

Review Article

Applications of Air Mass Trajectories

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Air trajectory calculations are commonly found in a variety of atmospheric analyses. However, most of reported research usually focuses upon the transport of pollutants via trajectory routes and not on the trajectory itself. This paper explores the major areas of research in which air trajectory analyses are applied with an effort to gain deeper insights into the key points which highlight the necessity of such analyses. Ranging from meteorological applications to their links with living beings, air trajectory calculations become important tool especially when alternative procedures do not seem possible. This review covers the reports published during last few years illustrating the geographical distribution of trajectory applications and highlighting the regions where trajectory application research proves most active and useful. As a result, relatively unexplored areas such as microorganism transport are also included, suggesting the possible ways in which successful use of air trajectory research should be extended.

1. Introduction

Atmospheric processes such as air pollution, dispersion of hazardous substances, or meteorological episodes have a noticeable impact on the life of human beings. These processes may be better understood when air trajectories are also included in the studies. Although a simple approach is to assume straight trajectories, experience reveals a more complex evolution [1]. Among the techniques used to investigate air trajectories, experimental determination is not commonplace, since complex and expensive measuring campaigns are involved. Another choice is the use of satellites [2, 3], although mathematical models are systematically applied.

Most applied models include HYSPLIT, where dispersion and deposition may be considered [4], the FLEXTRA model, which permits boundary layer trajectories and calculations with the vertical wind component equal to zero [5], or the recent METEX, which accepts meteorological data in different formats [6]. There are several reasons why models are widely used. The main reason is that these are freely available and prove extremely easy to apply since a reference

site is considered where trajectories either arriving or leaving are calculated. In addition, input requirements are minimal. A further advantage is their extreme versatility, since they may be used not only for providing information about air pathways but also, together with additional variables such as temperature, moisture, or concentration, for giving information about sources. Moreover, models are subject to calibration and evaluation processes [7] and seem to evidence a similar ability to simulate air trajectories, with differences in formulations playing a secondary role [8]. The limitations inherent in models are the same as in conventional weather forecasts, since their accuracy may only be affected when their input variables are sparse. Uncertainty visualization methods have been proposed [9], and their results must be interpreted applying knowledge of meteorology, location, and the nature of possible pollution sources [10].

One noticeable feature of air trajectory models in any study is that their use may not be the objective of the research, but they may be taken as the basis for further calculations. Prominent among such applications is the widely used potential source contribution function [11]. However, other

less frequently applied applications should also be mentioned. The proposal of wind direction sectors is a simple way for classifying air trajectories [12], which provides the basis for trajectory sector analysis [13] and for the more elaborate cluster analysis, which may be applied following different techniques [14], with the aim to obtain flow patterns. The recirculation factor was proposed some time ago although it has rarely been used [15]. By contrast, roundness has recently been applied in these calculations [16]. Trajectories are also used for smoothing and interpolating concentrations through the nonparametric regression procedure [17]. Tools such as TrajStat have recently been developed to simplify and facilitate easy visualisation of these calculations [18]. Trajectory statistics may be combined with detailed land cover analysis and meteorological data to obtain information concerning the history of air masses [19]. In addition, transport models combined with satellite observations provide a spatial and temporal distribution of concentrations and improve air quality forecasts [20].

The current paper focuses on applications of air trajectories. Due to the satisfactory features of the models, fields of application vary enormously. One application of trajectories is identification of pollution sources such as deserts, which are considered as natural sources of particulate matter [21]. Although urban and industrial areas are also identified as sources of particulate matter, these are considered as anthropogenic sources. Since the distance travelled by air mass may differ from local to regional or long-range transport affecting various atmospheric depositions and phenomena, broad areas of trajectory applications should be considered. In these latter cases, the air parcel may receive injections from varying sources during its trip due to which its initial properties may be altered considerably depending on surface characteristics and travel time [22]. Moreover, models may be validated and compared [23–25]. Widespread application of air trajectories, which ensures their usefulness, justifies a specific study in order to fill a gap in the area of applied atmosphere research.

To accomplish this objective, research reports published in recent years have been reviewed. One possible choice is certain representative papers and the removal of collateral treatments. However, the current paper considers an extensive number of studies in order to secure precise knowledge of research fields where the said technique is used, this ranging from only meteorology to air pollution or pollen spread. Proposing a classification is by no means easy due to overlaps in the research covered by the various groups suggested. However, establishing classes seems necessary if information is to be simplified and if insights concerning the type of application and targets pursued are to be gained. The groups proposed are inhomogeneous both in the number of papers published and in their geographical distribution. This results in generation of knowledge more effectively out of the research that involved multiple resources and the regions where this analysis is applied. The reported studies have been grouped into five categories, namely, (i) meteorological applications, (ii) air chemistry, (iii) hazardous substances, (iv) aerosols, and (v) living beings. These groups are divided into several subgroups where the main applications or results are

presented. Although a close relationship between papers in each group would be desirable, it is not easy to link various studies as some workers analyse isolated events, time intervals of the studies do not overlap, airflows are conditioned by the orography, there may be differences in measuring height, and so forth.

However, air trajectory analysis sometimes fails to reveal differences in air masses from widely varying geographical regions. In such cases work needs to be carried out in order to secure more precise knowledge of air trajectory application limits.

2. Meteorological Applications

2.1. Cyclones and Synoptic Meteorology. Cyclone evolution has been studied worldwide, particularly over oceans, such as the southwestern South Atlantic Ocean [26] or over the North Atlantic with the interpretation of potential vorticity inversions [27]. Over the Northern Hemisphere, extratropical cyclones have been tracked and predictions verified [28]. The “Perfect Storm” cyclogenesis over the North Atlantic has been analysed [29]. Determining the trajectory of medicanes, intense storms over the Mediterranean similar to tropical ones, is valuable because of the enormous potential damage given the fact that coastal regions are densely populated [30]. The role of sea surface heat fluxes was considered over this sea, the properties being modified in numerical simulations to observe the evolution of the cyclone [31]. Over subtropical East Asia, in spring 2004, air masses transported low O_3 concentrations to higher latitudes following the circulation associated with the Sudal typhoon and the northern Hadley cell [32]. The hybrid characteristics of a low pressure system over the Tasman Sea with an erratic track before decay were studied [33].

Other cyclonic circulations that have been analysed include US tornadic environments [34], which are substantially higher than their European counterparts due to blocking by the Alps and the colder sea surface over the Atlantic Ocean [35]. Severe weather events (intense hail, major convective gusts, or strong tornados) associated with elevated mixed-layer air were investigated in the northeastern US [36]. The evolution of remnants of a haboob, a convectively driven dust storm, was analysed in Phoenix, AZ, where this is an unusual event [37]. Backward trajectories were used to examine a warm-core meso- β -scale vortex formation associated with the “Super Derecho” convective event observed on 8 May 2009 at Kansas [38].

Several examples illustrate general applications of air circulation. The relationship between air trajectories and the spatial synoptic classification was considered at Martinsburg, WV [39]. A polar vortex was responsible for an advective cooling event over almost the whole of Iran [40]. Generalised frosts over southern South America were favoured by remotely excited Rossby waves [41]. Air trajectories were used to investigate transport from the planetary boundary layer to the Asian summer monsoon anticyclone [42]. Eight weather regimes were described in southeastern Queensland, Australia. Four wet regimes observed preferentially during summer were linked with shorter trajectories at lower levels

than dry regimes, which were observed throughout the year [43]. Two trajectory clusters were considered in the Ross Sea Region, Antarctica, the oceanic/west Antarctic, and continental/east Antarctic [44].

The relationship between wind and air trajectories has occasionally been analysed and has revealed that the regional prevailing NW winds over the East Mediterranean are the strongest prior to cool events [45] and the air mass transformation over the western North Pacific controls the characteristics of the Yamase wind [46].

Recirculation processes are the meteorological features responsible for high pollutant concentrations, such as those observed over the East Mediterranean region [47] and during O₃ episodes in the Lower Fraser Valley, Canada [48]. Stagnant airflow was another noticeable meteorological feature that determined enhanced concentration of particles in summer over the coastal areas of the Yellow Sea and near Japan [49].

Orographic effects sometimes have a marked effect on airflow, such as uplift in the Eastern Pyrenees, which determined and maintained heavy precipitation from 6 to 8 November 1982 [50], flow splitting and cyclogenesis in the lee of Greenland, Denmark [51], atmospheric circulation at Mount Rwenzori, Uganda [52], or the lifting process over the North Pacific west of the California coast prior to heavy precipitation over the Sierra Nevada [53].

Singular meteorological applications of air trajectories include temporal changes in angular momentum used to diagnose trajectories over large scale distances [54], investigating the spatial structure of surface temperature by quantification of the time that an air parcel spends over ocean and land [55], the influence of fog on visibility [56], and the influence of large scale subsidence in the meteorology of major wildfire events in the northeast US [57] or describing troposphere-stratosphere exchange over Asia [58, 59].

2.2. Atmospheric Moisture. Several studies have shown the link between the origin of air masses and their moisture content. Analysis of tropical moisture exports to the Northern Hemisphere revealed that it made a significant contribution to regional precipitation and showed four activity centres: the central and eastern Pacific Ocean, east South America and the adjacent Atlantic Ocean, the western Indian Ocean, and western Australia [60, 61]. Analysis of the transport and transformation of water in the tropical tropopause layer revealed that deep convection moistened this layer [62]. Latitudinal advection of moisture over the ocean has been investigated and has provided negative correlations with latitude [63]. Two clusters of intense water vapour transport from the Pacific Ocean to the western coast of North America have been established, the first associated with zonal trajectories and the second with meridional flows [64]. The major direct moisture sources for the Yangtze River Valley are over the valley itself, with major moisture transport being over land, and the ocean proving important in initiating moisture transfer [65]. The Tibet Plateau, which has a major impact on the water cycle, was revealed as a crossroad of air masses, air entering from the NW and NE and flowing in two streams, one SW over the Indian Ocean and another SE through the western North Pacific [66]. High column water vapour conditions at Nauru,

in the western equatorial Pacific, were frequently associated with weakened inflow from dry regions to the east of Nauru [67]. Moisture corridors responsible for water vapour transport from remote sources to the Snowy Mountains region, Australia, where they determined precipitation events, were identified [68]. Two moisture sources were detected in the Galician/northern Portugal region: the Bay of Biscay and the Tropical and Subtropical North Atlantic corridor [69] and potential temperature and specific humidity of trajectory clusters affecting the southwest of the Iberian Peninsula were analysed [70]. The variability of H₂O in the Antarctic PBL has also been explained, since a minimum H₂O is observed when air transits over the Antarctic Plateau [71].

2.3. Clouds. Air trajectory analysis revealed the noticeable effect of aerosol on clouds. In Oklahoma, aerosols associated with maritime and northerly air trajectories have a greater effect on clouds than those from northwesterly trajectories, which also exert local influence [72]. The influence of previous meteorological conditions on properties of subtropical clouds in the northeast Atlantic and their evolution were studied by trajectory analysis [73]. Pollution from the Shanghai-Nanjing and Jinan industrial areas in China affected wintertime clouds and precipitation over the East China Sea [74]. The region off the west coast of Africa was divided into 1° × 1° grid boxes where boxes associated with aerosols of oceanic origin had a lower cloud fraction than those associated with continental origin [75].

Trajectory analysis revealed that subsidence and advections from the SE and SW maintained an unusually dense regional advection-radiation fog over Anhui, China, while the northwesterly dry wind determined dissipation of the fog [76].

Research into haze episodes in northwestern Thailand revealed that air masses passed over dense biomass hotspots before reaching the measuring site [77].

The relationship between ice in clouds and aerosols was investigated in an extratropical cyclonic storm over the western Pacific Ocean [78], and nucleation of ice was studied on polar stratospheric clouds [79].

2.4. Precipitation. Establishing an initial relationship between precipitation and air masses involves identifying the origin of precipitation episodes. In Europe, over half the observed precipitation in Belgrade, Serbia, corresponded to airflow from the SW, SE, and NW [80]. Two flow types were responsible for extreme rainwater pollution episodes in the protected area of Wielkopolski National Park (western central Poland) [81]. Back trajectories reaching four stations in Europe, Oslo, Bremen, Smolensk, and Budapest, for days with the highest amount of snowfall revealed that humid air was transported over long distances and was shifted from the low troposphere to the upper layers [82]. Wet deposition in the southeastern Adriatic region is dominated by precipitation from the Mediterranean Sea [83], and Saharan dust transport across Europe determined “red” or “blood” rains [84]. In South America, precipitation events in the southern Peruvian Andes mainly occurred under

weak flow regimes from nearby Amazon basin sources [85]. In North America, upstream air trajectories provided information on moisture source regions and low level flow affecting the southern Appalachians [86], and trajectories with a Great Lakes connection determined higher snowfall totals on parts of the higher elevation windward slopes in the southern Appalachians [87]. Certain precipitation events in Newfoundland, Canada, were associated with trajectories originating in the Gulf of Mexico [88, 89]. In Asia, isotopic composition of water across the Himalaya and eastern Tibetan Plateau was controlled by local processes, although air trajectories indicated changes in the mixing over the plateau [90]. Westerly air masses in summer, and westerly and polar air masses in winter, transported moisture for precipitation events in the upper Urumqi River Basin, central Asia [91]. Varied air masses affected Beijing, China, during the Asian monsoon period [92]. Low pH of rain water has been reported due to air masses originating from Gulf region arriving at Hudegadde site located in an ecological sensitive area of Western Ghats of India [93].

The contrast between marine and terrestrial air masses was observed in Aveiro, Portugal [94], on the island of Bermuda by nitrate composition [95], in Florianopolis, Brazil, by air pollutant content [96], in the Yangtze River Basin with $\delta^{18}\text{O}$ and δD concentration [97], and also near Sydney, Australia, by the $\delta^{18}\text{O}$ composition of precipitation [98]. Aerosol concentration may identify the type of air mass. The advection of subtropical and tropical moisture caused the most isotopically enriched precipitation in southern California [99]. Two basic raindrop size evolutions were observed during the Queensland Cloud Seeding Research Program, one associated with continental air masses, with relatively high aerosol concentrations and long air trajectories over land, and the other related to maritime air masses with lower aerosol concentrations [100].

Pollution sources may also be identified since enhanced concentrations of trace elements in precipitation in a rural area of South Korea were associated with industrialized areas of China and metropolitan areas of South Korea [101]. Aerosol and precipitation data at the Maldives Climate Observatory have been divided into two groups with pollution days with airflow from the Indian subcontinent in a northeasterly sector during winter and clear monsoon days with southerly flow from the Indian Ocean with high concentrations attributed to long-range transport from the Australian or African continents [102].

Trajectory analysis in height may provide information about pollution sources, such as advection in the middle troposphere from Western Poland and Germany, which was a possible source of pollution by fluorides in atmospheric precipitation in Wielkopolski National Park, west central Poland. However, short distance transport from local emitters was the main source in the lower troposphere [103].

Increased concentration due to the absence of precipitation has also been analysed at a remote site, Mt. Norikura, Japan, where aerosol transport from sources to surface without precipitation scavenging after entrainment in the free troposphere enhanced mass concentration [104].

Types of trajectories may be identified by the composition of rainwater. A classification based on the relationship between rainfall chemistry and air trajectories was established in Minnesota [105].

Organic chemicals may be transported in the free troposphere by clouds, such as those formed in midwestern and southeastern US, which determined hail storms in Toronto, Canada, where these chemicals were recorded [106] and hail occurrence in the North German Lowlands was studied by the influence of atmospheric circulation [107].

Different air mass movement was responsible for unequal sea-salt concentration of snow deposited in the Japan Alps during the winter monsoon [108]. The relationship between ice nuclei concentrations and air pathways was studied at different altitudes in the Huangshan Mountains, SE China [109]. Atmospheric transport from NW India and Nepal was detected in snow composition from the Jima Yagzong glacier in the central Himalayas [110], and high concentrations of black carbon from south Asia were observed in the ice cores of the Everest region in the monsoon season [111]. High dust concentrations in snow on Mt. Elbrus, Caucasus Mountains, were transported from the Sahara, although the Middle East was revealed as a secondary source [112]. Blocking high pressure systems over Scandinavia and the advection of western European pollution determined high concentrations of nitrogen deposited over Svalbard, Norway [113]. Transport pathways and source regions of climate proxies were considered in polar ice core analysis [114–116].

3. Air Chemistry Applications

3.1. Common Air Pollutants. Study of air pollution transport is a direct application of air trajectory analysis. In Israel, most air pollution is a consequence of long-range transport from eastern and southern Europe [117], since most air masses reaching this area reflect 2–3-day transport times. On the contrary, severe air pollution atmospheric conditions in Istanbul, Turkey, were attributed to a high pressure system, which led to the formation of an exceptional ground-based temperature inversion, long-range transport of Saharan dust being excluded [118]. Large scale synoptic air pollutant transport has been observed at high elevation sites in the Alps [119]. Daily variations of pollutants in a heavily industrialized area in central Spain have been studied [120]. The scale of the NO_2 spatial-temporal variability in the near-surface layer was estimated in the vicinities of St. Petersburg, Russia [121]. In Asia, long distance sources contributed to SO_2 recorded over Delhi, India, during winter, with marine influence being noticeable during monsoon, whereas regional sources prevailed during summer [122]. The heaviest air pollution episodes in Ürümqi, China, have been analysed with synoptic patterns of atmospheric circulation and air mass characteristics [123]. The close relationship between air pollution and winter monsoon meteorology was analysed in Hanoi, Vietnam [124]. In North America, trajectories were also considered in a cluster analysis of pollutant concentrations in Boston, MA [125]. The presence of long-lived contaminants at remote sites was also investigated, as

in the Yukon Territory where the Arctic Ocean, northern Siberia, Canadian Yukon, and Northwest Territories were sources of semivolatile organic compounds [126].

In contrast, clean sectors may be also identified. A study of air mass trajectories arriving at Mace Head, Ireland, revealed that the eastern North Atlantic is one of the cleanest regions in the Northern Hemisphere [127].

Air transport between the US and Windsor, Canada, is very frequent. However, its air quality should not be only analysed from the air masses originating in the US [128].

Singular applications are the investigation of potential sources of odour problems [129], identifying upwind sources, which might affect air quality levels in Seoul, South Korea, and downwind areas affected by this city [130] or identifying sources from seven regions affecting two receptors in the eastern US [131].

3.2. Ozone and Photochemistry. Several studies have proved the usefulness of air trajectory analysis in photochemistry, since precursors may be transported to form secondary pollutants, which are also transported. This section first focuses on O_3 records. In North America, increases in O_3 and CO concentrations at Whistler Mountain in British Columbia, Canada, were attributed to fires in the Russian Federation or Alaska and the Yukon Territory that were transported by the prevailing westerly winds [132]. GIS and back trajectory analyses indicated that mobile sources contributed to O_3 formation over the Jackson region, MS [133]. Weather patterns and trajectories were classified to study high O_3 episodes in the Houston-Galveston-Brazoria area [134]. The impact of wildfires on O_3 events was analysed in the western US [135]. The warm conveyor belt of a cyclone lofted pollutants responsible for O_3 high concentrations over the western North Atlantic Ocean into the free troposphere [136]. In Europe, exceptional meteorological conditions have been considered to explain very high levels in Madrid, Spain [137]. Air masses from industrialized continental Europe and wildfire emissions determined high O_3 levels in southern Italy, whereas the North African desert region was associated with lower concentrations [138]. O_3 trends at Jungfraujoch, Switzerland, were linked to the origin of air masses [139]. Two major routes of long-range transport were observed in the Balkans, though both appeared with the same direction of local winds in Patras, Greece. During the cold months, the amount of O_3 transported was greater than that due to local formation, with the opposite being true during warm months [140]. In Asia, O_3 episodes in Malaysia were attributed to regional transport from biomass burning in Sumatra, Indonesia, as well as long-range transport from Indo-China [141]. Moreover, transport, airflow pattern, stagnation, and the boundary layer height determined the concentrations recorded at certain sites in India and the Bay of Bengal [142–148]. In China, transport from eastern, central, and southern China, specifically linked with tropical cyclones, was a factor determining the high levels measured in Hong Kong [149]. Stagnation and recirculation of air, together with intense solar radiation, high temperature, and long-range transport of pollutants, were responsible for O_3 episodes at urban Jinan [150]. High biogenic volatile organic carbon emissions from

the vegetation of the Qinling Mountains caused the three longest O_3 pollution episodes in Xi'an [151].

Another source of O_3 in the low atmosphere is its transport from the stratosphere, where three phases have been identified, tropopause crossing, free descent, and quasi-horizontal dispersion in the lower troposphere [152]. Trajectory analysis revealed an important direct stratospheric impact in greater Athens, Greece, causing a noticeable increase in surface concentrations with no photochemical origin [153]. Moreover, vertical transport from aloft has emerged as the main mechanism to replenish the atmospheric boundary layer at Alert, Nunavut, Canada [154]. Contrastingly, bubbles of low O_3 concentration were observed in the tropical tropopause layer in the equatorial region around Central and South America originating from deep convection in the equatorial eastern Pacific and/or Panama Bight regions [155].

The rest of the section is devoted to other pollutants involved in atmospheric photochemistry. Plumes analysed revealed that peroxyacetyl nitrate, PAN, another less studied secondary pollutant, recorded at Mt. Bachelor, OR, was of both Asian and North American origin [156].

Air trajectories have also been used to study precursors of photochemical pollutants such as volatile organic compounds, VOC. Air masses from Eurasia contained the lowest VOC levels compared to others from China and India at the Mt. Waliguan station in the northeast part of the Qinghai-Tibetan Plateau [157]. Moreover, high CH_4 concentrations at this site were associated with advection from heavily populated regions and rice-growing areas [158]. Another site where the relative contribution of anthropogenic VOC sources to O_3 formation has been investigated is the region of Kaohsiung, Taiwan, where precursors from land sources were transported offshore determining high VOC concentrations overseas [159, 160].

3.3. Trace Gases. CO_2 in the atmosphere is considered a trace gas in most of the measurements. Transport influence was revealed, since possible maxima or minima observed in the CO_2 trend at two European remote sites could be due to contamination of the air mass during the whole of its trip [161]. The impact on this gas concentration of emissions from the city of Valladolid, Spain, and recirculation processes were assessed at a rural site [162]. The effect of long-range transport from industrial and natural sources on CO_2 has been observed at the remote site of Lampedusa Island, Italy. The back trajectory study associated with in situ data demonstrated that industrial activities and forests located in Eastern Europe and Russia may strongly affect the recorded CO_2 [163].

Other trace gases such as SO_2 and NO_x have also been considered which were transported to the Hyytiälä Forestry Field Station, Finland, mainly from Eastern Europe [164]. Emissions in the UK and Europe have a noticeable effect on NO_2 concentrations recorded at sites not directly influenced by major local sources in Ireland [165].

A low CO episode in northern Japan was attributed to rapid transport of pristine air masses from the Pacific Ocean under anomalously stronger easterly flows [166].

Air trajectories have been considered with less investigated substances, such as halogenated very short lived substances, whose research has revealed that air masses from the open North Atlantic prevailed in the Mauritanian upwelling area [167] or concentrations of dimethyl sulfide emitted by oceans, which were followed by an aircraft over the Pacific Ocean [168].

4. Applications in Transport of Hazardous Substances

4.1. Radionuclide Transport. The plume from the Fukushima reactor released on 11 March 2011 remained over the ocean due to westerly winds [169]. However, the arrival of artificial radionuclides was confirmed during the first days after the accident at nearby stations in Vietnam [170] and at such distant locations as the Iberian Peninsula and Lithuania [171, 172]. For about one month, the radioactive plume reached South Korea by surface westerlies followed by a period characterised by a direct impact of air masses from Japan [173]. Precise determination of the area affected by this radioactive plume has been obtained at various places in the Northern Hemisphere [174].

Direct tropospheric transport of fallout from atmospheric nuclear detonations at the Semipalatinsk test site, Kazakhstan, to Norway through large areas of Europe was observed [175]. Moreover, at least one unannounced low yield nuclear test in North Korea was investigated from radionuclides measured in South Korea, Japan, and Russia [176]. Several models were compared with ^{85}Kr air concentrations in the area surrounding a nuclear processing plant in North West France where mean concentrations were estimated during steady wind conditions, although peaks were not accurately predicted under changing wind conditions [177]. Possible sources of Xe and Kr radionuclides were determined by back trajectory analysis in St. Petersburg, Russia, from Sweden and Finland [178]. Integrated effects of transport and meteorology have been observed in radionuclide activities in southern Spain and the transitional location of the Iberian Peninsula was revealed [179].

Additionally, radiological risk was assessed in the metropolitan area of Seoul, South Korea [180], and dispersion and deposition of radioactive fallout could be simulated with trajectory models to estimate the magnitude of the deposited activity at different test sites [181].

4.2. Insecticides/Pesticides/Persistent Organic Pollutants (POPs). The seasonal evolution of trajectories may illustrate the behaviour of concentrations. Northwestern air mass pathways reaching Lake Small Baiyangdian, northern China, were linked with high concentrations in winter, southern pathways being relatively clean in summer and trajectories in autumn and spring being associated with high pollution from the Shanxi and Henan provinces [182].

Transport described by air trajectories may be extremely useful to reveal the origin of these pollutants. The Himalayas might be influenced by the major source regions in both India and China [183]. Air masses from China, India, Southeast Asia, and West Asia influenced concentrations recorded in

Lhasa on the Tibetan Plateau [184]. Pesticides over the Pearl River Delta Region were transported from potential source regions, northern China, and local usage was also noticeable [185]. Some of the air masses reaching Singapore came from the west of Papua New Guinea where DDT was still in use [186]. However, in seven major cities in India, source areas of polychlorinated biphenyls were confined to local or regional proximity [187].

Pesticides have been recorded at the Antarctic continent due to air masses from the Indian and Atlantic Oceans [188], and insecticides used extensively in southern East Europe and around rivers flowing to the Aral Sea were transported to Arctic areas [189].

In America, transport of these substances has also been observed. Four main pathways with high pollutant concentrations were identified at Arcadia National Park, ME, and not exclusively linked with the major urban centres along the eastern Atlantic seaboard [190] and different models were used to quantify atmospheric transport of POP concentrations to the Great Lakes [191].

4.3. Toxic Metals. Transport of various toxic metals such as mercury, lead, and arsenic has also been studied using air trajectories. In northeastern North America, shipping ports along the Atlantic coast emerged as the main Hg sources and the contrast between oceanic and land/coastal trajectories was also observed [192]. In northern Mississippi, events of atmospheric Hg were linked with air masses from the northern continental US region [193]. In Canada, major sources affecting Windsor extended from Ohio to Texas [194], and unseasonable high total gaseous Hg concentrations at Fort McMurray were associated with air from the SE and W, whereas low concentrations were from Arctic air [195]. The Hg highest concentrations at a tropical site in Nieuw Nickerie, Suriname, were obtained with marine trajectories from the North Hemisphere [196]. Hg concentrations recorded in the Fujian province, China, are diluted by air masses from the ocean [197]. Northern India may also be a noticeable Hg source for the Northeastern Tibetan Plateau [198]. Hg concentrations at Oxford, UK, are highest with wind from the E/SE, probably due to emissions from London/mainland Europe [199].

Six meteorological regimes were determined at Bondville, IL, where differences in Pb isotopes in precipitation were observed [200].

Air trajectories were used to analyse As transport and dispersion from a Cu smelter in southwestern Spain with satisfactory results under sea breeze circulations or flow dominated by synoptic scale prevailing winds [201].

5. Applications on Sources and Transport of Aerosols

5.1. Particulate Matter. Seasonal variation of the particulate matter composition in agreement with the air trajectories was observed in eastern India [202] and high concentrations are sometimes due to transport from sources, as was detected in North America [203], South America [204], Asia [205–212],

especially in China [213–217], the Middle East [218], Africa [219], Australia [220], and Europe [221].

Stagnant conditions caused the highest mass concentrations in Ulaanbaatar, Mongolia [222]. Internal sources of particles were less relevant in South Korea than external, which were the industrial areas in inland China and the Gobi desert. However, anomalous meteorological factors favoured both long-range transport from external sources and local accumulation [223, 224]. Strong land-sea breeze led to accumulation and ageing of particles in Hong Kong, China [225]. Dust aerosols from the Gobi Desert and the Loess Plateau are likely to propagate eastward but aerosols from the Taklamakan Desert propagate slowly westward [226] and both deserts were responsible for dust events over northern China [227]. Transport patterns were obtained in Beijing [228]. Potential sources of particulates recorded near the terminal of the Laohugou No. 12 Glacier in northwestern Qilian Shan were identified in the NW from the station due to industrial activities, urbanization, and residents' emissions [229]. Different air mass types were considered in Guangzhou, where transboundary transport played a critical role in the formation of PM₁₀ pollution events [230]. Air mass pathways at New Delhi, India, revealed the difference in the levels of particulate matter during monsoon and winter air mass circulations [231]. Long-range transport from the Thar Desert, Iran, and Pakistan prevailed in Agra in summer, whereas short trajectories from local areas revealed anthropogenic emissions in winter [232]. Northern and central part of India contributed to high black carbon levels in Mumbai [233]. Dust storms from the Middle East reached Rawalpindi, Pakistan [234]. Similar kind of storm has been simulated over Iran [235]. Some extreme soil dust events originated in major agricultural regions in Australia and not in deserts [236]. In Europe, seven fingerprints of urban aerosols were identified in Helsinki, Finland, during 2006, where local or regional origin was considered [237]. Several methods were combined to distinguish long-range transport, regional transport, and local pollution in Central Eastern European urban areas [238]. Coarse material was transported over distances of 1400 to 2000 km from Ukraine to the Czech Republic [239]. Local and regional scale aerosols transported were studied over Belgrade, Serbia [240], and long-range transport from Europe and the Sahara has a major influence in Italy [241, 242]. Trajectory calculations confirmed the origin of different size dust in Rome and Bari [243, 244]. Over the Mississippi Gulf Coast region, backward and forward trajectory analysis revealed particulate matter origin near the region and the relative contribution of some power plants to concentrations measured [245]. Local regions were the main contributors to sulphate concentrations estimated at Brigantine National Wildlife Refuge, NJ, and the Great Smoky Mountains National Park, TN [246]. A contrast between local and distant sources was observed in the composition of particulate matter recorded in northern Chile [247].

Long-range transport has also been revealed by vertical analyses in Greece and Antarctica [248, 249].

The contrast between air masses from continent and ocean has been observed on recorded concentrations. Two

classes of aerosols were identified during the World Exposition 2010 in Shanghai, China, class I linked with ocean-oriented air masses and class II associated with regional pollution transport from the surrounding areas [250]. Air masses reaching Iksan, a suburban area in South Korea, came from arid Chinese regions and caused high particulate concentration during the yellow dust period. However, air masses during a rainfall period were mostly from the Pacific Ocean or the East China Sea, and their concentrations were relatively low [251]. Four classes of air trajectories were observed over the Bay of Bengal and Arabian Sea showing differences in the composition of the aerosols measured [252]. Marine aerosols from the North Sea and English Channel were identified by trajectory analysis at northern Bohemia [253]. Maritime transport had a noticeable influence on air quality in Lisbon since anthropogenic aerosol concentration decreased significantly [254]. Along a cruise track in the eastern North Atlantic Ocean, air masses were characterised as European-influenced, primarily marine, or North-African influenced and aerosol composition was analysed [255]. Sea salt origin was noticed in aerosols over the Niger Delta region [256]. Particulate measurements taken at Santiago, Chile, revealed three main sources, marine air masses combined with anthropogenic sources, copper smelters surrounding the city, and wood burning [257].

Continental air masses are normally more polluted. Aerosols from Asian dust source regions and eastern China increased element concentrations at Gosan, South Korea. However, these concentrations decreased in air masses that passed over marine regions [258, 259]. Air masses from Eastern Europe led to significantly higher airborne concentrations of non-sea salt Ca and K in rural areas of Norway [260].

Specific features of maritime air masses have been considered in certain analyses. Prevailing pathways were observed over the “Maritime Continent,” the tropical Southeast Asia area extending across the Indonesian archipelago, the Malay Peninsula, and New Guinea [261]. Moreover, these masses allow aerosol formation to be investigated, as over a midlatitude forest in Japan, where new particle formation occurred in clean maritime air masses from the North Pacific, which had low mass concentrations of aerosol components [262].

Dust intrusions from deserts are frequent sources of particles in Eastern China, Europe, West Africa, and the Subtropical Eastern North Atlantic region [263–269].

One specific source is volcanic ash whose dispersion may be analysed using air trajectories. An intense relationship between surface particle distribution and rain intensity was observed from volcanic ash at Mount Merapi, Indonesia [270].

5.2. Forest Fire and Biomass Burning. Transport of pollution from active fires is sometimes observed long distances away, as at the southeastern Tibetan Plateau from fires in the SE Asia subcontinent and from northern South Asia [271]. The influence of sea and land breezes has also been evidenced in Borneo [272]. This transport was determined by a lidar, model trajectory calculations and satellite observations in Canada [273]. Moreover, influence of biomass burning was

observed in precipitation events in the southern Appalachian Mountains from November to April [274]. Soil aerosols, industrial areas, and biomass burning were responsible for particulate matter recorded in the Mexico urban area [275, 276]. Black carbon at the background station in Preila, Lithuania, was explained by air mass trajectory analysis from biomass burning at the Kaliningrad region, Ukraine, and southwestern Russia [277]. Biomass burning particles originating in Canadian forest fires were observed at the EARLINET Granada station, Spain [278], and different influences were observed in South Korea [279].

A strong link between CO episodes from biomass burning in Borneo, Sumatra, New Guinea, and Northern Australia and El Niño-southern oscillation activity has been observed [280]. PM₁₀ load increased in the Brahmaputra Valley, India, during festive biomass burning called *meji* burning and its carbon content was more pronounced due to the long-range transport of carbonaceous aerosols to the region [281].

5.3. Atmospheric Optics. Some papers focus on the optical properties of the atmosphere. Local and remote sources of dust storms were identified in Saudi Arabia [282]. Maximum aerosol optical depth at Khyber Pakhtunkhwa, Pakistan, was due to local sources, long-range transport of air masses from India and Afghanistan, and explosions detonated by the Pakistan army [283]. Differences between pre- and postmonsoon air masses as well as trajectories with high loading of atmospheric aerosols were observed in the Gangetic plain, Hyderabad, India, and the Bay of Bengal [284–287]. The optical properties of biomass burning aerosols in Sinhadag, India, have also been studied [288]. A persistent “aerosol low” was recorded over the Arabian Sea and the Bay of Bengal prior to the formation of cyclones [289]. A bimodal distribution pattern of aerosol optical depth was observed over both the western and the southeastern tropical Indian Ocean [290]. Optical properties of aerosols were analysed over Anhui, China, and related with the origin of air masses [291]. Transport from the Asian continent to the free troposphere over Japan has been studied [292]. Saharan dust events were recorded by lidar observations over Thessaloniki, Greece [293], and three desert dust sources were considered for African air masses reaching Granada, Spain, (1) N Morocco and NW Algeria, (2) Western Sahara, NW Mauritania, and SW Algeria, and (3) eastern Algeria and Tunisia [294]. Some episodes with high aerosol optical depth over Finland were linked to the transport of polluted air masses from industrial areas in Central Europe [295]. Additional information about the origin of the aerosol layers detected at Sofia, Bulgaria, was obtained by air trajectories [296, 297]. The vertical structure of aerosol optical properties in coastal areas depends on air mass advection direction and altitude, as observed in Crete, Greece, and Rozewie, Poland [298]. Volcanic ash transported from Iceland to the Polish Polar Station, Svalbard, Norway, has been confirmed by trajectory analysis [299] and was also detected in Minsk, Belarus, Tomsk, and Vladivostok, Russia [300]. Different air mass source regions reaching the southern Arizona region have been considered [301]. Specific episodes of large values of aerosol optical depth at Córdoba, Argentina, were explained by fires and/or long-range transport [302].

Air masses in Skukuza, South Africa, had longer advection pathways where their properties could be affected during autumn and winter [303]. A detailed classification of air trajectories at Niamey, Niger, revealed the origin of the air sampled [304].

However, some studies have highlighted the suitability of sites from the noticeable optical quality of the atmosphere. One site in Namibia is favoured to install the Cherenkov Telescope Array due to its satisfactory conditions [305], and air mass trajectories have also been studied above the Pierre Auger Observatory, in the Pampa Amarilla, Argentina [306].

6. Applications on Living Beings

Some substances harmful to human health such as polycyclic aromatic hydrocarbons, which are carcinogenic and mutagenic, originated from local pollution sources in Zaragoza, Spain, with long-range transport from European countries being infrequent [307]. However, long-range transport of these substances caused by particulates from coal or biomass burning in China might have strongly influenced their levels and patterns at Gosan, South Korea [308]. Intrusions of Saharan dust were identified in summertime in Delhi, India, where cancer risk due to inhalation exposure to different chemicals has been observed [309]. Remote regions may be affected, since polychlorinated naphthalenes, which have been associated with liver damage in humans, were studied by air trajectory analysis at two background stations in Sweden [310]. Semivolatile organic compounds hazardous to health released during the “Allied Force” operation in the spring of 1999 in the Former Republic of Yugoslavia were transported across borders over large distances [311]. An analysis of human exposure to air pollution, based on the risk of being hospitalised for respiratory illness, enabled meteorological patterns associated with “polluted” air parcels and “clean” air parcels in the state of New York to be identified [312].

Bioaerosol sources have also been investigated using trajectory analysis. Pollen produced by certain species causes intensive allergies in sensitive individuals. Two kinds of sources of one of the most feared pollens were identified in the atmosphere of Istanbul. The first sources were local and the second were formed by regional and remote sources [313]. Atmospheric pathways affecting pollen in Thessaloniki, Greece, Szeged, Hungary, and Hamburg, Germany, have been studied [314]. Pollen grains of ragweed from the Pannonian Plain, Central Europe, were transported to the Nordic countries [315]. Potential sources of *Olea* Pollen were identified, and transport caused high concentrations at night in the Southwest Iberian Peninsula [316]. Moreover, complex terrain affects trajectories, and transport of this pollen under this specific flow has been analysed [317], as well as pollen transport from the west to the east slope of the Andes [318]. Cedar pollen prevailed in Fukuoka Prefecture, Japan [319], and Asian soybean rust urediniospores in the Midwestern US were transported from southern Texas and the Yucatan Peninsula in Mexico [320].

Air trajectories may also prove helpful in investigating the transport of organisms such as microbial populations probably originating near China or Japan, recorded at the Mt.

Bachelor Observatory, Oregon [321]. Since the Himalayas are a barrier to atmospheric transport, analysis of soils revealed that dust and microbes deposited came from continental, lacustrine, and marine sources [322]. Air trajectories also enabled early detection of diamond back moth infestations on the Canadian Prairies [323]. Different microorganisms have been detected in dust storms affecting Iran [324]. Dispersion patterns of the adult wheat midge, *Sitodiplosis mosellana*, were studied at the Hebei province, China, and showed that male midges mated before dispersal [325]. Cattle and insects in northern Australia were infested by viruses introduced via windborne dispersal of *Culicoides* whose spatial extent of the source across Indonesia, Timor-Leste, and Papua New Guinea and arrival regions were suggested [326]. Transport of infected *Culicoides imicola* from southern to northern Spain was investigated due to the expansion of the bluetongue disease of ruminants [327].

7. Conclusions

Most of the papers reviewed in this study have used air trajectories as an ancillary technique, but not as the central part of the research.

Backward trajectories are the most commonly calculated type, the HYSPLIT being the most widely used model and particulate matter being the kind of pollutant most frequently investigated.

Geographical distribution of applications has focused on Asia, especially on rapidly developing countries such as China whose pollution impact may be observed on surrounding countries.

Air trajectories show that emissions from distant sources may cross boundaries and impact remote unpolluted areas or places where emission control strategies have been implemented or where the use of certain substances has been restricted or even banned.

Urban and industrial areas are not the only sources of pollution since many widespread crops in Asia may release noticeable concentrations of different pollutants into the atmosphere.

Injections during transport may considerably change features of air mass, which may impact remote places where potentially dangerous substances have been observed.

Dry and perhaps polluted air masses from the continents are loaded with moisture and cleaned when they travel over the ocean. However, marine aerosols may be dragged to the continent where they are mixed with polluted air modifying the properties of local parcels.

The influence of air masses from or over central Africa and the long-range transport of microorganisms require further investigation.

Finally, although trajectory calculation is a powerful tool, it should be used in conjunction with other procedures. Therefore, research focusing on air trajectories remains an open field, and extending it is recommended in order to gain further insights into the atmospheric pathways affecting the regions under analysis and their influence on living beings. The underlying factors for the air mass trajectories are basically linked to the synoptic wind regime, wind

flow, and inversions. This review has shown the multiple applications of air trajectories on various issues depending on the Lagrangian or Eulerian perspectives of the flow field.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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