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Coastal marine fog, a characteristic feature of climates generated at the eastern boundaries of ocean basins worldwide, evokes different feelings in those who experience it (see Figure 1). Authors and poets use fog to represent mystery, bleakness, and confusion. Film directors seek out fog to shroud scenes in eerie gloominess. Tourists visiting beaches bemoan the cool and damp conditions that create a striking contrast to the sunny warm conditions typically found less than a few kilometers inland. Airline passengers delayed by fog impatiently wait for the skies to clear. Residents get used to the Sun "rising" in midday after fog dissipates.

To climate scientists, fog's physical opacity symbolizes how much remains to be discovered about it. They know the importance of the summertime shade and moisture provided by the onshore transport of fog arriving as a wall of marine cloud. However, empirical data or physical models capable of characterizing fog as a climatological phenomenon are surprisingly sparse.

One pressing question involves how global climate change will influence fog and how fog may be affected by rising surface temperatures and secondary effects such as coastal wind strength, inland marine layer intrusion, and increased evaporation. For example, a recent study of coastal fog in the eastern Pacific, which relied on long-term airport records, indicated that the occurrence of summertime fog has declined by 33% over the course of the 20th century [*Johnstone and Dawson*, 2010]. How representative is this finding of worldwide changes in fog patterns that may come? Can long-term cycles in ocean temperature such as the Pacific Decadal Oscillation explain the centennial trend?

These questions, and others like them, are not purely academic: Changes in fog frequency have implications for a wide range of sectors, including coastal ecology, agriculture, urban energy and water consumption, and public health. To help coastal communities, many climate scientists are taking a close look at fog with the aim of developing models of future fog patterns.

Forming Marine Fog

The frequency of marine coastal fog events and the extent of inland penetration depend on both simultaneous and sequential processes across an extremely broad range of the planet's spatial and temporal scales [*Koračin et al.*, 2014]. Semipermanent anticyclones (high surface pressures), which tend to develop on the eastern sides of the world's ocean basins, result in alongshore surface wind stresses. These alongshore stresses act in concert with the Coriolis force to drive offshore oceanic (Ekman) transport that in turn pumps deep, cold water up to the coastal margins.

These ocean upwelling conditions occur beneath a complementary downwelling branch of the atmosphere's Hadley circulation —a planetary-scale flow pattern in both hemispheres that takes humid air ascending at low latitudes, heats and desiccates it in deep precipitating tropical clouds, and then sinks it at midlatitudes, where it is considerably warmer and drier than it was.

The cold nearshore waters couple with the descending, adiabatically warmed air aloft to form a stable lower atmosphere with a strong temperature inversion, which has long been linked to a prevalence of low stratiform clouds. As this sinking air mass weighs on the marine layer, the latter compresses into a thin layer with a relatively high concentration of water vapor. This process also warms and dries the top of the marine layer, establishing a delicate balance with the moistening ocean below. If the dew point temperature of the trapped moisture rises to the surface temperature of the ocean, then fog can form like condensation on a cold windowpane.

Ecological and Societal Value of Coastal Marine Fog

Declines in fog frequency may be good news for Sun-seeking tourists and for air traffic controllers at coastal airports, but the trend seen in the eastern Pacific alarmed the global

Fig. 1. Fog engulfs the Golden Gate Bridge, as seen from Twin Peaks, San Francisco, on 26 January 2014. This is an average of several exposures taken over the course of a few minutes. "Here Comes the Fog," taken by Daniel Parks, CC BY-NC 2.0.

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community of natural resource managers working in affected coastal zones. In California, Chile, South Africa, and other Mediterranean regions with dry summers, a future with less marine fog could cause significant changes to terrestrial, riparian, and intertidal habitats.

The water transported by marine fog into coastal ecosystems creates a cascade of ecological effects. Fog liquid water content accessed via fog drip and direct uptake by leaves enhances plant vigor and growth. It may also increase soil microbial activity, evidenced by increases in soil respiration rates [e.g., *Carbone et al.*, 2011].

Fog also benefits coastal human systems; for example, as pressure on water resources grows globally, fog water harvesting for human supply has garnered increased research interest (see http://www.fogquest.org). Strategies to harvest fog drip are also improving restoration effectiveness on the denuded hillsides of California's Channel Islands.

Costs of Reductions in Fog Occurrence

The lower relative humidity and increased temperatures that would result from potential reductions in fog and low cloud cover could increase plant evapotranspiration rates, raise soil water deficits, and accelerate risks of forest fire. Species at the drier edge of their climatic envelopes, including those characteristic of endemic coastal forests, would be especially vulnerable [*Baguskas et al.*, 2014].

Reduced coastal fog could impact agriculture by causing a greater demand for irrigation. Vulnerable human populations such as the elderly would be at increased risk of heat-related impacts: Summers with fewer fog events are strongly correlated with higher levels of emergency response requests and hospital visits [*Gershunov et al.*, 2011].

Global Changes to Fog Due to Regional Forcing

Studies of fog are currently driven by regional concerns. For example, the relatively cold ocean waters off California currently lead to year-round fog formation, which penetrates to a variable yet relatively consistent extent inland. Will these fog-forming conditions and distribution patterns continue?

Answering this question starts with using past data to model future scenarios. A regional climate model simulation of coastal fog driven by the National Oceanic and Atmospheric Administration's (NOAA) 20th century reanalysis data set [*O'Brien*, 2011; *O'Brien et al.*, 2013] shows a century-long decline along the California coast, and a climate projection with the same model hints at a slight decline in the future. However, O'Brien and colleagues found that this result is highly uncertain because the development and incidence of coastal marine fog are dependent upon interactions among three systems—atmospheric, oceanic, and terrestrial—which are each subject to broad ranges of variability.

On the other side of the Pacific, *Sugimoto et al.* [2013] attribute declines in coastal fog frequency in Hokkaido, Japan, to synoptic-scale shifts controlling atmospheric inversions. Their conclusion highlights the influence of upper air dynamics, a globally coherent system, and its importance to the moisture content of air near the surface, a regional phenomenon with strong local patterns.

Insights From Theory

Although it may be reasonable to assume that the Hadley circulation will weaken as the atmosphere warms, the fate of coastal sea surface temperatures worldwide is much more ambiguous. The ocean as a whole is warming; however, coastal upwelling may ultimately be enhanced by alongshore winds, which strengthen in proportion to the temperature contrast between the oceanic and continental air masses [*Sydeman et al.,* 2014].

Even less certain is the fate of the moistened marine layer as it blows onshore into regions characterized by low topography. Forecasts of rising temperatures inland, and therefore stronger across-shore temperature gradients, suggest increased onshore advection of marine air. However, this pattern could also lead to increased turbulent mixing at its top, which would, in turn, tend to dry the incoming marine layer.

A Global Perspective on Fog-Forming Aerosols

In addition to the complex physics of fog formation and transport, recent research suggests that microscopic aerosol particles may be critical players in fog dynamics and its effect on coastal human and ecological systems. Fog forms as atmospheric aerosol particles absorb moisture and water condenses into droplets around these cloud condensation nuclei (CCN). CCN that readily attract moisture can initiate droplet formation at relative humidities as low as 33%. The evolving marine fog advects onshore as a complex, reaction-rich mixture of liquid, dry, evaporating, and deliquescing particles surrounded by gaseous interstitial space [*Valsaraj*, 2012].

An impressively wide range of aerosols can serve as fog CCN: sea spray, metabolically active bacteria, protozoa, fungi, pollen, dust, and biogenic fragments [*Després et al.*, 2012]. Recent research even shows the presence of methylmercury—a toxic bioaccumulator—in "pristine" coastal fog, which apparently originates naturally from marine aerosol [*Weiss-Penzias et al.*, 2012].

Although very few measurements have been made of aerosol composition in Pacific coastal fog, large differences in fog water chemistry have been reported from other regions. These studies suggest potentially strong variations in geographic and seasonal signatures that reflect air parcel bidirectional trajectories across marine and terrestrial surfaces. The reactivity and degree of water affinity of fog CCN become potentially even more complex when taking into account back trajectories of air masses over industrial and urban landscapes. Given that CCN for fog can come from far away and droplet-forming processes occur over a majority of our watery planet, insights from fog research can have broad application.

Developing a Marine Fog Monitoring Program

The demand for improved fog projections inspired the U.S. Geological Survey (USGS) to facilitate an interdisciplinary community of researchers and resource managers now known as the Pacific Coastal Fog Project (PCF; see http://geography.wr.usgs.gov/fog/). The goal of PCF is to fill two major categories of disciplinary gaps: (1) communication gaps between researchers based in a diversity of disciplines unaware of the complementarity of their coastal fog studies and (2) data accessibility gaps that prevent efficient responses to questions regarding fog and how it affects coastal resources.

PCF has been rapidly filling both of these kinds of gaps via a series of ongoing webinars, workshops, and AGU meeting sessions initiated in 2011. The latest offering of the resulting community includes a 2014 AGU Fall Meeting session titled "Fog: Atmosphere, Biosphere, Land, and Ocean Interactions"(sessions A11C and A14B).

FogNet: A Fog Monitoring and Research Sensor Network

In April 2012, PCF began collaborating to implement FogNet, a coastal fog observation system. The long-term goal is an integrated empirical foundation of global atmospheric, oceanic, and terrestrial data for coastal fog research.

To achieve this, a phased implementation using the "core" and "satellite" monitoring station approach [*Gultepe et al.,* 2009] was initiated in July 2012. Scientists involved with FogNet reviewed ongoing established climate and biodiversity monitoring stations and selected three "core" sites at which to begin colocating their research efforts. These sites include two hydrometeorological test bed sites operated by NOAA Bodega Marine Laboratory (BML) and Trinidad Head. The third site is inland, located 50 kilometers east of BML at Pepperwood Preserve (PPW). PPW is a station in the Terrestrial Biodiversity Climate Change Collaborative (http://tbc3.org) that is measuring a range of hydrological and ecological parameters to track wildlife, pathogen, and ecophysiological responses to climate shifts (Figure 2). Several "satellite" sites that have less instrumentation than the core sites are currently in the pilot stages of implementation.

Current joint measurement projects include assessment of liquid water volume from passive fog collectors (run by scientists at

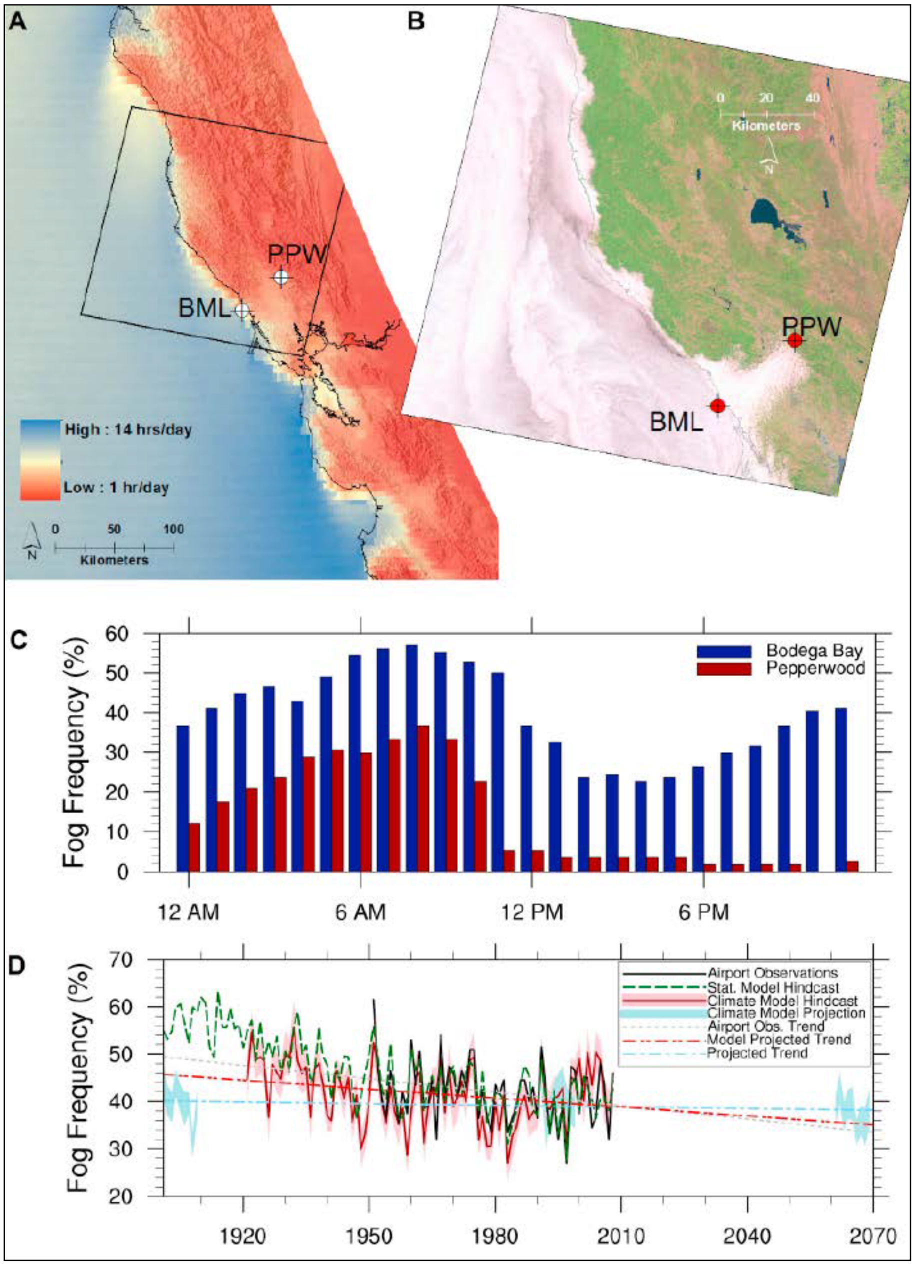

*Fig. 2. Fog frequency along a coastal (Bodega Marine Laboratory (BML)) to inland (Pepperwood Preserve (PPW)) transect. (a) A fog frequency map derived from roughly 30,000 hourly Geostationary Operational Environmental Satellite (GOES) day and night images [*Combs et al.*, 2010] displaying average daily hours of fog/low cloud cover (June–September 1999–2009) ranging from 1 to 14 hours per day. Crosshairs indicate locations of surface visibility stations referenced in Figure 2(c). (b) High-resolution view of low cloud patterns in the San Francisco Bay area from a 12 June 2002 Landsat image. (c) Diurnal patterns of fog observed in 2012 from surface visibility stations located at the coastal Bodega Marine Laboratory and at Pepperwood Preserve approximately 50 kilometers inland. Surface fog at the coastal site exhibits a diurnal pattern very similar to marine stratocumulus, whereas the inland site tends to exhibit complete fog dissipation by 11:00 a.m. Pacific Daylight Time. (d) Observed [*Johnstone and Dawson*, 2010] and simulated [*O'Brien*, 2011] centennial-scale variations in Northern California fog frequency. The model hindcast utilized boundary conditions derived from the U.S. National Oceanic and Atmospheric Administration's 20th century reanalysis, whereas model projections were based on the business-as-usual scenario from Intergovernmental Panel on Climate Change's Fourth Assessment Report.*

California State University, Monterey Bay, and NASA Ames Research Center), active fog sampling for mercury (run by researchers at the University of California, Santa Cruz), and measurement of droplet size and distribution (run by Georgia Southern University researchers). Studies of the seasonal hydrologic patterns in the fog-dependent forests of the Bosque Fray Jorge National Park in Chile (run by scientists at the University of Chile) will provide comparisons of the phenomenon in geographically distinct regions.

Scientists involved with FogNet envision a network capable of monitoring air parcel movements across ocean and land-based sites, with ocean sites on buoys or ships and terrestrial sites located on a coast-to-inland gradient to track the occurrence and consequences of change in fog patterns. Coordination efforts are focused on standardizing measurement techniques to improve fog-related data comparison from projects worldwide.

Tying the ground-based network to remotely sensed observations from Earth-observing satellites will bridge measurement scales to form a molecular- to global-scale observation platform. Through a collaborative and transdisciplinary approach that includes researchers and natural resource managers, PCF is among the first concerted efforts to clear the fog that currently conceals the complex dynamics between the air, sea, land, and biota. More projects like PCF will help improve fog forecasts and clarify its role in our future.

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