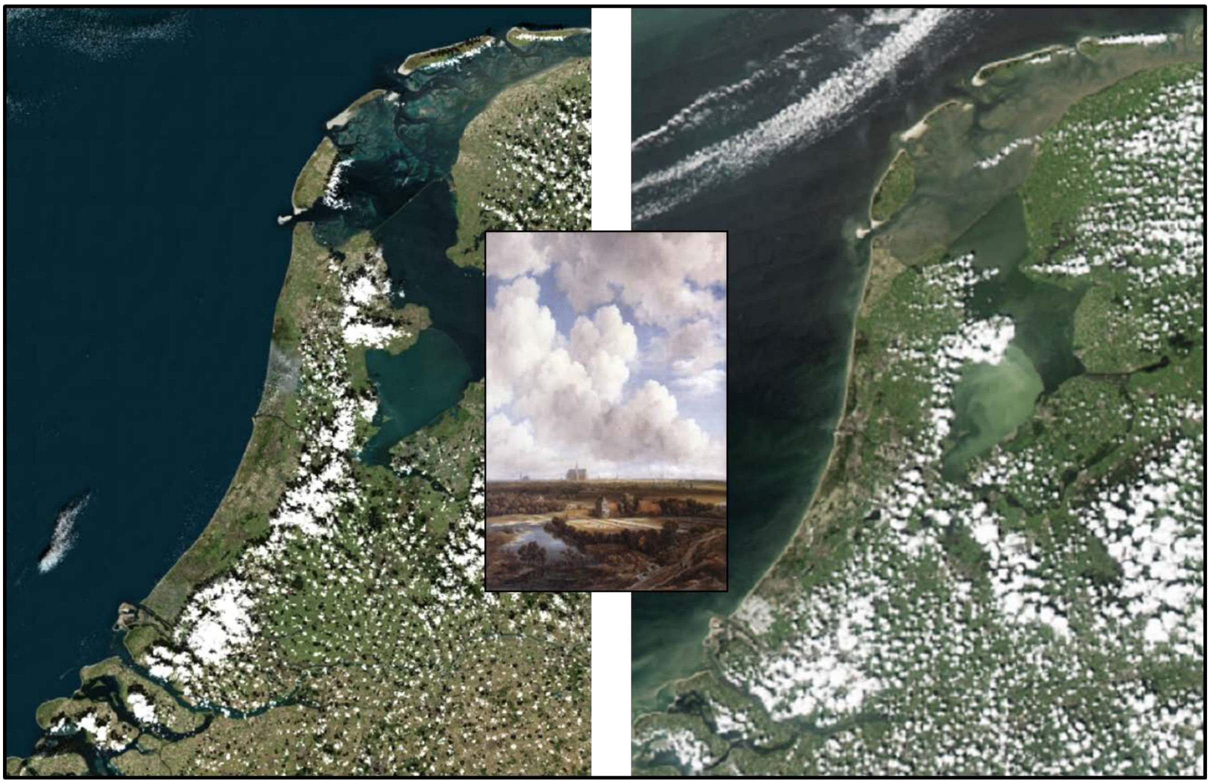
KONINKLIJKE NEDERLANDSE
AKADEMIE VAN WETENSCHAPPEN

Skies over Holland:
The Ruisdael Observatory



Model prediction of cloud fields	***Skies over Holland, observations from the ground by Jacob van Ruisdael***	***Cloud structures in the satellite image***

The *Ruisdael Observatory* integrates high-resolution observations and models of the *Skies over Holland* for climate, weather and atmospheric chemistry over a wide range of spatial scales.

The Future of the Atmosphere

Since the Industrial Revolution we have increasingly altered the composition of the atmosphere by emitting carbon dioxide, aerosols and more trace gases. This has structurally changed the atmosphere, but only by approximation we understand how these emissions modify atmospheric processes and, consequently, weather patterns, climate and air quality.

The atmospheric system is complex and dynamic. Dust particles modify cloud systems. Vegetation alters the amount of moist. Cities accumulate heat and change air motions while doing so. A small surface disturbance changes the local weather. Greenhouse gases warm the atmosphere. Aerosols cool the atmosphere. A small scale creates a large one, and a large scale a small one.

We have no deep understanding of how the atmosphere might evolve. The weather forecast is limited to days – partly due to the nature of weather itself – but mostly because we lack insight into the chemistry and physics of small scale processes and how they are coupled to the larger scales of the atmosphere. The weather forecast is only aiming at the short term of daily life, but we also need to know the long term trends of mean weather: how is the altered atmosphere affecting our climate, and consequently: our living environment?

With the increasing availability of computational and observational power the atmospheric community is now at the brink of a new revolution. With the coupling of large flows of detailed observations to atmospheric models and simulations we are getting close to the realm of first principles: characterizing the atmosphere based on the laws of nature only without the need for, too often too crude, approximations of small scale phenomena.

The Ruisdael Observatory is set up to meet this goal. With a combination of ubiquitous sensors and high-resolution models we will create an unprecedented three-dimensional motion picture of the sky over Holland and study the atmosphere in all its glory. It will give us the deeper insights we need to understand the atmosphere of today, of tomorrow and of the decades to come.

With Ruisdael Observatory we will study the Future of the Atmosphere.

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AKADEMIE VAN WETENSCHAPPEN

GENERAL PART

Program	Skies Over Holland
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Abstract

In the next decades, governments worldwide are planning to spend enormous amounts of public funds to cope with expected climate change. To effectively prioritize measures to be taken, there is an urgent need for reliable short term forecasts of weather, and to assess the effects of climate change on local extreme weather events – especially at a regional and local scale. Reliable predictions are however severely hindered by an incomplete representation of short-lived climate forcers and processes that operate in the climate system, and specifically their small-scale spatial and temporal variability. Present facilities to study these processes lack the required ability to couple data and models at different spatial and temporal scales, and lack the capability for producing high resolution 3D information at the appropriate scales. The Ruisdael Observatory will remove these barriers.

The Ruisdael Observatory will operate at the full scale of The Netherlands at the unprecedented spatial resolution of one kilometre, augmented with selected urban regions at an even higher resolution to zoom in on specific processes. Considerable progress has been made on global atmospheric modelling, with resolutions approaching the 1 km and even 100 m scale. However, these atmospheric models are still too coarse, and not able to resolve crucial small scale phenomena, such as turbulence and cloud microphysics and the interaction with surface energy fluxes. The Ruisdael Observatory will merge observations and models in real time, at different spatial and temporal scales, to form a virtual laboratory for studying multi-scale processes in atmospheric chemistry and physics, and by doing so improve the accuracy of climate, weather and air quality models. By reducing the need for parameterizations, atmospheric models will increasingly be based on first principles of atmospheric physics.

The Ruisdael Observatory will consist of
- a nationwide ubiquitous network of stationary and mobile sensors to measure the 3D physical and chemical state of the atmosphere and its interaction with the land surface,

- two advanced anchor stations: the already existing, rural, CESAR Observatory and a new urban station in the Randstad agglomeration;
- a computational facility for real-time assimilation of the data high-resolution atmospheric models.

The Ruisdael Observatory will be of the highest level yet achieved in atmospheric sciences, and reinforce the leading role of The Netherlands worldwide.

Key words
weather, climate, air quality, high-performance computing, high-resolution, forecasting, observations, modelling

PROPOSAL

A. SCIENCE AND TECHNICAL CASE

The Ruisdael Observatory will consist of

- a nationwide ubiquitous network of stationary and mobile sensors to measure the 3D physical and chemical state of the atmosphere and its interaction with the land surface,
- two advanced anchor stations: the already existing, rural, CESAR Observatory[1] and a new urban station in the Randstad agglomeration;
- a computational facility for real-time assimilation of the observations into high-resolution atmospheric models.

Even though the observatory includes existing observational networks of (largely) localized point measurements, the major advancement of the observatory will lie in its expansion with new stations that are capable of three-dimensional measurements, and the real-time assimilation of data in atmospheric models. The observatory will operate at the full scale of The Netherlands at the unprecedented spatial resolution of one kilometre, augmented with selected (urban) regions of even higher resolution to zoom in on specific processes and the role of small-scale heterogeneity.

A1: THE SCIENCE CASE

Background

The climate is changing, but the understanding of the future degree of change and the impact on regional weather and water resources, weather extremes and air quality leaves out many open questions and challenges. After the 2015 Paris Conference of the Parties – where the world community agreed to reduce the greenhouse gas emissions to such amounts that global warming will remain below two degrees with respect to pre-industrial times – governments will need to find efficient ways to enable the energy transition into a decarbonized society. Governments use scenario predictions to devise policies and develop protective measures against the effects of climate change, e.g. protection against extreme precipitation that causes flooding of urban areas, and against flooding in general caused by extreme peak flows in rivers and canals. Spending planned is huge. For the Netherlands alone estimated costs for water safety alone in the period until 2050 are 20 billion euro.[2] In 2011, The World Bank estimated global costs connected with a temperature rise of 2°C at 70 – 100 billion USD/year for the period 2010 – 2050, so a total of 2.5 – 3.6 trillion euro.[3], excluding the investments needed to mitigate climate change below the 2 degree target as agreed upon at the 2015 Climate Conference in Paris. Clearly it is important that government spending is well targeted and useless spending of public funds is avoided. A major problem is the present uncertainty in climate change predictions, especially uncertainties connected with atmospheric pollution, clouds and precipitation and the interaction with surface conditions, such as soil moisture, vegetation or urban areas. The investment proposed here will enable the large improvements in reliability in the short-term prediction of potentially catastrophic weather events, and the effects of climate change on their occurrence. The development of such a high-resolution and validated modelling system is urgently needed, and knowledge in this field can be applied to assess local effects of climate change world-wide.

[1] www.cesar-observatory.nl

[2] Werk aan de Delta, Deltaprogramma 2014, Ministeries van Infrastructuur en Milieu en Economische Zaken, september 2013 (Report of the Dutch Government)

[3] Economics of Adaptation to Climate Change, June 6, 2011

Scope of the research field

The atmosphere plays a dominant role in the climate system. There are large knowledge gaps related to both the effects of trace gases, aerosols, clouds and precipitation on climate change and the mechanisms underlying these effects. For instance, observations show that the intensity of extreme precipitation increases with temperature at a rate much higher than 7% per ^{o}C that one would expect theoretically. Present climate models do not agree on the role of clouds in regulating the radiation balance of the atmosphere, and sometimes even give contradictory results, although there is growing consensus that in a changing climate clouds will amplify global warming[4]. The regional effects of clouds however may vary largely. Clouds and aerosols have a cooling effect by reflecting solar radiation, while their trapping of infrared radiation emanating from the earth will have a warming effect. Current models predominantly rely on 'average' parameters for scattering and reflection and do not properly include the spatial and temporal variability and composition of clouds, aerosols and other short lived climate forcers, as well as their interaction with evaporation and sensible heat fluxes at the surface.

The role of the atmospheric water cycle is poorly understood. Rainfall reduces cloud water and aerosol content but at the same time raises soil moisture content as well as ground and surface water levels. Thus new clouds may be formed through enhanced evaporation. The bi-directional energy and water fluxes are influenced by the - highly variable - vertical structure of the planetary boundary layer and the heterogeneity in the surface properties acting at different spatiotemporal scales. This complexity has rendered it very difficult to decipher all elements of the atmospheric energy budget. Present models do not adequately describe these phenomena[5], and improved coupling of, for instance, atmospheric and hydrological models is needed.

One of the key problems with reliable predictions of cloud formation and precipitation is that clouds and precipitation are the resultant of atmospheric processes at very different temporal and spatial scales. Much improvement has been made in numerical modelling of the atmosphere. Driven by improvements in computational power, the skill of numerical weather prediction models has steadily improved and the resolution from grids of typical size of hundreds of kilometers (early seventies of the last century) to the present scale of km's. First experimental runs have been reported at scales of 1 km globally and 100 meters regionally[6]. For such fine-resolution models some vital assumptions regarding the vertical transport of quantities break down, requiring further refinements of both numerical techniques and physical understanding. This regime of high resolution is referred to as the Grey Zone, e.g. by the World Meteorological Organization. Future developments will be increasingly based on a new hierarchy of models, where detailed models – largely based on first principles of physics - are 'nested' in models of coarse resolution, with the outlook of routinely running simulations at 100 meter scale.

Air quality models, also known as transport-chemistry models, describe the state of the atmosphere in terms of gaseous, solid and liquid chemical components other than water. Such models are crucial to understand causal relations between spatially distributed and time-varying emissions of trace gases and aerosols on one hand and air pollution on the other. Current air quality models have demonstrated reasonable skill with respect to some air pollutants (e.g. nitrogen dioxide, ozone, secondary organic aerosol), but a reliable simulation of aerosols – important for climate and air quality – remains challenging, due to the multitude of chemical and physical processes that drive their formation,

[4] Dufresne J.-L.,and S. Bony, *J. Climate* , Oct. 2008, Vol. 21, No. 19, p. 5135-5144, doi: 10.1175/2008JCLI2239.1
[5] Guillod et al, Nature Communications 6, doi:10.1038/ncomms7443;
Taylor et al, Nature 489,423–426, doi:10.1038/nature11377
[6] Miyamoto, Y. *et al.* Deep moist atmospheric convection in a sub-kilometer global simulation. *Geophys. Res. Lett.,* 40, 4922–4926 (2013)

evolution, and removal. The formation of aerosols and their transport leads to perturbation of the radiation reaching the surface. This modulated energy distribution at the surface yields changes in evaporation and sensible heat flux, affecting turbulence and the transport of moisture in the atmosphere.

The challenge for the next decades is to explicitly simulate and measure the highly variable distributions of aerosols and other short lived climate forcers at the scales relevant to be used for local climate modelling over urbanized regions. This requires a dynamic model capable of simulating atmospheric turbulence at a scale that is unprecedented for transport-chemistry models. Specific attention needs to be given to secondary (organic) aerosols, particle dynamics in source regions and the modelling of climate relevant parameters (such as size and hygroscopicity). Furthermore, the system needs to be able to cope with the expected strong decrease in air pollutant emissions associated with major technological advancements. The energy transition will also increase the variability in emission strengths, which anyhow need to be much more detailed to fulfil the modelling needs.

We have learned from weather forecast models that it is essential to couple a high-resolution prognostic model for air quality to a dense network of sensors that are complementary with respect to the chemical components that are measured and with respect to the spatial representativity: in-situ monitors constrain the surface concentrations, space borne sensors and ground-based remote sensing constrain the upper part of the atmospheric boundary layer as well as the free troposphere above. Especially sensors sensitive to the fine mode of aerosols are crucial, as this is the pollutant with most adverse health and climate effects. Present understanding of aerosols and their role in the climate system needs to be improved in order to better assess the effectiveness of measures taken by local and national authorities to mitigate air pollution and climate change.

With the Ruisdael facility we aim to address the following fundamental weaknesses of current models:

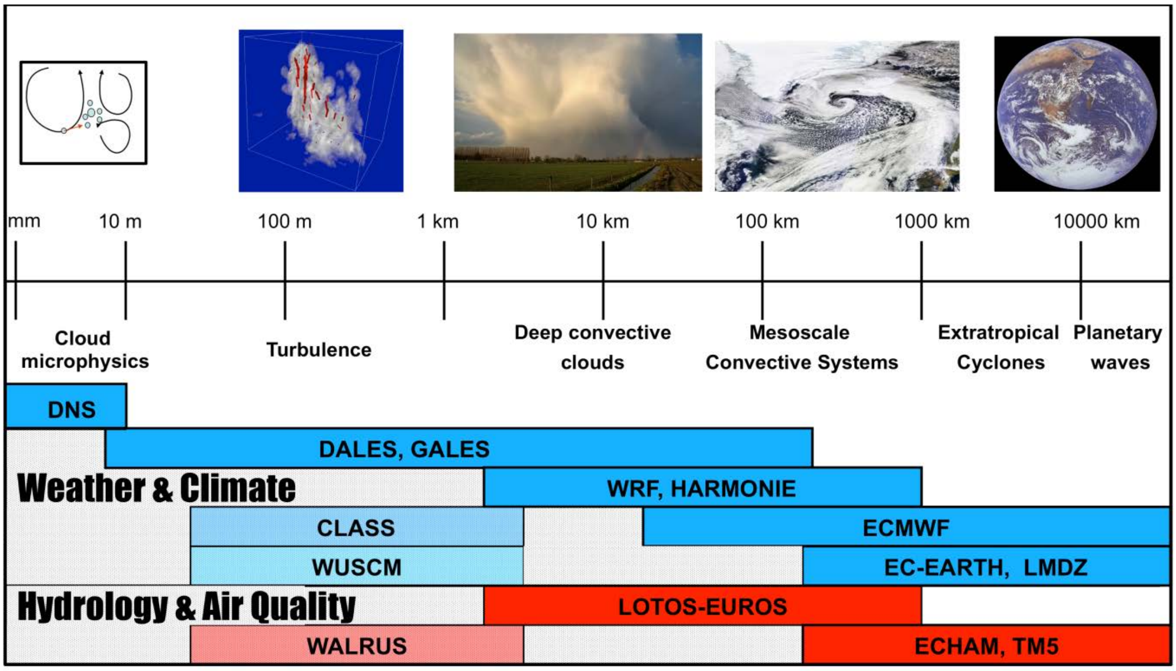
- Computational power limits extending resolution to the point that small-scale chemical and physical phenomena can be properly described. Current models still have to use approximations (parameterizations based on, often empirically-derived, mean properties) of these phenomena. It is expected that this technical barrier will diminish in the next decade.
- Thorough understanding of the small scale physical phenomena is lacking. So, even if computational power increases, these phenomena cannot be included in a reliable way. Here, a breakthrough is needed in observational and modelling capabilities to understand both the factors driving small scale phenomena and the influence on these phenomena of variation of atmospheric conditions (e.g. radiative properties, composition, and temperature) on a larger scale.

The Ruisdael Observatory will offer unique opportunities to study the basic processes driving climate change, weather and air quality. New instrumentation will outperform the capabilities of other advanced observatories around the world. The location – in a coastal climate and amidst major European industrial areas and cities - implies that a large variety of air masses and weather types are available for research. The Dutch landscape is well defined and regularly monitored. This unique combination of features means that the Ruisdael Observatory is very attractive to international researchers working on improvement of both observational capabilities and modelling tools for climate change predictions for regions around the world.

Scientific challenges
The atmosphere manifests itself on a wide range of temporal and spatial scales. The nucleation of trace gases and activation of aerosols into cloud droplets occurs at scales of nano to micrometers, while complete cloud and precipitation systems develop at scales up to hundreds of kilometers. Advancing

our knowledge of the full interactions within the atmosphere – *how do the phenomena at different scales influence each other?* - is of prime importance for a better understanding of the climate and weather system. This is also advocated by the Intergovernmental Panel on Climate Change (IPCC)[7] in its fifth assessment report and is selected by the World Climate Research Programme (WCRP)[8,9] as one of the five Grand Challenges.

Impression of atmospheric scales and corresponding models



The proposed investment in the Ruisdael Observatory facility provides the means to study small scale physical phenomena and coupling of observations and models with the full range of spatial and temporal scales. Note that the philosophy behind such effort can be appreciated from the cover figure, which nicely illustrates the necessity of multi-dimensional information for model and assimilation purposes. Key is the combination of instruments which simultaneously measure physical and chemical atmospheric parameters at different spatial and temporal scales, using advanced in-situ and remote sensing techniques, fields of research in which Dutch researchers have been excelling over many years. The atmosphere is not a laboratory with controlled conditions. Therefore, it is essential to collect and build coupled datasets over long periods. The Ruisdael Observatory facility will create such sets, accessible for atmospheric researchers worldwide. The research planned at the Ruisdael Observatory facility, coined as the 'Skies over Holland' program, addresses the following fundamental aspects:

Understanding the physics: Most of the relevant phenomena are entangled in a complex system of chemical and meteorological processes and regimes, at different spatial and temporal scales and with varying degrees of mutual coupling. An example is the role of aerosols in cloud formation and

[7] Intergovernmental Panel on Climate Change, 5th assessment report, https://www.ipcc.ch/report/ar5/
[8] http://wcrp-climate.org/gc-clouds ;
[9] Bony et al, , Clouds, circulation and climate sensitivity, Nature Geoscience 8, 261-268 (2015)

precipitation. The cloud-aerosol interaction is a crucial element in the process of cloud formation, but its effect can be very diverse. For instance, an increase of the number concentration of aerosol particles can lead to an increase of the number of small cloud droplets, suppress the formation of rainfall and hence increase cloud lifetime. However, smaller cloud droplets may also evaporate more easily and thereby shorten the cloud lifetime. Cloud formation depends on the chemical and physical composition of the aerosols and water vapour. Aerosols are from both natural and anthropogenic origin (air pollution). To quantify co-benefits and estimate the impacts of air pollution mitigation on climate change and vice versa, it is important to study the aerosol formation process to quantify the relative degree of the natural and anthropogenic contributions; quantify the chemical process that transforms trace gases into aerosols and cloud condensation nuclei. Supersaturation of water vapour is a pre-requirement for droplet formation. The degree of saturation not only depends on the amount of water vapour (humidity) but also on the temperature and water vapour variations which in turn are driven by larger scale land-atmosphere energy exchange processes. Key questions are:

- Surface water budget: what are the relative contributions of evaporation and transpiration, regulated by the vegetation state and soil moisture, to the total evapo-transpiration flux from the surface to the atmosphere?
- Radiative transfer: how do trace gases, aerosols and clouds perturb the radiative transfer yielding different partitions of direct and diffuse radiation influencing evapotranspiration?
- Land-atmosphere interaction: how are spatial patterns of turbulence and precipitation interacting with the vertical exchange of energy and water vapour over various types of land coverage? How is convection triggered?
- What is the radiative forcing from greenhouse gases and what is the feedback of weather conditions on the land-atmosphere of these species (CO_2, CO, CH_4, N_2O)?
- Evaporation: most rain never reaches the ground, but how much evaporates underway? And how does this evaporation affect thermo-dynamical properties of the atmosphere?
- Cloud physics: how is the microphysical and spatial structure of clouds related to atmospheric dynamics? How does cloud organization affect precipitation patterns?
- Cloud condensation nuclei (CCN) chemistry: how does the composition of CCN change with time (ageing), and how does this affect the overall properties of the clouds?
- Aerosol formation: which precursors and physicochemical processes lead to the formation of new aerosols, and how are they related to weather conditions?

Atmospheric models: climate, weather, hydrology: It is essential to couple models at the full range of temporal and spatial scales. Small scale phenomena are influenced by the large scale atmospheric conditions and the variability of those conditions. As mentioned above, the resolution of atmospheric models is improving but the coupling of atmospheric conditions and small scale phenomena is still lacking. Only a few observatories in the world have the capability to perform combined observations of greenhouse gases, aerosols, evaporation, clouds and rainfall. However, these stations are mainly taking observations in a narrow vertical column and lack in horizontal representativeness. The conversion of the time series of these column observations to a spatial grid involves the assumption of a stationary atmosphere, while non-stationarity and heterogeneity are the rule rather than the exception. This limits the capability to use observations to study the spatial variability of atmospheric processes severely, and hampers the future development of forecast models to go towards high resolutions. Assimilation of Ruisdael data will allow to develop smarter models that develop skills to assess the realistic situation. Eventually the 'stationary assumptions will be replaced by superior algorithms. The Ruisdael Observatory will be the most advanced observatory worldwide - with a wide range of *in situ* and vertically-profiling remote sensing instruments. such that we can observe the 3D spatial variability of the relevant processes in the atmosphere. Important questions to be addressed are:

- How is the spatial organization of trace gases, aerosols, clouds and rainfall related to the spatial structure of atmospheric dynamics and the heterogeneous land surface? How does it impact the radiation and energy balance and local air quality?
- What is driving the spatial distribution of greenhouse gases and aerosols, and what are the major sources and sinks

Combined model-observations systems: Atmospheric physics and chemistry has been subject of study for a long time, using a wide spectrum of observations: from a global overview using satellites to detailed observations from the ground at smaller temporal and spatial scales. The scientific enterprise of atmospheric observationalists and modelers however took place in separate communities. In recent times we have witnessed a paradigm shift: because the spatial scales of observations and models are approaching each other, direct comparisons between measurements and calculations are becoming possible. This is a new development where the Dutch atmospheric community can be found at the forefront, due to the pioneering and successful development of the KNMI Test Bed at Cabauw[10,11,12,13]. Here, local high-resolution models are continuously running with realistic boundary conditions and confronted with a dedicated real time data flow of observed parameters, such as cloud cover, radiation, CO_2 and evaporation. In this environment not only models can be tested, evaluated and improved, but also the representativeness of observations can be assessed.

The KNMI Test Bed at Cabauw can be regarded as a proof of principle, but still only for the local scale. The Ruisdael Observatory will now take this to the required large spatial (national) domain, while covering all spatial scales. It will strengthen and enhance the excellent international position of the Dutch atmospheric and hydrological scientific community, and attract many international researchers. Due to the cooperation across different disciplines *(hydrology, meteorology, atmospheric physics and chemistry, remote sensing engineering, physical mathematics, computer science)* and the unique measurement set-up, important breakthroughs in our understanding of the interplay of climate change, weather and air quality are to be expected. The observatory will be the main facility for the Skies over Holland research program.

The Skies over Holland Program

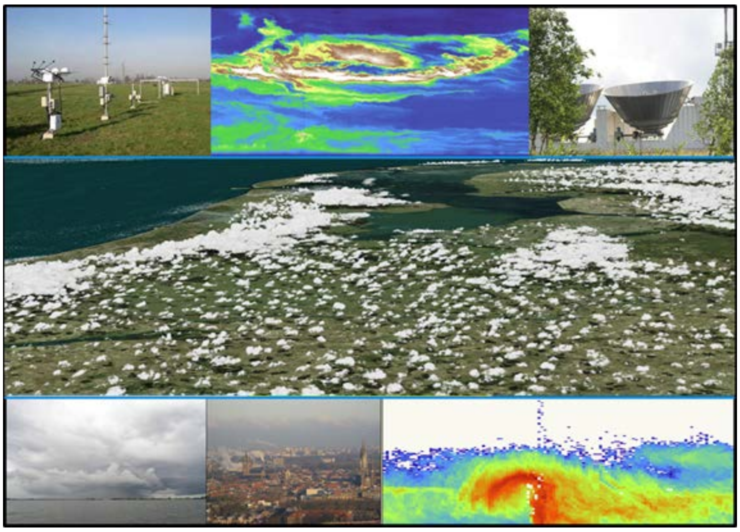
The Dutch atmospheric community has a long collaboration track record in the above mentioned fields. Over the years this has organically grown into a joint research program on climate, weather and air quality, aiming at

- quantifying the anthropogenic influence on air quality, the water cycle, and (regional) climate change;
- understanding the interplay of aerosols, clouds, and radiation;
- improving the ability to forecast weather and air quality through a better description of small-scale chemistry and physics in the models.

The existence of a long standing (successful) collaboration and multiple adjoining research programs will ensure use of the observatory by a wide range of scientific groups and fields.

[10] http://science.energy.gov/~/media/ber/pdf/CESD_EUworkshop_report.pdf, page 1-3,
[11] Schalkwijk et al, Weather Forecasting using GPU-based Large-Eddy Simulations, Bulletin of the American Meteorological Society 2014 ; doi: http://dx.doi.org/10.1175/BAMS-D-14-00114.1,
[12] Neggers et al, Continuous single-column model evaluation at a permanent meteorological supersite, Bulletin of the American Meteorological Society, 93, 1389-1400 (2012),
[13] Neggers, R. A. J., and A. P. Siebesma, Constraining a system of interacting parameterizations through multiple-parameter evaluation , J. of Climate 26 6698-6715 (2013)

Skies over Holland: instruments, observations, simulations



The results of the Skies over Holland research program will be used to develop the 'first principles approach' for the representation of atmospheric processes in models – that is to minimize the impact of parameterizations by letting the models resolve the small scale processes based on physical laws rather than approximate them empirically. Most notably we will use the following models:

- DNS: Direct Numerical Simulation model that solves the governing equations up to the smallest turbulence eddy scales, which can be used to study cloud droplet formation and their collisions
- DALES: three-dimensional LES model including the meteorological state variables, land representation including photosynthesis, gas-phase chemistry and inorganic. organic aerosol formation;
- GALES: real-time GPU-based three-dimensional LES model including the meteorological state variables
- CLASS: a mixed-layer model to study the same processes as DALES in a conceptual manner
- WUSCM (Wageningen University Single Column Model): One-dimensional model based on the state of the art ECMWF physics.
- WRF: a three-dimensional weather research and forecasting model, which can also include CO_2 and chemistry.
- HARMONIE: the high-resolution weather forecast model and regional climate model operated at KNMI
- EC-EARTH: European coupled Earth system model
- ECHAM: the general circulation model developed at Max Planck Institute in Germany
- LDMZ: the general circulation model developed at IPSL in France
- WALRUS: a hydrological model for lowland areas developed at Wageningen University
- LOTOS-EUROS: a regional; chemistry transport including dynamic aerosol formation schemes, jointly developed, operated and maintained by TNO, RIVM, KNMI and PBL.
- TM5: a global three dimensional transport and chemistry model including zoom-in capabilities

Note that the above mentioned models allow for nesting and zooming in order to grid resolutions needed for specific heterogeneous areas, such as cities.

The research program is organized in five themes:

Theme	Title	Principal investigator	Participating research groups
A	From trace gas to cloud condensation nucleus	Prof. Thomas Roeckmann - UU	WU, DUT, KNMI, TNO, ECN, RIVM, UU
B	Cloud dynamics	Prof. Pier Siebesma – DUT and KNMI	KNMI, WU, TNO, DUT, UU
C	Land-atmosphere interaction	Dr. Jordi Vila – WU	WU, DUT, UU, KNMI, ECN
D	Rainfall	Prof. Herman Russchenberg - DUT	DUT, WU, KNMI, UU
E	Air Quality	Drs. Daan Swart - RIVM	RIVM, TNO, KNMI, ECN, DUT

A: From trace gas to cloud condensation nucleus. This sub-program aims at enhancing knowledge of the physical and chemical processes through which secondary aerosols are formed via nucleation from trace gases in the atmosphere and knowledge on how primary and secondary aerosols become cloud condensation nuclei: the building blocks of cloud droplets. Since trace gases and primary aerosols have both natural and anthropogenic sources, this theme also deals with the question of the anthropogenic influence on cloud formation. Key questions addressed are:

- What are the prevailing chemical and physical characteristics of aerosols that determine their capacity to act as cloud condensation nuclei?
- What are the dynamics of water partitioning between the gas phase and condensed phase? Can that partitioning be better understood by using the isotopic composition of water vapour and its relation to supersaturation?
- How do organic components affect the nucleation, mixing state and hygroscopic properties of aerosols? What is their average lifetime and how does this influence aerosol formation?
- What is the spatial distribution of aerosols? How are cloud condensation nuclei related to local sources and sinks of aerosols? Can we distinguish natural and anthropogenic sources?
- How do aerosols and cloud condensation nuclei change during vertical transport towards the cloud base?

Models: DALES, GALES, WRF, ECHAM, LMDZ, LOTOS-EUROS, TM5

B: Cloud dynamics. The processes through which cloud droplets are formed is complex: not only does it depend on the aerosol background, but also on thermo-dynamic processes in and outside the cloud. Key questions are:

- What is the relationship between cloud condensation nuclei and the resulting cloud microstructure? How do aerosols change the cloud lifetime and precipitation efficiency?
- Can we understand and predict the ventilation of heat, moisture and aerosols from the boundary layer into the cloud layer?
- What are the dominant factors controlling cloud dynamics and how do they relate to the observed cloud properties?
- How do in-cloud processes (condensation, evaporation, coalescence, clustering) determine the cloud droplet statistical distributions?
- How does the 3D spatial distribution of clouds impact the radiative transfer processes?

Models: DNS, DALES, GALES, HARMONIE, EC-EARTH

C: Land – atmosphere interaction. Clouds and aerosols exist due to multi-scale exchange processes at the land surface and they influence the radiation and energy at the surface. Water vapour and aerosols need to be lifted upward. This transport occurs through the turbulent formation of thermals that as roots of boundary-layer clouds. Key questions are:

- Can we realistically model the conditions under which convection can be initiated? What is the influence of surface heterogeneity on the spatial and temporal distribution of energy and water fluxes?
- How does the vertical structure of the boundary layer impact the energy balance at the surface, and more specifically the different responses of vegetation to direct and diffuse radiation perturbed by clouds and aerosol?
- How does the surface energy partitioning influence cloud formation?
- What are the responses of vegetation that regulates surface evaporation under extreme weather situations like heatwaves and droughts?
- What is the response of greenhouse gas exchange to changing climate conditions?

Models: *GALES, DALES, CLASS, WUSCM, WRF*

D: Rainfall. The process of rainfall formation is still poorly understood. Forecasting rain – timing, location, and amount - is even more difficult. This is due to the intertwining of in-cloud microphysical processes and multi-scale atmospheric dynamics. This sub-program aims at a better description of the micro and macro structure of rainfall, and the embedding in atmospheric dynamics. Key questions are:

- How are raindrops formed – in cold and warm rain processes? Which processes (turbulence, evaporation) determine the evolution of the raindrop size distribution from cloud base to ground level?
- How do meso-scale dynamical processes drive local extremes in rainfall (intensity, location, duration)?
- What is the temporal and spatial distribution of rainfall within a large-scale meteorological system?
- Most rain never reaches the ground. Which percentage of rain evaporates while falling? How does this affect the evolution of raindrop size distributions from cloud base to ground level? Does this leave an imprint on the isotopic composition of rain?

Models: *GALES, DALES, HARMONIE, WALRUS*

E: Air Quality. The driving force behind air quality questions is changing: from meeting thresholds to optimising both health-impact and economic consequences in an integral approach. As densely populated areas contain the vast majority of the population in western Europe, there is a strong need for more detailed, higher resolution air quality information in urban areas. In addition, new information sources are becoming available, like high resolution satellites and the cheaper sensors of city-projects and citizen science projects. Key questions are:

- How do we set up a model scheme for air quality at an adequate resolution, at least in the urban areas, to facilitate the integrated health and economics driven approach indicated above?
- How do we include dynamic real time emissions at adequate scale (e.g. dynamic traffic info)?
- How do we include meteorology at adequate scale (e.g. heat island, wind in street canyons, interaction with buildings and trees)?
- How do we optimally assimilate measurements, both existing (national monitoring networks) and new (satellites, cheap sensors)?
- How do we assess and maintain the quality of the new data streams, as information sources now become widely diverse both in type and quality?
- What are the consequences of climate change for air quality, and vice versa: what are the implications of changes in air quality for the (mitigation of) climate change? Here too, an integrated approach is called for.

Models: Lotos-Euros, OPS, other models in the EU Copernicus ensemble

A2: THE TECHNICAL CASE

The Ruisdael Observatory will consist of
- a nationwide ubiquitous network of stationary and mobile sensors to measure the 3D physical and chemical state of the atmosphere and its interaction with the land surface,
- two advanced anchor stations: the already existing, rural, CESAR Observatory[14] and a new urban station in the Randstad agglomeration;
- a computational facility for real-time assimilation of the observations into high-resolution atmospheric models.

Dictated by the inhomogeneity of the landscape, the network of Ruisdael Observatory will be of a heterogeneous nature: not all nodes will be equally equipped with instrumentation, and the nodes will not be evenly spatially distributed. The domain of the network will also extend over parts of the North Sea and include sensors at the offshore wind farms. Particular emphasis will be given to the Randstad domain: densely populated urban areas are critically sensitive to the consequences of climate change. To this end we will develop an advanced anchor station – a scaled-down version of CESAR-Observatory in Cabauw – in the urban environment, as well as an instrumented mobile vehicle to enable measurements in dedicated campaigns. The observatory will operate at the full scale of The Netherlands at the unprecedented horizontal spatial resolution of one kilometre, augmented with selected (urban) regions of even higher resolution to zoom in on specific processes, and vertical observations with a resolution of 50 meter.

Even though the observatory includes existing observational networks of (largely) localized point measurements, the major advancement of the observatory will lie in its expansion with new stations that are capable of three-dimensional measurements, and the real-time assimilation of data in atmospheric models. These next-generation stations will be developed under the Ruisdael Observatory umbrella and will significantly extend the capabilities of the current state of the art. A next generation station will include – aside from current technology (such as the present weather sensors and in-situ air quality monitoring) - new remote sensing instruments such as scanning radars, radiometers and lidars (see Table 1 for an overview of possible instruments). The optimal combination of instruments and the optimal configuration of the network will follow from Ruisdael research in a separate design study.

The computational facility is the crucial unifying factor in Ruisdael Laboratory for enabling the real-time assimilation of data in the atmospheric models. The approach of joint real-time modelling and measurements is, however, not straightforward. New information-communication technology is required to collect, assimilate, store, visualize and disseminate the data in real time. The Netherlands eScience Center (NLeSC) will play a coordinating role in the development of the Ruisdael computational facility.

Existing networks and instruments that will be integrated in Ruisdael Observatory are:
- the measuring network of RIVM (50 measurement points include: PM2.5, PM10, NO2, SO2, CO, benzene, toluene, xylene, ozone, rainwater composition, particulate composition);
- the weather observation field of Wageningen University;

[14] www.cesar-observatory.nl

- KNMI's network of 40 synoptic stations for meteorological reference measurements (temperature, humidity, air pressure, wind, radiation, cloud height etc.);
- the network of measuring points on offshore oil platforms which supplies data to the KNMI, offshore windfarms
- the research radars of TU Delft in Delft and Rotterdam.

The standard instruments in the network will be based on state-of-the-art, but proven technology. After all, quality assurance and control is key here to ensure 24/7 operation. In addition, at the CESAR anchor station scientifically advanced instrumentation, or new prototypes thereof, will be deployed; the CESAR station also serves as a test bed for new technology. Of particular interest are new and fast developments in new data sources such as citizen science/crowd sourcing/big data and unmanned air vehicles. We will develop strategies to include these in the observation programs of Ruisdael Observatory. Furthermore, we will investigate the inclusion of 'networks of opportunity' like data collected by telecom providers, transport companies and energy providers. The data base of Ruisdael Observatory will be connected to data bases of the operational KNMI weather radars, and satellite observations from Meteosat, Modis, TES, IMG, GPM and upcoming missions such as TROPOMI, ADM-Aeolus and EarthCare.

Typically, the next generation stations will consist of a selection of instruments from Table 1. The selection per station depends on the heterogeneity of the environment, and the specific research questions at hand.

Table 1 Instruments for Ruisdael Observatory

#	*Instrument*	*Parameters*	*Specifics*
1	35 GHz cloud radar	Spatial structure of cloud microphysics; wind, turbulence	Water, ice, mixed-phase clouds only; no rain
2	10 GHz urban rainfall radar	Spatial structure of microphysics, of rain and clouds; wind, turbulence	Mainly rain; limited sensitivity to clouds
3	3 GHz rain and clear air radar	Vertical profile of microphysics of rain and ice clouds; wind, turbulence	No water clouds; rain, ice and mixed phase clouds; above 200m
4	Micro rain radar network	Vertical profile of microphysics of rain	Rain below 200 meter
5	Disdrometer network	Rain microphysics at the ground	Horizontal distribution of drop size spectra at the ground
6	Distributed Temperature Sensor	Soil temperature and moisture, and evaporation; air temperature, humidity profiles	Shallow sub-surface, evaporation, surface layer
7	Doppler wind lidar	Aerosol optical properties, wind vector	Horizontal distribution
8	Scanning backscatter lidar	Horizontal fields aerosol optical properties	Horizontal distribution
9	Scintillometer network	Turbulent fluxes of heat and water vapour	Horizontal distribution
10	scanning-TD-PTR-MS (thermal-desorption proton-transfer-reaction mass-spectrometer)	Aerosol chemical composition, aerosol pre-cursor trace gases	Local observation, size resolved (range 10-800nm) organic aerosol composition, organic aerosol pre-cursor trace gases.
11	ACSM (aerosol chemical speciation monitor)	Aerosol chemical composition	Local observation, major chemical aerosol species (ammonia, nitrate, sulphate, organics, chloride)
12	Light-weight/Compact SMPSs (Scanning Mobility Particle Sizers)	Aerosols particles size distribution	Local observation, size distributions (10 – 500 nm)
13	Nano-SMPS (size distribution	Nucleation-mode aerosol size	Local observation, size

	measurement: sub-10-nm range)	distribution	distribution (range 1 – 10 nm)
14	HTDMA (hygroscopic tandem differential mobility analyzer)	Aerosol particle hygroscopicity	Local observation, size resolved hygroscopicity (range 10-800 nm)
15	Picarro L2120-i analyzer (isotopic water analyzer)	Isotopic composition atmospheric water	Local observation
16	CCN counter	Size distribution cloud condensation nuclei	Local observation
17	Pyranometers	Variability of broadband solar irradiance at ground level	Horizontal distribution
18	IR cameras	IR soil temperature	Horizontal distribution
19	Mast energy fluxes	Turbulent fluxes	Local observation
20	Raman lidar	Water vapour and temperature	Vertical profile
21	Lysimeter	Evaporation by vegetation	Local observation
22	Mobile phone radiowave links	Rainfall	Horizontal distribution
23	Marga ion chromatography	Aeroscol and reactive gas chemical composition.	major chemical aerosol species (ammonia, sulphur sixide, ammonium, nitrate, sulphate, chloride, sodium, calcium etc)
24	MaxDoas	trace gases and aerosol	Vertical column
25	High quality in situ air quality monitoring instruments	NO, NO2, NH3, Ozone, Aerosols: PM10, PM2.5, soot, aerosol composition	Vertical profile
26	Air quality lidars	NO2, NH3, Ozone, aerosols	Vertical profiles
27	Sunphotometer	Aerosols	Vertical column

B. EMBEDDING AND CONTEXT

International context

Worldwide, the present facilities to study the atmosphere lack the ability to routinely link data and models at different spatial and temporal scales, which is essential for improvement of the reliability of climate change predictions. The pioneering Dutch approach of real time confrontation of observations and thermodynamic atmospheric models to test and evaluate model performance is currently findings its way to other observatories as JOYCE in Germany[15] and the ARM observatory in Oklahoma in the USA. Following the recommendations of the first ARM-ACTRIS workshop[16], we now have to go to the required next level: including large-scale three-dimensional observations of clouds, aerosols and their interaction with the land surface, as well as confrontation with chemical and micro-physical models. In addition, Ruisdael Observatory will offer valuable, interesting datasets for validation of satellite based retrieval schemes as well as the development of new satellite missions. The Ruisdael Observatory is therefore a unique site with a large appeal to foreign scientists. It will maintain the Dutch position at the forefront of the international research community.

By Dutch law all data will be open and available to the community. The Ruisdael Observatory database will be coupled to the database infrastructure of ACTRIS to enable easy dissemination of data. The facility is open for scientists worldwide. The Ruisdael Observatory facility will play an important role in many international programs and networks (see Table 2). Most notably:

- it will be the Dutch contribution to the ESFRI-ACTRIS infrastructure for aerosol, trace gases and clouds;
- It will play an important role in the Dutch contribution to the greenhouse gas observations in ICOS

[15] Loehnert et al, Bull. American Meteorological Society 2014 ; doi: http://dx.doi.org/10.1175/BAMS-D-14-00105.1
[16] http://science.energy.gov/~/media/ber/pdf/CESD_EUworkshop_report.pdf

ERIC by improving transport models needed for using ICOS data

- COPERNICUS: Copernicus offers European information services based on Earth Observation satellite and in-situ (non-space) data analysis. Copernicus is a cooperation of the EU Member States, the European Space Agency (ESA), the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), the European Centre for medium-range Weather Forecasts (ECMWF), EU Agencies and Mercator Océan.

Table 2 Ruisdael Observatory and international networks

Program
WMO-GAW: Global atmosphere watch program GAW
CloudNet and ARM: US and European cloud and radiation program
GEWEX- CEOP: Coordinated Enhanced Observations Program
EMEP Superstation
AERONET station
ACCENT: European network of excellence on atmospheric composition change
EARLINET: European Aerosol Research Lidar Network to Establish an Aerosol Climatology
WMO-BSRN: Baseline surface radiation network
ACTRIS: Aerosol, clouds and trace gases infrastructure
ICOS: Integrated Carbon Observation system
InGOS: Integrated non-CO2 Observation System
GRUAN: GCOS Reference Upper Air Network
GMES/Copernicus: Global Monitoring for Environment and Security
GEOSS: Global Earth Observation System of Systems
GABLS: GEWEX Atmospheric Boundary Layer Study
GCOS: Global Climate Observation System

In short, the Ruisdael Observatory will be pivotal in many international programs and will attract a large number of international researchers and students for joint projects. The Ruisdael Observatory will strengthen the Dutch internationally leading position and attractiveness for international cooperation.

Socio-economic impact

There are at least two areas where Ruisdael will have a socio-economic impact: climate change and air quality. In both fields society has to develop effective strategies to counteract a potentially impeded economic growth and limit the costs of mitigation measures. More detailed and accurate knowledge as acquired in Ruisdael will facilitate an optimized balance between economic interest, public health and the impact of climate change. It will help assure that the Netherlands and Europe get the best environment at the lowest price. For air quality, current Dutch policies already try to seek this optimum balance by developing avenues to link economic growth to emission reductions. Such an approach is considered to be the blueprint for future environmental policies. It will be greatly facilitated by better data of human exposure to air pollution, more detailed observations and better process knowledge and modelling generated by Ruisdael Observatory. The consequences of predicted climate change are severe and large (public) investments are needed to cope with the effects of climate change. The current scenarios point to more frequent occurrence of extreme events such as heatwaves and severe rainstorms. These events will affect both urban and rural areas with potentially high economic and social damages:

- Cities are areas with high concentrations of population and industry. Worldwide, urbanization is continuing at a rapid pace. In 2014, already 54% of the world's population lived in urban areas with

a percentage of 66 predicted by 2050.[17] The capability of cities to cope with sudden heat stress or heavy rainfall is limited, and urban flooding will occur more frequently than in the past.
- Sudden heavy rainfall will cause a rise of surface waters which may cause flooding of large (rural) areas. Recent events in the UK, and the 2011 cloudburst in Copenhagen, have shown that this is by no means a phenomenon exclusive to developing countries.

Governments and other social stakeholders need reliable information to devise effective policies for both short term (operational) and long term (strategic) interventions[18]. The Ruisdael Observatory and associated research program cover both public needs:
- It clarifies the role of clouds and precipitation in climate change and enables more *accurate prediction of long term trends* to describe the context of future water management systems. This can be used in risk-based cost-benefit analyses to determine which structural measures should be taken to increase the storage and discharge capacity of the water system. The Netherlands has a long tradition in innovative water management, and the research teams of the Skies over Holland program are optimally suited to tackle the multi-disciplinary questions at hand.
- It enhances the capacity to design combined climate change and air pollution mitigation strategies, making cities healthier places to live in.
- KNMI Climate scenario's reveal that the probability of occurrence of droughts will increase in the next 50 years. This will lead to water scarcity. Then responsible governmental bodies should allocate the scarcely available water resources to different water consumers, such as agriculture, water transport, nature reserve areas, industry, energy supply, public water supply and sewage treatment. To this end reliable data are needed of soil moisture and actual evaporation of agricultural, nature reserve regions, rivers and lakes and urban regions.
- After the 2015 Paris Conference of the Parties – where the world community agreed to reduce the greenhouse gas emissions to such amounts that global warming will remain below two degrees with respect to pre-industrial times – governments will need to find efficient ways to enable the energy transition into a decarbonized society. The Ruisdael Observatory will be instrumental in optimizing the production of wind and solar energy farms, by producing accurate short term forecasts of wind and solar radiation as well as high resolution energy revenue atlases for planning activities.
- It enables early warning systems with improved reliability through the development of advanced observation and modelling strategies. A more accurate prediction of heavy rainstorms and other extreme weather events to enhance public safety and reduce economic damage will be possible. The expected international market for the needed decision support systems amounts to many million euros.

Knowledge transfer

The knowledge transfer and exchange approach consists of a comprehensive set of actions aimed at the different stakeholders:
- The Ruisdael Observatory partners publish results of the research in both scientific journals and journals for the non-scientific target groups
- The Ruisdael Observatory partners will regularly organise stakeholder workshops on resilience of cities to climate change, in cooperation with the Amsterdam Institute for Advanced Metropolitan Solutions and the Rotterdam Climate Initiative
- All Ruisdael Observatory data and model output will be freely available; selected data sets will be made available via the ACTRIS portal.
- The Ruisdael Observatory consortium will participate in many international programs and

[17] United Nations, Department of Economic and Social Affairs, Population Division (2014). *World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352).*
[18] Typical socio-economic stakeholders can be found in the realms of urban and rural water management, traffic, agriculture and tourism.

networks to ensure international dissemination of results and utilization of the facility

- The facility will be used as a training site for young scientists at MSc, PhD and post-doc level
- The observatory can be used by industry to test new technologies
- The universities of Utrecht, Wageningen and Delft are co-founders of the Climate KIC (www.climate-kic.org) and use the KIC to actively promote innovations based on Ruisdael Observatory developments. Note, one of the activities of the KIC is early-stage financing of start-up companies.
- Through KNMI, RIVM, TNO and ECN the knowledge gained within the Ruisdael Observatory will be applied to provide national and international policy support.
- The Ruisdael Observatory partners cooperate with new start-up companies on the development of high resolution forecasts of wind and solar energy.

C. ORGANIZATION

Organization

The Ruisdael Observatory is a joint initiative of the following research institutes and universities: the universities of Delft, Wageningen and Utrecht, KNMI, TNO, ECN, RIVM, NLeSC, and ESA-ESTEC. When it comes to observations, satellites and models Dutch atmospheric scientists are among the world leaders. The consortium has a long collaborative track record in national and international programs. The Skies over Holland research program is embedded in the strategies of the consortium members. The facility has a central and strong integrating effect on atmospheric and environmental science in The Netherlands: the multi-disciplinary character of atmospheric sciences naturally stimulates cooperation, and provides fertile grounds for the results of joint observations and campaigns. The consortium will continue to support the observatory during the exploitation phase of this program. The Netherlands eScience Center (NLeSC) is the national hub for the development and application of domain overarching software and methods for the scientific community. It is a joint initiative of the Dutch national research council (NWO) and the Dutch organization for ICT in higher education and research (SURF). NLeSC competence is the 'effective' analysis and 'efficient' computing of large amounts of complex data for streamed data and decision management. KNMI, TNO, RIVM also cooperate within National Modelling and Data Centre (NMDC), allowing for an efficient coordination of activities. Through the different cooperation schemes major advances have been made in an integrative approach, leading to a worldwide recognized leading position of the Dutch atmospheric research community. Table 3 list the Ruisdael Observatory partners, and key scientists.

Potential organization structure

The main organizational challenges of Ruisdael Observatory are efficient operation of the facility and effective cooperation between the stakeholders. Ruisdael Observatory relies on both scientific and programmatic coordination as well as the long term operation of integrated, well maintained facilities. This will require a clear and targeted organization structure of the observatory, structural funding, and full dedication of the involved staff. This calls for an autonomous organization with its own budget and governance. This organization could be a virtual institute, affiliated with the participating parties, an NWO/KNAW Institute, or an independent foundation on behalf of the participating parties. The foreseen stakeholders in this organization are the Ruisdael partners, possibly extended with the universities of Amsterdam and Groningen. As example may serve the National Centre for Atmospheric Research NCAR[19] in the US.

External users of Ruisdael's data products, such as space agencies and institutes, airports, railway and

[19] https://ncar.ucar.edu/home

other transport organizations, energy companies, offshore companies, or water boards, will be invited to participate directly in development, employment and exploitation of the observatory. This also applies to developing companies for apps and services based on Ruisdael's freely available data, to IT companies and to manufacturers of instruments and sensors.

Table 3: The Ruisdael partners

Institute	Expertise	Principal scientists
Delft University of Technology (DUT)	Atmospheric remote sensing, modelling and simulation, hydrology, aerosol characterization, mathematical physics, data assimilation, extreme statistics, boundary layer processes	Herman Russchenberg, Harm Jonker, Nick van de Giesen, George Biskos, Stephan de Roode, Miriam Coenders, Arnold Heemink, Bas van de Wiel, Alex Yarovoy, Pier Siebesma, Tim Vlemmix, Pieternel Levelt, Pepijn Veefkind
Wageningen University (WU)	Hydrology, meteorology, land-atmosphere interaction, scintillometry, atmospheric dynamics and chemistry modelling	Remko Uijlenhoet, Bert Holtslag, Jordi Vila, Maarten Krol, Ryan Teuling, Wilco Hazeleger
Utrecht University (UU)	Atmospheric chemistry, sensing, modelling	Thomas Röckmann, Rupert Holzinger, Maarten Krol
Royal Netherlands Meteorological Institute (KNMI)	Atmospheric sensing, climate, meteorology, modelling, forecasting, atmospheric chemistry	Pier Siebesma, Arnoud Apituley, Erik van Meijgaard, Dave Donovan, Reinout Boers, Hidde Leijnse, Henk Klein-Baltink, Wouter Knap, Fred Bosveld, Albert Klein Tank, Pieternel Levelt, Pepijn Veefkind, Henk Eskes, Folkert Boersma, Peter van Velthoven.
Energy Reseach Center of the Netherlands (ECN)	Atmospheric chemistry, mesoscale processes, aerosol physics, greenhouse gas measurements	Arjan Hensen, Ernie Wijers
Netherlands Organization for Applied Scientific Research (TNO)	Atmospheric physics	Bas Henzing, Martijn Schaap
National Institute for Public Health and the Environment RIVM	Modelling and measuring atmospheric composition for public health	Daan Swart, Guus Velders, Hester Volten, Stijn Berkhout, Erik Tielemans, Kees van Luijk
Netherlands eScience Center (NLeSC)	Computational Science	Wilco Hazeleger
European Space Agency	Satellite development and validation	Nicolas Floury

D. DEVELOPMENT STEPS

The following steps need to be taken:

1. Organize consortium and stakeholders:
   Organization structure, legal and financial aspects, data policy, business models, embedding in international programs, organizations and networks, organization of stakeholders, outreach

2. Design study:
   optimal spatial structure of the network, operational and research instruments, mobile/fixed sensors, synergy of data flows, measurement parameters, data assimilation techniques and procedures, modelling structure, data products, data base system

3. Prototype cases and build infrastructure for data processing:
   development of new network nodes with new functionalities, optimal computation facilities,

4. New instrument development:
   advanced scientific instrumentation, involvement of industries and new startups

5. Deployment:
   Integration of existing networks, expansion with new nodes and anchor stations

A 10-year development and implementation time is needed to fully realize Ruisdael Laboratory as a completely integrated measuring and computational facility.

Ruisdael Laboratory will be operational when the first existing networks are connected and the first existing models are integrated. Ruisdael Laboratory will be expanded gradually in terms of equipment and manpower needed.