Overview

Investigating El Niño-Southern Oscillation and society relationships

Stephen E. Zebiak,[1*] Ben Orlove,[1,2] Ángel G. Muñoz,[1,3] Catherine Vaughan,[1] James Hansen,[1,4] Tara Troy,[5] Madeleine C. Thomson,[1,6] Allyza Lustig[1] and Samantha Garvin[1]

Throughout at least the past several centuries, El Niño-Southern Oscillation (ENSO) has played a significant role in human response to climate. Over time, increased attention on ENSO has led to a better understanding of both the physical mechanisms, and the environmental and societal consequences of the phenomenon. The prospects for seasonal climate forecasting emerged from ENSO studies, and were first pursued in ENSO studies. In this paper, we review ENSO's impact on society, specifically with regard to agriculture, water, and health; we also explore the extent to which ENSO-related forecasts are used to inform decision making in these sectors. We find that there are significant differences in the uptake of forecasts across sectors, with the highest use in agriculture, intermediate use in water resources management, and the lowest in health. Forecast use is low in areas where ENSO linkages to climate are weak, but the strength of this linkage alone does not guarantee use. Moreover, the differential use of ENSO forecasts by sector shows the critical role of institutions that work at the boundary between science and society. In a long-term iterative process requiring continual maintenance, these organizations serve to enhance the salience, credibility, and legitimacy of forecasts and related climate services. © 2014 John Wiley & Sons, Ltd.

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INTRODUCTION

The El Niño-Southern Oscillation (ENSO) is today recognized as the most prominent mode of climate variability that operates on seasonal-to-interannual time scales. Accounting for large swings in both oceanic and atmospheric conditions in the tropical Pacific region, it is also closely associated with climate anomalies throughout much of the globe. Through its effect on the global atmospheric circulation, ENSO influences patterns of temperature and precipitation—including extreme events such as drought, floods, and tropical cyclones—in many regions of the world. These conditions have impacts on societies—through agriculture and food security, water resources, health, disaster occurrences, and numerous other means.

ENSO has been the subject of much study and observation, particularly over the past few decades. Research on ENSO has been significant

*Correspondence to: steve@iri.columbia.edu

[1]International Research Institute for Climate and Society, The Earth Institute, Columbia University, Palisades, NY, USA

[2]School of International and Public Affairs (SIPA), Columbia University, Palisades, NY, USA

[3]Centro de Modelado Científico (CMC) (This institute is part of the Latin American Observatory partnership), Universidad del Zulia, Maracaibo, Venezuela

[4]CGIAR Research Program on Climate Change, Agriculture, and Food Security, Palisades, NY, USA

[5]Department of Civil & Environmental Engineering, Lehigh University, Bethlehem, PA, USA

[6]Department of Environmental Health, Mailman School of Public Health, Columbia University, New York, NY, USA

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not only in terms of understanding the phenomenon itself, but also in terms of understanding tropical atmosphere–ocean interaction, its role in climate dynamics generally, and its implications for climate predictability. The prospects for seasonal climate forecasting emerged from ENSO studies, and were first pursued in ENSO studies.

New knowledge about ENSO and its impacts, and new information—particularly predictions—have opened a new pathway for society to relate to ENSO: to anticipate its impacts and to take actions to manage them. The ways in which this process has played out in different settings have revealed a great deal about social and institutional dynamics, and have provided insights into how the effective uptake of climate information can be achieved in practice.

In this article, we survey these aspects of ENSO–society relationships. First, we review the developments in the study of ENSO, ENSO predictions, and the present-day climate predictions and programs that derive from these. Next we review critical aspects of ENSO impacts on society through consideration of three key sectors—water, agriculture, and health—which present a range of impacts as well as societal responses. Then we review some of the social dimensions of societal responses to ENSO and more general climate forecasts and information, including a cross-sectoral analysis addressing the differential use of climate information across the water, agriculture, and health sectors. Finally we present some concluding remarks.

DISCOVERY OF THE ENSO PHENOMENON

Our understanding of ENSO has always been linked to its societal impacts. At least since the early 1500s, fishermen off the coast of Peru have recognized that periodic warm waters affected their anchovy catch. Around the same time, Peruvian farmers noted that warm seawaters were associated with increased rainfall. Because the oceanic warming phenomenon tended to occur around Christmas, it was named El Niño, after the Christ child. At the end of the 19th century, Peruvian geographers further explored climate conditions along the coast,[1] noting a typical shift from cold to warmer ocean conditions at the end of the year that they attributed to a southward warm current.[2,3] The geographers observed that in some years the onset of warm conditions was stronger than usual and was accompanied by atypical oceanic and climatic phenomena.

Independent of this work, the British physicist Sir Gilbert Walker studied the relationship between the Indian monsoon and meteorological conditions elsewhere around the world. He discovered what he called the Southern Oscillation (SO)—a large-scale interannual fluctuation in sea-level pressure between the western and eastern Pacific,[4] with opposite poles located near Darwin, Australia, and Tahiti. Walker's discovery of the SO was the first scientific indication of the connectivity between weather conditions in distant parts of the tropical Pacific.

Linking El Niño and the Southern Oscillation

It was not until the 1960s that scientists came to realize that the episodic warming of sea surface temperature (SST) off the Peruvian coast is part of an ocean-wide perturbation that extends westward along the equator out to the date line, and that these changes in SST are associated with the Southern Oscillation. Berlage[5] was the first to recognize this linkage and, the term 'El Niño' thus became associated with unusually strong warming events that occur every 2–7 years in concert with basin-scale tropical Pacific Ocean anomalies.

Building on this discovery, the Norwegian-American meteorologist Jacob Bjerknes was able to suggest a mechanism to connect the two phenomena. In his scheme, El Niño was the oceanic realization of a large-scale ocean–atmosphere interaction. Bjerknes used observed data to provide evidence that the long-term persistence of climate anomalies associated with Walker's SO,[4] including changes in the tropical Pacific trade winds, was closely associated with slowly evolving SST anomalies in the equatorial Pacific. In brief, Bjerknes postulated that warming (cooling) of SST in the Pacific causes the trade winds to slacken (strengthen); this in turn drives ocean circulation changes that reinforce the SST tendency—a positive feedback process.[6] Although this reasoning explains the development of El Niño warming conditions, or of the opposite extreme cooling conditions (now known as La Niña), Bjerknes recognized that an understanding of the successive transitions back and forth between these states was still lacking. This explanation would await research some 20 years later. Following Bjerknes' groundbreaking work, oceanographers and meteorologists explored these atmospheric and oceanic phenomena together in what we now call the ENSO. Figure 1 presents the major oceanic and atmospheric signatures of ENSO.

Over the course of the 1970s and 1980s, a number of landmark studies furthered our understanding of the connection between El Niño and the Southern Oscillation. Wyrtki[8] realized that basin-wide changes in sea level occur at the same time as ENSO events,

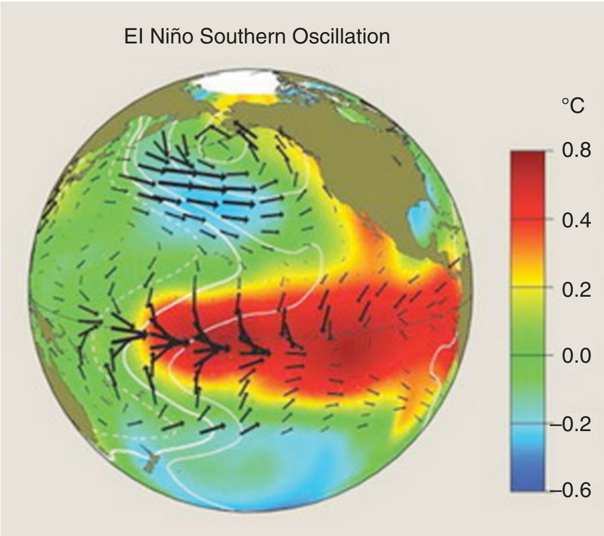

FIGURE 1 | El Niño anomalies in sea surface temperature (SST) (color shading and scale in °C), surface atmospheric pressure (contours), and surface wind stress (vectors) in the Pacific basin. Pressure contour interval is 0.5 mb, with solid contours positive and dashed contours negative. Wind stress vectors indicate direction and intensity, with the longest vector equivalent to $\sim$1 N m^{-2}. The patterns in this graphic are derived from a linear regression against SST anomalies averaged over 6°N–6°S, 90°W–180° in the eastern and central equatorial Pacific. All quantities scale up or down with the intensity of anomalies in this index region (reproduced from McPhaden et al.[7]).

specifically noting sea-level rise in the eastern Pacific associated with warm ENSO phases. He also showed that changes in initial wind conditions occur in the central and western Pacific, far from the locations of sea-level rise (and increased SST) in the eastern Pacific. This, Wyrtki suggested, indicated that the sea level and SST effects could be induced by the action of equatorial Kelvin waves; large-scale ocean dynamics were thus introduced into the conceptual understanding of ENSO. A series of studies further developed the theory of wind-forced equatorial ocean dynamics, and demonstrated the ability of numerical models (forced by observed winds) to capture principal features of observed El Niño-related oceanic variability.[9–11]

A key advance toward understanding the atmospheric dimensions of ENSO was made in 1980 when Gill proposed a simple but useful model for tropical atmospheric circulation. Later, Zebiak[12] showed the relevance of this model specifically to ENSO, by simulating near-equatorial wind variability as a response to prescribed observed El Niño SST patterns. Another line of research was directed at simulating and understanding the global-scale atmospheric responses associated with ENSO.[13]

Concurrently, Rasmussen and Carpenter[14] conducted a seminal observational study that provided the first detailed picture of basin-wide wind, SST, and rainfall anomaly fields throughout an El Niño event, constructed from composites of six major warm episodes occurring during the period 1950–1976. This provided the observational basis to further explore ENSO theory and ENSO models.

While research was proceeding along these lines, an historic El Niño event—the largest on record at the time—played out in the period 1982–1983, and this catalyzed a greatly intensified effort to better observe, understand, and ultimately predict ENSO. The 1982–1983 El Niño was remarkable in several ways, beyond its strength. The event was associated with far-reaching impacts around the world, placing El Niño in the focus of public attention as never before. The event was not detected until well underway, owing to the lack of real-time oceanic observing system. The timing and evolution of the event were different from the several preceding events (as depicted in Rasmussen and Carpenter's composites). And the 'buildup' of sea level in the western Pacific that Wyrtki had hypothesized was a precursor of El Niño was not evident.

In these ways, the 1982 El Niño catalyzed a new wave of scientific interest, and eventually the creation of a 10-year international research program—the Tropical Ocean-Global Atmosphere Program (TOGA)—to study and predict ENSO and its global impacts.[15] One important outcome of this project was the creation of a near-real-time ENSO observing system that now includes an array of moored buoys,[16] an island tide-gauge network, surface drifters, a volunteer ship observing program, and a variety of satellite observations.

The TOGA program also promoted important work in ENSO modeling and led to the development of several models that helped to bolster our understanding of the ENSO phenomenon. Zebiak and Cane[17] and Schopf and Suarez[18] introduced coupled dynamical models that produced plausible simulations of ENSO. With realistic parameter settings, the models produced anomalous SST and wind comparable to the observed ENSO anomalies in both structure and magnitude. The simulations moreover featured a succession of warm and cold events that recur with a time scale of 3–4 years (analogous to the observed ENSO, though more regular), and quite realistically captured the timing of peak warming toward the end of the calendar year.

These modeling successes went far to demonstrate the essential physics underlying ENSO, and additionally set the stage for considering ENSO predictability. In quick succession, a number of studies developed a more refined theoretical interpretation of the initial model results, particularly the mechanisms responsible for the quasi-regular, multiyear ENSO oscillation. Suarez and Schopf[19] and Battisti and Hirst[20] demonstrated that while westerly (eastward) wind anomalies in the Central Pacific generate eastward-propagating Kelvin waves, which deepen the thermocline in the region of propagation, they also produce westward-propagating Rossby waves that shallow the thermocline in their path. These Rossby waves reflect off the western boundary and propagate to the east as Kelvin waves, that in turn, act to shallow the thermocline in the eastern equatorial Pacific and reverse the initial SST warming around 6 months after the onset of the initial SST warming in the east—a sort of delayed negative feedback. Thus emerged the central idea that the positive (Bjerknes) feedback process, in conjunction with this delayed negative feedback process, can result in an ENSO oscillation like that observed. This so-called 'delayed oscillator theory', and variants on it that followed, are key accomplishments of the TOGA period.[21]

ENSO Forecasting and Climate Prediction

Prior to the modeling studies just described, efforts were already underway to predict El Niño using statistical approaches.[22] Inoue and O'Brien[23] were the first to apply a physical ocean model to El Niño forecasting. They were able to demonstrate skill in predicting the onset of major El Niño extremes at lead times of a few months, based solely on specified, observed wind anomalies over the tropical Pacific basin.

The successes in simulating ENSO with the first coupled models motivated a new round of forecasting efforts based on these tools. Cane et al.[24] were the first to demonstrate prediction skill in forecasting ENSO conditions several seasons in advance using a fully coupled model.

Following these early successes, a suite of models with varying degrees of complexity has been developed for ENSO prediction. These models can generally be divided into three categories: purely statistical models,[25] physical ocean–statistical atmosphere hybrid models,[26] and fully physical ocean–atmosphere coupled models. Most of the coupled model-based prediction systems that have been developed utilize ocean–atmosphere general circulation models (GCMs) and increasingly sophisticated data assimilation systems to initialize the forecasts.[27–29] Today more than 20 ENSO prediction systems are run at centers throughout the world on a routine basis.[30]

As ENSO prediction has matured, the issue of skill assessment has become increasingly relevant. Studies in the 1990s, for instance, showed real-time ENSO prediction capability at a moderate level, and generally indicated a comparable level of skill between statistical and dynamical approaches.[31] More recent assessments suggest a slight improvement in the performance of dynamical models relative to statistical models, but also show evidence of changing skill levels over time (lower skill more recently) possibly associated with the observed changes in the strength of ENSO variability.[32]

Seasonal Predictions Emerge

It is difficult to overstate the significance of the work on ENSO that demonstrated for the first time the potential for prediction of some characteristics of climate/weather at long range (i.e., 1–3 seasons). This, together with the empirical and modeling work showing the relationships between ENSO and seasonal climate across many regions of the globe, established a basis for potential predictability of seasonal climate.

In theory, coupled models employing a global GCM for the atmospheric component could provide predictions of regional climatic conditions (e.g., seasonal precipitation and temperature patterns). However, the coupled GCMs that were initially applied to ENSO prediction generally exhibited significant forecast tendency errors associated with errors in the models' baseline climate. An alternative approach proved more effective: the so-called two-tier prediction scheme.[33] In the initial version of this, a forecast of tropical Pacific SST was first produced using a regional coupled ENSO model (as discussed above). The global climate was then predicted using an atmosphere-only GCM, forced with the predicted SST field in the tropical Pacific. In recognition of the large internal variability of the atmosphere (that is, chaotic variability unrelated to any forcing from the land or ocean), ensembles of atmospheric simulations are generated, in order to identify statistically significant signals in the predicted climate.[34]

Not long after research on ENSO-based seasonal prediction had begun, another historic El Niño event unfolded in 1997.[35] This event, even larger then the previous record-breaking 1982 event, was no less significant in terms of its impact. By this time, awareness about ENSO, its predictability, and its influences on regional climate was widespread. As this event played out, there was high demand for information on the predicted evolution of both the event itself, as well as its associated regional climate conditions. In response, Climate Outlook Forums (COFs) were introduced in several regions around the world. These meetings brought together scientists, weather services, and in many cases potential 'users' of forecast information to create consensus outlook for the regional climate over the next 1–2 seasons and promote its application.[36]

Concurrent with the establishment of the COFs (and in support of them), the first global-scale seasonal prediction products were introduced in 1997.[37,38] These forecasts, based on a generalized two-tier process, pioneered the use of multi-model-based ensemble prediction, and introduced a probabilistic format to describe the forecasts (an example is provided in Figure 2). These approaches have been widely adopted and are still in use today. The incorporation of probabilistic formats is particularly significant; this is essential to conveying what we observe in the models and understand in nature—that the predictability of seasonal climate is intrinsically limited. However, probabilistic forecasts have proven difficult to understand and to use in many real-world settings.

As seasonal prediction has matured over the past decade and a half, a number of challenges have been recognized. First, for many regions of the world remote to the tropical Pacific seasonal climate is more influenced by local ocean conditions than by ENSO.[39] While the long-range predictability of conditions in the tropical Indian and Atlantic oceans and extratropical regions is not demonstrated, at short range (one season or less) there is a degree of predictability associated with the 'persistence' of SST patterns, which prediction schemes attempt to capture through specification of initial ocean conditions from observations. But, it is recognized that the ability to predict seasonal climate in many areas, even given ENSO, is modest. Secondly, we have come to appreciate that the characteristics of ENSO can and apparently do vary over time. The 'flavor' of ENSO variability after the early 2000s has been notably different from that of the preceding few decades, with relatively more variability in the central Pacific SST and less in the eastern Pacific SST.[40] As already mentioned there is evidence that this recent period has been characterized by lower prediction skill, and possibly lower intrinsic predictability. This has raised a number of questions concerning our ability to assess skill of seasonal predictions reliably both in terms of ENSO conditions and also in terms of associated regional climate patterns—all questions of ongoing research.

The current age of climate prediction has brought many technical innovations, in addition to new ideas, programs, and initiatives that seek to draw on new knowledge and new kinds of information. Seasonal climate forecasts are now operational in many meteorological services and

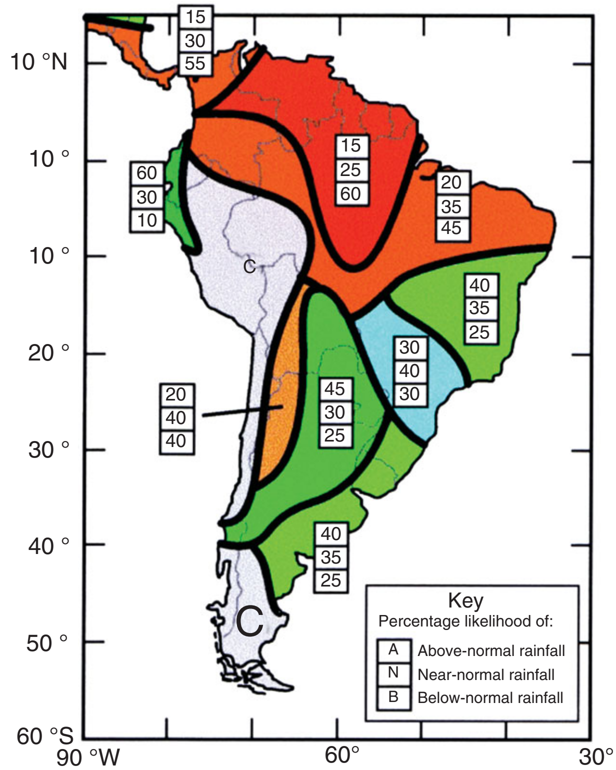

FIGURE 2 | IRI probabilistic seasonal forecast for January–March 1998 precipitation, produced in January 1998. The figure depicts for each of the colored zones the probability (in percent) of above-normal (upper box), near-normal (center box), and below-normal (lower box) precipitation for the season January–March 1998, as defined by terciles of the climatological distribution of rainfall for those regions and season. 'Red' colors refer to regions where below-normal precipitation is most probable, and 'green' colors refer to regions where above-normal precipitation is most probable.

centers throughout the world. Meanwhile, climate services initiatives,[41] which are broadly aimed at enabling climate-informed decision making, planning, and policy across a myriad of climate-sensitive sectors of society, are advancing at national and international levels. Many challenges remain to be addressed, but the opportunity to even consider these advancements is newfound and owes heavily to the foundational work in discovering ENSO.

ENSO IMPACTS AND SOCIETAL RESPONSES

Because climate variability affects so many facets of society, the influence of ENSO and the social and economic applications of ENSO forecasts have been studied across many sectors and in a range of contexts. Here, we will focus on three important climate-sensitive sectors that represent a range of impacts as well as societal responses: water, agriculture, and public health. A substantial body of published research exists for each of these sectors, focused on understanding the influences of ENSO and the use of ENSO information to predict impacts and improve management. Several noteworthy differences among these sectors have shaped the development of ENSO-related research. First, the complexity of the system and its connection to climate—simplest for water and most complex for health—has influenced the evolution of modeling tools used for prediction and decision support. For water resource management and some facets of agriculture (e.g., growth and yield of annual crops), quantitative modeling approaches that use weather data for prediction and decision support were already in place well before ENSO research raised the prospect for seasonal forecasting. Meanwhile in the health sector, seasonal climate prediction catalyzed research on new methods for using both predictive and historic climate information. The second contrast relates to the decision environment. Within the water and health sectors, the targets of research on use of ENSO information have generally been institutional decision makers. Agriculture presents a decision environment that is more complex, generally more decentralized, and inclusive of larger numbers of individual actors (farmers who make local climate-sensitive decisions, often in remote settings under severe resource and infrastructure constraints). A third contrast is the degree to which decision making focuses on the full range of climate variability (e.g., reservoir management, and most farm management decisions), or on response to extremes (e.g., response to floods or climate-sensitive disease epidemics). In the following three segments, we discuss research on the impacts of ENSO, and the potential use of ENSO-related climate information on each of the water, agriculture, and health sectors. Following that, we present some more general considerations, as well as examples of actual use of climate information to support decision making in these sectors.

Water Resources

The impacts of ENSO on various sectors, such as health and agriculture, are often felt through the effects of ENSO on the hydrologic cycle. For example, an increased likelihood of drought is a hydrologic phenomenon, which then impacts agricultural yields. Similarly, an increased likelihood of an above-normal rainfall season may negatively impact the agriculture sector, the cultivators having to monitor the possibilities of floods. It is thus critical to understand how ENSO affects the hydrologic cycle in different regions and how these influences then propagate into effects on water resources. Numerous papers have documented the impact of ENSO on global and regional precipitation, both annually and seasonally. Before documenting where ENSO affects precipitation, it is important to first note that only 20–30% of the land surface experiences a change in the probability of high or low precipitation due to ENSO, and the majority of these regions are located in the tropics.[42] Globally, El Niño is associated with below-normal precipitation; La Niña is associated with above-normal precipitation.[43] However, considerable geographic differences exist. Through the use of contingency tables, Mason and Goddard[43] showed that for the season December to February El Niño results in high precipitation over southern Brazil and below-normal precipitation across central Indonesia, the southern Philippines, and much of South America and southern Africa. On the other hand, during June–August there is above-normal precipitation in parts of North America, but below-normal precipitation in India and Pakistan. During La Niña, there is above-average precipitation in Australia and northwest South America during March–May, above-average precipitation during December–February in northeast Brazil (DJF), and below-normal precipitation over the central United States during June–August. Strong signals that are symmetrical with El Niño are seen in the September–November period. For more details, see Refs 43–45. In India, an eastward shift of the Walker circulation in the tropical Pacific during warm episodes of ENSO typically results in reduced rainfall during the Indian summer monsoon[46,47] and the South China monsoon,[48] regions where monsoonal rainfall is critical for food production.

Besides affecting the mean variables, ENSO can also have impacts on the severity of hydrologic extremes, both in terms of heavy precipitation, flood, and drought.[49–52] For example, in the United States, El Niño years lead to more frequent high precipitation events and streamflow over the Southwest and less frequent high precipitation and streamflow over the Northwest,[49] and a statistically significant reduction in Similkameen River (US Pacific Northwest) annual maximum floods.[50] The ENSO signal is also seen in the statistics of extreme rainfall, where a relationship between the frequency of extreme events and ENSO was shown over parts of South America[53] and over the Yangtze basin.[54] ENSO has been linked to changes in tropical cyclone occurrence and preferred tracks, affecting the likelihood of extreme precipitation (as well as wind hazards) in regions of the Caribbean, North America, and southeast Asia (see Ref 55 and references therein).

Globally, Lyon and Barnston[51] documented that the spatial extent of tropical drought is linearly related to the severity of an El Niño event, which agrees with the findings about the effect of ENSO precipitation in Ref 43. Floods also show a spatial signature associated with ENSO: tropical basins have a positive correlation with ENSO such that La Niña is likely to result in higher annual maximum streamflow. In the extratropics, the picture is more complicated with negative correlations in the southern United States and parts of Eurasia and positive correlations in Australia and the Pacific northwest of the United States and Canada.[52]

Because ENSO impacts precipitation and temperature over different regions of the globe, there is a corresponding significant impact on streamflow, and therefore water resources, in these regions. Strong teleconnections exist between streamflow and ENSO over Australia, New Zealand, South and Central America, with weaker connections in North America and Africa.[56] For example, the Blue Nile River is more likely to have high flows during La Niña and low flows during El Niño.[57] The teleconnection pattern between ENSO and precipitation is reflected globally in the terrestrial water storage, with a time lag in some regions. The largest correlations are found in the tropical regions, particularly at large tropical rivers.[58] In addition to affecting the hydrologic cycle, ENSO has also been linked to snow depth over the Tibetan plateau[59] as well as water quality[60] and groundwater levels in the winter in the southeastern United States.[61] Few to no studies explore the impact of ENSO on water quality and groundwater outside the United States and Canada, even though the effect of ENSO in the tropics is large. It stands to reason there are also effects in other regions globally that have yet to be studied and/or published.

The connection between ENSO and streamflow allows for seasonal forecasting of streamflow to inform water management decisions, such as water allocation, reservoir operations, and flood planning.[62–64] Similarly, the connection between ENSO and seasonal rainfall in the monsoon regions is used to develop total monsoon rainfall forecasts. For example in India, a number of seasonal forecasts of the All-India monsoon are available, and the dominant predictors in these models are ENSO indicators.[65,66] ENSO information has also been used to predict the flow of the Ganges[67] at lead times of up to one year, which can then be used to make decisions about crop choices based on forecasted irrigation demands. In regions where ENSO plays a role in influencing rainfall and streamflow, such as northeastern Brazil and the Philippines, studies have shown that reservoir operations can in principle be optimized to take advantage of skilled seasonal forecasts.[64]

Water resource management would appear to be an obvious sector for uptake and use of seasonal climate forecasts, given that water managers are accustomed to using quantitative information and short-term weather forecasts (~3 days lead time). Through interviews with water managers, studies have shown that this is not the case where water managers are risk-averse with institutional, legal, and infrastructural constraints that limit the usefulness of the forecasts.[68] Significant barriers to seasonal forecast use in the water management sector exist, and they include a perceived lack of accuracy, preference for established practices, and a culture of risk aversion (see Ref 69 for a broader summary). Many water managers themselves fail to grasp the risk of relatively low-frequency events.[70] In contrast to the United States, Brazil has had the flexibility to introduce seasonal forecasts due to institutional reforms in the 1990s,[71] and in Peru, long experience with ENSO leads many residents to take measures to reduce flood vulnerability.[72] In addition to these barriers, there can also be a scale disconnect between the forecast information (large spatial scale) and water managers (smaller, localized spatial scale).

There is potential in the water sector to take advantage of ENSO-related climate information in those regions of the world where ENSO has a strong relationship with precipitation, such as Brazil, India, and the Philippines. The water sector has the technical expertise and models needed to accomplish this, but the use of this information in the water management sector is hampered by the risk-averse nature of water management institutions and the limited geographic scope of ENSO-influenced precipitation.

Agriculture

Although some of the early empirical research on links between ENSO and agriculture[73] in the United States and[74] in Australia) was an extension of climate research on ENSO teleconnections, subsequent work has been motivated largely by the prospect of using ENSO information to anticipate and manage the impacts of climate fluctuations on agriculture and food security.

ENSO has been shown to influence yields and production of rainfed crops in most major rainfed cropping regions where it is known to influence rainfall (e.g., parts of Australia, the United States, India, Sri Lanka, Southeast Asia, Southeast South

America, Mexico, and Zimbabwe). Under dryland conditions, crop response is generally consistent with the influence of ENSO on growing season rainfall, and tends to be strongest in drought-prone environments. Beyond the tropics, since ENSO activity peaks in the northern winter, it stands to reason that its influence on rainfed summer crop production would tend to be stronger in the southern hemisphere, but that the ENSO state might provide information farther in advance of planting in the northern hemisphere. However, to our knowledge, these generalizations have not yet been tested systematically.

Irrigation buffers the impacts of climate on crops, and the connections between ENSO and production are therefore less widespread, but often more complex, for irrigated than for rainfed crops. The influence of ENSO on irrigated rice production in Southeast Asia, for example, has been attributed to variations in both yield, due to delayed planting, and area cultivated, due to variations in water available for surface irrigation.[75–77] In at least one setting, in northern and northwestern China, irrigation supply systems appear to have eliminated previously prevailing ENSO impacts on rice yields.[78]

Empirical research on the influence of ENSO on agriculture has extended beyond crop production to include impacts on other factors, e.g., crop prices,[76,79–81] agricultural pests and diseases,[82–84] and potential for groundwater pollution from agriculture.[85]

ENSO forecasting has also come into play in the agricultural sector. A study showing that ENSO-related Pacific SSTs were more strongly correlated with maize yields than with seasonal total rainfall in Zimbabwe[86] contributed to the expectations that seasonal forecasts could benefit vulnerable farmers in the developing world, particularly in Africa. This optimism was tempered by counter arguments—also in the African context—that any predictability of climate impacts on crops would be too weak to be useful at the farm scale,[87,88] and that farmers and pastoralists face fundamental obstacles to acting on uncertain predictions.[87,89,90] There was little empirical evidence to inform either side of the debate, until the strong and widely publicized 1997/1998 El Niño event prompted a surge of research on the potential use and value of seasonal forecasts around the world. Subsequent research demonstrated that crop yields can be predicted with greater skill than growing season rainfall, even before planting,[91] and that downscaling seasonal forecasts to a scale relevant to farm decisions may result in only moderate loss of skill.[92]

Research on predicting impacts of seasonal climate fluctuations on agricultural systems then shifted from almost exclusive use of ENSO indexes, to development of methods that exploit global and regional climate models (reviewed in Ref 91). Research on the use and value of ENSO information for agriculture has included model-based studies of economic value for particular management decisions, and more qualitative research on the factors that either constrain or enhance the ability of farmers and other decision makers to access, understand, or act on the information. From their review of 33 model-based studies, Meza et al.[93] argued that the potential value of seasonal forecasts is likely to be underestimated unless the scope of research expands to more farming situations, management responses, and mechanisms by which advance information can contribute to farmer livelihoods. Hansen et al.[94] are among several authors who highlight a widespread gap between the needs of farmers, and the scale, content, format and timing of information that is routinely available, which unnecessarily constrains the benefits of ENSO information.

Health

Pathogens that cause human disease are commonly sensitive to their surrounding environment, and climate plays an important role in determining their spatial and seasonal occurrence. Climate-sensitive diseases frequently exhibit year-to-year variability; some of which is likely driven by non-climatic, intrinsic factors (such as the proportion of susceptible hosts in the population and population mixing). However, over the last two decades climate, particularly ENSO, has been the focus of research around a number of cyclical diseases. Evidence to date indicates a substantial impact on certain parasitic, viral and bacterial infections in particular regions of the world.[95,96] In the cooler climes of the United Kingdom high burden diseases such as respiratory infections, cerebrovascular, and ischemic heart disease (IHD) have also been shown to possess a strong association with simple descriptors of winter climate. However, the predictability of the key climate indices (such as temperatures below a threshold) by coupled climate models is too limited for operational use by the health sector.[97] In contrast infectious diseases including vector-borne (e.g., malaria, dengue, rift valley fever), airborne (e.g., influenza, meningococcal meningitis), and water-borne (e.g., cholera) which dominate the health challenges of poor populations in developing (primarily tropical) countries in Africa, Asia and Latin America, are not only highly sensitive to climate but also their control may benefit from the higher levels of ENSO-related predictability observed in the tropics.

ENSO has been extensively studied in relation to cholera—a devastating, but easily curable, epidemic disease caused by the bacterium *Vibrio cholera*. The natural habitat of this ancient pathogen is riverine, coastal, and estuarine ecosystems where it is found in association with plankton—especially copepods.[98] ENSO has been widely indicated as a cause of cyclical cholera epidemics in different parts of the world through the associated warming of coastal SSTs, which support algal blooms favorable to an increase in *V. cholerae* bacterium.[99] Despite these observations, however, identified relationships of ENSO to cholera may not be consistent over time. Rodo and colleagues found a strong and consistent signature of ENSO in a time series of cholera prevalence data from Bangladesh during the period 1980–2001, but the relationship was weaker and eventually uncorrelated during the first parts of the last century (1893–1920 and 1920–1940, respectively).[99] Indeed, ENSO may have a more complex relationship to cholera than simple amplification of the pathogen hitherto suggested. For example, while the 1992 cholera epidemic in Peru was reported to be associated with a warmer environment,[100] the findings of a recent study, which takes a holistic view regarding ENSO's impact on cholera epidemics, have revealed multiple pathways for potential impact. These include rainfall extremes, social vulnerability, and the localized geography affecting teleconnections within Peru.[101]

Public health outcomes to climate may also be substantially influenced by impacts in other sectors, such as agricultural or water. For instance, aflatoxins, produced by *Aspergillus* fungi, are known human carcinogens whose widespread occurrence in a range of staple food crops, including maize and peanuts, poses a challenge to public health as well as to trade in affected commodities. Contamination pre-and postharvest is influenced by many factors including climate, and a strong association with ENSO has been found in some regions prompting the development of early warning systems. Hydrometeorological disasters also pose a significant public health threat: the global impact of such disasters being measured in terms of both health (morbidity and mortality) and economic losses. The relationship of health-related disasters to ENSO has been observed in a number of regions, including southern Africa,[102] but results are inconsistent at the global scale.

A constant challenge in ENSO and health research based on observed phenomena is to ascertain whether or not the identified relationships are coincidental or causal. A study by Shaman and Lipsitch[103] found that the four most recent human influenza pandemics (1918, 1957, 1968, and 2009), were first identified in seasons preceded by La Niña conditions in the equatorial Pacific.[103] Potential mechanisms to explain the association have been proposed but not verified.

Where significant public health outcomes are clearly related to SST in the equatorial Pacific (and therefore to ENSO events)[104] and the causal mechanisms are clearly understood, the scientific community has been able to create seasonal climate forecasts tailored for decision makers from the health community.[105] Such forecasts might be used in disease early warning systems, such as those produced for malaria.[106] Integrating climate information into routine health decision making requires buy-in at the policy level[107–109] as well as extensive engagement with decision makers at the national and local levels who oftentimes must overcome institutional barriers[110] while building cross-sectoral capacity[111] and ensuring that appropriate methodologies,[112] tools,[113] and data[102,114] are available.

Although early warning systems for diseases such as malaria have existed for over a century,[115] new opportunities now exist for better management of climate-related health risks. These are made available through advances in climate science (predictability of ENSO events in particular), satellite-based environmental monitoring technologies[116] especially when combined with ground observations,[114] rapidly advancing data management, analysis, visualization and dissemination technologies (impacting on data and knowledge sharing), a new global focus on effective management, and even the elimination/eradication of certain infectious diseases.

SOCIAL DIMENSIONS TO THE USE OF ENSO INFORMATION

In the decades since ENSO and related climate forecasting began, information has expanded beyond the realm of academic research to include concrete applications in different economic and social sectors in a number of countries. In reviewing the expanding reach of climate variability, several points have come to light. Firstly, the definition of use in the context of ENSO forecasts is not always straightforward. Secondly, the expansion of use has been uneven in space, time and across societies and sectors. Thirdly, the uptake of forecasts is far from automatic. Forecast providers have learned the importance of tailoring their products and services, working with others for promotion, and modifying their products to meet the needs of users, in the intended target audience and beyond.

There are methodological challenges to assessing both the use and effectiveness of use of ENSO and related climate information. It is not hard to tell whether farmers use tractors rather than plows, for example, or chemical fertilizer rather than manure. But if information is presented to farmers at meetings, on radio programs, or online, this does not assure that they will recall and incorporate it when they make decisions about agricultural activities. Moreover, even if farmers report that they were influenced by forecasts to alter their behaviors, the extent to which the forecasts informed their decisions is still unknown. This question is rarely addressed in studies that discuss adoption of forecasts. More often, the studies simply link the presentation of forecasts and shifts in behavior in a manner consistent with the forecast, or they report on surveys of users and take their statements about levels of use at face value.

Regarding the effectiveness of use, it is difficult to determine the changes brought on by forecast use. It is not always possible to distinguish between individuals, firms, or organizations that have received forecasts and those that have not, since forecasts are often publicly available and can be shared via social networks. This sharing is facilitated by the fact that forecasts can be used independently by many individuals, firms, or organizations. Lastly, it is difficult to use random assignment methods to assess the effects of forecast. Instead, researchers must generally rely on postseason interviews and surveys.

In the following, three case studies on use of ENSO forecasts in both developed and developing countries are presented. They reveal patterns that continue to present. In particular, they indicate the importance of ongoing communication between researchers and users, facilitated by 'boundary organizations' which bridge the gap between the two, and they show the value making forecasts usable by tailoring products to specific sectors and regions. In these cases, the significant changes in user behavior and the reduction in negative consequences of climate variability overcome the methodological issues in assessing use that are mentioned above.

Case Example: Queensland, Australia. Interannual variability of precipitation has long created problems for the agricultural and livestock sectors of northeastern Australia, and has also led to periods of drought and of flooding. Climate researchers at Australia's national Bureau of Meteorology (BoM) in the 1970s and early 1980s used statistical models to link seasonal rainfall patterns with the Southern Oscillation. The first forecast of an ENSO event and its associated impacts in September 1982 attracted attention from Queensland's Department of Primary Industries (DPI), a rural economic development agency. The two institutions began working together in the mid-1980s, integrating climate and crop models. The DPI presented extension officers and farmers with different sorts of information to see which they liked best and what forms of delivery were most useful to them. In 1991, DPI released initial models that allowed them to obtain a three-year grant from the state, which in turn led to the formation in 1997 of a new Queensland Centre for Climate Applications (QCCA). The QCCA provided agricultural and pastoral producers with information that led them to modify their productive strategies and cope effectively with the 1997–1998 ENSO event.[117] Building on these experiences, the QCCA later folded into the Queensland Climate Change Centre of Excellence.

Case Example: Washington State, United States. Summer heat and delayed autumn rains associated with the 1986–1987 ENSO event produced extreme and unexpected low levels in the city of Seattle's reservoirs. The consequences, including poor water quality and costly measures to access alternate water sources, led the Seattle Public Utilities (SPU) to develop a Water Shortage Contingency Plan, and a state-of-the-art reservoir management model which drew on National Weather Service streamflow forecasts.[118] Low winter and spring precipitation associated with the 1992 ENSO event created problems once again, and the SPU expanded its monitoring network and partnered with the US Geological Survey to improve reservoir management model through snowpack projections and forecasts. In the later half of the 1990s, the SPU developed ties with the Climate Impacts Group, a research and applications unit at the University of Washington founded in 1995. Through these ties, the SPU was able to use ENSO forecasts in the spring and summer of 1997 to manage reservoir releases and to create communication products with the public. The following winter proved to be normal to unusually wet across Washington State, an atypical pattern during an ENSO event, so the relative absence of negative impacts of the 1997–1998 ENSO event, compared to the previous ones, cannot be attributed directly to the use of forecasts. Nonetheless, the relationship developed and expanded. SPU continues to work closely with CIG researchers to incorporate ENSO forecasts and information on other elements of climate variability in their management and communication activities.[119]

Case Example: Horn of Africa, 2011. The framework for malaria early warning systems developed by the World Health Organization[107] embeds the use of seasonal climate forecasts information in a climate risk management strategy that incorporates a thorough understanding of the historical climate-related risks and population vulnerability to epidemics, up-to-date information on the current climate and predictions of the future climate which are deemed to be reliable. During the 2011 humanitarian crisis in the Horn of Africa, WHO requested risk information from the International Research Institute for Climate and Society (IRI) for malaria epidemics in the burgeoning refugee camps in northeastern Ethiopia for Somalis who had fled the drought-related crisis. The seasonal climate forecast for the 2011 short rains from the Greater Horn of Africa Climate Outlook Forum (GHACOF) was considered by WHO as a source of potentially valuable information. However, given the forecast's high uncertainty and the conflicting predictions from other forecasting centers, the IRI provided additional historical information on the climate suitability for malaria transmission in the region.[120] Although the risk of malaria in the camps was considered low, the high vulnerability of the population prompted the WHO and its partners to provide an additional five million doses of the highly effective antimalarial drugs, Artemesin-based combination therapies, to the camps.

The importance of communication and usefulness in these cases supports the insights of Cash et al.[121]: knowledge systems will be used when they provide information that potential users recognize as salient (relevant to their needs), credible (supported by evidence and arguments that are acceptable to them), and legitimate (unbiased, fair and consonant with users' values and beliefs). Forecasts achieve salience and credibility when they are modified or tailored to address the specific needs of users, and they are legitimate when built on the prior experience of users. Moreover, usability is not achieved in a single effort, but rather a process of iteration that may extend over years. In the cases above, communication was facilitated by an intermediate or boundary organization[122] to which both forecast producers and users were affiliated (i.e., Centre for Climate Applications in Queensland, Climate Impacts Group in Washington, IRI in the Horn of Africa). These groups are keys in explaining the producers' capacities and the users' needs to enhance salience and promote trust to build credibility and legitimacy. It bears noting that these three characteristics require maintenance, as shown by the example of the state of Ceará in northeast Brazil, where the perception among users that forecasts had been manipulated for political ends eroded credibility and legitimacy.[123]

These patterns are evident in a bibliographic review that we conducted, based on published papers that discuss ENSO and the use and application of ENSO forecast information for management and decision making (see Supporting Information for a discussion of the methods). We wish to emphasize several points. Firstly, as Figure 3 shows, there are significant differences in the uptake of forecasts in different

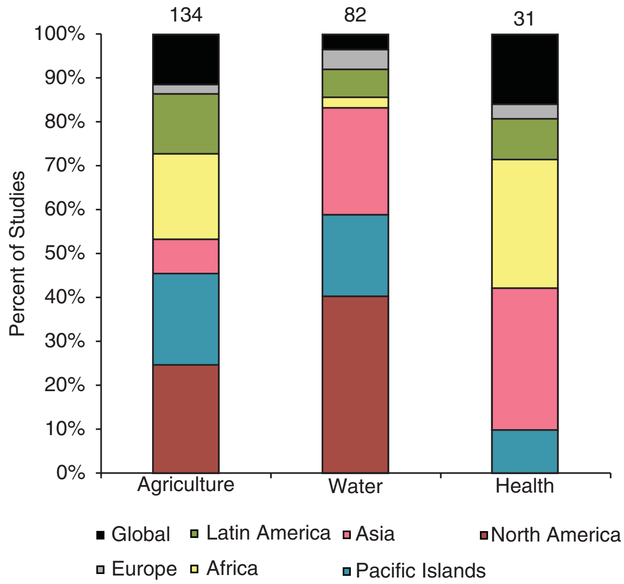

FIGURE 3 | Distribution of research articles addressing El Niño-Southern Oscillation (ENSO) forecast use, by sector and region. The numbers on top of each column correspond to the total number of articles on each sector.

sectors, with the highest levels of use in agriculture and the lowest levels in the health sector. Water resources management represents an intermediate level. Figure 4 shows that this difference has been fairly steady over time, though water applications have increased somewhat in the last 5 years, while agricultural applications have fallen off. As suggested earlier, the complexity and variability of applications in the health sector, and the relative novelty of the use of climate information, contribute to the difficulties of producing forecasts that are useful (or, in the terminology of Cash et al.,[121] salient).

The issues of credibility and legitimacy are important as well. In agriculture, forecast use has been supported by institutions which link directly or indirectly with farmers and whom they trust, including international agricultural organizations such as the Food and Agriculture Organization and the Consultative Group on International Agricultural Research, national agricultural extension services, and independent farmers' organizations. The prior experience of farmers in receiving technical information customized to their circumstances is also of importance; it can be noted as well that in many cases farmers had sources of forecasts in their empirical, or folk knowledge, which encouraged them to develop a planning orientation around climate variability.[117,124] In contrast, water managers face issues of legitimacy. They are concerned that they would be blamed for any negative outcome that resulted in a shift from established operating

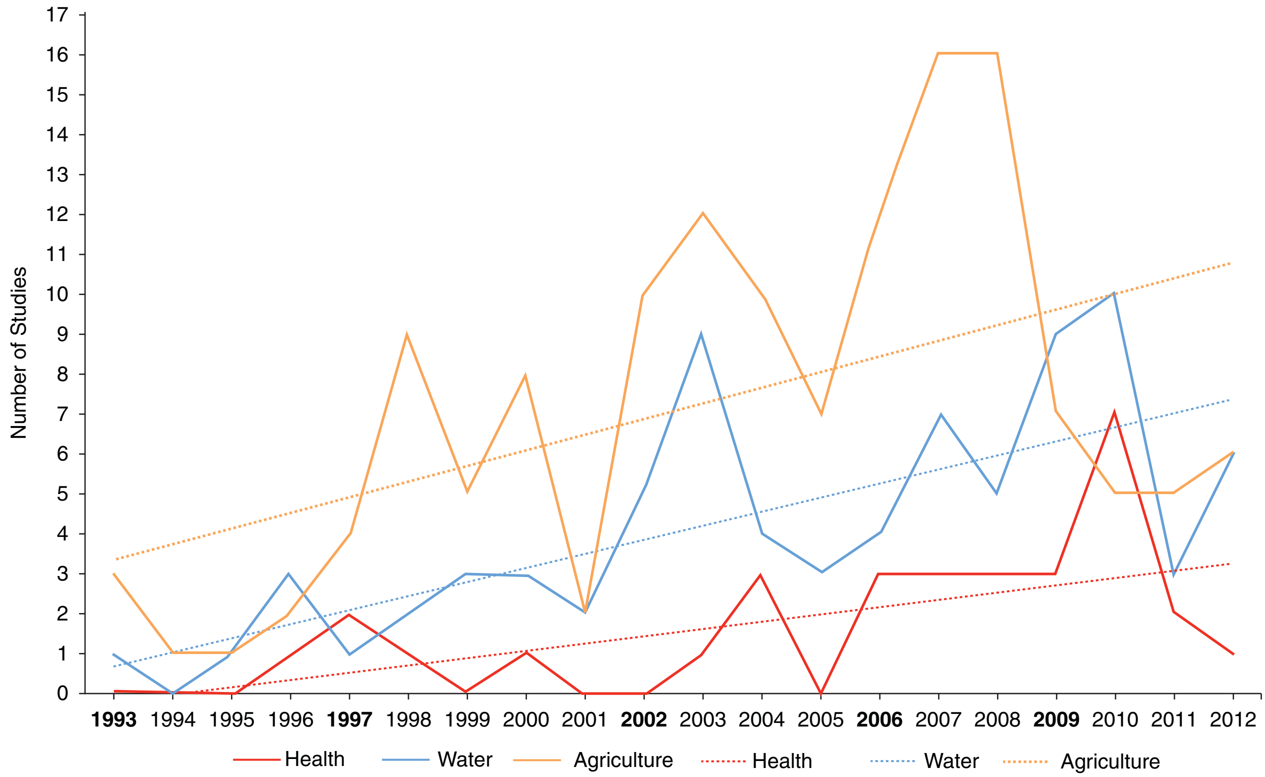

FIGURE 4 | Time evolution of the number of research articles addressing El Niño-Southern Oscillation (ENSO) forecast use. Solid lines show the actual time series for each sector, while the dotted lines sketch their long-term linear trend. El Niño years appear in bold in the *x*-axis.

procedures; the use of forecasts has often fallen under this limitation. The credibility issue may be larger in the case of health, granted the great diversity of diseases which limits the ability of medical and health organizations to adapt forecast-related responses from one disease or place to another. Taken together, these examples indicate how legitimacy and credibility can combine to raise issues of accountability. In many settings, water managers are legally responsible for the management of water supply to a range of users and can be taken to court to justify their decisions. Similarly, health officials have to be able to justify any changes in practice through solid evidence of benefits and through broad agreement among stakeholders using agreed procedures, or face challenges in political arenas and in the media. In contrast, farmers may blame advisors or other institutions when forecasts are not borne out, but the political pressures are less severe—in part because of the long experience of farmers in using weather-based technical advice.

The importance of institutions may also be seen in the spatial distribution of forecast use by sector (see Figure 5). As suggested earlier in this article, forecast use is low in areas where ENSO linkages to climate are weak, such as Europe. But the strength of linkage alone does not guarantee use, as shown, for example, by the relatively small number of cases our methods have located in the region including Colombia, Peru, and Ecuador. Although the ENSO signal is strong in this region and there are regional forecasting efforts coordinated by the Latin American Observatory[125,126] and the Centro Internacional de Investigaciones del Fenómeno de El Niño (CIIFEN),[127] the main focus in the region in terms of ENSO seems to be related mainly to disaster risk reduction, a sector that was not included in our analysis. Our analysis also did not include fisheries, though there is evidence that ENSO information has been used extensively in that sector along the western coast of South America.

Moreover, the distribution of uses by sector shows the role of institutions. In Australia, for example, agricultural applications dominate, even though one might think that water applications would be of great value as well in this country, where periodic drought has had impacts in many sectors besides agriculture. Factors that may account for this pattern include the strength of agricultural extension services and the weakness of water institutions in a nation where few mechanisms exist to promote cooperation among competing water groups. The success of agricultural applications in southern South America reflects the strength of agricultural

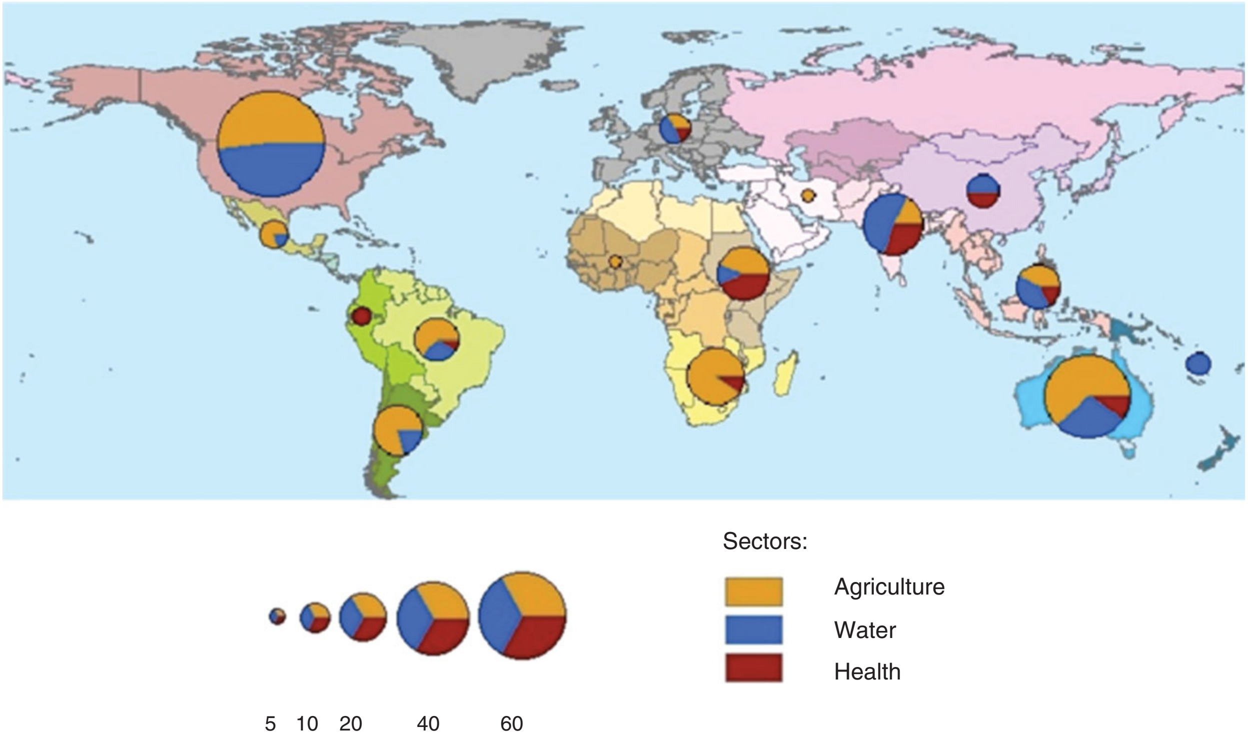

FIGURE 5 | Spatial distribution of research articles addressing El Niño-Southern Oscillation (ENSO) forecast use. The size of the pies is proportional to the number of studies. Regions are indicated on the map by background color.

institutions in that region as well.[117] By contrast, one might have expected to see a larger importance for agricultural applications in South Asia, where agrarian populations remain very large. But for this region, the powerful water institutions have contributed to active research in that sector.

The importance of institutions is reflected in the division of forecast use into two broad categories. The first is the longer lead time (and often the larger spatial coverage) of early warning systems, seen in agriculture with alerts for the risk of famine or food security crises, in water with projections of droughts, and in health with warnings of possible epidemics or disease outbreaks. The second is the shorter lead time (and often more localized spatial coverage) of on-going management—recommendations for operational decisions (e.g., crop choice and input levels) for farmers and for water release plans (e.g., timing of releases to optimize different uses of water) for reservoir managers. (Such forecast-based ongoing management is rarely found in the health sector.) These two categories represent different forecast products and different planning frameworks of social actors. They also follow the separation between humanitarian and development organizations, a distinction[128] that is not as clear as it was 20 years ago but that still remains significant. These two types of organizations—often the descendants of private charities and bilateral aid, respectively—retain somewhat different networks of national and local organizations that link forecast producers and forecast users.

Ultimately it is the user, rather than the producer, of the forecast who makes the critical final decision in the adoption of forecasts—and, in many cases, it is an intermediary who supports that decision. The accuracy and demonstrable value of the forecast can encourage this decision to adopt, but they are not sufficient for it to be made. As Cash et al.[121] have shown, institutions that recognize the concerns of forecast users can play a critical role in promoting this decision.

CONCLUDING REMARKS

ENSO has played a significant role in human experience throughout at least the past several centuries of recorded history. Over time, awareness of its myriad impacts on human activity and the environment has grown, leading to increased attention and interest. This process continues within academic and applied contexts, as demonstrated by the growing number of publications regarding use of ENSO and related climate information documented here. But the significance of ENSO for society has been more than experiential. ENSO has also been the source of tremendous learning and discovery about environmental science and policy, at times with far-reaching consequences.

Today we face yet new and important questions regarding ENSO. Perhaps foremost among these are questions about ENSO and climate change. As greenhouse gas concentrations continue to increase, will we see among other effects a change in ENSO, or its predictability, or its regional manifestations? There is a growing literature on this subject (see the recent review in Ref 129). While there is not conclusive evidence at this time regarding specific changes in ENSO associated with anthropogenic climate change, research results do indicate the possibility of ENSO-related changes figuring prominently in the expression of global climate change, with possible ramifications in both the trends and the predictability of regional climate. These will surely be topics of continuing research and discovery.

Arguably, the study of ENSO has led to the creation of new scientific disciplines (e.g., ocean–atmosphere dynamics), new tools (e.g., coupled models), and the discovery of (seasonal-to-interannual) climate predictability. By extension, it has prompted the development of seasonal climate forecasting and experimentation in the use of climate forecasts at multiple time scales. These efforts, in turn, have supported—and been supported by—new interdisciplinary institutions and practices in the production, translation, communication, and uptake of climate information for decision making in many sectors of society. These innovations can be considered a societal transformation in progress—one still with many recognized challenges to be addressed—but of great significance nonetheless. As ENSO has been the source for discovery, for new knowledge, and for inspiration for society, there is still more to learn.

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