caused by the falling of impalpably fine dust, which was found to slightly injured the astronomical instruments. The morning before we anchored at Porto Praya, I collected a little packet of this brown-coloured fine dust, which appeared to have been filtered from the wind by the gauze of the vane at the mast-head. Mr. Lyell has also given me four packets of dust which fell on a vessel a few hundred miles northward of these islands. Professor Ehrenberg finds that this dust consists in great part of infusoria with siliceous shields, and of the siliceous tissue of plants. In five little packets which I sent him, he has ascertained no less than sixty-seven different organic forms! The infusoria, with the exception of two marine species, are all inhabitants of fresh water. I have found no less than fifteen different accounts of dust having fallen on vessels when far out in the Atlantic. From the direction of the wind whenever it has fallen, and from its having always fallen during those months when the harmattan is known to raise clouds of dust high into the atmosphere, we may feel sure that it all comes from Africa. (Darwin 1897, 4–5)

Fig. 1. Map identifying a portion of the world voyage made by the H.M.S. *Beagle* from 1831 to 1836 with specific detail on Atlantic and South American locations mentioned in the text.

In the first edition of the Journal of Researches into the Geology and Natural History Darwin (1839) stated more concisely, "[The dust] is produced, as I believe, from the wear and tear of volcanic rocks, and must come from the coast of Africa" (Darwin 1839, p. 4). Darwin's theory of African origin for the dust, however, was put into doubt by C. G. Ehrenberg—a leading scientist of the time—who went on record as supporting a South American origin:

> It is, however, a very singular fact, that although Professor Ehrenberg knows many species of infusoria peculiar to Africa, he finds none of them in the dust which I sent him; on the other hand, he finds in it two species which hitherto he knows as living only in South America. The dust falls in such quantities as to dirty everything on board, and to hurt people's eyes; vessels even have run ashore, owing to the obscurity of the atmosphere. It has often fallen on ships when more than thousand miles from the coast of Africa, and at points sixteen hundred miles distant in a north and south direction. In some dust which was collected on a vessel three hundred miles from the land, I found particles of stone, above the thousandth of an inch square, mixed with finer matter. (Darwin 1897, 4–5)

With the advent of satellite evidence and trajectory modeling, it is obvious that Darwin's supposition as to the origin of the Verde Islands' haze, rather than Ehrenberg's, was correct. Numerous modern studies have indicated that airborne dust over the Cape Verde

Islands does originate from Africa (Karyampudi et al. 1999; Ozsoy et al. 2001). But, of equal importance to the meteorological problem, Darwin's dust origin work (Darwin 1846) demonstrated his avid interest in dispersion. As Darwin's son noted in a book discussing his father's work, "A sentence occurs in this paper of interest, as showing that the author was alive to the importance of all means of distribution:—The fact that particles of this size have been brought at least 330 miles from the land is interesting as bearing on the distribution of Cryptogamic plants.'" (Darwin 1959, p. 296)

EL NIÑO—SOUTHERN OSCILLATION.

Argentina. The phenomenon known as ENSO is a climate-forcing mechanism involving large-scale interactions between the Pacific Ocean and atmosphere. This phenomenon is responsible for climatic shifts and environmental impacts throughout most of the globe. From a historical perspective, credit is given to Sir Charles Todd, a South Australian government observer, for making initial observations in the late 1880s, and to Hugo Hildebrandsson, for noticing "an opposition of pressure between Sydney and Buenos Ayres" in 1897 (Walker and Bliss 1932). These observations aided Sir Gilbert Walker and colleagues in their development of the concept of the "Southern Oscillation" ("SO"), a longitudinal oscillation of atmospheric sea level pressure across the Pacific Ocean (Allan et al. 1996).

Although El Niño, the ocean component of ENSO, had been identified by natives of western South America for centuries, the strong 1891 El Niño event was the impetus that inspired scientific research into the effects of the warm ocean current episodes on local climate (Allan et al. 1996). Yet, as presented below, Charles Darwin should also be given some credit in discerning periodicities in South America climate that we now identify as being ENSO related.

Before reviewing Darwin's comments on Argentine climate variability, a brief summary of the ENSO climatic teleconnections to the region is useful. Aceituno (1988) noted a weak negative correlation between the Southern Oscillation Index (SOI) and the Paraná River discharge in southern southeast South America, which is consistent with an earlier analysis (Kousky et al. 1984). Although the hydrologic basin of the Paraná is extremely extensive and, consequently, there is an inherent filtering of any climatic signal, Aceituno (1988) cited this correlation as supportive of his strongly negative correlations between the SOI and regional precipitation for the central southeast portion of South America from southern Brazil to northern Argentina. Rogers (1988) confirmed this with his observation that precipitation is significantly higher during the low (warm) phase of the SOI in the spring and autumn over southern Brazil, Paraguay, and Argentina.

In accord with these modern observations, Darwin addressed the weather over Argentina in his diary of 4–8 May 1832: "During the greater number of these days there have been torrents of rain & heavy thunderstorms. The whole country is in a state of inundation, even so that many lives have been lost: the oldest inhabitants have never seen such weather before" (Darwin 1933, p. 146). An updated chronology of historical El Niño events (Ortlieb 2000) indicates that the year 1832 can be classified having a "moderate" to "moderate +" El Niño event. Darwin's precipitation anomaly is, therefore, likely the result of the teleconnection between the Pacific ENSO phenomenon and southeastern South American climate.

Of potentially greater interest, however, is the extensive description that Darwin made of the drought conditions directly preceding this "torrent" of rain:

> While Travelling through the country, I received several vivid descriptions of the effects of a late great drought ... The period included between the years 1827 and 1830 is called the *gran seco* or the great drought. During this time so little rain fell, that the vegetation, even to the thistles, failed; the brooks were dried up, and the whole country assumed the appearance of a dusty high road. This was especially the case in the northern part of the province of Buenos Ayres, and the southern part of St. Fé. Very great numbers of birds, wild animals, cattle, and horses, perished from the want of food and water . . . The lowest estimation of the loss of cattle in the province of Buenos Ayres alone, was taken at one million head. (Darwin 1897, p. 134)

He continued,

> I was informed by an eyewitness that the cattle in herds of thousands rushed into the Parana, and being exhausted by hunger they were unable to crawl up the muddy banks, and thus were drowned . . . Without doubt several hundred thousand animals thus perished in the river . . . Subsequently to the drought of 1827 to '32, a very rainy season followed, which caused great floods. Hence it is almost certain that some thousands of the skeletons were buried by the deposits of the very next year. (Darwin 1897, p. 135)

Although a historical chronology of strong La Niña episodes has not been created in the same fashion as that for El Niño events, existing teleconnections suggest an ENSO explanation of this Argentine drought. Following the statistical analyses of Aceituno (1988) and others demonstrating strongly negative correlations between SOI and regional precipitation for the central southeast portion of South America from southern Brazil to northern Argentina, this extensive drought would appear to be linked to La Niña.

Darwin displays an avid curiosity concerning the fundamental cause of this extended drought. In a footnote to the above drought entry (only in the first edition of Darwin 1839), he stated, "These droughts to a certain degree seem to be almost periodical; I was told the dates of several others, and the intervals were about fifteen years" (Darwin 1839). If one examines the updated historical El Niño chronology, there were extended periods between El Niños from 1808 to 1812, from 1792 to 1802, and from 1779 to 1782. If one can assume that stronger La Niña conditions (and a greater likelihood of Argentine drought) would tend to occur in the middle of these intervals between El Niños, then Darwin's rough 15-year-interval drought cycle could correspond to occurrences of stronger La Niña events. It must be noticed, however, that Darwin's periodicity of roughly 15 years may also be tied to other potential forcing mechanisms, such as the luni–solar cycles identified in many climate records by Currie (1897); although, recent research also suggests a possible linkage between ENSO and lunar cycles (Cerveny and Shaffer 2001).

One question might be posed as to why Darwin saw potential periodicity in the occurrence of Argentine drought (linked to La Niña) as opposed to flood (linked to El Niño), particularly given that he arrived in Argentina during a major wet episode. According to the reconstructed historical record of El Niño events, in the 20 years prior to Darwin's arrival in South America, there were a total of eight El Niño events with a marked clustering of events between 1812 and 1824. Consequently, strong La Niña conditions, at least for the first part of the nineteenth century, would be the more noticeable anomaly with regards to Argentine climate.

In the second edition of the journal Darwin expanded on his musing regarding drought:

> A tendency to periodical droughts is, I believe, common in most dry climates: such certainly is the case in Australia. Captain Sturt says they return after every ten and twelve years, and are then followed by excessive rains, which gradually become less and less, till another drought is the consequence. The year 1826 and the two following were singularly dry in Australia, and the latter were the first of the 'gran seco.' (Darwin 1897, p. 157)

Darwin immediately follows this discussion by hypothesizing geographic drought linkages (i.e., climate teleconnections), perhaps being one of the first scientists to do so:

> I mention this, because General Beatson in his account of the island of St. Helena, has remarked that variations in climate sometimes appear to be the effect of the operation of some very general cause. He says [Beatson 1816], "The severe drought felt here in 1791 and 1792, was far more calamitous in India. Doctor Anderson states, that, owing in a failure of rain, during the above two years, one half of the inhabitants in the northern provinces had perished by famine; and the remainder were so feeble and weak, that on the report of rice coming from the Malabar coast, 5000 poor people left Rajamundy, and very few of them reached the sea-side, although the distance is only miles. It appears by Mr Bryan Edward's *History of the West Indies* [Edwards 1806], that the seasons 1791-2 were unusually dry at the island of Montsserat." Barrow [Barrow 1806] in the latter part of 1792, when at the Cape de Verd island says, "In fact a drought of three years' continuance, and consequent famine for almost the same period, had nearly desolated the island." (Darwin 1897, 157–158; relevant references for Darwin's sources appear in brackets)

According to the updated historical El Niño chronology (Ortlieb 2000), the year 1791 was a strong to perhaps "very strong" (according to Quinn) El Niño event. In the paragraph above, Darwin's first source, Major General Alexander Beatson (1816), directly linked drought conditions at two distinct locations for that year: a) the Caribbean Sea and b) India; while Darwin added reference to another location: c) Cape Verde/West Africa and, implied by juxtaposition, drought in a fourth location: d) Australia. Modern research has indicated that El Niño is associated with drier-than-average conditions in a) the Caribbean Sea (e.g., Giannini et al. 2001; Ropelewski and Halpert 1987), b) India (e.g., Lau and Nath 2000), and c) Cape Verde/West Africa (e.g., Camberlin et al. 2001; Janicot et al. 2001), and d) Australia (e.g., Cai et al. 2001). Darwin's speculations on "some very general cause" to these four widely separated drought areas are undoubtedly some of the first thoughts on the existence of the global-scale climatic-forcing mechanism, the El Niño–Southern Oscillation phenomenon.

Western South America. Darwin continued traveling around to the west coast of the South American continent, reaching Peru by 1835. Modern climatological research has identified the Pacific coastal region of South America from Ecuador southward as one of the most visibly affected regions during a severe ENSO event. For example, Rasmusson and Carpenter (1982) have documented a tendency for anomalous wet conditions along the arid coast of northern Peru and southern Ecuador during El Niño episodes. The particularly strong El Niño/negative SO event of 1982/83 produced major floods in northern Peru (Horel and Cornejo-Garrido 1986). Aceituno (1988) notes that the flooding events of this region appear to be associated with an extended southward displacement of the near-equatorial trough over the eastern Pacific and has identified—by satellite measurements of outgoing longwave radiation—an extensive area of enhanced convection in the eastern equatorial Pacific.

As Darwin journeyed northward into northern Chile on 28 April 1835, he observed,

> At night there was a very light shower of rain: this was the first drop that had fallen since the heavy rain of September 11th and 12th, which detained me a prisoner at the Baths of Caugquenes. The interval was seven and a half months; but the rain this year in Chile was rather later than usual. (Darwin 1839, p. 307)

He again noted the lack of rainfall on 6 June 1835:

> But it may be well imagined how bare the hills must have been, since a shower had not fallen for 13 months . . . After two or three very dry years,—that is perhaps with not more than one shower during the whole time, a rainy year generally follows, & this does more harm than even the drought. The river swells & covers with gravel & sand the narrow strip of ground which along is fit for cultivation; the flood also injures the irrigating ditches: great devastation had thus been caused three years ago. (Darwin 1839, 317–318; Darwin 1897, 427–428)

Darwin apparently is referring to stories that he garnered from locals of the last major rainfall in 1832 (three years earlier), which, in the updated chronology of historical El Niño events (Ortlieb 2000), is classified as having a "moderate" to "moderate +" El Niño event. Interestingly, unlike his Argentine drought speculations, Darwin does not draw any parallels between the floods that he witnessed three year earlier in Argentina (see above) and those he apparently heard about in Peru for that same year.

CONCLUSIONS. Darwin's voyage to South America on board the *Beagle* has long been hailed as a landmark in the biological sciences. Study of Darwin's observations indicates that a similar appellation could be made from the perspective of the geophysical sciences. His notes on lightning suppression (the *Beagle's* inclusion of Harris's lightning protection measures) and damage, as well as his discussion of the aerial transport of dust, are marked by the thoughtful, detailed annotations of a trained scientist.

In particular, his observations on the extended drought in Argentina, which ended upon his arrival and his speculations on "some very general cause," which would explain simultaneous occurrences of drought around the world must place him as one of the founding scientists in the study of global teleconnections and, in particular, the El Niño–Southern Oscillation phenomenon. Given these findings, it is particularly appropriate that one of ENSO's fundamental measures—the SOI—incorporates sea surface pressure values of an Australian town named directly after Charles Darwin by one of his shipmates on board the H.M.S. *Beagle.*

REFERENCES

Aceituno, P., 1988: On the functioning of the Southern Oscillation in the South American sector. Part 1: Surface climate. *Mon. Wea. Rev.,* **116,** 505–524.

Allan, R., J. Lindesay, and D. Parker, 1996: *El Nino Oscillation and Climatic Variability.* CSIRO Publishing, 405 pp.

Barrow, J., Sir, 1806: *A Voyage to Cochinchina.* (1975; reprint, Oxford University Press, 447 pp.)

Beatson, A., 1816: *Tracts Relative to the Island of St. Helena; Written during a Residence of Five Years.* W. Bulmer and Co., 330 pp.

Botley, C. M., 1938: *The Air and Its Mysteries.* G. Bell and Sons, Ltd., 296 pp.

Brocklesby, J., 1851: *Elements of Meteorology.* Pratt, Woodford and Co., 240 pp.

Cai, W., P. H. Whetton, and A. B. Pittock, 2001: Fluctuations of the relationship between ENSO and northeast Australian rainfall. *Climate Dyn.,* **17,** 421–432.

Camberlin, P., S. Janicot, and I. Poccard, 2001: Seasonality and atmospheric dynamics of the teleconnection between African rainfall and tropical sea-surface temperature: Atlantic vs. ENSO. *Int. J. Climate,* **21,** 973–1005.

Cerveny, R. S., and J. A. Shaffer, 2001: The moon and El Nino. *Geophys. Res. Lett.,* **28,** 25–28.

Currie, R. G., 1987: Examples and implications of 18.6- and 11-yr terms in world weather records. *Climate: History, Periodicity, and Predictability,* M. R. Rampino, et al., Eds., Van Nostrand Reinhold, 378–403.

Darwin, C., 1839: *Journal of Researches into the Geology and Natural History.* (1952; reprint of 1st ed. Hafner Publishing Company, 615 pp.)

——, 1846: An account of the fine dust which often falls on vessels in the Atlantic Ocean. *Geol. Soc. J.,* **2,** 267–274.

——, 1897: Journal of Researches into the Natural History and Geology of the Countries Visited during the Voyage of the H.*M.S. Beagle Round the World, under the Command of Capt. Fitz Roy, R.N.* 2d ed., D. Appleton and Company, 519 pp.

——, 1933: *Charles Darwin's Diary of the Voyage of the H.M.S.* "*Beagle.*" Cambridge University Press, 451 pp.

Darwin, F., 1959: *The Life and Letters of Charles Darwin.* Basic Books, 558 pp.

Edwards, B., 1806: *The History, Civil and Commercial, of the British Colonies in the West Indies.* James Humphreys, 427 pp.

Giannini, A., M. A. Cane, and Y. Kushmir, 2001: Interdecadal changes in the ENSO teleconnection to the Caribbean region and the North Atlantic Oscillation. *J. Climate,* **14,** 2867–2879.

Hartwig, G., 1887: *The Aerial World.* Longmans, Green and Co., 556 pp.

Horel, J. D., and A. D. Cornejo-Garrido, 1986: Convection along the coast of northern Peru during 1983: Spatial and temporal variation of clouds and rainfall. *Mon. Wea. Rev.,* **114,** 2091–2105.

Humphreys, W. J., 1947: *Ways of the Weather.* Jacques Cattell Press, 400 pp.

Janicot, S., S. Trzaka, and I. Poccard, 2001: Summer Sahel-ENSO teleconnection and decadal time scale SST variations. *Climate Dyn.,* **18,** 303–320.

Karyampudi, V. M., and Coauthors, 1999: Validation of the Saharan dust plume conceptual model using lidar, Meteosat, and ECMWF data. *Bull. Amer. Meteor. Soc.,* **80,** 1045–1075.

Kousky, V. E., M. T. Kagano, and I. F. A. Cavalcanti, 1984: A review of the Southern Oscillation: Oceanic-atmospheric circulation changes and related rainfall anomalies. *Tellus,* **36A,** 409–504.

Lau, N.-C., and M. J. Nath, 2000: Impact of ENSO on the variability of the Asian–Australian monsoons as simulated in GCM experiments. *J. Climate,* **13,** 4287–4309.

Ortlieb, L., 2000: The documented historical record of El Niño events in Peru: An update of the Quinn record (Sixteenth through Nineteenth centuries). *El Niño and the Southern Oscillation (Multiscale Variability and Global and Regional Impacts),* H. F. Diaz, and V. Markgraf, Ed., Cambridge University Press, 207–295.

Ozsoy, E., N. Kubilay, S. Nickovic, and C. Moulin, 2001: A hemispheric dust storm affecting the Atlantic and Mediterranean in April, 1994: Analyses, modeling, ground-based measurements and satellite observations. *J. Geophys. Res.,* **106,** 18 439–18 460.

Rasmusson, E. M., and T. H. Carpenter, 1982: Variations in tropical sea surface temperature and surface winds fields associated with the Southern Oscillation/El Nino. *Mon. Wea. Rev.,* **110,** 354–384.

Rogers, J. C., 1988: Precipitation variability over the Caribbean and tropical Americas associated with the Southern Oscillation. *J. Climate,* **1,** 172–182.

Ropelewski, C. F., and M. S. Halpert, 1987: Global and regional scale precipitation associated with the El Niño/Southern Oscillation. *Mon. Wea. Rev.,* **115,** 1606–1626.

Talman, C. F., 1931: *The Realm of the Air.* Bolls-Merrill, 318 pp.

Tomlinson, C., 1860: *The Rain-Cloud and the Snow-Storm: An Account of the Nature, Formation, Properties, Dangers and Uses of Rain and Snow.* Society for Promoting Christian Knowledge, 402 pp.

Walker, G. T., and E. W. Bliss, 1932: World Weather V. *Mem. Roy. Meteor. Soc.,* **4,** 53–84.