Working with Weather: Atmospheric Resources, Climate Variability and the Rise of Industrial Meteorology, 1950 – 2010

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Accurate and timely weather, water and climate information and products have critical importance in world economies but their development and their relevance in the economic and meteorological contexts have generally received a poor treatment by historians and sociologists of science. The reason might be in that such information remains hidden in routine executive decisions. This may create a perception that such information is scientifically less important than the research, modelling and numerical weather prediction, the areas that currently attract most public and scholarly attention. This relative public invisibility of industrial uses of meteorological research is mirrored by the fact that there has been relatively little historical study on the applied, service and industrial meteorology compared to that devoted to research meteorology. Historians of science have generally found these areas of expertise less gripping than the historical developments in the meteorological knowledge related to numerical weather prediction, climate modelling and theoretical atmospheric research.[1] Yet throughout the twentieth century, applied meteorology – an area of research where weather data, analyses and forecasts are put to practical use – became increasingly prominent, with an emerging number of national services and private consultancies providing services in the domains of agricultural risk assessment, air quality, transportation, construction, utilities and retail.[2]

Since the 1980s in particular, there has been an unprecedented growth in the production of weather information designed to hedge against socio-economic losses caused by stochastic weather events or improve operations across industrial and service sectors sensitive to weather variations. Applied climate and weather products have since become global in reach, diverse in purposes, data-intensive and subjects of research in academic, government, and private institutions. In 2006, the total value of the commercial weather services in Europe was estimated to be 550m Euros. In the US, this market is

[1] Brant Vogel, 'Bibliography of Recent Literature in the History of Meteorology,' *History of Meteorology* 5 (2009): 23 – 125.
[2] John Thornes and Samuel Randalls, 'Applied Meteorology and Climatology,' *Progress in Physical Geography* 34 (2014): 389 - 391

estimated to be worth 1.8 billion dollars.[3] Meteorological products have application in around forty percent of weather sensitive industries, in which managers and decision makers use them to reduce the financial harm caused by weather-induced reductions in outputs or productivity. The monetary impact is significant: for example, the median operational downtime caused by weather conditions costs US based small businesses around 3000 dollars daily.[4] Part of this decline is associated by high-impact weather events which have an increasing impact on the insurance industry's ability to absorb mounting damage claims: between 1980 and 2004, the total loss incurred by high impact weather events totaled 1.4 trillion USD, of which 340 mil USD were insured.[5]

The rise in the production of weather and climate information over the past fifty years stands in contrast to the situation before the 1960s, when, outside agriculture, shipping and aviation, industries usually did not possess mechanisms for a systematic uptake and use of weather information in their operations and risk management procedures. Outside sporadic calls to apply weather expertise in the construction and engineering sector, there were few signs of institutional awareness about how such information might be used in sectors such utilities, retail, ground transportation, urban planning, logistics, manufacturing, and extraction industries. Since the 1960s, however, the World Meteorological Organization, national hydrometeorological services, and research community increasingly argued for the need to recognize the substantial economic value of weather information and to develop a means to communicate such information to potential users.

This paper provides an account of key institutional, methodological and theoretical developments informing the growth of applied and industrial meteorology during the last fifty years. While the increasing importance and use of meteorological expertise in businesses has been subject of recent scholarship, this paper considers the historical factors behind these developments.[6] More specifically, I argue that the so-called 'golden age' of applied and industrial meteorology between 1980 and present[7] resulted from a conjuncture of at least four main sets of scientific, environmental and socio-economic processes, namely: (1) a strengthening policy role of the 'atmospheric resource' agenda in the geographic and atmospheric sciences in the industrialized world during the 1960s, (2) the growing need to assess (and thus justify) the monetary value of meteorological information in the context of investment in national meteorological services, (3) increasing losses from high-impact weather events during the 1960s, followed by major climate anomalies during the early 1970s that caused political tensions, environmental soulsearching and security crises in both the developed and

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[3] R. E. W. Pettifer, 'Towards a Stronger European Market in Applied Meteorology,' *Meteorological Applications* 15 (2008): 305 – 312; B. Spiegler, 'The Private-Sector Meteorology,' in James R. Fleming (ed), *Historical Essays on Meteorology 1919 – 1995* (Boston: American Meteorological Society, 1996).

[4] Valley Vision http://valleyvision.org/projects/business-resiliency-in-the-capital-region, accessed 28 March 2015.

[5] Evan Mills, 'Insurance in a Climate Change,' *Science* 309 (2005): 1040 – 1044.

[6] John Thornes and Samuel Randalls, 'Applied Meteorology and Climatology,' *Progress in Physical Geography* 2014 (38): 389 – 391; Marc Tadaki, Jennifer Salmond and Richard Le Heron, 'Applied Climatology: Doing the Relational Work of Climate,' *Progress in Physical Geography* 38 (2014): 392-413; Stanley A. Changnon, 'The Past and Future of Climate-Related Services in the United States,' *Journal of Service Climatology* 1 (2007): 1-7;

[7] Stanley A. Changnon, 'Applied Climatology,' in J.E. Oliver (ed), *Encyclopedia of World Climatology* (Dordrecht: Springer, 2005), 54 – 58.

developing worlds and (4) the resulting representation of *The Environment as Hazard*[8] that ushered in the cultures of 'climatological impact assessment.'

The paper understands 'industrial meteorology' as a constellation of knowledge practices, modes of communication and delivery of weather information related to the application of meteorological information to industrial problems. This definition includes the more specific understanding of industrial meteorology as the collection of *private* sector organizations, such as meteorological consultancies and media outlets, that provide tailored weather information to various stakeholders. The emphasis here is therefore on the purpose, nature and use of knowledge products rather than the institutional profile of information providers. I will also refer to industrial meteorology as the field of expertise involved in the creation, delivery and use of so-called 'weather products': the meteorological information and tools designed to assist decision makers in mitigating weather-related risks and operational costs in the face of short-term atmospheric events and seasonal variations. The weather products can include sector-specific forecasts, nowcasts, predictive models, feasibility studies, financial instruments, and a suite of custom-designed indices such as degree days, windiness, snowpack, econoclimatic indices, and so on. The present discussion provides an account of the recent history of the effort to provide such products and knowledge in a systematic, organized and institutionalized way.

Industrial Meteorology: Sources of Growth

<u>Atmospheric resources and the value of weather information</u>

The relationship between atmospheric conditions and economic activities has long been recognized. Improving agricultural production during the eighteenth and nineteenth-century provided rationales for systematic data collection and the insitutionalization of meteorological research and forecasting.[9] Meteorology was closely allied to interests of colonial governments, offering a means of acquiring knowledge about unfamiliar weather and environments and assisting colonial government planning.[10] During the first half of the twentieth century, geographers, agronomists and climatologists demonstrated the interaction between atmospheric processes and physical and social systems as diverse as forests, mountains, river flows, cities, and water resources – all perceived as of direct relevance to national economies.[11] Major investments in meteorological research and

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[8] Ian Burton, Robert W. Kates and Gilbert F. White, *The Environment as Hazard* (New York: Oxford University Press, 1978).

[9] Vladimir Janković, 'Climates and Commodities: Jean Pierre Purry and the Best Climate on Earth,' *Studies in the History and Philosophy of Modern Physics* 42 (2010); Katharine Anderson, Predicting the Weather: Victorians and the Science of Meteorology (Chicago: Chicago University Press, 2005), Chapter Six; D. R. Whitnah, *A History of the United States Weather Bureau* (Urban, Il: University of Illinois Press, 1961);

[10] Emily O'Gorman, 'Soothsaying or Science?' H. C. Russell, Meteorology and Environmental Knowledge of Rivers in Colonial Australia,' in James Beattie, Emily O'Gorman and Matthew Henry (eds), *Climate, Science and Colonization: Histories from Australia and New Zealand*, Chapter Nine.

[11] Stanley Changnon, 'Applied Climatology,' in John E. Oliver (ed), *The Encyclopedia of World Climatology* (Dordrecht: Springer, 2004, 54 – 58; Vladimir Janković and Michael Hebbert, 'Hidden Climate Change: Urban Meteorology and the Scales of Real Weather,' *Climatic Change* 113 (2012): 23 – 33.

application were the hallmark of the World War Two.[12] Following World War Two scientists and government officials in Europe and North America argued that meteorological knowledge (and later forecasting) could make a significant difference in the efficiency and profitability of economic activities, including manufacturing, transport, engineering, land-use and the building industry.[13]

During the post-war period, influential climatologists such as Helmut Landsberg considered the atmosphere as an underused 'natural resource' and weather information an element in planning of national economies. Landsberg's list of the uses of meteorological information included housing, heating requirements, special purpose buildings, the planning of airports, 'all weather' highways, dam construction and flood control measures. He called these uses 'the exploitation of climatic income.'[14] The concept of atmospheric resources played a fundamental role in the subsequent development of applied meteorology by accentuating its political and security relevance. It allowed meteorologists and decisions makers to think on how to activate latent economic 'values' inherent in the atmosphere and to conceptualize the atmospheric science as an instrument in economic planning and operational management of industrial activities.[15]

In promoting these agendas during the period between 1945 and 1980, the World Meteorological Organization, the national meteorological services and a community of atmospheric scientists acted as chief brokers in promoting meteorological applications in industry and public sectors.[16] The WMO took steps in studying the economic advantages of Meteorological Services and called for closer ties between atmospheric scientists and professionals.[17] It encouraged national governments and meteorological services to carry out cost-benefit studies of climatological services in agriculture, town planning, and the construction industry. Its officials argued the gains from weather data far outweighed their costs and that meteorological consultancy in the planning, development and conservation of resources could save about five times the total running cost of a service.[18] Calls were issued for a systematic development of applied weather knowledge in national meteorological services,[19] and for a more organized approach in providing weather

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[12] Woodrow Cooper Jacobs, *Wartime Developments in Applied Climatology* (Boston: American Meteorological Society, 1947); Kristine C. Harper, *Weather by the Numbers: The Genesis of Modern Meteorology* (Boston: MIT Press, 2008)

[13] *Weather and Building Industry: Research Correlation Conference Proceedings* (Washington D.C: National research Council and Building Research Advisory Board, 1950); K. H. Jenn, 'Some Aspects of Engineering Meteorology,' *The Scientific Monthly*, January 1953: 3-10; J. A. Russo, 'The Economic Impact of Weather on the Construction Industry,' *Bulletin of the American Meteorological Society* 47 (1966): 967 – 972.

[14] Helmut Landsberg, Climate As a Natural Resource,' *The Scientific Monthly* 63 (1946): 293 – 298.

[15] James A. Taylor (ed), *Climatic Resources and Economic Activity* (Newton Abbot: David and Charles, 1974); J E Hobbs's *Applied Climatology: A Study of Atmospheric Resources* (Boulder: Westview Press, 1980); W. J. Maunder, *The Human Impact of Climate Uncertainty* (London: Routledge, 1989), 3-4.

[16] *Building Climatology*. Technical Note 109 (Geneva: World Meteorological Organization, 1970), T. J. Chandler (ed), *Urban Climatology and Its Relevance to Urban Design*. Technical Note 149 (Geneva: WMO, 1976); R. Berrgren, *Economic Benefits of Climatological Services*. Technical Note 145 (Geneva: WMO, 1975).

[17] J. C. Thomson, *World Weather Watch Planning Report No. 4* (Geneva: WMO, 1966).

[18] W. J. Gibbs, 'What is Weather Worth,' Papers presented to Productivity Conference, Melbourne Sept 1964 (Melbourne: Australian Bureau of Meteorology, 1965).

[19] Alexander Hall, *Risk, Blame, and Expertise: The Meteorological Office and Extreme Weather in Post-War Britain* (PhD, University of Manchester, 2012), 215 – 216.

information for economic sectors including energy utilities, mining, manufacturing, the built environment, and the tertiary sector.[20] The first private weather consultancies appeared under the names of Travellers Research Center (1956) and Accu-Weather (1962).[21] By the mid 1960s, air pollution research had made advances in understanding the weather conditions favoring pollution episodes, demonstrating the social and economic potential of applied research to both national and local governments.[22] These contribution coincided with a growing need to add social value to existing regimes of meteorological investigation: 'During the first half of [twentieth century], argued an influential New York health official in 1964, 'observations were geared to the needs of crops and livestock; during the last fifty years to the need of aircraft. We have yet to provide a national system of observations designed specifically *to meet the needs of people*, particularly those who congregate in cities.'[23]

In Britain, the Meteorological Office argued that a nation's weather services should extend the scope of their activities beyond traditional fields of expertise (aviation and marine operations), to cover other sectors of society. Hydro-meteorological services were to consider the economic benefits of its work and seek to understand how their activities and products could help the nation in economic and financial terms.[24] Relying on the 'economics of information' approach,[25] analysts worked to evaluate the monetary impact of weather applications and the 'return-on-investment' for national meteorological services.[26] In Germany, George Bell pioneered in 1956 one of the first cost-benefit analyses of the value of meteorological information. Soon, neologisms such as 'weather economics,' 'econoclimate,' and 'the business of weather' received attention at

[20] R. R. Rapp and R. E. Huschke, *Weather Information: Its Uses, Actual and Potential*. Memorandum RM-4083-USWB (Santa Monica, CA, RAND Corporation, 1964);

[21] Robert D Elliott, 'History, Policy and Future of Industrial Meteorology,' *Bulletin of the American Meteorological Society* 57 (1976): 1318 – 1342; Samuel Randalls, 'Weather Profits: Weather Derivatives and the Commercialization of Meteorology,' *Social Studies of Science* 40 (2010): 705-730.

[22] H Wexler, 'The Role of Meteorology in Air Pollution,' in *Air Pollution*. Geneva: WHO Monograph Series, 1961, 49 – 62; E C Halliday, 'A Historical Review of Atmospheric Pollution,' in *Air Pollution* (Geneva: WHO Monograph Series, 1961), 9 – 38; Jack M Leavitt, 'Meteorological Considerations in Air Quality Planning,' *Journal of Air Pollution Control Association* 10 (1960): 246 – 250; Mark Whitehead, State, *Science and the Skies: Governmentalities of the British Atmosphere* (London: Wiley, 2009), 63-64; Scott Hamilton Dewey, Don't Breath the Air: Air Pollution and U.S. Environmental Politics, 1945 – 1970 (Houston TX: Texas A&M University Press, 2000), Vladimir Janković, 'Air Chemistry and the Making of Urban Meteorology in New York City during Mayor Wagner's and Mayor Lindsay's Office Terms,1954-1973' Gordon Cain Conference Chemical Heritage Foundation, Philadelphia, May 2011.

[23] Arthur Stern, 'On Meteorological Tools for Air Pollution Control,' *Journal of Air Pollution Control Association* 14 (1964): 86-87, my italics.

[24] B. J. Mason, 'The Role of Meteorology in the National Economy,' *Weather* 21 (1966): 382-393, B. J. Mason, 'Recent Developments in Weather Forecasting and their Application to Industry,' *ICE Proceedings* 38 (1967): 1-20; Hall, *Risk, Blame and Expertise*, 217.

[25] J. C. Thompson and G. W. Brier, 'The Economic Utility of Weather Forecasts,' *Monthly Weather Review* 83 (1955): 249-254; F. Linden, 'Weather in Business,' *Conference Board Business Records* 16 (1959): 90 – 94; F. Linden, 'Merchandising Weather,' *Conference Board Business Records* 19 (1962): 15 – 16; J. D. McQuigg, 'The Economic Value of Weather Information,' PhD Dissertation, The University of Missouri, 1964; R. R. Nelson and S. G. Winter, *Weather Information and Economic Decisions*. A Preliminary Report RM-2060 (Santa Monica: RAND Corporation, 1960).

[26] Lester B. Lave, 'The Value of Better Weather Information to the Raisin Industry,' *Econometrica* 31 (1963): 151-164; B. J. Mason, 'Recent Developments in Weather Forecasting and their Application to Industry,' ICE *Proceedings* 38 (1967): 1-20.

international meetings *What is Weather Worth* (Australia, 1965) and *Urban Climate and Building Climatology* (Brussels 1968). In 1969 WMO established the Panel on the Applications of Meteorology to Economic and Social Development, whose reports testified to the interest of both WMO and a European Commission panel of experts in seeing meteorological experts serving on governmental planning committees.[27]

During this period industrial meteorology grew in stature with the rise of university courses such as the University of Birmingham's (UK) MSc in Applied Meteorology and Climatology (1963) and the launching of the international *Journal of Applied Meteorology in Climatology* in 1962 which featured a broad coverage of topics, from optimization of ship routing, to weather sensitivity of raisin industry, to the probabilistic analyses of completion of outdoor work. The field rapidly grew during the late1960s and the early 1970ssaw a string of classic publications and synthetic overviews including John Maunder's (1970) *The Value of the Weather*, John E. Oliver's *Climate and Man's Environment* (1973), J. R. Mather's *Climatology: Fundamentals and Applications* (1974), K. Smith's *Principles of Applied Climatology* (1975). At the tail-end of this 'spur-growth' period, J E Hobbs published his *Applied Climatology: A Study of Atmospheric Resources* (1980), and Professor John Thornes from the University of Birmingham, wrote two important conceptual excursions into the problematic of atmospheric management.[28] Barring Thornes's interventions, most of these publications worked under within the framework of what Tadaki, Salmond and Le Heron have termed a 'politics of biophysical': 'the applied climatology [and industrial meteorology even more so] makes no claims about the subjects beyond the fact that they sustain biophysical economic losses or benefits form certain events.'[29]

These research and institutional developments in industrial meteorology were cumulative in their effects on the user's awareness of the field's importance. For the most part, however, they reflected concerns that were local to meteorological and geographical professions and those of the national weather services. On the American side, for example, one of the key protagonists in this busy period was James McQuigg from the Missouri office of the US Weather Bureau's. During the late 1960s, McQuigg worked to promote applied research and economic analyses of weather information, many of which preceded the landmark synthesis of John Maunder.[30] In the lecture given at the fifth session of the WMO Commission for Climatology (Geneva 1969), McQuigg explained that the 'rapid increase' of interest in the economics of weather since the World War Two owed to three key factors. One involved budgetary pressures to justify projects in terms of high benefit-cost ratios resulting from projects' outcomes. The second factor was the conviction that planned weather modification could become a means to reduce the socio-economic risks posed by high-impact weather and adverse climatic conditions in sectors such as agriculture and hydroelectric power production. The National Science Foundation had already appointed a Commission for Weather Modification whose first report

[27] R. Schneider, J.D. McQuigg, L. L. Means and N. K. Klyukin, *Applications of Meteorology to Economic and Social Development*. Technical Note 132 (Geneva: WMO, 1974), 5.
[28] John Thornes, 'A Paradigmatic Shift in Atmospheric Studies?' *Progress in Physical Geography* 5 (1981): 429-440 and John Thornes, 'Atmospheric Management,' *Journal of Geography in Higher Education* 7 (1983): 189 – 198.
[29] Tadaki, Salmond and Le Heron, 'Applied Climatology,' 397.
[30] John Maunder, Interview with author, 25 July 2013.

appeared in 1968.[31] Thirdly, development of computers and communication systems allowed for effective investigations into the quantitative assessment of the economic value of meteorological information.[32] The fourth factor, which McQuigg did not discuss, was the mounting toll of economic losses due to air pollution and severe weather events: the fact that actual losses exceeded compensated losses by an order of magnitude indicated a major lack of the meteorological risk assessment and preventative use of meteorological information.[33]

Climate anomalies of the 1970s

This last factor became apparent after 1968 when the world faced a series of dramatic short-term climatic variations, including the drought in the Sahel and crop failures in Russia that resulted in an agro-political crisis of international dimensions. These developments furthered buttressed the importance of weather and climate variations for the military, economic and national security issues during the Cold War.[34] The correlation was cast in sharp relief in 1972, when the postwar complacency about world food security suffered a major blow from simultaneous crop failures, mostly climate induced, that led to a tripling in the price of wheat and rice, and the rapid decline in carryover stocks. In the autumn of 1975, the Soviet Minister of Agriculture announced that bad weather in Russia had forced the government to import US grain. American dock workers threatened strikes unless they were assured that the sales would not affect domestic prices. President Ford initially embargoed grain exports but changed the policy following the bi-lateral trade agreement with the Soviet Union. The US Secretary of Agriculture considered this decision and subsequent Russian purchases as 'one of the great destabilizing forces in the world grain markets.'[35] The US Central Intelligence Agency issued a 'A Study of Climatological Research as it Pertains to Intelligence Problems' which concluded that 'a climatic change is taking place and it has already caused major economic problems throughout the world […] new alignments will be made to ensure a secure supply of food resources.'[36] Reminiscing about the events of six years on, the renown Canadian climatologist Fredrick Kenneth Hare commented that the

[31] W.R. D. Sewell (ed), *Human Dimensions of the Atmosphere* (National Science Foundation, Washington DC: US Government Printing Office, 1968), and W.R.D. Sewell 'Emerging Problems in the Management of Atmospheric Resources,' *Bulletin of the American Meteorological Society* 49 (1968): 326-336.

[32] James D. McQuigg, 'Some Attempts to Estimate Economic Response of Weather Information,' *Weather* 26 (1971): 72-78.

[33] W. R. F. Derrick Sewell and J. Elizabeth McMeiken, 'Emerging Problems in the management of Atmospheric Resources in Canada,' *Atmosphere* 5 (1967): 34 – 38.

[34] R.E. Huschke, R. Robert Rapp and C. Schultz, *Military Weather Calculations for the NATO Theater* (Santa Monica, CA: The RAND Corporation,1980); Kristine Harper and Ronald Doel, 'Environmental Diplomacy in the Cold War: Weather Control, the United States and India, 1966 – 1967, in J. R.McNeil, Corrina R. Unger (eds), *Environmental Histories of the Cold War* (Cambridge University Press, 2010), 115 – 138; Simone Turchetti, 'The Storms of Doctor Strangelove: Meteorological Studies Sponsored by NATO during the Cold War,' *Working Atmospheres: Weather and Climate Services in Historical and Contemporary Perspectives*, University of Manchester, November 2013.

[35] Quoted in Walter Orr Roberts and Henry Landsford, *The Climate Mandate* (San Francisco: WH Freeman,1979), 16. See also John Borchert, 'The Dust Bowl in the 1970s,' *Annals of the Association of American Geographers* 61 (1971): 1-22; James E. Newman and Robert C. Pickett, 'World Climates and Food Supply Variations,' *Science* 186 (1974): 877 – 881.

[36] *A Study of Climatological Research as it Pertain to Intelligence Problems*, CIA, 1974.

'Western politicians became persuaded, for the first time since the 1930s, that climate might have a major destabilizing effect on the food system.'[37] In the United States the perception of security 'destabilization' was enhanced by the fact the tensions over agro-meteorological 'shocks' coincided with the OPEC embargo on oil imports and rising inflation – creating a major political challenge for the Ford Administration.[38] Popular and academic books took to the task of explaining the causes and economic fallout of weather and climate extremes, while scientists and policy makers called for a more robust understanding of socio-economic costs of the short-term to seasonal change, seeking urgent attention of the economists and business elites.[39] Concerns such as these, as Andrew Ross shrewdly observed, transformed climatology from a branch of geography concerned with weather averages into 'a volatile, political commodity of the first rate of importance.'[40]

The WMO's Commission for Climatology, established in 1951, responded to the 1970s events with a series of meetings, initiatives and reports that sent a strong signal about the socio-political importance of applied and industrial meteorology. In 1973 the World Meteorological Congress gave the Commission new terms of reference and a new name that reflected the increasing concerns with socio-economic outputs of research and the threat of high-impact weather variations: the Commission became the Commission for Special Applications of Meteorology and Climatology (CoSAMC). WMO's Session in Bad Homburg (Germany) in 1973 introduced fourteen new rapporteurs and working groups on subjects of direct economic importance, including the new Working Group on Climatic Fluctuations and Man. In 1982 WMO renamed CoSAMC as the Commission for Climatology and Applications of Meteorology (CCAM).[41] Furthermore, the Executive Committee of WMO convened in 1979 a high-level scientific and technical conference to be attended by both physical and social scientists, including the representatives of weather-sensitive branches of national economies such as agriculture, energy, water resources, fisheries and health. The conference led to the formation of World Climate Program that had, as two of its four programs, the World Climate Applications Program and the World Climate Impact Program.[42] In the same period, the United States established the Climate Dynamics Program (1974) and passed the National Climate Program Act (1978) which had a decisive social component.[43] The Program's outcomes were envisaged in terms of weather and climate products intended for private and public users, including farmers, water managers, manufacturers and consultancies. The members

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[37] F. Kenneth Hare, 'Climate: The Neglected Factor,' *International Journal* 36 (1981): 371 – 387, 373.

[38] Yanek Mieczkowski, *Gerald Ford and the Challenges of the 1970s* (The University of Kentucky Press, 2005), 95 – 110.

[39] *International Perspectives on the Study of Climate and Society* (Washington DC: National Research Council, 1978), Reid Bryson and Thomas J. Murray, *Climates of Hunger* (Madison WI: The University of Wisconsin Press, 1977); Howard Matthai, *Hydrologic and Human Aspects of the 1976-77 Drought* (Washington, D.C.: U.S. Government Printing Office, 1979).

[40] Andrew Ross, 'is Global Culture Warming up?' *Social Text* 28 (1991): 3-30, 7.

[41] *Commission of Climatology: over Eighty years of Service* WMO: No. 1079, 2011

[42] Eugene W. Bierly, 'The World Climate Program: Collaboration and Communication on a Global Scale,' *Annals of the American Academy of Political and Social Science* 495 (1988): 106 – 116; see also Committee on Atmospheric Sciences, 'The Atmospheric Sciences: National Objectives for the 1980s,' *Bulletin of the American Meteorological Society* 62 (1981): 226 – 231.

[43] Vladimir Janković, 'Climatological Data Archiving and the US National Climate Program,' in Lorraine Daston (ed), *Science of the Archives* (forthcoming University of Chicago Press, 2015).

of National Climate Board, who defined the Program's principles, argued that the Program would be judged on grounds of its economic impact and the extent to which the dissemination of climate data could increased the industrial productivity and GDP in times of environmental adversity witnessed in the 1970s: 'A major objective of the USCP [United State Climate Program] is to improve productivity in all sectors of US economy through effective application of knowledge of climate.'[44]

Through these legislative moves immediately following the 1970s disturbances, an increasing institutional presence of applied/service meteorology began to recast the purpose of atmospheric knowledge from one that (mostly) served the research and forecasting communities, to one more oriented towards the needs of the market, national security and public welfare. This change has resulted in a wider and more routine application of weather products in both the public and private spheres during the last thirty years. Meteorologists have begun to provide regular advice on the effects of the atmosphere on industrial activities and worked to ensure a representation of user interests throughout the information and research systems.[45] Concurrently, business demand stimulated a growth of private meteorological services and consultancies catering for diverse businesses' needs.[46] Atmospheric scientists in government agencies, universities, and consultancies have become vital in decision making, moving weather and climate information to the forefront of institutional thinking that ushered in Changnon's 'golden age' of applied atmospheric sciences. Tadaki, Salmond and Le Heron offer that 'climate applications have never been more embedded into human organizations than at present, and the industries with strong histories of climate application – agriculture, urban design, tourism – have developed their own communities and structures within and external to applied climatology to deal with their concerns.'[47] These trends gave industrial meteorology the status of an 'infrastructural science' designed to provide standardized information for regulatory purposes, to hedge risk in routine weather-sensitive operations, and to avert losses from high-impact atmospheric events.[48] Put another way, industrial meteorology became a macroeconomic tool designed to mitigate against losses from high-impact weather events and to help optimize routine weather-sensitive operations across economic sectors.

Impact assessment studies

This socio-economic framework has shaped the applied atmospheric research during the last thirty years, especially as the losses from short-term atmospheric variability and severe weather events continued to rise. The first organized approach to understanding the relationship between human activities and climate variability (including periods of adverse weather and hydrometeorological disasters) was developed under the auspices of the World Climate Program (1979) and the specialized World Climate Impact Program,

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[44] *Toward a U.S. Climate Program Plan*, (Washington D.C.: National Academy of Sciences, 1978), 3.

[45] A. H. Perry, 'Econoclimate: A new Direction for Climatology,' *Area* 3 (1971): 178 – 179; *Atmospheric Climate Data: Problems and Promises* (National Academy Press: Washington, D.C., 1986).

[46] David Changnon and Stanley A. Changnon, 'Major Growth in Some Business-Related Uses of Climate Information,' *Journal of Applied Meteorology and Climatology* 49 (2010): 325 – 331.

[47] Tadaki, Salmond and Le Heron, 'Applied Climatology,' 399.

[48] Roger Turner, *Weathering Heights: The Emergence of Aeronautical Meteorology as an Infrastructural Science*, PhD University of Pennsylvania, 2010.

one of which mandates included improvement of the knowledge of the impact of climatic variability in terms of primary responses of human systems such as agriculture, water resources, fisheries, energy transportation, human health, and land use.[49] The Program explicitly drew on the disasters and crises of the 1970s, aspiring to develop methodologies to address the necessity of 'tuning' weather-sensitive sectors of the economy to adapt to or amortize climate variations. A major review of methodologies and approaches was undertaken by the Scientific Committee on Problems of the Environment (SCOPE), under the coordination of Robert W. Kates, Jesse H. Ausubel and Mimi Berberian.[50] In the volume, the geographer William E. Riebsame from the University of Colorado discussed the historical construction of the notion of 'climate as hazard,' making a direct connection between the reaction to the anomalies of the 1970s and the scientific and political interest in studies of the socio-economic impact of severe weather events. Drawing on insights Hubert Lamb publicized in the his influential *Climate, History and the Modern World* (1983), Riebsame wrote that the 'perception' of world climates entering a 'more variable state' 'amplified the message of those concerned that society's sensitivity to climate disruption might also be increasing.'[51] Clearly the perception of the 1970s as a major watershed in the public and political understanding of the role of weather and climate in world affairs profoundly influenced the international climate research towards the impact assessment agenda and closer communication with economic and public sector stakeholders. As Lamb succinctly put it referring to the world famine crisis of 1972, 'in the leading scientific, technical and administrative institutions in the advanced countries, there was some confusion about how to interpret the climatic event [of 1972] and *revise attitude to climate*.'[52]

Echoing these sentiments were researchers who recognized the need and responsibility to monitor the impacts of weather events on national economies and develop methodologies for the estimation of monetary costs of such impacts.[53] Already during at the First Climate Conference in 1979, Kates and R. d'Arge reported on the humanitarian and monetary effects of natural disasters;[54] a study on the impacts of severe winters on household economies has been conducted by Stanley Changnon of Illinois State Water Survey in 1979. The US Center for Environmental Assessment Services (CEAS) of NOAA estimated that the severe winter of 1982 led to direct losses of the

[49] World Meteorological Organization, *Outline Plan and Basis for the World Climate Programme* (Geneva: WMO, 1980), 32.

[50] Robert W. Kates, Jesse H. Ausubel and Mimi Berberian (eds), *Climate Impact Assessment* (New York: John Wiley and Sons, 1985). Before this comprehensive review, SCOPE issued twenty seven reports in the period between 1971 and 1985 under the editorial hand of the Canadian micro-meteorologist R.E. Munn.

[51] William E. Riebsame, 'Research in Climate-Society Interaction,' in Kates, Ausubel and Berberian (eds), *Climate Impact Assessment*, 69 – 84, 72.

[52] Lamb, *Climate, History and the Modern World* (London: Methuen, 1982), 282.

[53] Jean Palutikof, 'The Impact of Weather and Climate on Industrial Production in Great Britain,' Journal of Climatology 3 (1983): 65 – 79; R. W. Kates, J. H. Ausubel and M. Berberian (eds), *Climate Impact Assessment Studies: Studies of the Interaction of Climate and Society*. ICSU/SCOPE Report 27 (New York: Wiley, 1985).

[54] R. W. Kates, 'Climate and Society: Lessons from Recent Events,' *Proceedings of the World Climate Conference* (Geneva: World Meteorological Organization, 1979), 682-691; R. D'Arge, 'Climate and Economic Activity,' *Proceedings of the World Climate Conference* (Geneva: World Meteorological Organization, 1979), 652 – 681.

order of eight billion dollars in a three month period.[55] The scientists at the UK Climatic Research Unit performed similar analyses to determine the impact of weather and climate on industrial production in Great Britain.[56] It is worth noting that these and more recent studies could suffer from methodological deficiencies of double counting, select identification of losses, omission of indirect losses and inaccurate data.[57] Nevertheless they suggest that the weather has become a critical operational variable in a world experiencing a growing vulnerability to precipitation shortages associated with aging infrastructure,[58] obsolete water management, failure to keep pace with urban demand, and inefficient monitoring and warning systems.[59] More recently, complementing the impact assessment approach, there has been a revival in the attempts to determine the monetary *value* of meteorological information, products and services.[60] Both approaches, as shown in Table 1 have produced important data on the magnitude of socio-economic sensitivity to meteorological events and climatic anomalies which have been seen to justify the creation of a coordinating bodies such as the international Weather Risk Management Association (1999) that offers companies the opportunity to control their financial exposure to weather conditions.

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[55] Center for Environmental Services (CEAS), *Climate Impact Assessment United States.* (National Oceanic and Atmospheric Administration, US Dept. of Commerce, Washington, DC, 1982).

[56] Jean Palutikof, 'The Impact of Weather and Climate on Industrial Production in Great Britain,' *Journal of Climatology* 3 (1983): 65-79.

[57] Kates et al, *Climate Impact Assessment*, W. E. Easterling and W. Riebsame, 'The Climatic Impacts Perception and Adjustment Experiment,' *Bulletin of the American Meteorological Society* 67 (1986), E.P. Borisenkov, 'Problems of Applied Climatology,' *Meteorologiya i Gidrologiya* 3 (1985): 1-11.

[58] William E. Riebsame, Henry F. Diaz, Todd Moses and Martin Price, 'The Social Burden of Weather and Climate Hazards,' *Bulletin of the American Meteorological Society* 67 (1986): 1378 – 1388.

[59] N. S. Grigg and Evan C. Vlachos (eds), *Drought Water Management* (Fort Collins: Colorado State University, 1990).

[60] Richard W. Katz and Allan H. Murphy (eds), *Economic Value of Weather and Climate Forecasts* (Cambridge: Cambridge University Press, 1997); Allan H. Murphy and Barbara G. Brown, 'Short-range Weather Forecasts and Current Weather Information: User Requirements and Economic Values,' *Proceedings of IAMAP Symposium*, Hamburg, 21-25 August 1985 (ESA-SP 165, June 1981), 279 – 290. For review see Melissa Dell, Benjamin F. Jones and Benjamin A. Olken, 'What Do We Learn from the Weather? The New Climate-Economy Literature,' *Journal of Economic Literature* 52 (2014): 740 – 798;

Annualized benefit from forecasts and warnings	$31.5 Billion (B)
Cost of generating forecasts and warnings	$5.1 B
Cost of weather disasters (1980 – 2009)	$96 B (1B in damages)
Annual weather fatalities (1999-2008)	629
Impact of adverse weather on US highways	1.5 million crashes, 7400 deaths, $42 B losses
Annual air traffic delays losses	$4.2 B

Table 1: The annual US weather-related losses and damages (in USD). Source: *When Weather Matters: Science and Service to Meet Critical Societal Needs* (The National Academies Press, Washington, D.C., 2010).

Conclusions and prospects for research

This paper has explored the four main sources of industrial meteorology during the last fifty years. I have argued that the current economic importance assigned to weather information assimilates the disciplinary growth of applied atmospheric research, environmental contingency and the changing priorities in science policies of the industrial world since the 1970s. More specifically, I have explored the combined effect of these developments in discussions relating the ascent of meteorological application with the researches in atmospheric resource, monetary value of weather products, economic cost of major climatic perturbations during the 1970s and the consequence emergence of weather and climate impact assessment models. But there are other important considerations that I hope should occupy the attention of historians of science, historical geographers and economic and environmental historians.

The framework of this future research is one defined by a paradox. As the use of weather products and services shows continued growth and diversification, why there is a parallel growth in weather-related losses observed during the last several decades. We may call the paradox the 'double growth' problem. The problem is important because the extraordinary expansion of industrial meteorology would suggest a world of increased stability and immunity from the impact of atmospheric hazards. And yet, it has been suggested that 'as industrial and business operations generally become more efficient, well-planned, and technical in nature, the effect of small environmental changes has become of obvious importance to the overall success of an operation.'[61]

In thinking about how the increased production and use of weather information relate to socio-economic vulnerability to weather impact, two sets of factors might be

[61] David Suchman, Brian A. Auvine and Barry H. Hinton, 'Some Economic Effects of Private Meteorological Forecasting,' *Bulletin of the American Meteorological Society* 60 (1979): 1148 – 1156.

identified. *Exogenous factors* are related to the changing state of the physical environment (recently associated with anthropogenic climate change). *Endogenous* factors relate to the changing state of socio-economic systems, policies and behaviors. This distinction does not imply that either set should be considered independently from the other, but it allows us to identify where historians may substantially enhance our understanding of the double growth problem. It is evident that any estimates on the economic impact caused by the atmospheric environment (exogenous factors) call for a methodological complexity that goes far beyond the scope of historical analysis and that used in the natural sciences. But the point at which the historical and social sciences may usefully intervene is in exploring the role of endogenous factors. This would help identify the economic, political and policy developments influencing the spatio-temporal trends in weather sensitivity and potentially lead to answering critical issues that inform both the past and present study of atmospheric processes, such as: what accounts for industries' increasing dependence on meteorological information? Have industries become more weather sensitive? If so, why? How effective is the communication between producers and users of weather products? Has the growth of applied meteorology been driven by an increased production and marketing of meteorological products, stricter environmental regulation, or advanced computing and information delivery? Is meteorological research addressing the *real* needs of user communities?

These questions are particularly relevant for the period following the 1970s, after which new efforts were applied to provide quantitative climatic impact assessments and economic modeling of climatic variability (and later 'change') that continue to inform current activities of IPCC Working Group II. The United Nations Environmental Program and national environmental agencies endorsed these analyses as part of disaster mitigation strategies, while research communities opened up questions about the societal role of meteorological research. These questions arose in the context of the 'pressure-and-release' model in the studies of vulnerability which asserts socio-economic and political conditions as root causes of exposure.[62] To take one example, Kenneth Kunkel alerted researchers to the discrepancy between the increasing economic impact of weather extremes and the absence of comparable increases in the frequency of high-impact weather. 'This suggests,' Kunkel argued, 'that increasing losses are primarily due to increasing vulnerability arising from a variety of societal changes.'[63] If his conclusion is correct, would the improved monitoring, warning systems, and the better use of weather information counteract the risks created by socio-economic behaviors? And how exactly have these behaviors affected industries and their reliance on weather products?

Select examples from the history of economic globalization may help us get a sense of how we can begin to tackle these questions. We know that environmental risk has become a key aspect of industrial management during the last several decades. We also know that environmental risk increases with the increase of some elements of global production of goods: area-focused manufacturing, centralized distribution, reduction of

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[62] P. Blaikie, T. Cannon, I, Davis, and B. Wisner, *At Risk: Natural Hazards, People's Vulnerability and Disasters* (London: Routledge,1994).

[63] Kenneth E. Kunkel, Roger A. Pielke Jr., Stanley A. Changnon, 'Temporal Fluctuations in Weather and Climate Extremes That Cause Economic and Human health Impacts: A Review,' *Bulletin of the American Meteorological Society* 80 (1999): 1077 – 1098.

supplier base, volatility of demand, and the global expansion of supply chains.[64] None of these factors have so far been brought into connection with the evolution of applied meteorology even as these factors have an impact on how managers optimize operations in construction, transport and retail industries. For example, the shift towards leaner supply creates more vulnerable networks because it is based on a reduced inventory to 'buffer' any interruption caused by adverse weather. Partial damage and downtime at any node in the supply chain – e.g., production facility, supplier, or distribution center – can be mitigated with timely, sector-specific forecasts and passed onto users in the language they can understand and use operationally.[65] Or, the trend of increasing interregional trade has made manufacturers in one region more dependent on inputs from other areas, making the production in one place highly sensitive to high-impact weather events in other locations.[66] These vulnerabilities have been exacerbated by deregulation of the 1980s that led to the reduction of so-called 'redundant' capacity in a bid to increase efficiency and reduce production costs. As a result, in industries with thin redundant capacities, adverse weather quickly reduced available capacity below its normal operating levels and caused production cuts. And similar effects can be observed in industries relying on just-in-time production based on low inventory-to-output rates.[67]

Are these trends merely coincidental with the rise of socio-economic application of atmospheric sciences, including the user-oriented national climate programs and industrial meteorology? The question cannot be answered without a detailed contextualization of the industrial meteorology. Are the processes of globalization and deregulation at the heart of the expansion of atmospheric knowledge into the industrial domain? The question cannot be answered without looking into the rationales and institutional drivers behind national and international studies of applied meteorology during the last fifty years. The same holds for the question as to whether the restructuring of the global economy triggered a long-term suboptimality of which the industrial weather sensitivity has been only one manifestation. The late Stanley Changnon suggested in 2010 that 'financial pressures resulting from enormous weather-caused losses during the 1990s in the US, coupled with deregulation of the utility industry and growing global economic competition affecting agribusiness and other industries, led many firms to seek climate products that could be used to explain the frequency, or risk, associated with various weather conditions.'[68] On that note, I believe we should welcome historical research into contact areas between atmospheric sciences and economy, seeking to understand how the communication between scientists, science brokers and science users evolved in the past and how it may illuminate our current debates about the public and private governance of atmospheric resource and climate change policies.

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[64] *Supply Chain Vulnerability*, Executive Report on Behalf of Department of Transport, Local Government and the Regions (Cranfield University, 2002).

[65] On supply networks see 'http://www.som.cranfield.ac.uk/som/dinamic-content/research/lscm/downloads/Vulnerability_report.pdf.

[66] Susan Cutter and William H. Renwick, *Exploitation, Conservation, Preservation: A Geographic Perspective on Natural Resource Use* **(**New York: Wiley, 2003).

[67] *From Facing Hazards and Disasters: Understanding Human Dimension*, (Washington, D.C.: National Academies Press, 2006), 47 - 48.

[68] Changnon and A. Changnon, 'Major Growth in Some Business-Related Uses of Climate Information,' *Journal of Applied Meteorology and Climatology* 49 (2010): 325 – 331