Fog Research Frontiers:
An Interdisciplinary Research Agenda for Coastal Fog Systems

White Paper

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Executive Summary

Fog is a critical source of water and nutrients in coastal ecosystems such as the redwood and olivillo forests along the Pacific coasts of North and South America. Fog can also be environmentally detrimental, scavenging pollutants from the atmosphere and impacting ecosystem and human health, especially in urban areas affected by fog.

Fog moderates the local and regional climate, bringing cool nights and foggy mornings that burn off by midday, a maritime effect appreciated by winemakers and farmers in fog-dominated coastal regions throughout the world. It also disrupts transportation, creating hazardous conditions and costly traffic delays in the airline, shipping and trucking industries.

Scarce data show that a changing global and regional climate is already affecting fog frequency and distribution in coastal California (Johnstone and Dawson 2010, Baldocchi and Waller 2014).

Despite its importance on the Pacific coast of the U.S., the current understanding of the coastal fog system is limited, and the full range of ecosystem services and economic impacts of fog is still poorly understood. There is an urgent need to understand fog as a system in order to be able to predict, model and understand the connections among ocean, atmosphere, and land as well as the impact of fog on climate, ecology, agriculture, and human health and well being.

To date our understanding of the whole-system phenomenon of fog formation, transport, and integration into hydrological and biogeochemical cycles has remained elusive due, in part, to lack of a concerted interdisciplinary approach to the problem. The emphasis of past fog research has been to examine it primarily in terms of physical and chemical processes within disciplinary domains. More recent research is aimed at other aspects of the fog system, including its chemical formation and biological composition as well as deposition and delivery of water, nutrients and microbes to human and natural systems.

Recognizing the need for an interdisciplinary approach to fog research, groups of fog researchers were convened to identify interdisciplinary research frontiers. This community-based planning process was headed by Dr. Kathleen Weathers, Cary Institute of Ecosystem Studies, in collaboration with a steering committee (Dr. Jeffrey Collett, Colorado State University; Dr. Rene Garreaud, University of Chile; Dr. Carolyn Jordan, University of New Hampshire; Dr. Patricia Matrai, Bigelow Laboratory for Ocean Sciences; Dr. Michael O'Rourke, Michigan State University; and Alicia Torregrosa, US Geological Survey) that help guide the process.

The one-year planning effort included three steering committee meetings; a 'town hall' discussion and survey responses from a subset of attendees at the 6th International

Conference on Fog, Fog Collection, and Dew; and a workshop held in Pescadero, CA in June 2013. For the latter, about 25 participants representing various disciplines of active fog research attended a two-and-a-half-day workshop to further develop a coastal fog research agenda. Feedback was also obtained from members of the fog research community who could not attend either the International Conference or the Pescadero workshop.

The research dialogue confirmed the need for an interdisciplinary approach and conceptual framework and resulted in the identification of both interdisciplinary and disciplinary coastal fog research frontiers. An important outcome was the articulation of conceptual frameworks for considering coastal fog as a system.

Interdisciplinary fog research frontiers are grouped into four over-arching themes:

(1) *Understanding coastal fog as a system* – Perhaps one of the most important research frontiers is to conceptualize and understand fog as a system: its linkages and feedbacks among the ocean, atmosphere and terrestrial ecosystems, as well as the chemical, biological and physical processes within the system.

(2) *Determining the impacts of fog on human and natural systems* – Researchers identified the need to determine how fog impacts human and natural systems, and how changes in these systems affect coastal fog systems.

(3) *Documenting changes in fog frequency and distribution* – Changes in fog frequency and distribution as a result of changes in climate and land use, and vice-versa, are poorly understood and require interdisciplinary research.

(4) *Developing and integrating new tools, technologies and approaches for studying fog* – New and existing tools, technologies and approaches, including more sophisticated sensors, automated samplers, increased computing power and machine learning techniques, remote sensing products, UAVs, and network science, create opportunities for enhancing study of the complexities of the coastal fog system.

Disciplinary fog research frontiers identified are organized by subject area: (1) chemistry and biology, (2) terrestrial ecology, (3) atmospheric science, (4) oceanography, (5) modeling, (6) climatology, and (7) social science. Researchers concluded that not enough is known about documenting the presence of fog using remote sensing tools, or about the biology and the socio-economic impacts of fog, in particular, and these were identified as immediate research priorities towards an interdisciplinary understanding of the coastal fog system.

The report concludes with a recommendation for implementing an interdisciplinary fog research agenda. Immediate actions include collaboratively-initiated research projects and the promotion of interdisciplinary research, in general, as well as implementation of this fog research agenda, within and among existing institutions, scientific communities and funding agencies.

I. Introduction

A. Why Understanding the Coastal Fog System is Important

Fog is a graphic phenomenon that is commonplace in many coastal geographies, notably the west coasts of California, Chile, and Africa. Some of the first concerns about fog and human health arose over 50 years ago in foggy cities around the world, such as London and Los Angeles, where thousands of excess deaths have been attributed to the presence of acidic fog particles (e.g., Weathers and Lovett 1995). Further, the mere presence of fog also results in airplane, ship, and automobile traffic delays and accidents costing multiple millions of dollars annually, especially in coastal areas around the world (http://www.noaa.gov/features/economic_1108/fog.html, Tardiff and Rasmussen 2007). In many Pacific coastal systems, fog is the primary—sometimes the only—source of water for plant communities and human settlements, it is a fundamental moderator of local and regional climate (e.g., Rahn and Garreaud 2010a, b, Gültepe et al. 2007), and it influences productivity of near-coast terrestrial ecosystems. Fog has been identified as a vector for deposition of limiting nutrients such as nitrogen and phosphorus (Weathers and Likens 1997, Jordan and Talbot 2000, Weathers et al. 2000), pollutants and organic material (e.g., Jacob et al. 1983, Weathers et al. 1986, 1988, Collett et al. 2002, Weiss-Penzias et al. 2013, Herckes et al. 2013), and microbes (including human pathogens; Dueker et al. 2012); a strong link to marine productivity and biogeochemical cycling has been suggested in some of these studies. Researchers have also started inquiring into the importance of fog and low clouds in modulating weather as well as local, regional and, global climate dynamics (Lawton et al. 2001, Pounds et al. 1999).

Data on fog frequency and extent are scarce (see research priorities, below), climate change has been demonstrated to already be affecting fog frequency and distribution. A study of northern California coastal fog occurrence using data going back to the early 1900s found that fog frequency has decreased over the last century (Johnstone and Dawson 2010). In fact, the number of winter fog days has decreased by 46% in the Central Valley of California since 1981, which is expected to have negative impacts on fruit and nut farming (Baldocchi and Waller 2014, Baldocchi and Wong 2008). Changes in fog occurrence could potentially have impacts well beyond transportation, such as the California wine industry, which was valued at $13.4 billion in fog-affected Sonoma County, in 2012.

While there are many kinds of fog (e.g., Chuang 2013), for developing this research agenda, we chose to focus on coastal fog and near-coast low clouds for several reasons, including the pragmatic need to narrow an otherwise numerous and disparate variety of systems to study. Further, coastal fog provides a uniquely interdisciplinary challenge that we deemed tractable. Nonetheless, many findings in this report can be transferred to other systems.

From its formation in marine systems to deposition in terrestrial systems, understanding the coastal fog system is an intellectual, interdisciplinary, and potentially transdisciplinary challenge that, to date, has gone unmet. The lack of a framework and research agenda exists, in part, because the coastal fog system is complex: it involves feedbacks and coupling between physical, chemical, and biological systems in the ocean, atmosphere, and near-coast terrestrial systems. In addition, its formation is the result of large-scale processes, yet its distribution and impacts are local, with extreme spatial and temporal heterogeneity within and across landscapes.

Fog dynamics are the purview of many different disciplines and specialists, few of whom interact professionally or read each other's literature. For example:

a. Fog forms over the ocean as a result of the difference between sea-surface and air temperatures and in the presence of ample cloud condensation nuclei (e.g., sea salt). Traditionally, this has been studied primarily as a physical phenomenon but there is recent evidence that microbes from the ocean may play a critical role in the production of fog and clouds (Amato et al. 2007a,b, Knopf et al. 2011, Orellana et al. 2011) and therefore changes in oceanic conditions are likely to affect fog formation; these dynamics need to be better understood.

b. Fog formation and distribution are subject to complex boundary layer dynamics (e.g., the interaction of ocean bathymetry/sea floor depth, terrestrial topography, wind speed and direction, air and sea surface temperature and aerosols). These processes are often considered the domain of atmospheric and marine physicists and chemists.

c. Forecasting the density, duration, and direction of transport of fog is mainly done by meteorologists.

d. Once blown inland by off-shore winds, fog deposition is governed by both abiotic—such as fog liquid water content, drop size, and wind speed—and biotic factors, such as the exquisitely complex architecture and morphometry of plants and animals, the built environment, and the orientation of vegetation across the landscape (Kerfoot 1968, del Val et al. 2006, Barbosa et al. 2010). Historically, hydrologists, and to a lesser extent ecologists and plant physiologists, as well as epidemiologists, have studied the distribution and influence of fog water.

e. Still nascent are the studies of biogeochemical impacts of fog, its chemistry, microbiology, and the magnitude, spatial extent and the direction of cross-system transfers from ocean to air to land.

A systems approach (e.g., Hogan and Weathers 2003, Weathers et al. 2013) to fog research not only provides a mechanistic understanding of the controls on fog formation, but also of the feedbacks to its formation, dissipation, and distribution (e.g., the fields of atmospheric and marine physics, biology, and chemistry), flows (movement of fog from ocean to land), and stocks or pools (deposition and distribution within adjacent terrestrial systems). To accomplish this, domain scientists must be catalyzed to work collaboratively toward a common framework and strategic plan that defines an interdisciplinary research agenda.

Aspects of coastal fog system research have been constrained not only within disciplinary but also within funding and operational agency boundaries. For example, while USGS' focus (broadly speaking) has been primarily in the hydrology of fog (e.g., Scholl et al. 2002), NASA's interest is likely to be more oriented toward using the tools of remote sensing for understanding and modeling fog distribution and cross-system dynamics. NOAA's focal area is to understand ocean-atmosphere coupling, weather prediction as well as forecasts of visibility for transportation needs, and USDA Forest Service's purview has been forest impacts and interactions. The Office of Naval Research has invested in fog research to understand the role of fog in battle space considerations, and the Federal Highway Administration is vested in detecting, predicting, and ameliorating fog events that impact vehicular traffic.

A deeper mechanistic understanding achieved from studying fog as a system is expected to lead to better fog models and forecasting ability from all perspectives.

B. Approach and Goals

The Gordon and Betty Moore Foundation awarded a grant to the Cary Institute of Ecosystem Studies to develop an interdisciplinary framework and research agenda through a bottom-up, community-driven exercise to identify research frontiers that consider coastal fog as a system. A diverse group of multidisciplinary scientists was engaged over the course of several meetings to identify gaps in knowledge and interdisciplinary research frontiers.

The community-based process was designed to catalyze an interdisciplinary approach to understanding coastal fog as a complex phenomenon. There is a need to better understand the entire coastal fog system from the processes related to the formation, distribution, transport, interaction with other systems (e.g. climate) to its deposition and impact on natural and human systems. This white paper is one of the key outputs of the planning process.

As part of the approach, a team of leading fog scientists developed conceptual frameworks for coastal fog research that could be used to catalyze collaboration across the many disciplines involved in fog research as well as to communicate with funding agencies.

Additional innovative (and pragmatic) goals of the approach for developing a research framework include understanding more about fog ethnography, the science of team science, and how new, interdisciplinary scientific collaborations are initiated and sustained.

The purpose of this report is to identify interdisciplinary research frontiers that are critical for advancing coastal fog research and modeling beyond examining fog solely as a product of physical or chemical processes to a more holistic approach that integrates physical, biological and chemical processes, and considers humans as key components. It focuses on understanding coastal fog as a complex system. This report is aimed at the fog research community as well as funding agencies that are interested in investing in cutting-edge interdisciplinary research. A short brochure will be developed by Fall 2014.

A process overview, including the use of conceptual frameworks in developing a fog research agenda, is described in Section II, and a review of the current state of research is provided in Section III. Interdisciplinary and disciplinary research frontiers are detailed in Section IV. The final two sections include a discussion of lessons for interdisciplinary science, in Section V, and immediate priorities for implementing the fog research agenda, in Section VI.

Terms and definitions are provided in Appendix 1. Participants in the fog research planning dialogue are listed in Appendix 2. A summary of survey results administered at the International Conference on Fog, Fog Collection and Dew is provided in Appendix 3. Examples of follow up activities are summarized in Appendix 4.

A summary of the Fog Research Frontiers Pescadero Workshop, held in June 2013, is provided in a companion document.

Fog Terminology at a Glance

The main difference between fog and clouds is the location in the atmosphere. Fog is located at or near the Earth's surface – it is a cloud that touches or is close to the ground or ocean surface. As a result, fog is influenced by local conditions and interacts more directly with terrestrial and marine ecosystems.

Fog droplets are tiny water droplets or ice crystals that form as a result of supersaturation generated by cooling, moistening and/or mixing of near surface air parcels of contrasting temperature.

Fog droplets form on the surfaces of fine solid particles or liquids suspended in the air known as ***aerosols***. These organic and inorganic particles on which water vapor condenses are referred to as ***cloud condensation nuclei***.

The dissipation of fog is known as ***fog burnoff***, usually referring to the effect of morning sun in dissipating fog.

Stratiform clouds are thin clouds with a large horizontal extent. ***Stratocumulus clouds*** are a type of stratiform cloud that has identifiable features (bumps and rolls) typically seen along the Pacific coast of North and South America. ***Stratocumulus fog*** is a stratiform cloud that is at or near the Earth's surface.

For more fog terminology, see Appendix 1.

Photo of marine stratocumulus cloud bank seen from above. Photo Credit: P. Chuang.

II. Process Overview

The Coastal Fog as a System research planning process was launched in December 2012, under the leadership of Kathleen C. Weathers, senior scientist at the Cary Institute of Ecosystem Studies and veteran fog researcher.

A seven-member Steering Committee (SC) comprised primarily of fog research scientists who are interested in developing a fog research framework was convened to guide the community-based planning process. Members include: Dr. Kathleen Weathers (Chair), Cary Institute; Dr. Jeff Collett, Colorado State University; Dr. Rene Garreaud, University of Chile; Dr. Carolyn Jordan, University of New Hampshire; Dr. Patricia Matrai**,** Bigelow Laboratory for Ocean Sciences; Dr. Michael O'Rourke, Michigan State University; and Alicia Torregrosa**,** USGS. Lisa Borre was scribe for the process.

The Steering Committee met in-person and via teleconference a half dozen times to plan the workshop, finalize the research agenda, and prepare this report.

Weathers, Dr. Jonathan Kramer (facilitator) and Emily Shepard (illustrator), and the Steering Committee planned and organized a workshop, "Coastal Fog as a System: Developing the Research Agenda" held 25-27 June 2013 in Pescadero, California. The workshop brought together about 25 broad-thinking participants with expertise in the many disciplines that have considered coastal fog in their research purview. A summary of the workshop is provided in a separate report.

International Conference on Fog, Fog Collection, and Dew "Town Hall"

An important input to the process was a "Town Hall" session held at the International Conference on Fog, Fog Collection, and Dew in Japan in May 2013. Steering Committee member Jeff Collett, who was the Scientific Chair of this conference, agreed to introduce and guide the session, and administer a survey on behalf of the Fog Steering Committee. Approximately 125 participants attended the conference from 30 countries. During the Town Hall session, conference participants were informed about the fog research planning effort and asked for input on what they considered to be interdisciplinary research frontiers related to coastal fog as a system. Surveys were distributed to 110 Town Hall participants, who provided helpful feedback on the diagram, and 17 submitted written survey responses (see summary in Appendix 3). The international fog research community was very engaged in this discussion at the conference.

Using conceptual frameworks to catalyze interdisciplinary research

Process for developing conceptual frameworks for fog research

The starting point for the research planning exercise was for the fog research community to think more broadly about fog from a systems perspective: Systems have various parts, and an important component of understanding systems is defining boundaries, and identifying fluxes, pools, movements, controls, and, especially feedbacks (Weathers et al. 2013). By using a systems approach, researchers can more easily identify gaps in knowledge and opportunities for interdisciplinary research.

As the first step toward engaging a broader community of fog researchers, Weathers in a face-to-face meeting of the SC, charged the committee with: (1) creating a conceptual diagram or artistic rendition of his/her view or understanding of fog as a system, (2) a list of what is known and unknown about the coastal fog system, (3) a list of people and disciplines who might know the answers to the unknowns, and (4) three key questions regarding fog as a system.

Steering Committee members presented a drawing or diagram of fog as a system, which was then discussed by the group. The diagrams ranged from simple to complex and represented various aspects of the coastal fog system, including:

- Fog as a mechanism for moving water, nutrients, microbes and toxic materials between marine and terrestrial ecosystems in coastal areas
- Boundaries between the physical, chemical and biological aspects of the coastal fog system, with little known about the latter two
- Spatial and temporal scales ranging from the microscopic (micrometer) to regional (thousands of meters) scale and from seconds to decades
- Processes and fluxes affecting fog
- Marine, terrestrial, atmospheric and human components of the coastal fog system
- The effects of fog on both human and natural systems at the various scales

Discussion about the diagrams included the following observations:

- There is a need to identify the controls, mechanisms and feedbacks within the coastal fog system.
- Biological interactions are of particular interest, especially near the ocean surface, and are also potential sources of pathogens to and from humans.
- Fog system boundaries are delineating lines for geographic, disciplinary and spatial/temporal aspects of research. For planning purposes, they can also be

thought of as boundary objects, or attractors, to figure out how to talk across disciplinary and other boundaries (Star and Griesemer 1989).

- A systems approach must address the formation, evolution, transport, deposition, composition and impact of fog.

Although much work has been done to understand individual aspects of the coastal fog system, members of the Steering Committee agreed that little is known about the system as a whole.

Conceptual Frameworks

Three conceptual frameworks emerged from the Steering Committee discussions and are described below.

a. Coastal Fog as a System

The Coastal Fog as a System diagram (Fig. 1) represents processes that govern the overall system, including marine, terrestrial, atmospheric and human components. The left side of the diagram is a representation of the processes contributing to the coastal fog system in the marine environment, and the right side of the diagram also shows the effects of fog on or by the terrestrial environment.

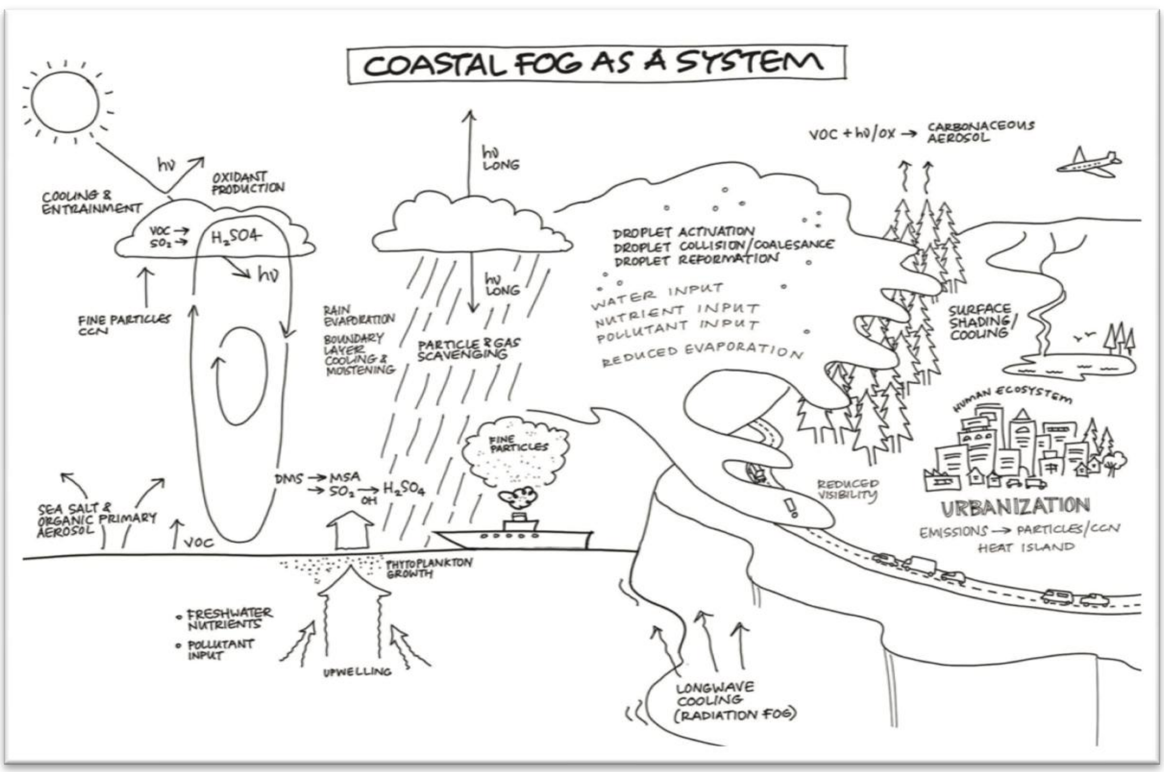


Figure 1. Coastal Fog as a System conceptual framework.

b. Spatio-Temporal Framework

The Spatio-Temporal Framework diagram (Fig. 2) represents the spatial and temporal scales of the coastal fog system. The x-axis displays a time scale ranging from seconds to decades, and the y-axis displays a spatial scale ranging from the microscopic (micrometers) to the synoptic (thousands of meters).

The items in the “bubbles” are components of the coastal fog system that fall broadly within the ranges depicted. Droplet formation, for example, is a process that occurs at the micrometer to meter and seconds- to minutes- scales. The effects of fog on canopy and vegetation structure, on the other hand, usually occur at the centimeter to 30-meter and years to decades scale. Topography and bathymetry are boundary conditions to the coastal fog system.

The arrows show how the various components interact. For example, black arrows show how upwelling is affected by bathymetry, ocean circulation, differential air masses, air pressure and winds. As shown with the blue arrows, upwelling affects droplet formation and ultimately contributes to the formation and dissipation of marine stratocumulus fog.

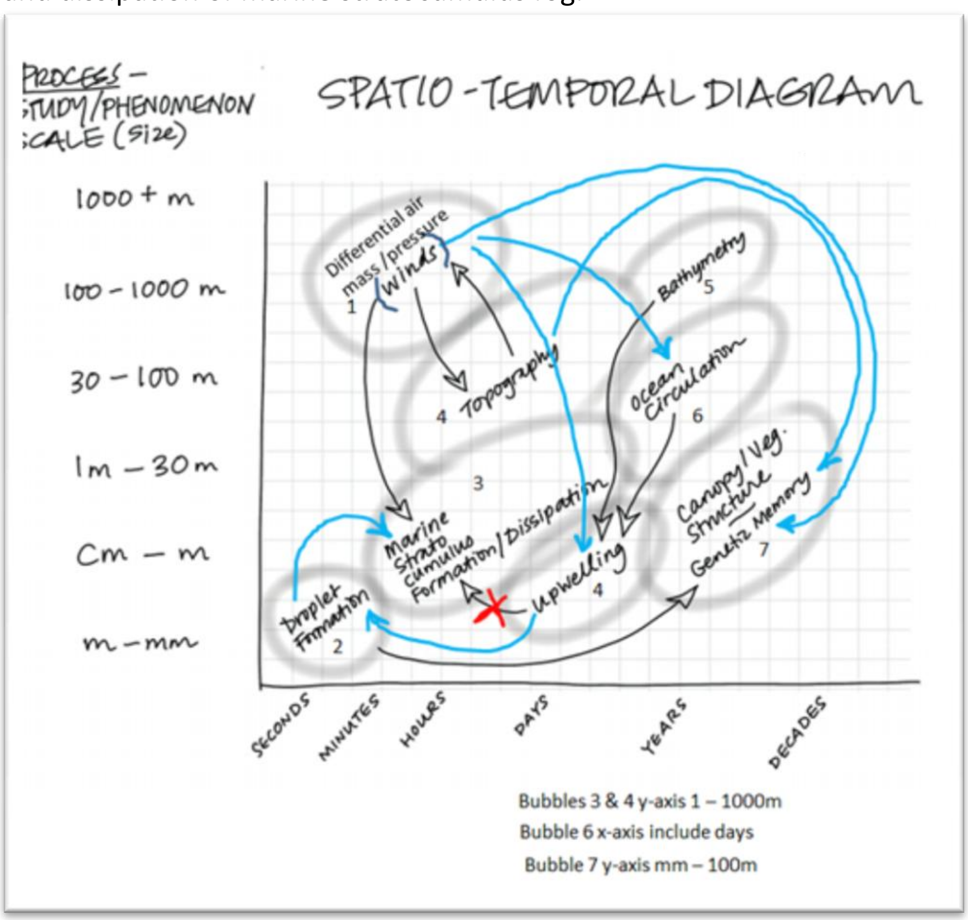


Figure 2. Spatio-temporal framework for coastal fog research.

The Spatio-Temporal diagram brings attention to the important issue of scale in fog research; this is a topic that was identified as both important and vexing. Scientists are not only studying different aspects of fog, their research is often conducted at vastly different scales. Weather forecasters and researchers studying the frequency and distribution of fog are using data covering broad geographic areas, while atmospheric chemists and microbiologists are studying inorganic and organic particles at the fog droplet scale. Similarly, oceanographers and atmospheric scientists studying the physical processes involved in fog formation, evolution and dissipation are concerned with time scales on the order of seconds, in the case of droplet formation; hours to days in the case of a fog event; and seasons of the year, in the case of ocean upwelling and atmospheric conditions. When studying its effects on natural and human systems, ecologists and climatologists are interested in decades and even centuries of fog history.

c. Research Disciplines, Tools and Approaches ("Spiderweb")

The "Spiderweb" diagram (Fig. 3) emerged from a small group discussion among Steering Committee members about fog research disciplines, tools and approaches. A spider web was chosen as the graphic representation, not only because spider webs capture fog droplets in nature, but because the threads symbolize interconnections in fog research.

Fog research topics are represented by green threads, and tools and approaches are represented by blue threads. Examples of research topics include: climate change, transportation, human well-being (human health and water supply), pollution, and ecology. Examples of tools and approaches include: remote sensing, modeling, *in situ* measurement and theory.

The fog research community is at the center of the web and includes disciplinary scientists such as ecologists, biologists, hydrologists, engineers, economists, atmospheric scientists, oceanographers, epidemiologists, and humanists. The level of understanding of the coastal fog system decreases moving out from the center of the diagram. A spider moving around the web symbolizes the research community working on key questions. (No hierarchy is implied with the diagram.)

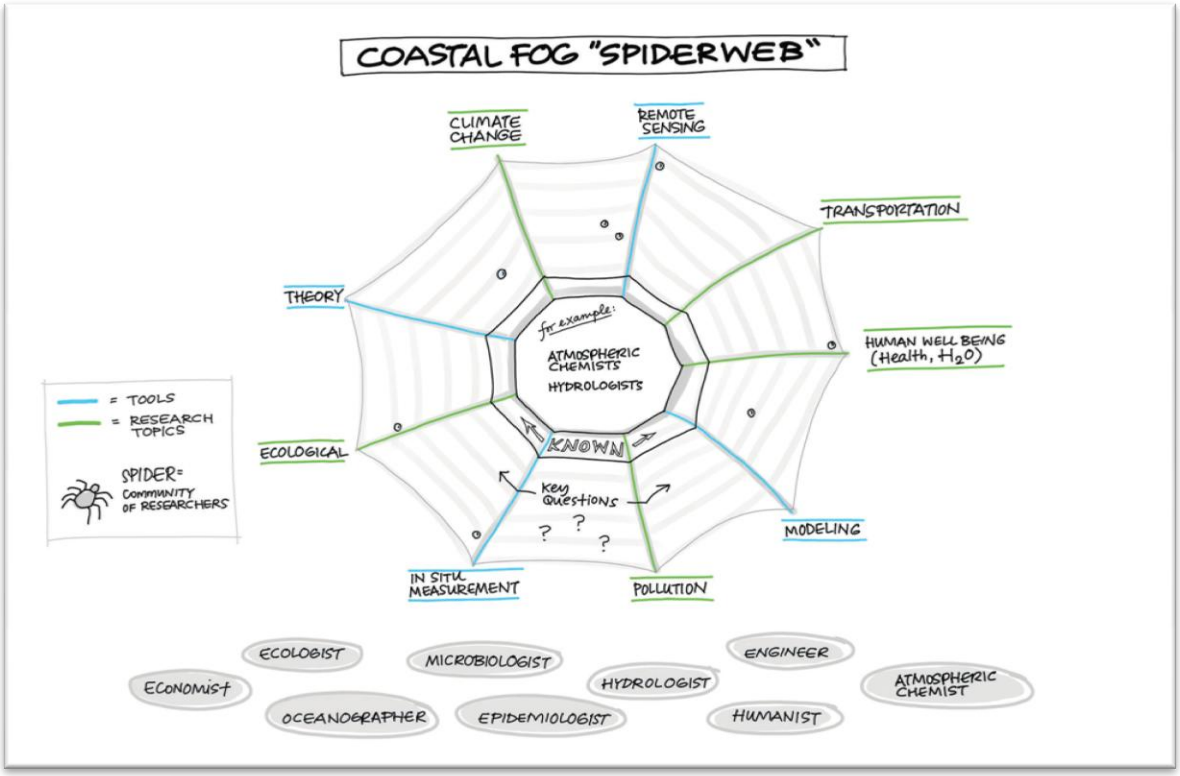


Figure 3. “Spiderweb” conceptual framework for tools, disciplines and approaches.

The “Spiderweb” diagram defines the various disciplines, tools, approaches, and research topics of the fog research community. In developing this diagram and the Coastal Fog as a System diagram, it became clear that studying fog as a system will not only require involvement of experts in the social sciences as well as the natural sciences, but practitioners in fields such as weather forecasting, transportation, agriculture, forestry and other industries and stakeholder groups affected by fog. The “Spiderweb” diagram is perhaps most useful in designing a path forward for implementing the fog research agenda.

Use of conceptual frameworks in developing a fog research agenda

The Coastal Fog as a System diagram (Figure 1) was used as a tool to catalyze and focus discussions at both the International Conference on Fog, Fog Collection, and Dew in Japan, and at the June Pescadero workshop. It proved remarkably useful for members of the fog research community to visualize coastal fog as a system and place themselves, and their research foci, within the context of discussions regarding interdisciplinary research frontiers. The diagram was used—to great effect— during participant introductions, plenary and breakout discussions, and the meeting wrap-up session (see Workshop Summary for details).

By the end of the workshop, participants reached consensus that the Coastal Fog as a System diagram, in particular, is a useful conceptual framework for developing an interdisciplinary fog research agenda.

In part because of the focus of the workshop agenda on developing interdisciplinary research priorities, the other two diagrams were introduced at the June workshop but not discussed at length in plenary or breakout discussions. They are, however, useful outcomes of this community planning process that help define aspects of the coastal fog system and provide important insights for both designing interdisciplinary research projects and creating a mechanism to facilitate ongoing research collaborations.

III. Current State of Fog Research

The emphasis of much past fog research was to examine fog solely as a physical process. An excellent review of the physics of fog can be found in “Fog Research: A Review of Past Achievements and Future Perspectives” by Gültepe et al. (2007).

More recent research is aimed at other aspects of the fog system, including its chemical and biological composition as well as deposition and delivery of water, nutrients and microbes to human and natural systems. There is now a sizeable literature on the subject of fog, but definitive literature reviews addressing all aspects of fog research have yet to be accomplished.

Much of the fog research to date has fallen within clear disciplinary boundaries. Fog scientists in these fields typically belong to professional associations and societies that do not overlap, so they rarely interact. A quick scan of the references for this report indicates the variety of journals and professional meetings where the results of important fog research are published and discussed. The example of Gültepe et al. (2007) cited above was published in *Pure and Applied Geophysics*, a journal that most ecologists and hydrologists do not follow. Similarly, a synthesis letter to the ecological community by Weathers (1999) about the importance of cloud and fog in the maintenance of ecosystems was published in *Trends in Ecology & Evolution*, a journal geophysicists do not typically read.

The disciplinary approach to fog research to date presents a challenge for understanding fog as a system. Prior to this research planning effort, there were limited opportunities for researchers from different disciplines to meet face-to-face, share research findings, or plan research collaborations.

One example of a fog research gathering is the International Conference on Fog, Fog Collection, and Dew, held every three years in different locations around the world. As the title implies, these conferences tend to focus on the science of fog (chemistry and physics) and fog collection, for both research and water supply, although the latter has received less attention in recent years. Steering Committee member Dr. Jeff Collett and several other participants in this research planning process are also active in these conferences; Dr. Kathleen Weathers is on the scientific steering committee for the next international conference. Another example is the ‘fog session’ at the American Geophysical Union Fall meetings (e.g., 2006, and more recently in 2012 and 2013).

Types of Fog

This White Paper focuses primarily on stratocumulus fog. Other types of fog include:

Advection fog forms when warm, moist air passes over a cool surface, such as warm tropical air flowing over cooler ocean water. The Yellow Sea fogs are a classic example of advection fog, where southerly winds bring warm air over an area with sea surface temperatures that get colder as the air moves north. When the sea surface temperature is colder than the dew point temperature of the air, it will cool the air, causing fog to form.

Radiation fog forms by the cooling of the land after sunset, by thermal radiation in calm conditions with a clear sky. Classic studied examples are large-scale fogs that form in the Central Valley of California and in Italy's Po Valley.

Ice fog is a type of fog consisting of fine ice crystals suspended in the air that forms in cold areas of the world, such as in the Arctic.

Stratocumulus fog is the type of fog that forms along the Pacific coast of North America (California), South America (Chile) and the west coast of southern Africa – regions of atmospheric subsidence and cold sea surface temperatures. Stratocumulus clouds formed over the ocean are termed fog when they intercept coastal headlands.

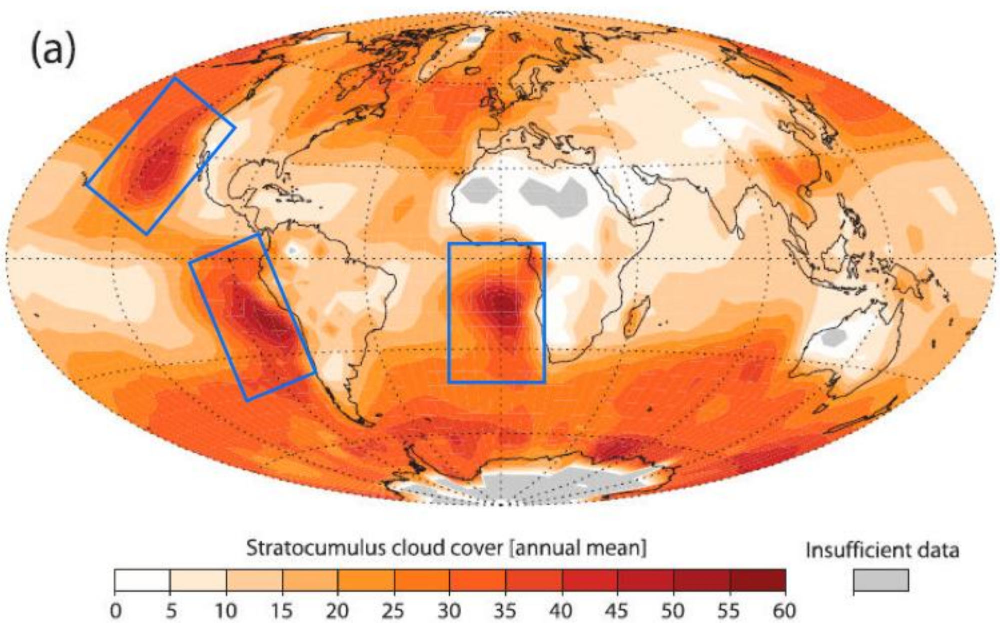


Figure 4. Stratocumulus cloud cover (%). Source: Wood (2012).

Key Knowledge Gaps and Research Challenges

The following knowledge gaps were identified at the Fog Research Frontiers Workshop:

1. **Improve understanding of fog precursor aerosols**
   Understanding aerosols is important in determining where the material in fog comes from, how it evolves, and how chemicals and biota interact. Studying these interactions requires dedicated process studies involving aircraft and Unmanned aerial vehicles (UAV).

2. **How does the fog activation process differ from cloud activation?**
   In atmospheric science, researchers describe nucleating cloud particles as a function of super saturation (how air moves up and cools off). Parcel models used to study cloud formation look at the process of nucleation, but the fog formation process is different than a typical updraft leading to cloud formation. One of the unique things about fog is figuring out how the nucleation process happens. Existing theoretical work on this topic needs to be pulled together and evaluated to determine future research needs.

3. **Fog and aerobiology**
   The influence of marine and terrestrial ecosystems on the microbial content of fog is an exciting and new area of research.

4. **What makes fog different in different locations?**
   And more specifically in terms of biological and chemical inputs, how do these inputs impact different ecosystems in different locations? How do the impacts compare to other fog regions at the national and global scale?

5. **Literature review of fog research to date**
   As described earlier in this section, a series of reviews of fog research literature are expected outputs of this planning process.

6. **Need to consider cold fog**
   When fog reaches a certain temperature, it becomes freezing fog. This type of fog can have important impacts on agriculture, but this topic tends to be overlooked. Fog research has tended to focus on heat and warming climate related topics, but cold fog needs to be considered, too, especially in Arctic regions.

7. **Finding ways to link non-uniform data and make those data available to fog researchers**

An immediate challenge for the fog research community is to create a structure for collecting and linking relevant data and then designing and managing a system to make those data available online.

8. **The role of topography in fog formation.**
   The interaction of fog with the topography and land surface is a complicated aspect of the coastal fog system that needs to be better understood.

9. **How can we better predict the wind three-dimensionally, in addition to temperature?**
   One area for new thinking and innovation with forecast models is to develop ways to predict wind in three dimensions.

10. **What is the correct scale?**
    A major challenge for fog research will be figuring out how to deal with scale, from the droplet-scale to the synoptic-scale.

11. **Understanding how climate change and variability will affect fog**
    Research shows that climate change and variability is already having an effect on the frequency and distribution of coastal fog (e.g., Johnstone and Dawson 2010), but due to the complexity of this research, gaps remain in the understanding of how this will impact fog.

12. **Lack of information about paleo-fog and the history of fog**
    Perhaps because fog is so nebulous in nature, there is a lack of information about fog in the paleontological record (e.g., Gutiérrez et al. 2008). A gap also exists in the study of fog climatology, with relatively little information available about the history of fog (but see Johnstone and Dawson 2010).

13. **Lack of climate proxies**
    One approach to studying fog climatology is to use climate proxies. More work is needed in this area of research, including the collaboration among climatologists, biologists and ecologists.

14. **Better decision support and prediction of fog events on a short-term time scale**
    Certain business sectors and people living in coastal fog regions depend on accurate fog prediction. More accurate decision support tools would improve forecasting and public safety and could potentially provide useful decision-making information for power management (electrical loads), air traffic control, water management and agriculture (for irrigation decisions and frost predictions), fire control (controlled burns need to understand fog conditions), maritime traffic, military and for the beach going public. Forecasting and decision support needs more accurate information at the local level and at the 1–3 day time scale.

15. International collaboration

For example, international colleagues have developed a high-resolution, three dimensional fog model at the one meter scale (e.g., Cermak 2012). Collaboration with these and other fog researchers would advance the fog research agenda. Arctic fogs over coastal ice and land are likely to change and are not yet studied.

16. Research Platform Restrictions

The extent of fog research that can be conducted from the deck of a ship or from traditional aircraft is greatly limited. Not only are the research vessels and aircraft expensive to operate, it is a logistical challenge to move them into the proper position for fog research. Their movements are further limited by weather and sea conditions. For safety reasons, ship captains tend to avoid rough conditions that give rise to sea spray and aerosol formation at the air-sea interface and airplane pilots cannot safely maneuver close to the mountainous coast in dense fog. Overcoming these platform restrictions is a major challenge for the fog research community.

17. Common definitions and standard methods

Interdisciplinary research will rely on common definitions for fog properties and types as well as standard methods for measuring fog.

Additional input was obtained from a written survey completed by 17 participants in the Town Hall gathering at the International Conference on Fog, Fog Collection and Dew.

The most important questions and knowledge gaps identified by survey respondents included many of those identified at the Pescadero Fog Research Frontiers workshop in June 2013, including: changes in fog frequency and distribution due to climate change, chemical reactions and processes in fog, impacts of the spatial (micro- to kilometer-scale) and temporal scale in modeling fog, importance of remote sensing and geostationary satellites, in particular, and understanding the interactions and feedbacks among fog processes. Additional summary of the survey can be found in Appendix 3.

Fog Definitions

Different scientific disciplines have different definitions of fog, depending on what aspect of the coastal fog system is being studied. Physicists focus on the size of fog water droplets to distinguish between fog and drizzle, for example. Fog is defined as having water droplets and ice crystals that are typically 5 to 50 µm in diameter (Pruppacher and Klett, 1997).

Weather forecasters define fog in terms of visibility. NOAA's definition of fog is a reduction of horizontal visibility to below 1 km (5/8 of a statute mile). If the visibility is greater than 1 km, then it is called mist (World Meteorological Organization).

Fog is also defined by its location in the atmosphere: a cloud that is at or near the Earth's surface. Along the Pacific coast of North America, fog is typically associated with stratocumulus cloud formations that intercept coastal headlands.

At the fog workshop in June 2013, researchers identified the need to develop a common definition of fog as a starting point for interdisciplinary research on coastal fog as a system.

IV. Coastal Fog System Research Frontiers

The fog research dialogue(s) confirmed the need for a system-level approach and resulted in the identification of both disciplinary and interdisciplinary fog research frontiers. System-level research frontiers are outlined below followed by descriptions of interdisciplinary research frontiers.

A. Interdisciplinary Research Frontiers

Interdisciplinary research frontiers are grouped into four over-arching themes: (1) fog as a system, (2) impacts of fog on human and natural systems, (3) changes in fog frequency and distribution, and (4) new tools, technologies and approaches for studying fog.

1. Understanding Fog as a System

One important research frontier is to understand fog as a system, beginning with the linkages between the ocean, atmosphere and terrestrial ecosystems, as well as the chemical, biological and physical processes involved. Learning more about these connections is a fundamental requirement for future fog research.

Example Hypothesis: *Fog is a critical bi-directional connector between marine and terrestrial systems.*

a. Connections between marine and terrestrial ecosystems

Bi-directional relationships among the components of the system, such as the exchange of water, nutrients, chemicals, microbes and energy between land and sea, are important considerations in coastal fog system research. As shown in the Fog as a System diagram (Fig. 1) fog carries these components from the ocean onto shore. The terrestrial landscape is also responsible for producing emissions and that affect the coastal fog system offshore.

Examples of frontier areas include:

1) ***Nutrients and other chemical formation and fluxes*** – As water moves from the sea through the atmosphere to the land and back offshore again, it carries nutrients and other chemicals along with it. In particular, what nutrients are being brought onshore/offshore? What pollutants are being taken offshore and how does this affect the coastal fog system? How are chemicals, including nutrients, being transformed as they move between the land and sea and are processed through the fog.

2) ***Fog and Aerobiology*** – Researchers are very interested in learning more about whether fog is also a bi-directional vector for moving microscopic organisms. Recent research has demonstrated that fog can bring

microbes from sea onto land. A critical unknown question is whether it also transmits microbes on land back out to sea. Another unknown is how microbial activity changes the chemistry of fog and how terrestrial and marine sources of particles end up joining in fog and evolving in ways that they would not otherwise in relatively unimpacted (by humans), isolated conditions.

3) ***Energy Transport and Cooling*** – Energy transport in the coastal fog system is another topic of interest. As water condenses offshore and evaporates onshore, these processes create a feedback and connection within the fog system and should account for a component of the energy balance of the coastal system. Fog also provides a cooling mechanism along the coast. Researchers are interested in learning more about whether energy transport is a critical part of the energy balance in the coastal fog system.

b. Characteristics and processes of the coastal fog system responsible for generation, evolution and dissipation of fog

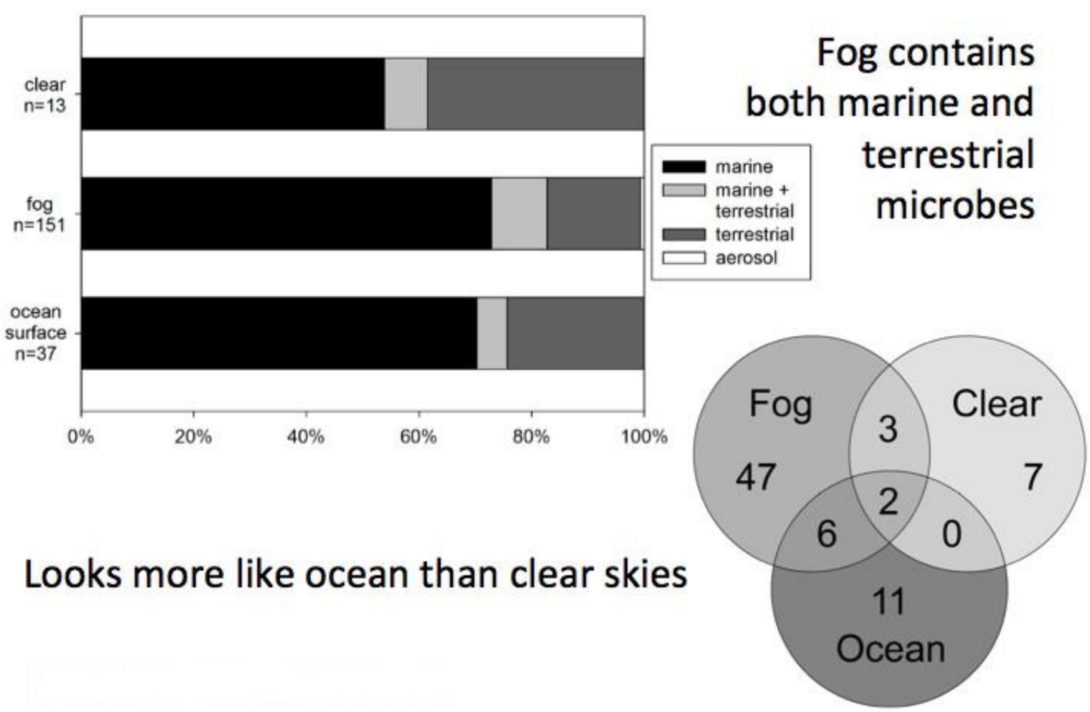
1) ***Fog precursors*** – Much remains unknown about the sources of cloud condensation nuclei (CCN) aerosols. What is the composition of fog droplets? How do those fog droplets evolve through uptake of soluble gases and through aqueous chemical reactions? What does that mean in terms of deposition and availability of water, nutrients, pollutants and microbes to natural and human systems? What role do microbes play in the transformation of nutrients in fog? These are questions posed by researchers when thinking about fog precursors in the context of the coastal fog system.

2) ***Air mass history*** – What is the relative importance of air mass history and what materials come into an air mass versus the evolutionary and transformational processes that happen within it? These questions were posed as examples of learning more about the interaction of the physical, chemical and biological aspects of the coastal fog system and how those interactions impact the generation, evolution and dissipation of fog.

Fog Aerobiology

Recently, fog has been identified as capable of supporting microbial viability and serving as a vector for human, plant and animal pathogens. This discovery comprises part of a nascent field of aerobiology, which investigates the microbiota of the atmosphere. Fundamental questions about the biology of fog remain to be answered: What microbiota lives in fog? Where do these microbes originate and where are they being transported? What factors make microbial life in fog possible? How and where do they serve as condensation nuclei? Do pathogens move from ocean to land via fog?

A study by Dueker et al. (2012) was an initial effort to address some of these questions on the East Coast of the U.S. Their research found both marine and terrestrial sources for microbes in fog in near-coastal environments, with many from marine sources. They also found that the biological composition of fog looks more like the ocean than in samples collected from clear skies. Expanding on this area of research is an important frontier in understanding coastal fog as a system.



Source: Dueker et al. 2012.

2. Changes in fog distribution and frequency

Changes in climate and land use have the potential to affect the distribution and frequency of fog. For this reason, research on how the coastal fog system is affected by a changing climate as well as land use changes are longer-term research priorities.

Example Hypothesis: *A changing climate will reduce the occurrence of fog in coastal zones.*

a. Document the impacts of climate change and variability

Determining the response of coastal ecosystems to climate change is a complex undertaking that depends on local conditions. Fog occurrence on the coast of California, for example, is controlled by a number of factors that are already being affected by climate change, including ocean upwelling, ocean temperature, and air temperatures over both land and water, which may be affected in different ways, creating a greater temperature differential in coastal systems.

Although much needs to be learned before the impacts of climate change and variability on fog can be fully assessed, changes in regional climate are an important consideration in fog research. As described above, research indicates a trend of intensification of the California Current and cooling of water in recent decades. Understanding how changes such as these affect fog frequency and distribution is an immediate research priority.

Example research topics include:

1) ***Study Regional Impacts of Climate Change*** – As the planet warms, many coastal climates are likely to change, and this will likely affect the frequency and distribution of fog. Some areas might become less foggy while other areas may experience an increase in fog. Researchers are interested in what role fog plays in the radiative balance of the earth's system, especially on a regional basis, and how feedbacks in the coastal fog system would be affected with the loss of fog.

2) ***Measure Impacts to Regional Circulation*** – How does fog affect regional circulation patterns and how might those change as a result of climate change? These research questions are important for determining whether climate change will impact the movement of water and other materials within the coastal fog system.

b. Study how land use changes affect fog frequency and distribution

Changes in climate are not the only causes/triggers researchers are concerned about when evaluating changes in fog frequency and distribution. Research on the heat island effect in urban areas is one example of how land use affects fog.

A research site in Sonoma, CA provides another example, where a measurable difference in wet deposition occurred in a forest versus an open field and more nutrients were deposited at the leading edge of the forest during fog events (Ewing et al. 2009). Determining how land use changes affect fog in coastal California and other fog regions of the world is an important consideration in understanding changes in fog frequency and distribution.

3. Impacts of fog on natural and human systems

Researchers identified the need to document how fog impacts human and natural systems, and in turn, to determine how these systems affect coastal fog systems, including the chemical and biological content of fog and its frequency and distribution.

a. Determine the socio-economic impacts of fog

Fog is an integral part of some coastal systems and affects the lives and livelihoods of people living in these areas. Fog poses a threat to public safety with reduced visibility on roadways, at airports and on waterways. These also translate into negative economic consequences, but fog is beneficial for agriculture, water supply and the maintenance of natural ecosystems.

One example of the socio-economic impacts is decreasing fog in the Central Valley of California. The number of fog days between November and February has decreased by 46% since 1981 (Baldocchi and Waller 2014). This has important implications for fruit and nut farmers whose trees depend on winter chill to bring on a dormant period before producing. Fewer fog days corresponds to fewer cold days (NASA 2014). Other research has found a decrease in the number of winter chill hours, which are expected to have a deleterious economic and culinary impact on fruit and nut production by the end of the 21st Century (Baldocchi and Wong 2008).

Changing patterns in fog due to climate change will likely be a concern in California's wine regions, given the economic impact of the wine industry, estimated at $13.4 billion in Sonoma County alone, in 2012 (The Press Democrat 2014). Sonoma is a wine region where coastal fog is important in growing grapes with qualities prized by vintners (Wines.com 2011).

Because little is known about the socio-economic impacts of fog, positive or negative, socioeconomic analysis is considered an immediate research priority. Fog researchers identified potential opportunities for broadening modeling capabilities to integrate ecosystem valuation and include other parameters related to socioeconomic analysis. Inviting social science researchers to join the fog research community was identified as another immediate priority.

b. Determine how human and natural systems influence the coastal fog system
Different types of land use, decisions about wastewater treatment, emissions from automobiles, and other aspects of human systems can influence the chemical and biological content of fog, as well as its formation and dissipation. Urbanization and the resulting heat island effect further influences the physical properties of fog. Researchers are interested in better understanding the bi-directional movement of materials and energy between the coastal fog system and human systems. They are also interested in learning more about the relative importance of oceanic inputs versus terrestrial sources of water, nutrients, pollutants, microbes and energy. Example research questions include: oceanic versus urban sources, the cycling of those chemicals and microbes on the chemistry and evolution of fog, and what is ultimately being deposited and where.

As a starting point, researchers propose using a framework that defines a hierarchy of impacts on socio-economic systems:

1) ***Energy and radiation balance*** – Perhaps the most important impact of the coastal fog system on human and natural systems relates to the energy balance, particularly the radiation balance. What is the impact of radiation on the duration of fog, and what are the resulting impacts on the heating and air conditioning loads in coastal regions?

2) ***Water input*** – Another important impact to consider would be the water input from the coastal fog system. What are the contributions of water from fog to agricultural systems, groundwater systems and ecosystems? In forested ecosystems, this might relate to the relative likelihood of fire, something that might be affected by water inputs as well as the radiative balance.

3) ***What fog carries*** *(nutrients, pollutants and microbes)* – Nutrients are an important concern because of their concentration and pervasive nature in fog (e.g. Weathers et al. 2000, Jordan et al. 2000). In addition to nutrients, fog also carries pollutants and microbes that might be considered socio-ecological stressors (e.g., Weathers et al. 1986, 1988, 2006, Dueker et a. 2012). What are the human health effects of fog events? How do pollutants and microbes affect the functioning of coastal ecosystems?

4. Improve Fog Measurements with New Technology, Tools and Approaches

Improved fog measurements are critical to understanding fog as a system. New and existing technologies, tools and approaches, including improved models, more sophisticated sensors, automated samplers, increased computing power, remote sensing products, UAVs, and networked science, create opportunities for studying the complexities of the coastal fog system. Priorities for further developing fog research technology, tools and approaches are described below.

a. Develop new models

The development of new modeling frameworks is essential in bridging some of the disciplinary boundaries and achieving an interdisciplinary approach to understanding fog as a system. Currently, numerical models of the atmosphere are not capable of diagnosing/predicting fog, in part due to their limited resolution. Because of the complexity of the coastal fog system, researchers expressed the need for models, from simple drawings and conceptual frameworks to complex mathematical and physical models, to bring a cohesive vision and explanation to how the system is functioning. Models can be a valuable tool in identifying the important components of the system, how they interact, and assumptions being made. Models also help researchers understand what is not known about the system. Modeling is an integrator (e.g., Canham et al. 2003), bringing together the biology, chemistry, physics, and meteorology, and can build interdisciplinary collaboration in fog research. Immediate priorities include:

1) ***Develop high-resolution ocean-atmosphere model –*** An improved model that is more heavily coupled between existing ocean and atmosphere models would be transformational for fog research and help address some of the system-level research questions, especially research related to the energy balance of the system, but also research on how fog has changed, the role of chemistry in fog and questions about fluxes in the coastal fog system. A resolution at a scale of 10 kilometers or less is recommended. The ocean-atmosphere model requires improved measurements (see recommendations below) to validate and improve the model, including remote sensing and other data related to movement of fog, its chemistry and effects on energy balance.

2) ***Develop coupled models to understand fog occurrence*** – In order to reach a point where researchers can predict fog occurrence over time and understand its impact on natural and human systems, unprecedented coordination of research must occur among disciplines and at different spatial and temporal scales. Coupled modeling can be used as a framework to integrate across disciplines and at different scales. Not only does much work need to be done to understand fog within disciplines, coupling this with atmospheric chemistry, physics and climate science and trying to bring this together at different scales (both upscaling and downscaling) creates a

myriad of challenges. New frameworks are needed around which fog researchers can come together and study specific topics.

One example of a research topic where coupled modeling would be useful is determining whether the climatology of the occurrence of fog in space and time can be developed based on existing fog data, coupled with information about ecosystems, landscapes and human development. Researchers want to learn more about the potential impacts of fog on the ecosystem and the potential feedback of those systems on the physical processes that lead to fog formation, and ultimately fog occurrence over time, especially at the landscape scale.

3) ***Incorporate earth system/ecosystem models into climate models*** – Researchers identified this as important for understanding how climate change will affect fog, especially with feedbacks occurring among the physical, biological and chemical aspects of the system. Climate models need to incorporate these bi-directional relationships, especially the coupling of fogs with vegetated ecosystems in terms of water and energy transfers; however, an immediate challenge is that climate models and ecosystem models are implemented at vastly different scales. Climate models also need to address deposition, otherwise a major part of the transport of materials from the marine system onto land will be missed.

b. Improve tools for measuring fog

1) ***Use remote sensing to study the vertical structure of fog*** – Remote sensing would be useful for establishing fog climatologies. It could also be used to reveal the fog height above ground, intersections with the urban environment and terrestrial ecosystems, the depth of the fog layer and the persistence of fog.

2) ***Use paleoclimate proxies of fog presence*** – To understand long-term changes or how climate and land use impact coastal fog, there is a need to look back further than current measurements can provide. Climate proxies can be used along with remote sensing and ground-based measurements (e.g., Gutiérrez et al. 2008, Johnstone and Dawson 2010). Creating a paleoclimate record, requires combining current measurements with a metric that allows researchers to go back in time; overlap of measurements is needed going forward and backward in time to validate paleoclimate proxies.

3) ***Develop improved sensors and measuring devices*** – Better ways to collect fog data across broad temporal and spatial scales are critically needed. Ideally fog sensors and automatic samplers could be developed to collect fog

water samples (volume, chemistry and biota) and make the data accessible online in near real-time. Combining these data with improved remote sensing products would greatly advance fog research.

4) ***Improve satellite technology, including geosynchronous satellite technology, and other remote sensing products*** – Satellite derived products are essential for creating a comprehensive cloud atlas with global coverage and mesoscale resolution. However, most satellite sensors only "see" the cloud top so they are unable to detect if the cloud is touching the ground forming fog. Geosynchronous satellite technology is being used successfully to study fog in the Yellow Sea. Plans are underway in the U.S. to further develop geosynchronous satellite technology for ocean-atmosphere studies as part of the NASA GEO-CAPE mission. Improved satellite technologies would transform coastal fog systems research. Incremental advances could be made with remote sensing products developed for fog research using existing satellite technology.

5) ***Develop UAVs for fog research*** – Because it can be challenging to position measuring devices in the right place to catch fog, UAVs would allow fog researchers to gather much needed high-resolution data and valuable above ground-based observations. One benefit of using UAVs in fog research is that they do not disturb the environment that they document. Another benefit is that small UAVs with basic sensors can be sent out into a fog event once it forms. The use of UAVs in addition to traditional aircraft would transform coastal fog research by allowing for more convenient sample collection during a fog event.

c. Expand real-time measuring systems

1) ***Conduct a Lagrangian experiment to follow fog evolution*** – Designing a study, or unifying research campaign, to look at evolution over the course of a fog event and to study the coastal fog system from different disciplines (meteorologists, biologists, etc.) using intensive measurements would be a good first step to examining what is going on inside a fog bank.

2) ***Establish a "Super Site" research location*** – A well-designed "Super Site" would be a heavily instrumented research location where it would be easier to make high frequency measurements and conduct intensive research experiments. Such a site would create synergy and provide base measurements and logistical support for visiting investigators to deploy fog measurement equipment and validate new measurement technologies against community standards. Ideally such a "Super Site" would be located among a larger network of research sites along the coast of California (see "FogNet" below).

3) ***Create a ground-based sensor network ("FogNet") with embedded "Super Site"*** – Researchers envision creating a distributed network of sampling sites that includes sampling sites in the ocean, on shore and further inland where cloud base height, liquid water content, and cloud depth, as well as the chemistry and biology of fog, can be measured. The sampling network would include deposition and microphysical measurements and be spatially extensive along the coast of California and samples would be collected frequently enough to provide larger spatial coverage than what is currently possible with independent research sites. A sensor-based network ("FogNet") with an embedded "Supersite" would create the necessary infrastructure for addressing the types of interdisciplinary research questions identified in this report.

B. Disciplinary Research Frontiers

The following questions can be addressed at smaller scales and are essential components of the previously discussed interdisciplinary (system-level) research frontiers.

1. Biology and Chemistry

Researchers concluded that not enough is known about the biological composition of fog and identified this as an immediate research priority. Development of a more focused (and prioritized) implementation plan was identified as the next step.

Examples of research frontiers at the interface of the fields of biology and chemistry include:

a. Determine the importance of fog to terrestrial plant species.

b. Study how spatial/temporal patterns of fog influence distribution of terrestrial plant species.

c. Overcome limitations in knowledge about microbes in fog, especially related to infectious diseases. Do bacteria "catch a ride" or live/grow in fog?

d. Understand chemical reactions in fog droplets, including aqueous reactions and the organic composition of fog precursors. This requires physical knowledge about droplet size and liquid water content.

e. What are the biological effects of fog and fog chemistry?

f. Understand the fog mediated bi-directional flux of microbiological and chemical components between atmospheric and marine/terrestrial pools, as well as the partitioning of natural and anthropogenic sources of these components.

g. Quantify fluxes and interactions among water, solutes, and terrestrial biota, including microbes.

h. Understand cloud water interception with terrestrial biota at the leaf to landscape scale.

i. Measure the composition of fog water and cloud water to enable time series flux calculations on organics, nutrients, acidity, metals, and microbes.

2. Atmospheric Science and Oceanography

Examples of research frontiers in atmospheric science and oceanography include:

a. Study the lower atmosphere over coastal upwelling zone.

b. Determine physical factors and scales that control fog processes (droplet size, dynamics, evolution, and other physical drivers).

c. Study particle-fog feedbacks and fog's effect on gases.

d. What are fog supersaturations? What controls the peak supersaturation in coastal fogs? How does this influence particle activation?

e. Determine fog droplet lifetimes and the effects of biological activity, chemical reactions and deposition rate.

f. Study time series of vertical profiles of temperature and moisture in fog.

g. Better characterize entrainment processes.

h. Study the timing of fog onset, evolution and burn off to provide societally relevant information at different scales.

3. Modeling

Examples of research frontiers in modeling include:

a. Model multi-scale fog variability and dynamics to bridge gaps in spatial/temporal scales and to cover the full range of scales, from the smallest to the largest.

b. Determine variables/parameters needed to capture and model fog physics and chemistry.

c. Conduct micro-scale modeling to understand biological interactions.

d. Utilize regional-scale models to examine fog effects on surface energy and moisture budgets.

4. Climatology

Examples of research frontiers in the field of climatology include:

a. Develop fog climatology using information on past changes in spatial/temporal occurrence to understand the processes that govern the occurrence of fog.

b. Study how climate dynamics impact the regional coastal fog system.

c. Determine how fog will change in future climate and with current trends and determine what to measure to help predict this (e.g. biosphere records versus fog deposition and paleoclimate proxies).

d. Understand how land use changes impact fog climatology, including urbanization and deforestation.

5. Social Science

Social scientists were not among the researchers who convened for this initial fog research planning exercise; however, there was general consensus about the importance of socio-economic analysis in an interdisciplinary fog research agenda. Including social scientists was identified as a goal for future planning and research.

One area of potential future research is determining the social impact of fog, including monetary costs related to changes in fog frequency. Documenting the impacts of fog on public safety and developing a socio-economic framework are two immediate fog research priorities.

V. Lessons for Interdisciplinary Science

A. Science of Team Science

Given the nature of studying coastal fog as a system, the development of this framework was treated as an opportunity to study how a community of disciplinary scientists could come together to develop a common framework to study a system. Dr. Michael O'Rourke, a philosopher and Science of Team Science scholar, participated in and guided the fog research planning process as a member of the Steering Committee. He and others also conducted a study of the planning process, which is summarized in Appendix 4.

B. The Art of Catalyzing Interdisciplinary Science

This planning process used innovative techniques to facilitate creative thinking and encourage research scientists to visualize fog as a system, identify fog research frontiers and simply get to know one another. In the process of developing a fog research agenda, it became clear that in addition to applying concepts from the Science of Team Science, there is also an art to catalyzing interdisciplinary research opportunities. Other factors contributing to the successful outcome of the planning process included:

- An emphasis on developing drawings, diagrams and conceptual frameworks to represent the coastal fog system.
- Involving an artist/illustrator, Emily Shepard, in the refinement of the diagrams and as a graphic facilitator during the workshop itself.
- Well-designed steering committee meetings and workshop that allowed time for project participants to get to know one another over shared meals and through informal conversations during unstructured time in the agenda.
- Leadership with experience in facilitating interdisciplinary science (Weathers engaged Dr. Jonathan Kramer as facilitator).
- In designing the project, it was recognized that bringing the fog research community together was an important goal, in addition to developing a fog research agenda.
- Project participants were carefully selected because of their demonstrated interest in interdisciplinary collaboration and to achieve a balanced and diverse group. But even the best planning cannot account for the good chemistry among individuals and positive dynamics of the group overall.

An interested, active and capable research community is a prerequisite to successful implementation of a fog research agenda. At the June workshop, fog researchers from various disciplines were able to meet, learn about research in other disciplines, share ideas, and establish a basis for future collaborations. Researchers left the workshop feeling energized by the discussions about an interdisciplinary fog research agenda and many commented that the experience changed their own thinking about fog as a system and transformed how they plan to approach future fog research.

In addition to the Science of Team Science study, members of the fog research community have already initiated follow up activities to advance this research framework. Examples are provided in Appendix 4.

Among the challenges going forward will be to build upon the collaboration that has begun with this planning process. The fog research community would benefit greatly from the experiences and lessons learned in similar interdisciplinary efforts, including appropriate procedures for developing funding proposals and publishing papers that give due recognition to the collaborative process, as well as the intellectual property of the various individuals involved.

VI. Immediate Priorities for Coastal Fog Research

The planning process confirmed the need for an interdisciplinary approach to advance fog research, one that considers coastal fog as a system, addresses the wide range of spatio-temporal scales, takes full advantage of the multidisciplinary expertise in the research community, and integrates new or existing technologies, tools and approaches.

An important outcome was the articulation of three conceptual frameworks to guide implementation of the fog research agenda:

(1) ***Coastal Fog as a System*** – Consensus was reached on this overall framework to guide system-level fog research.

(2) ***Spatio-temporal framework*** – This framework brings attention to the important issue of scale in fog research, with timescales ranging from seconds to decades, and spatial scales ranging from the microscopic to the synoptic scale. This is a topic that was identified as both important and vexing for the fog research community.

(3) ***Disciplines, tools and approaches*** – This framework defines the complex "spiderweb" of disciplines, tools and approaches in fog research.

Immediate priorities for interdisciplinary fog research relate to the four over-arching themes:

(1) ***Understanding coastal fog as a system***, including linkages and feedbacks among the ocean, atmosphere and terrestrial ecosystems, as well as the chemical, biological and physical processes within the system. An immediate research priority is to understand more about the bi-directional relationships among the components of the system, such as the exchange of water, nutrients, chemicals, microbes and energy between land and sea.

(2) ***Determining the impacts of fog on human and natural systems*** and how changes in these systems affect coastal fog systems is another important area of fog research that requires an interdisciplinary approach. Immediate research priorities include understanding more about the impacts of fog on energy and radiative balance, water inputs, and what fog carries, including nutrients, pollutants and microbes. Additional human health priorities include understanding the socioeconomic impacts of fog and inviting social scientists to join the fog research community.

(3) ***Documenting changes in fog frequency and distribution*** as a result of changes in climate and land use, and vice-versa, are poorly understood and require an

interdisciplinary approach. An immediate research priority is to understand how changes in climate and land use affect fog frequency and distribution at a regional scale, such as the Pacific coast of the U.S.

(4) ***Developing and integrating new tools, technologies and approaches for studying fog*** creates opportunities for enhancing study of the complexities of the coastal fog system. Of particular interest is the use of remote sensing tools, including the application of existing technologies for fog research and the development of new geosynchronous satellite technologies, to document the presence of fog. Other immediate research priorities are to improve fog measurement and sensor technologies and expand real-time measuring systems.

As a result of this planning effort, the fog research community has come together to identify research frontiers and is now poised to implement that ambitious agenda. Collaboratively-initiated research projects and the promotion of interdisciplinary research is essential to the successful implementation of this fog research agenda. With the publication of this White Paper, the fog research community intends to promote collaboration, secure funding commitments and engage in further dialogue within and among existing research institutions, scientific communities, and funding agencies interested in moving towards an interdisciplinary understanding of the coastal fog system.

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APPENDICES

A.1 List of terms and definitions

A.2 List of participants, Coastal Fog as a System Workshop, June 2013

A.3 Coastal Fog as a System Town Hall Survey Summary, 6th International

A.4 Follow up activities

Appendix 1: Terms and Definitions

advection fog – forms when warm, moist air passes over a cool surface, such as warm tropical air flowing over cooler ocean water on the Pacific coast of the U.S.

aerobiology – a branch of biology that studies organic particles, such as bacteria, fungal spores, pollen grains and viruses, which are passively transported by the air.

aerosol – a fine solid particle or liquid suspended in air.

boundary layer – the lowest part of the atmosphere, the behavior of which is directly influenced by contact with the earth's surface that displays turbulence and strong vertical mixing.

cloud – a visible mass of liquid droplets or frozen crystals suspended in the atmosphere.

cloud condensation nuclei (CCN) – organic and inorganic particles on which water vapor condenses.

dew point – the temperature below which the water vapor in a volume of humid air at a given constant barometric pressure will condense into liquid water at the same rate at which it evaporates.

ecosystem valuation – a widely used tool in determining the impact of human activities on an environmental system, by assigning an economic value to an ecosystem or its ecosystem services.

entrainment – the process where a turbulent flow (boundary layer) expands into and "annexes" and adjacent quiescent flow of air.

fog – a collection of suspended water droplets or ice crystals near the Earth's surface that lead to a reduction of horizontal visibility below 1 km (5/8 of a statute mile) (NOAA). If the visibility is greater than 1 km, then it is called mist (WMO).

fog burnoff – dissipation of fog, usually referring to the effect of morning sun in dissipating fog.

fog droplets – tiny water droplets or ice crystals, typically 5 to 50 µm in diameter, that form as a result of supersaturation generated by cooling, moistening and/or mixing of near surface air parcels of contrasting temperature.

geosynchronous (geostationary) satellite – provide hemispheric coverage at frequent intervals with moderate revolution.

heat island effect – an area which is consistently hotter than the surrounding area, such as an urban heat island, an urban area that is significantly warmer than its surrounding rural areas due to urban development.

ice fog – a type of fog consisting of fine ice crystals suspended in the air that forms in cold areas of the world.

microbe – a single cell or multicellular microscopic organism (microorganism).

radiation fog – formed by the cooling of the land after sunset by thermal radiation in calm conditions with a clear sky.

sea surface temperature (SST) – water temperature close to the surface of the ocean.

stratiform clouds – thin clouds with large horizontal extent.

stratocumulus clouds – a type of stratiform cloud that has identifiable features (bumps and rolls) typically seen along the Pacific coast of North and South America.

stratocumulus fog – a stratiform cloud that is at or near the Earth's surface.

subsidence – the descent of warm dry (free tropospheric) air that caps the boundary layer.

supersaturation – a solution that contains more of the dissolved material than could be dissolved by the solvent under normal circumstances.

science of team science – a field that encompasses both conceptual and methodological strategies aimed at understanding and enhancing the processes and outcomes of collaborative, team-based research.

synoptic scale – in meteorology (also known as large scale or cyclonic scale) is a horizontal length scale of the order of 1000 kilometers (about 620 miles), the typical scale of mid-latitude depressions (e.g. extratropical cyclones).

team science – initiatives designed to promote collaborative, and often cross-disciplinary (which includes multi-, inter-, and transdisciplinary) approaches to answering research questions about particular phenomena.

UAV – Unmanned aerial vehicle.

upwelling – an oceanographic phenomenon that involves wind-driven motion of dense, cooler, and usually nutrient-rich water towards the ocean surface, replacing the warmer, usually nutrient-depleted surface water.

Appendix 2: Pescadero Fog Research Frontiers Workshop Participants

Sara Baguska, University of California, Santa Barbara
Lisa Borre (Writer), Cary Institute of Ecosystem Studies
Jan Cermak, Ruhr-Universität Bochum
Patrick Chuang, University of California, Santa Cruz
Jeff Collett, Colorado State University*
Clive Dorman, Scripps Institution of Oceanography
Eli Dueker, CUNY Queens College
Gary Ellrod, NOAA
Holly Ewing, Bates College
Ian Faloona, University of California, Davis
René Garreaud, Universidad de Chile*
Ismail Gültepe, Environment Canada
Barbara Han, University of Georgia
Lelia Hawkins, Harvey Mudd College
Barry Huebert, University of Hawaii
Jim Johnstone, University of Washington
Carolyn Jordan, University of New Hampshire*
Jon Kramer (Workshop Facilitator), University of Maryland-SESYNC
Paty Matrai, Bigelow Laboratory for Ocean Sciences*
Mel Nordquist, National Weather Service NOAA
Travis O'Brien, Lawrence Berkeley National Lab
Michael O'Rourke, Michigan State University*
Zach Piso, Michigan State University
Kerri Pratt, University of Michigan
Martha Scholl, U.S. Geological Survey
Emily Shepard (Illustrator)
Armin Sorooshian, University of Arizona
Robert Tardif, University of Washington
Alicia Torregrosa, U.S. Geological Survey*
Kathleen Weathers, Cary Institute of Ecosystem Studies*
Chris Zappa, Columbia University

* Steering Committee members

Appendix 3: Town Hall Gathering at the International Conference of Fog, Fog Collection and Dew, Japan, 2013

Additional input to the fog research frontiers planning process was obtained from a written survey completed by 17 participants in the Town Hall gathering at the International Conference on Fog, Fog Collection, and Dew.

Survey respondents identified important disciplinary and interdisciplinary fog research questions, knowledge gaps, and barriers or bottlenecks that need to be overcome to close the gaps in understanding fog systems. Responses to these questions and comments on the definition of fog are summarized in Table A3-1 below.

After listening to three presentations at the Town Hall gathering and being presented with Figure 1 (main text of White Paper) as a fog system conceptualization, respondents to the survey identified exciting ideas, including: fog is effective at scavenging for anthropogenic pollutants; linkages between fog and climate change; collecting a three dimensional profile of fog with boats and/or UAVs; the complexity of coastal fog; and the role of fog in vegetation development.

The average age of respondents was 39, with 87% men and 23% women. 56% of those who responded were faculty, but responses were also gathered from corporate, government and nonprofit scientists, as well as one graduate student. Fields included atmospheric science, chemistry, physics, engineering, ecology, hydrology, geography, environmental science, and science education. Of the total, 67% listed a PhD and 25% listed an MS as the highest degree they held. The respondents devote an average of 46% of their time to research.

The survey respondents had considerable experience in interdisciplinary and collaborative research projects. 40% said they had more than six years of experience with interdisciplinary research, and 62% said they had more than six years of experience with collaborative research. The respondents have worked in 13 countries, including: USA, Canada, Norway, France, Germany, South Africa, Lebanon, Chile, New Zealand and Taiwan. More countries were represented in the Town Hall gathering, but likely due to language barriers, they did not complete the questionnaire.

Table A3-1. Summary of Survey Results – Fog, Fog Collection and Dew Conference						
Japan, 2013						
Questions/Knowledge Gaps	**Most Important Questions/Gaps (Disciplinary)**	**Most Important Questions/Gaps (Interdisciplinary)**	**Barriers to Overcome**	**Disciplinary Barriers**	**Interdisciplinary Barriers**	**Fog Definitions**
Changes in fog frequency and distribution due to climate change and variability	Chemical reactions and processes in fog.	Measurement and modeling without any diluting factors.	Direct measurement of chemical properties of fog, as is done with physical properties.	Chemical analysis and research on chemical reactions.	Analytical chemistry, analytical instrumentation developers, meteorology.	Fog is part of the larger atmospheric system that is involved in the global hydrologic cycle.
The formation and dissipation of organic/inorganic compounds in the aqueous phase of fog.	Human health effects.	Physics, chemistry and transport (mass, momentum, ecology) of fog.	Availability of funding for fog research.	Lack of funds to carry out long-term research in the field.	Involve biology and disciplines beyond traditional ecology.	Fog life cycle should include consideration of mist.
Bridging between different communities of researchers (climate change, aerosols, cloud).	Impacts of climate change.	Linking ecological-physical sciences studying fog (cloud physics, fog fluxes, fluxes of chemical compounds).	Clarification of terms and confusion about what fog is, how its dynamics work, etc.	Lack of affordable instrumentation for in-situ collection and analysis of fog.	Data and knowledge sharing.	Visibility below 1000m due to presence of cloud droplet (official WMO definition).
Improvements in fog forecasting and nowcasting.	Improved modeling of fog in order to improve fog forecasts at airports, on roads, etc.	Interactions among chemistry-meteorology-physics.	Thinking beyond typical chemistry, compounds, and nutrients.	Surface-cloud (fog) interactions.	Understand other perspectives.	Fog as a link between atmospheric water cycle and (eco, human) systems on the Earth surface.
impacts of scale on understanding of fog processes (micro- to kilometer-scale) in modeling applications.	Description of the boundary layer dynamic and the influence of exchange between soil and atmosphere.	Data assimilation so that accurate measurement can be used in forecast models.	Higher temporal and spatial resolution observations.	More observations in more diverse environments.	Need to work in teams where the different disciplines are covered.	Fog should be seen as one system.
The role of aerosols, heat islands, and ocean temperature in fog development.	Role of fog in aviation.	More projects and data sharing like the Paris fog project.	Bridge the gap between the microphysics of processes and turbulent processes (meter scale to synoptic scale).	Accurate measurement network and missing knowledge concerning soil processes and vegetation on fog formation.	Combining ground based remote sensing and satellite remote sensing.	

Questions/Knowledge Gaps	Most Important (Disciplinary)	Most Important (Interdisciplinary)	Barriers to Overcome	Disciplinary Barriers	Interdisciplinary Barriers	Definition
Contribution of fog to the watersheds.	The impact of fog/dew on the water cycle, particularly under the threats of a changing climate and land uses.	Collaboration between universities and institutions of developed countries and developing countries. Some research in US and Europe that was done long ago still needs to be done for the first time in developing countries.	Funding of research projects in developing countries.	New satellite geostationary mission by NASA/ESA, etc.		
Temporal and spatial information in fogs (horizontal and vertical).	Experimental observations of all particles (aerosols and droplets) in ambient conditions.	Water cycle and ecology.	Interdisciplinary exchange.	Better satellite sensors and active instruments on geostationary satellites.		
Harvesting fog as a water supply without the need for high energy consumption.	Dew and its potential as a water source.	Agriculture and GIS.	Involve more biology.	Bringing together oceanographic chemistry and fog physics.		
Active installments on geostationary satellites for clouds and its application for fog remote sensing.	Water distribution in fog as measured from satellites.	Fog is a common ground for experimentalists, modelers and theorists from multiple disciplines!	Understand instrument limitations of sources of error and work on improving the technology.	Surface properties coupling (human and energy exchange for different surfaces in different weather conditions).		
The change of fog coverage in the future and its influences on local energy balance of the ground.	Combining satellite data with actual data at the ocean-atmosphere interface.	Ocean-atmosphere interaction and interaction with biosphere and lithosphere.	Modeling with improved process understanding will help produce better models.	Sensitivity of aerosols to relative humidity and in-fog processing of aerosols.		
Better understanding of interactions and feedbacks between processes driving fog.	The change of energy balance on local ecosystems.	Combining in-situ and remote sensing data of ocean, land surface and atmosphere.	Better, cheaper remote sensing is important.	Need to address spatial and temporal resolution.		
	For each phase of fog development, is there a dominant process, or a subtle mix of different processes?	Relation of fog to vegetation in remote areas (tropics, boreal forests).	A better appreciation of the role of fog in the earth system.			
	Exchange growth and dissipation processes.	Fog impact on human activities and the biosphere.	Long-term measurement projects at one site with fully equipped stations on water and land.			

Appendix 4: Follow Up Activities

The fog research planning process was a community-based effort designed to catalyze collaboration. Several members of the coastal fog research community have initiated collaborative follow up activities to advance the research agenda. Three examples are provided below.

Science of Team Science Study

Steering Committee member Dr. Michael O'Rourke, a philosopher and Science of Team Science scholar, and doctoral student Zachary Piso documented the fog research process as a case study for the Science of Team Science, a rapidly emerging field concerned with understanding and managing circumstances that facilitate or hinder the effectiveness of large-scale, collaborative research initiatives.

O'Rourke and Piso, in collaboration with Weathers, designed and implemented an ethnographic study of the interdisciplinary processes used by the fog research community to identify and achieve their research objectives. The results are intended for use by the fog research community to guide reflection on what it is trying to accomplish and how different interdisciplinary processes bear on these accomplishments. These results are also important contributions to the broader community of people interested in the Science of Team Science, to illuminate the processes used by the fog research community.

The concept of *boundaries* was employed frequently during fog research discussions at the Pescadero workshop: in describing the boundary layer in the atmosphere, the boundary between the ocean and atmosphere, as well as the ocean and coastline. The notion of boundaries is important to understanding the scientific content of the coastal fog system.

The concept of boundary, used as a metaphor, also helps explain the challenge the fog research community confronts when engaging in interdisciplinary research. At the Pescadero workshop, participants from different disciplinary backgrounds worked to identify the various boundaries (e.g. technical languages, research scales, methods) and ways to work together given those boundaries. In the scientific process, a boundary can be seen as a barrier (obstacle) or an interface between parts of the system. The latter is the type of boundary that represents an opportunity, as opposed to an obstacle, and is a critical part of creating an interdisciplinary community.

A manuscript describing the results of the Science of Team Science study of the fog research community is in preparation and is expected to be published later in 2014.

NASA Atmospheric Composition Outstanding Questions Workshop

Steering Committee member Carolyn Jordan was supported on this award to attend a research planning workshop at NASA Ames Research Center, 6–8 May, 2014 (title of workshop noted above), and to bring forth some of the main conclusions of the Weathers et al. 2014 Coastal Fog White Paper. Jordan reported that workshop participants are acutely aware of the need to embrace interdisciplinary research in order to advance the understanding of earth system science.

Researchers interested in clouds are particularly receptive to interdisciplinarity and identified radiative forcing of low clouds, which include but are not limited to fogs, as one of the key uncertainties.

The potential for using remote sensing, not just of low cloud height and presence but of liquid water content and droplet size distribution for fogs specifically, is completely beyond current retrieval capability. NASA cloud researchers did not include fog-related science questions among their priorities because they currently have higher priority problems that are considered more tractable. There may be other NASA programs, such as Applied Science program, that are interested in improving retrieval capabilities but are separate from the programs hosting the workshop.

Discussion among researchers interested in tropospheric composition and atmosphere-surface exchange included a recognition of the importance of the oceans from an atmospheric chemistry point of view. In an overview talk for the workshop, air quality problems in developing countries, similar to the London fog and Los Angeles smog problems, were specifically mentioned. Of the nine priority research topics identified by this group of researchers, one (#8) related to boundary layer processes, including those in fogs.

Session at the Annual Meeting of the American Meteorology Society (AMS)

Steering Committee member Jeff Collett is organizing a session on Cloud and Fog Chemistry, Biology, and Deposition at the AMS annual meeting to take place 4–8 January 2015 in Phoenix, Arizona.

The session is being organized to allow those studying cloud and fog chemistry, biology, deposition or related topics to present their latest findings or overviews of prior work. The organizers are inviting findings from field, laboratory, or modeling studies from around the world. To this end, Dr. Dominik van Pinxteren of the Leibniz-Institut für Troposphärenforschung (TROPOS) in Leipzig, Germany, will join the session as an invited speaker.