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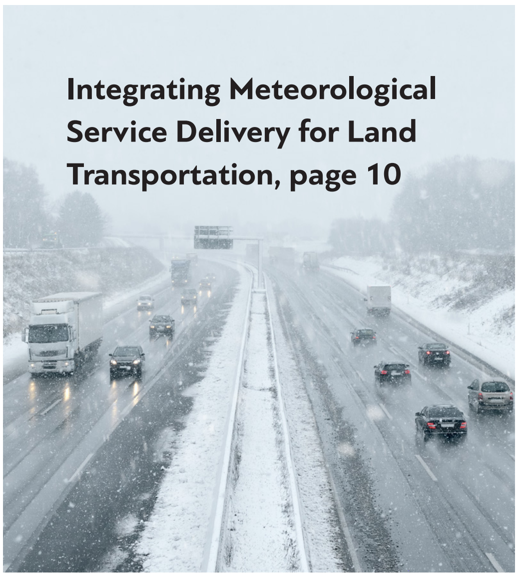
(Un)Natural Disasters: Communicating Linkages Between Extreme Events and Climate Change



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World Meteorological Organization (WMO)
7 bis avenue de la Paix Tel.: +41 (0) 22 730 8403
P.O. Box 2300 Fax.: +41 (0) 22 730 8040
CH-1211 Geneva 2 E-mail: publications@wmo.int
Switzerland

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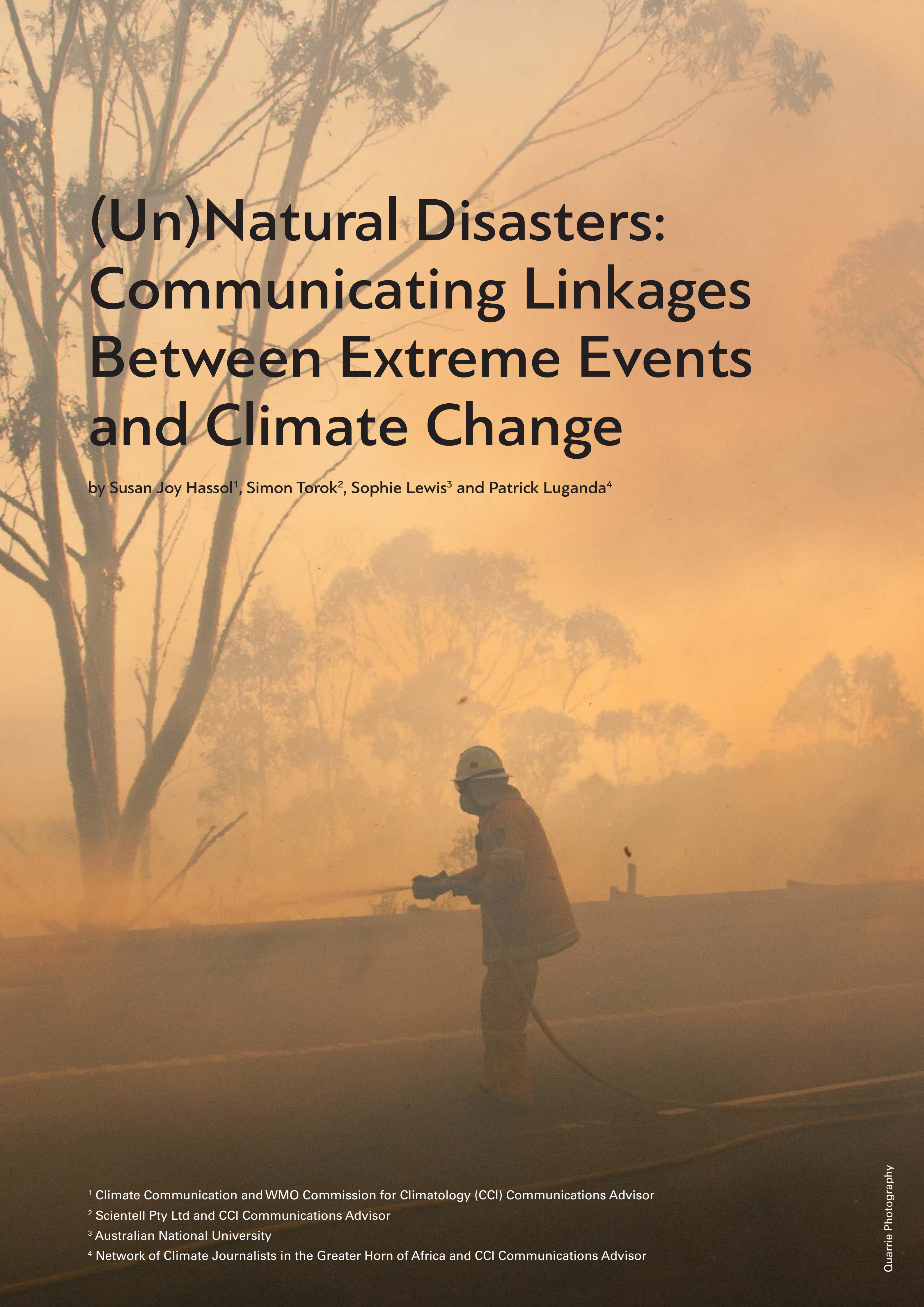

(Un)Natural Disasters: Communicating Linkages Between Extreme Events and Climate Change

by Susan Joy Hassol[1], Simon Torok[2], Sophie Lewis[3] and Patrick Luganda[4]

[1] Climate Communication and WMO Commission for Climatology (CCl) Communications Advisor
[2] Scientell Pty Ltd and CCl Communications Advisor
[3] Australian National University
[4] Network of Climate Journalists in the Greater Horn of Africa and CCl Communications Advisor

Quarrie Photography

The science of attributing extreme weather and climate events has progressed in recent years to enable an analysis of the role of human causes while an event is still in the media. However, there is still widespread confusion about the linkages between human-induced climate change and extreme weather, not only among the public, but also among some meteorologists and others in the scientific community. This is an issue of communication as well as of science. Many people have received the erroneous message that individual extreme weather events cannot be linked to human-induced climate change, while others attribute some weather events to climate change where there is no clear evidence of linkages. In order to advise adaptation planning and mitigation options, there is a need to communicate more effectively what the most up-to-date science says about event attribution, and to include appropriate information on linkages when reporting extreme weather and climate events in the media. This article reviews these issues, advancements in event attribution science, and offers suggestions for improvement in communication.

The weather seems to be getting wilder and weirder. People are noticing. What are the connections to human-caused climate change? And how can we best communicate what the most recent science is telling us about human-induced and natural changes to weather and climate?

When heavy rains led to devastating floods in the United Kingdom (UK) in January 2014, the then Prime Minister David Cameron stated that he "very much suspects" the floods were linked to climate change. A scientific analysis had concluded that climate change had increased the chances of the rainfall that caused the flooding by an estimated 43% (Schaller et al, 2016). The fact is that warmer air holds more moisture, which generally leads to heavier rainfall. The potential for damage from such extreme events is also increasing, as higher river levels put more properties at risk from flooding; the 2014 UK floods cost US$ 646 million (£451 million) in insurance losses, one of the highest in history (Schaller et al, 2016).

In Australia, the summer of 2013 was the hottest on record. The sustained high temperatures were linked to bushfires in the country's southeast and severe flooding in its northeast. Conditions were so severe it was dubbed "the angry summer" (Steffen, 2013). According to a scientific analysis, the record heat that summer was made at least five times more likely – a 500% increase in the odds of it occurring – by human-caused warming. This conclusion, using the observed temperature record and climate models, was made with more than 90% confidence (Lewis and Karoly, 2013).

The 2014 UK flooding and 2013 Australian heat wave are just two recent extreme events that scientists have determined were considerably more likely to occur due to human-caused climate change. Such heat waves and heavy downpours are among the classes of extreme events that tend to be more frequent and/or more severe in a warmer world.

Sergeant (Sgt) Mitch Moore/MOD

Flooding hits a town in Oxfordshire, United Kingdom, during the widespread floods of early 2014

But not all extremes are increasing. For example, there has been an overall decrease in the number of very cold days and nights, as would be expected in a warming world. Still, the Intergovernmental Panel on Climate Change (IPCC) in its 2012 report on extremes wrote: "A changing climate leads to changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events" (Field et al, 2012). Nonetheless, scientific findings that specific extreme weather and climate events can, in fact, be attributed to human-caused climate change have not been widely reflected in public understanding.

Lost in translation

While scientists have known for decades that changes in some classes of extreme weather would result from climate change, the science of attributing individual extreme events to global warming has only advanced significantly in recent years to cover a greater number of extremes and achieve a greater speed of scientific analysis. Unfortunately, the communication of this science outside the extreme event research community has, with a few notable exceptions, not fully reflected these advances. The media, politicians and some scientists outside this area of research still often claim that "we can't attribute any individual event to climate change." This may have been true in the 1990s, but it is no longer the case.

A changing climate leads to changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events. — *IPCC*

Part of the problem is that for a long time many scientists themselves repeated this message. They stuck to the generic explanation that many of the extreme weather events witnessed in recent years were consistent with projections of climate change, although the science had moved well beyond this general explanation to specific event attribution. However, there are some cases in which scientists can say more about attributing the underlying factors behind an extreme event than about the specifics of the event itself. This complexity can create confusion and lead to missed communication opportunities. Hence, it is not surprising that it is taking a while for public awareness to catch up with the science.

Another issue for communication is that the response of the climate system to warming includes intensifying the water cycle, leading, for example, to both more droughts and more floods. If the mechanisms by which this occurs – that is higher air temperatures dry out soils, and a warmer atmosphere holds more moisture leading to heavier precipitation – are not explained to non-scientists, the combination of both wetter and drier conditions can seem counter-intuitive.

Furthermore, the causes of specific extremes can be seen as politically charged in some countries where, unfortunately, climate change has become a partisan issue. For example, in the aftermath of an extreme event, such as a fire or flood, some people may see it as insensitive and/or political to discuss human-induced causes of loss of life or property.

The need for better communication

Why is it important to better communicate the linkages between extreme events and climate change? The scientific attribution of specific extreme events has become a research avenue with important benefits to society. Both under-attribution or over-attribution could lead to poor adaptive decision-making, jeopardizing infrastructure, human health and more. Being able to rapidly analyse the attribution of extreme weather and climate events and comment while an event is still in the media is a significant scientific

Los Angeles Times

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Climate plan tests familiar battle lines

Obama's new rules on emissions would burnish his legacy but also highlight a deep political divide.

BY DAVID LAUTER

WASHINGTON — With Monday's release of landmark rules to combat global warming, President Obama is putting into place what probably will be the last piece of his ambitious second-term agenda — one that highlights deep divisions in the country and helps shape the race to succeed him.

On immigration, health-care, same-sex marriage and now climate change, Obama has aggressively used the powers of his office to align public policy with the values and aspirations of a largely urban, liberal and minority constituency heavily concentrated on the East and West coasts.

In the process, he has courted a backlash from Republican constituencies and states — an older, whiter population concentrated in the South and the nation's interior.

That division was plain to see in reactions to the new rules, which are intended to change how the nation generates electricity in order to cut emissions of carbon dioxide and other gases blamed for warming the world's climate.

Over the next 15 years, the plan would aim to sharply reduce the use of coal and ramp up the use of wind and solar power. Currently, coal accounts for almost 40% of the nation's electricity, whereas wind and solar produce about 5%. By 2030, if the administration's plan works, renewables would account for 28% of U.S. power generation, edging past coal at 27%.

The plan would boost efforts already underway, mostly in coastal states and led by California, to greatly increase the use of renewable power.

But for those parts of the country still heavily reliant on coal, nearly all of them Republican-governed states in the Midwest, Great Plains and South, the rules would force a major economic transition that many elected officials have vowed to resist.

[See Obama, A4]

JUSTIN SULLIVAN Getty Images

OCEANSIDE FIRE DEPARTMENT Capt. Greg DeAvila shoots a flare into dry brush during a burn operation. The Rocky fire started Wednesday near Clear Lake, about 100 miles northwest of Sacramento.

Heat, drought-parched brush fuel ferocious fire

Official says Northern California blaze is unprecedented this early in the season.

the fire exploded, charring 20,000 acres in one five-hour stretch that a fire official called "historic, unprecedented." Throughout the night, when wildfires typically slow down in the rela-

Failure to connect the dots: This wildfire coverage is devoid of any mention of a climate change linkage. This is particularly ironic as it appears alongside an article about climate policy.

and communication advance, which has the potential to reduce future vulnerability to extremes. Such an assessment of risk requires a scientific basis, rather than an opinion based on personal perceptions, media reporting, or in response to political discourse.

Recent research suggests that personal experience of extreme weather has only a small, short-lived effect on what people think about climate change. If an extreme event was experienced more than three months ago, the effect on an individual's view on climate change largely disappears (Konisky et al, 2015). People do not necessarily make the connections that have been shown by scientific analysis to exist between extreme weather and climate change. If they had help connecting the dots – that is, if scientific linkages were clearly articulated and reported more often and more accurately in the media – perhaps the effect of extreme weather on peoples' views would be greater, leading to better planning to adapt to changes, improved behavioural change, and more action on climate change.

Media reporting of climate change and extremes

Even as occurrences of certain classes of extreme events have increased, the media in some countries have not kept pace in communicating the scientific understanding of the connection between climate change and extremes.

For example, in the United States of America (U.S.), an August 2015 study by Media Matters for America (MMA) showed that top newspapers ran coverage of wildfires and of the U.S. Clean Power Plan side-by-side (see image above), but failed to mention the role of human-induced climate change in an unseasonably early wildfire season (MMA, August 2015). While calling the wildfires "the new normal," major California newspapers neglected to give any explanation of the cause of this new normal (e.g., Westerling et al, 2006). Similarly, in June 2016 MMA noted a reversal of progress in attributing extreme events to climate change

when media failed to portray links between climate change and the May-June floods in Texas. They noted that major U.S. broadcast news networks ignored climate change in their coverage of the flooding, marking a deterioration in coverage of the linkages since 2015 when networks covered the science connecting climate change to the May 2015 Texas floods (MMA, June 2016).

When the media does cover climate change impacts, the focus is overwhelmingly on extreme weather events. A study of network television coverage in the U.S. in 2015 revealed that coverage of extreme events outpaced all other climate change impacts, including those to public health and the economy (MMA, March 2016). In June 2015, as powerful floods struck Texas, some media stepped up their coverage of the link between heavy rainfall and climate change (MMA, June 2015). While not as widespread as they should be, there have been other examples of good media coverage of the linkages between extreme weather and climate change. However, there is still room for improvement when it comes to media coverage of extreme weather events as the most visible impacts of climate change.

There is a clear opportunity for the media to discuss the most visible impacts of climate change in their coverage of weather disasters, though it is an opportunity that is missed far too often.

In terms of understanding the linkages between extreme weather and human-induced climate change, the public also tends to be swayed by the views of prominent leaders, even when those views are at odds with the science. For example, an analysis of the record-breaking spring high temperatures that occurred in Australia in 2013 and 2014 showed that the human influence on climate made those record high temperatures substantially more probable (Lewis and Karoly, 2014). Another analysis found that these extreme temperatures were very unlikely to have occurred in the absence of human-caused climate change (Gallant and Lewis, 2016). However, public statements from a prominent leader contradicted these analyses, promoting the view that natural variations and the lengthening period of record could account for the recent heat extremes. Although these views could not be reconciled with the science, they were widely reported and have persisted in public understanding of extreme events.

Evolving science

The science of attributing individual extreme weather events to climate change dates back to a 2003 commentary in Nature in which climate researcher Myles Allen raised the question of liability for damages from extreme events that may have been influenced by human-induced climate change (Allen, 2003). This was soon followed by a 2004 research study by Peter Stott and colleagues that examined the 2003 European heat wave associated with more than 35 000 deaths and found that climate change had more than doubled the risk of such extreme heat – the best estimate is that it made it four times more likely (Stott et al, 2004). These early studies laid the foundations of the techniques for using climate models to analyse the linkages between extreme weather events and human-induced climate change.

Many subsequent studies attributing extreme weather and climate events use a probabilistic approach to determine and communicate the Fraction of

Attributable Risk (Stone and Allen, 2005). This approach is widely used in health and population studies to quantify the contribution of a risk factor to the occurrence of a disease – for example, how much smoking increases the risk of lung cancer. Similarly, evaluating how much climate change alters the probabilities of certain classes of extreme weather events is central to the science of extreme event attribution. Scientists calculate the probability of an extreme weather event occurring in climate model experiments incorporating both human and natural factors; they then compare these probabilities to a parallel set of experiments that include only natural factors. In this way, natural and human climate influences can be separated to determine how much the risk of a particular event changed due to the human influence on climate.

The level of scientific confidence in an attribution result, and the uncertainty around the link between climate change and certain classes of extreme events, depends on several factors. First, scientists require a robust physical understanding of the mechanisms behind a category of events such as heatwaves, floods, hurricanes, or droughts. Next, scientists require high-quality observations so they can determine if the occurrence of this type of event is changing in the observational record. Finally, climate models must be able to accurately simulate and reproduce the relevant class of extreme event.

In several studies, these three factors have aligned and attribution statements have had a high level of confidence. For example, there is great clarity and confidence in attributing heat events that occur over large areas and extended time periods. The physics are well understood, changes are documented in observations, and they are simulated accurately in climate models. For example, in Australia, 2013 was a year of heat extremes with the hottest day, week, month, summer and year on record. Two separate studies found that the 2013 extreme heat in Australia would have been virtually impossible without human-caused climate change (Knutson et al, 2014; Lewis and Karoly, 2014).

Individual precipitation events present a different set of challenges than temperature extremes. Scientists are confident in the high-level understanding that human-caused intensification of the hydrologic cycle can generally lead both to more floods and more droughts. By increasing the amount of water vapour in the atmosphere, human-induced warming has increased the amount of rain falling in heavy downpours, which can lead to flooding. So there is confidence in both the mechanism and the observed trends, and this indicates a linkage to climate change even in the absence of a formal, model-based attribution study. However, for those relying on such modelling studies, high confidence in attribution of specific events requires that models simulate such processes correctly at small spatial scales, and this can be challenging. Furthermore, in addition to occurring more often in a warmer world, these events often have other mechanisms at work, weather conditions such as blocking high-pressure systems and sea surface temperature patterns (e.g., Dole et al, 2011). While attribution studies have found a human signal in some recent extreme flooding events (Pall et al, 2011; Schaller et al, 2016), the signal is smaller and often less clear than for temperatures as a result of modelling challenges and complex climate mechanisms.

Two separate studies found that the 2013 extreme heat in Australia would have been virtually impossible without human-caused climate change.

Scientific extreme event attribution studies typically focus on quantifying risks and likelihoods. It is also true that extreme weather events now occur within a climate system where the background conditions have changed. As such, no weather is entirely "natural" anymore, but rather occurs in the context of a changed climate. That is, "Global warming is contributing to an increased incidence of extreme weather because the environment in which all storms form has changed from human activities" (Trenberth, 2011, USA Today). Every event has been influenced by climate change to some extent through increases in heat, atmospheric moisture and sea level, which all influence how extreme events play out (Trenberth et al, 2015). A more detailed understanding of what the human-induced signal means for the risks of specific extreme events may enable us to more effectively advise decision-making.

In addition, all extremes are occurring in a naturally variable and chaotic climate system. Extreme events are always a result of natural variability and human-induced climate change, which cannot be entirely disentangled. Scientific attribution approaches focused on extremes of heat, drought, flooding, rainfall or storms aim to provide a meaningful understanding of the relative natural and human influences on an extreme event. Hence, each observed extreme event must be considered explicitly in order to provide the most useful information. Similarly, the failure to attribute an event to human causes with a high level of confidence does not negate or challenge the broader understanding of human-caused climate change. Attribution results that are clear and have a high level of confidence in a substantial human cause, or alternatively demonstrate a strong element of natural climate variability, can be equally useful for providing information for planning in a warmer world.

The latest evolution in attribution science is to analyse extreme events in near-real time. The World Weather Attribution project and a similar effort in Europe (EUCLIEA; Stott, 2016) are international efforts to sharpen and accelerate our ability to analyse and communicate the influence of climate change on extreme weather events. The World Weather Attribution project analysed the major flooding in France and nearby countries in June 2016 that closed the Louvre museum, forced the evacuation of thousands, left tens of thousands without power, killed more than a dozen people, and caused damages estimated at over a billion Euros in France alone. The researchers found that the probability of 3-day extreme rainfall in this season has increased by about 80% on the Seine and about 90% on the Loire (World Weather Attribution, 2016).

Improving communication

The suggestions below for more effective communication are based on many years of experience communicating climate science and the links between climate change and extreme weather. When interacting with the media following an extreme event, these suggestions may help scientists to more effectively and accurately communicate the role of climate change in influencing the event.

1. Lead with what is known. Rather than starting with caveats, uncertainties, and what we cannot say (Somerville and Hassol, 2011), a discussion of attribution of extreme weather should begin with how human-induced climate change is affecting the type of extreme weather at issue. For example, "We know that in a warming world, we experience more frequent and severe heat waves. And we see that trend clearly in the data. This event is part of that trend." Then discuss any studies relating to the specific extreme weather event being discussed, such as those that quantify the altered chances of the event when this information is available from research. For example, "Global warming made this heat wave at least four times more likely to occur, or increased the odds of this event by 400%."

2. Communicate clearly and simply the mechanisms behind the changes brought on by warming. For example, "A warmer atmosphere holds more moisture, leading to heavier rainfall."

3. Use metaphors, which can effectively help explain how human-induced warming changes the odds of extreme weather events. For example, "heat-trapping gases act like steroids in the climate system, increasing the odds of extreme heat, heavy downpours, and some other types of extreme events. We're now experiencing the weather on steroids." This communicates that even though extreme events do occur naturally, many types are now happening more frequently and more intensely. Similarly, global warming "is loading the dice toward more rolls of extreme events," or "is stacking the deck" in favour of such outcomes.

4. When discussing extreme weather events that have not been clearly attributed to climate change by scientific analyses, it is useful to reiterate our basic understanding of human-induced climate change and to decouple that from the attribution of a particular event. Explain that, "we know climate change is happening now, and is human-caused, even if we can't be certain that it is a direct cause of this particular event."

5. Reframe poorly posed questions. Scientists being interviewed are often asked, "Did climate change cause this event?" Reasons for asking such a

question can relate to liability, context, planning and more. However, it remains a poorly posed question, with no simple yes or no answer, due to the multiple factors involved in all events. Interviewees can reframe their responses to be more appropriate and informative, for example, describing how the probabilities of these types of events are changing as a result of human-induced warming and identifying particular events that are very unlikely to have occurred in the absence of human-caused climate change.

6. Communicate about confidence and uncertainty in language appropriate for the public. Scientists have a lexicon that can be useful for communicating with each other about these issues, but it is important to remember that many words mean entirely different things to scientists than they do to the public (Hassol, 2008; Somerville and Hassol, 2011). For example, scientists often use the word "uncertainty" to discuss the envelope of future climate scenarios, or the range of model results for a particular attribution finding, but to the public, "uncertainty" means we just don't know. Thus, referring to "a range" is better than calling it "uncertainty." Similarly, scientists may describe a finding as being "low confidence" for reasons having to do with data or model issues, but this does not mean there is no observed trend or no projected change as the public might assume from this language.

7. As with any public communication about climate change, try to avoid language that can lead to despair and hence inaction. For example, rather than calling further increases in extreme weather "inevitable," we can discuss the choice we face between a future with more climate change and larger increases in extreme weather, and one with less. The future is in our hands.

A community responsibility

Changes in extreme weather and climate events are the primary way that most people experience climate change. Human-induced global warming has already increased the number and strength of some extreme events (Melillo et al., 2014). The science in this arena is rapidly evolving. This makes it imperative that we accurately communicate the scientific linkages between extremes and climate change, so that people can make informed decisions about actions to limit the risks posed by these events.

As part of this rapid evolution in scientific capacity to attribute extremes to their causes, and given the increase in frequency and severity of extremes, some scientists have asked if the burden of proof should shift from having to prove that there is a human effect on a particular weather event, to having to prove that there is no such effect. Since the human influence on climate is well established, and all events take place in that changed environment, they argue that the question should no longer be "is there a human component," but "what is it?" (e.g., Trenberth, 2011).

...the choice we face [is] between a future with more climate change and larger increases in extreme weather, and one with less. The future is in our hands.

As climate change progresses, and the science of event attribution evolves, people will continue to ask questions about – and the media will continue to report on – how we are influencing extreme weather and how extreme weather is affecting us. It is the responsibility of the climate and weather science and communication communities to keep up with the evolving science and to work diligently at communicating the latest and best science for the benefit of society.

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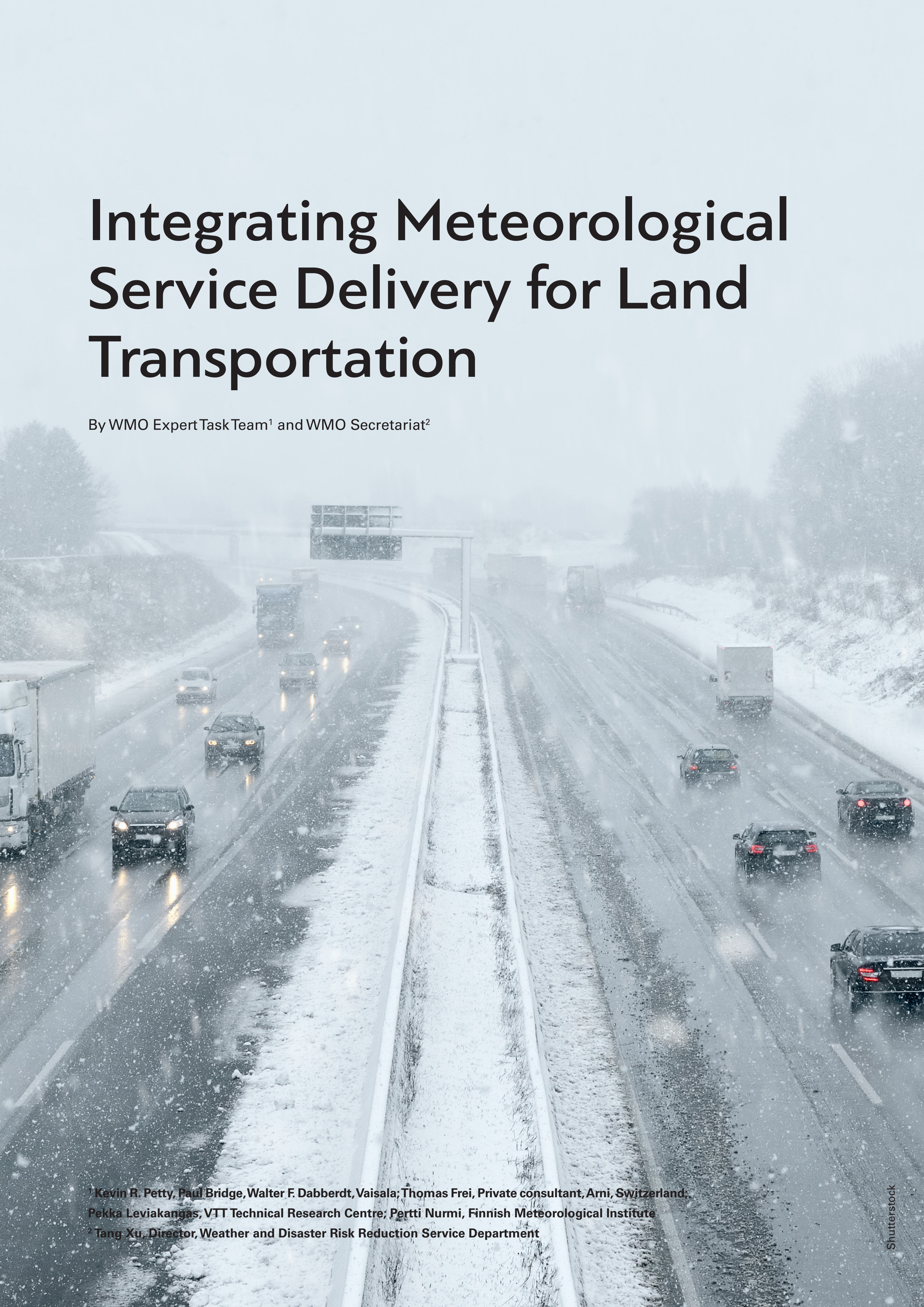

Integrating Meteorological Service Delivery for Land Transportation

By WMO Expert Task Team[1] and WMO Secretariat[2]

[1] Kevin R. Petty, Paul Bridge, Walter F. Dabberdt, Vaisala; Thomas Frei, Private consultant, Arni, Switzerland; Pekka Leviakangas, VTT Technical Research Centre; Pertti Nurmi, Finnish Meteorological Institute

[2] Tang Xu, Director, Weather and Disaster Risk Reduction Service Department

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Today, the aviation, marine and land transportation sectors each use their own approaches to deal with the effects of high-impact weather on the safety, efficiency and continuity of their operations. Each also uses its own distinct and separate customized weather information. However, the movement of people and goods in our modern world is mostly multi-modal and highly integrated. In order to mitigate the impact of weather on the performance of the transport system, there is a need to deliver meteorological services in an integrated, seamless manner.[1]

It is the integration of meteorological service delivery for land transport that will be the biggest challenge for National Meteorological and Hydrological Services (NMHSs). The land transport network is much less regulated and harmonized, especially at the national and international levels, than that of the aviation and the marine sectors[3]. The weather vulnerability of land transport compared to aviation and maritime transport is painfully apparent in the accident statistics. Data from the U.S.[4] indicate that weather-related road accidents result in nearly 6 000 deaths per year with more than US$ 40 billion in economic loss. The economic impact of air traffic delays attributed to weather, while considerable, is only about 10% of the economic impact of weather-related highway losses. With this in mind, there would seem to be considerable value in using the aviation and marine experiences as benchmarks that provide valuable "lessons learned" in the development of standards and guidance for the seamless, integrated meteorological service delivery concept for land transport.

NMHSs have a leading role to play in facilitating the development and implementation of integrated meteorological service delivery; however, public-private partnerships will be essential. In most cases, the NMHSs are well-positioned to provide the foundational elements to effectively support integrated service delivery. Nonetheless, it would be a mistake to minimize the relevance of private companies with long histories of providing user-specific weather guidance to the transport industry. The partnership model will depend on a plethora of factors such as NMHS capacity and capability, local practices and culture, resource availability, geography, types of end users, and transport system makeup and maturity. Public-private partnerships, in various forms, will be vital in fulfilling the integrated meteorological service delivery paradigm.

Requirements

Weather-based Integrated Service Delivery refers to the optimized network that results from a unified response to adverse weather conditions. That includes the common situational awareness and understanding that is gained through the seamless availability, use, and communication of tailored weather information and decision-support services. In the case of transportation systems, the ultimate objective is to achieve an "integrated service delivery" capability across multiple transport modalities.

This would mean that in moving goods or people from Point A to Point C, for example, it would be necessary to consider the net effect of adverse weather: at the departure terminal (Point A); along a rail line (Point A to Point B), at a transit hub (Point B), along a highway (Point B to Point C), and at the arrival terminal (Point C). And since the journey will last many hours and cover perhaps hundreds of kilometres, the weather impacts will need to be considered at different times and multiple locations. It is also important to keep in mind that the same weather conditions, for example, freezing rain could have very different impacts at different points – and for different users – along the route. It can be a very complex and complicated process.

[3] Meteorological service delivery is highly standardized for enroute flight operations while service delivery for (ground) terminal operations is not.

[4] National Research Council, 2010.

The impacts of extreme weather on transport are well understood for most sectors; however, it remains a significant challenge to quantify and mitigate these impacts across multiple sectors, across various time and space scales, and within and across geopolitical boundaries. This will require addressing a variety of considerations such as identifying user-specific requirements; optimizing weather, road, rail and traffic measurements; using and blending multiple forecasting techniques, including nowcasts and numerical weather predictions; improving communications and message delivery; and seamlessly integrating across multiple transport sectors. The minimum requirements are likely be a seamless suite of observations, forecasts and decision-support services. With integrated service delivery, reliability, relevance, quality and other key weather information value added attributes for end-users will often be common to multiple transport modes, yet there will be some information that is unique to each mode and even to each user within a mode.

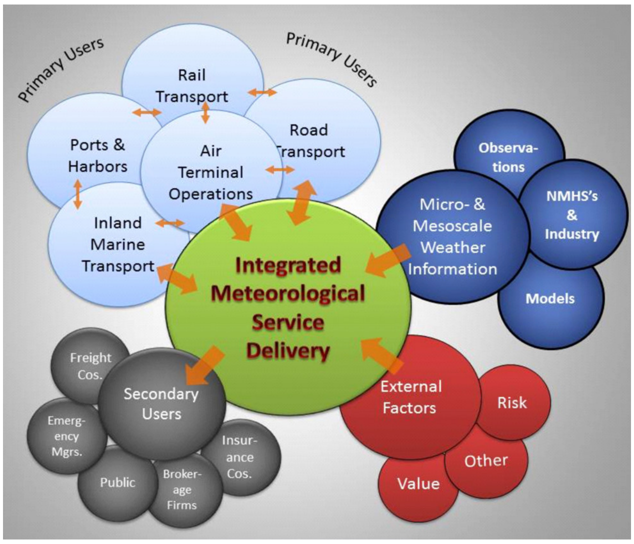
Integrated weather-based services will have to be tailored to fit the needs of the different user groups, including:

- Trucking, airline, bus and shipping companies
- Transport users (e.g. postal services, medical supply companies, general public)
- Airport operators, airline companies and service providers
- Public and private motorway maintenance organizations
- Emergency managers
- Harbour masters
- Railroad companies

To provide actionable guidance – that is, decision support – it will ultimately be necessary to fully assess and understand the implications of an integrated service delivery approach on all stakeholders. It will be equally important to educate users and decision-makers to understand the weather services provided in order for them to optimize use throughout their value chain. This essential step will underscore the added benefit from improved and seamless weather information services. As transport networks are increasingly global, the need for coordination and standardization is also urgent.

Framing the integration challenge

Advances in meteorological observations, in analysis tools and their application, in weather forecast models, unified approaches across transport modes, as well as cultural changes on both sides by the weather providers and the stakeholder organizations, will be necessary in order to attain a viable level of integrated service delivery. An evolutionary process – that could begin by ensuring there is a common situational awareness across the transport sector during high-impact weather events – would probably be best. Following that, the weather-related challenges that arise at and between the interconnections among modes (i.e. multimodal integration) and among stakeholders will need to be addressed. This latter step will ultimately be the most important challenge in the process.



"Integrated meteorological service delivery" is the seamless provision of standardized weather-dependent decision-support services across any or all interconnected surface transport modes: airports, ports and harbours, rivers, lakes, roads and rail.

A first step could be to use a relatively mature and well-focused user group to frame the multi-modal integration challenge. This would facilitate the creation of a strategy for developing, testing and documenting best practices, which could be translated to other end-user groups. Ideally, this mature user group would already be experienced with, and understand, the impacts of weather and the need for seamless meteorological service delivery across multiple transport modes – the "curb-to-curb" challenge. A candidate user group might be selected, for example, from among global

Weather Parameters	Category of Weather Advisory	Impacts
Precipitation elements	Freezing precipitation, snow accumulation, liquid precipitation, precipitable water vapour, soil moisture, flooding, water body depths, fire weather	Loss of traction and control, delays, reduced speeds, stresses on vehicle components and tyres, rules on tyre chains, wet road surface, road spray, flooding causing road closures, re-routing, weak and uneven braking, intermodal impacts, softened railroad beds, roadbed scouring; drought causing risk of dust and smoke reducing visibility, highway closures, intermodal impacts from barge shutdowns
Thunderstorm-related	Severe storm cell tracks, lightning, hail, straight line winds	Acute, rapidly changing conditions with multiple risks of collisions and damage from loss of control, impaired visibility; rock slides causing risk of collisions and delays, damage to infrastructure, blocked railroads
Temperature-related	Air and surface temperature, including maximum and minimum, first occurrence of season, heat index, cooling or heating degree days	Stresses on vehicle components, infrastructure and, at high temperatures, perishable cargoes, rail buckling, reduced speeds on rails
Winds	Wind speed	Vehicle instability, loss of control, blow-overs
Visibility	Restrictions from fog, haze, dust, smog and sun glare, upper atmosphere restrictions from volcanic and desert dust	Reduced speed, risk of collisions and damage from rapid change
Sea state	Tropical cyclones including tracks and elements affecting evacuation routs, open-water sea ice, high surf, storm surge, abnormal high or low tides, freezing spray, hurricane winds, sea state, flooding, wind wave height, sea wave height	Supply chain disruptions, road closures, extensive damage to infrastructure and vehicles, obstructions blocked rails; sea-level rise, risk and damage to infrastructure, changes in agricultural and manufacturing production and shipments

The weather parameters, a categorization of weather advisories based on those parameters, and their impacts on transportation (from McGuirk M. et al., 2009)

logistics service providers, emergency management responders or multimodal hub operators.

Integrated land transport services of the future will also depend on advances in a number of meteorological tools and capabilities, including atmospheric and "surface-state" measurement systems, data assimilation methods and numerical weather prediction (NWP) models, and localized nowcasting methods. For example, advances in measurement systems could provide enhanced capabilities to routinely and accurately determine the type and rate of precipitation as it reaches ground level, the depth, intensity and granularity of fog, and so forth. Better NWP models could improve the spatial and temporal resolution – and the accuracy – of the forecasts of atmospheric conditions. A review of the observational requirements for the surface transport sector with those for existing WMO application areas could also identify gaps.

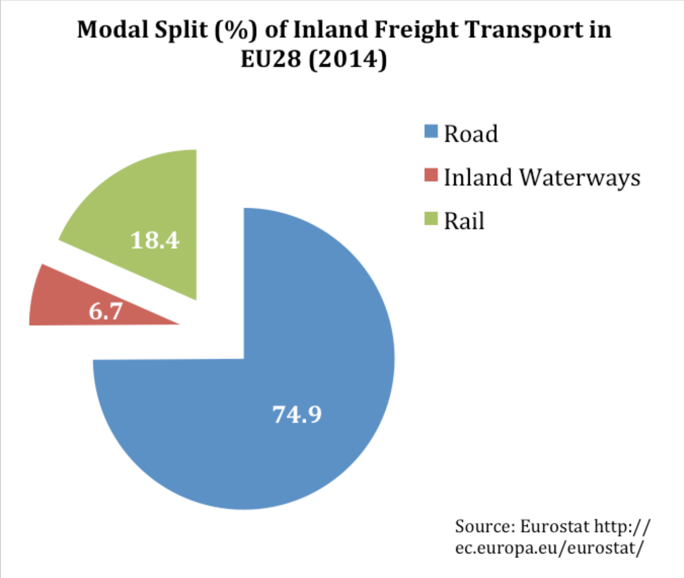
Leveraging change

Coming technical, cultural and climate changes will impact on the integrated meteorological service delivery paradigm. Below are a few examples of which service providers will have to keep abreast. Rapidly developing technologies throughout the transport system are opening new possibilities for more advanced weather services for transport system managers and end users alike. For example, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) capabilities are already in the testing phase and will be introduced in earnest over the next decade.The vehicles themselves will serve as weather sensing platforms, resulting in real-time mobile observations capable of enhancing weather analysis and forecasting.

The road sector is experiencing a technological revolution. Development of autonomous vehicles is quickly

Economic Transport Benefits

The transport sector is an important component of the economy. The level of economic development is highly dependent on the quantity and quality of transport infrastructure. In the European Union, for example, road freight transport is the main inland transport mode, accounting for over 70% of all inland transport activity.



moving forward. In fact, semi-autonomous features are already available on some production vehicles, and several manufacturers have announced they will introduce autonomous vehicles five years from now. Automation is also leading to broader-scale control strategies such as vehicle platooning, where the separation of vehicles is managed in an effort to increase safety, improve efficiency, optimize infrastructure usage, and reduce environmental impacts. However, the sensing technologies – LIDAR, radar, radio, etc. – being used in support of the automotive industry's transformation are sensitive to environmental conditions, thus impacting their performance. It will be essential to fully understand and address the impacts of extreme weather on these technologies in order to ensure the safety of the traveling public. On the other hand, these on-board systems might also serve as another valuable source of local weather and climate information.

Other emerging weather and climate observing platforms include unmanned aerial and marine systems. The proliferation of unmanned systems holds considerable promise for providing additional opportunities to gain a better understanding of weather and climate conditions, particularly in areas difficult to access with conventional measurement systems. The availability of timely, dense observations of the lowest few kilometres of the atmosphere, as well as observations in and over the oceans, will become more commonplace as these systems evolve. These observations will help advance the understanding and prediction of high-impact weather conditions that affect land transport.

Many public data streams that are currently only available for a fee are likely to become free and easily accessible. Cloud-based service models offer unprecedented prospects for wider use of weather and climate information and data. Communication channels are also certain to change in unpredictable ways. One thing is certain: meteorological information of all types will become more accessible to more interested user groups (public and private alike) at lower costs.

The increased availability of observations and computational resources, along with advances in numerical modelling, will contribute to ever-improving weather and climate information for end users. In addition, the rise of techniques such as data mining and machine learning will help to fuel new weather-related products and services. Those surrounding the communication of impacts are of special interest to many stakeholders. Through the combination of conventional weather data (e.g. observations, forecasts, etc.) and ancillary transport data (e.g. traffic, traffic flow, etc.), new weather-related, impact-based capabilities are emerging. These impact-based products and services can give transport operators and the traveling public improved insight into the anticipated impacts resulting from adverse weather conditions or climate change, enabling more effective mitigation strategies.

Contribute to a global effort

WMO recognizes the importance of weather and related environmental services for land transport as well as the role of public-private partnerships in service delivery. The Seventeenth World Meteorological Congress in June 2015 reaffirmed the commitment of WMO to the integrated service delivery paradigm.

The development of seamless integration of meteorological service delivery for land transport remains a considerable challenge but can be a fundamental step in mitigating the impacts of adverse weather on land transport systems, improving safety, efficiency and economic loss. It will not be easy. Development and implementation will likely require an evolutionary approach based on a succession of "baby steps" rather than a giant leap forward. WMO, through its programmes and the NMHSs of its Members, will have to take on a leading role.

The ultimate goal is service delivery that meets the needs of the transport operators and users, ensuring the safe, effective and efficient operation of the transport network, whether it is global, national, regional or local. Interestingly, the World Health Organization (WHO) has declared 2011-2020 as the decade of traffic safety; an integrated weather service delivery capability for land transport would surely make a significant contribution to this global effort.

The ultimate goal is service delivery that meets the needs of the transport operators and users, ensuring the safe, effective and efficient operation of the transport network, whether it is global, national, regional or local.

NASA

The Weather Enterprise: A Global Public-Private Partnership

by Alan Thorpe[1]

[1] Former Director General of the European Centre for Medium-Range Weather Forecasts (ECMWF)

At the recent WMO 68th Executive Council meeting in June, a special dialogue took place on co-operation between the public and private sectors in meteorology. Here a speaker at that session gives his personal view on the discussion and the next steps that are needed.

The weather enterprise is a well-established and successful global public-private partnership in which both sectors share common goals. There are new opportunities emerging to develop this partnership further that will enable the whole enterprise to grow and produce more accurate and reliable weather forecasts[2]. The urgency to do this comes from the need to be even more effective in saving lives and protecting infrastructure because of vulnerability to weather hazards in a changing climate.

The scientific and technological success story

The development of weather forecasting is a scientific and technological success story. In what amounts to a scientific revolution[3] – albeit a quiet one taking many decades of progressive innovations – by 2012 it was possible to predict as extreme and unusual a hurricane as Sandy with around one week of advance warning.

Yet today, and into the future, people and infrastructure are increasingly vulnerable to weather hazards because of population increase, where people live and climate change. Therefore, the requirements society, business and governments have for accurate and reliable weather forecasts are growing rapidly.

The public-private global weather enterprise is rising to this challenge but within a context that is radically different from the one that has pertained thus far. New approaches are required to grasp opportunities and to deliver what is needed.

How has the quiet revolution happened?

Three crucial ingredients came together over the last half century: Advances in weather science, including in modelling the global Earth system, innovation in observing the atmosphere, oceans and land surface, and a revolution in computing. Without all three, it would have been impossible to contemplate modern weather forecasting. When Vilhelm Bjerknes dreamed in 1904 of weather prediction using the laws of physics, it could not be realized[4] but today, through both public and private contributions, the necessary ingredients have been brought together to make his dream reality.

Whilst most weather science has come from academia and research institutes, including those within national meteorological and hydrological services (NMHSs), innovation in observing and computing has had major contributions from the private sector. Today, some of the world's largest companies at the heart of the global economy, for example in the space and computing industry, contribute to weather infrastructure. It is clear that the weather enterprise is a global public-private partnership.

It is crucial to recognize that this revolution, and so the public-private partnership, has required a fundamentally global approach as atmospheric circulation means that weather in one location is determined by prior events all over the world.

What of the future?

The need for more science, observations and computing power is enduring and continues to be the way forward to improve weather forecasts. However, the context for

2 See for example "Integrating Meteorological Service Delivery for Land Transportation" on page 10 of this issue.

3 Bauer, P., Thorpe, A. J., and Brunet, G.: The quiet revolution of numerical weather prediction. Nature, 525, 47-55 (2015)

4 Bjerknes, V.: Das Problem der Wettervorhersage betrachtet vom Stadtpunkt der Mechanik und Physik, Meteorol. Z., 21, 1-7 (1904)

the weather enterprise is evolving rapidly today as exponential improvements in technology, including those driven by other industries, are creating exceptional opportunities to deliver even higher quality weather forecasts.

A key challenge is to mobilize sufficient human ingenuity to bring about innovation for the creation of more science, observations and computing. In turn, this innovation requires that sufficient financial resources be brought to bear. In the public sector, the availability of funds from governments is under heavy pressure. However, the private sector is undergoing significant development and growth.

What can the private sector offer?

The private sector is efficient in raising and deploying private (venture) capital particularly for high-tech developments in measurement and computing/data technology. If providing a data service, the private sector would also enable a transfer of risk, such as that associated with building, launching and operating satellites, from the public sector. Using its resources, the private sector could also assist in technology transfer to developing countries, for example, through World Bank funding.

In general, the private sector is recognized as capable and efficient in operationalizing innovation that has arisen from public sector investment in research and development – many governments invest in science in large part for this purpose. Many small and large companies already add value to public numerical weather prediction (NWP) data and disseminate weather forecasts widely.[5]

Recent developments in the private sector

Two examples are illustrative of how the weather enterprise context is changing. The first is that the development of small satellites – CubeSat[6] – means that the cost of launching some new instruments into space for Earth observation is relatively low and also that the rapidity and number of new launches can be greatly increased. These facts mean that new small-to-medium sized companies are coming into existence utilizing private capital to launch satellites for meteorology – this is new and presents real opportunities.

These companies are interested in providing a data service – they see themselves in the data business as opposed to purely space hardware. This is also relatively new for the weather enterprise as in the past the cost and risk of launching and operating satellites was borne within the public sector. This requires new business models to be devised to ensure data availability; this would not imply more funding being made available but rather would require a re-structuring of how funding is allocated and risk apportioned. There are other companies which, building on the work originally carried out by some NMHSs, have developed instrument payloads for mounting on commercial aircraft that as a by-product enable a channel for aircraft-to-ground communications.

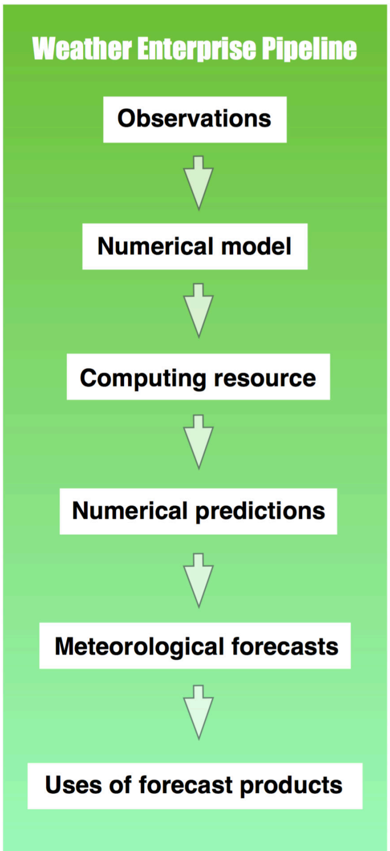
The second example relates to the countless developments and innovations in computing. For example, the growth of cloud computing or more generally distributed and remote computing capability has enabled companies and others to purchase computer cycles without the need to maintain their own supercomputing facilities. Then, there is the development of next generation computer chips that enable lower power consumption and enhanced performance. As NWP codes are not ideally structured for such next generation architectures, a much closer interaction between model developers and hardware/software vendors is needed if new technology is to be exploited. Typical procurement cycles by the major NWP centres are much slower - even ponderous- compared to the rapid developments in the computer industry. Another innovation is the growth of location-specific data, often generated by data analytics bringing diverse data sources together to stream them to mobile phones and tablets. As weather forecasts are the most popular applications on such platforms, private data companies see the potential to bundle many other data with the weather forecasts, thereby ensuring that weather forecasts get into the hands of those who most need them.

5 Pettifer, R.: The Development of the Commercial Weather Services Market in Europe 1970 – 2012, Meteorol. Appl. DOI: 10.1002/met.1470 (2014)

6 http://www.cubesat.org/about/

A consequence of these developments is that some companies are recognizing that it is within their reach, and of significant commercial interest, to perform operational global and regional NWP themselves and to use private observational data services. The market for tailored forecast data of relevance for a wide range of weather-dependent business sectors is expanding and providing new customers for the private sector.

Roles for both



What does this evolution and growth of the private sector component mean for the weather enterprise? Inevitably, because the private sector is becoming much more involved in nearly all elements of the pipeline that goes from observations to tailored weather products (see Figure at right), the respective roles of the public and private sectors are evolving. Secondly, the weather enterprise is growing because of scientific and technological innovation, the need to rise to the challenge of producing better weather forecasts, and the growth of the private sector.

This is good news. It means that there is a strong incentive for both the public and private sectors to work together in a more pervasive and sustainable partnership. Both sectors can benefit in these circumstances; the weather enterprise is not a zero-sum game.

But growing misunderstandings and even mistrust about the respective roles of the public and private sector are becoming stumbling blocks to further progress of the weather enterprise partnership. There needs to be a much greater engagement between the two sectors to dispel perceived obstacles and to change the underlying mindset. The mission statements of most organizations involved in the weather enterprise, whether they be from the public or private sectors, are very similar and focus on the need to enhance the ability of weather forecasts to save lives and protect property. Mistrust arises because of a lack of knowledge and clarity about the respective roles of the two sectors and regarding how they can best work together.

Evolution of the public sector role

An indication of the thinking taking place within NMHSs on these issues is provided by the recently approved "2016–2025 Strategy of the European NMHSs", which has been agreed by 35 European NMHSs. This strategy states that: "In response to the anticipated growth of the private meteorology sector, the distinct roles of the European NMHSs with respect to data collection, model development, research, warnings and alerts need to be established, while at the same time collaboration with the private sector is stimulated."

A key role for the public sector is in the long-term research and development needed to improve understanding of weather and in the use of that knowledge within NWP modelling codes. Private companies recognize

that the weather enterprise has been built, and must continue to be built, on public sector investment in both the backbone of global observations and in basic research and development. However, the private sector can contribute in these areas by, for example, funding specific research projects.

For this public sector responsibility to be carried out, taxpayers, that is to say governments, have to be persuaded to provide funding. The private sector needs to step up to provide the ammunition to win that argument. Many governments understand that at the heart of a modern knowledge-based economy is public investment in science and technology. It is an investment that pays back, amongst others, in the economic benefits that accrue from jobs and wealth creation due to private sector exploitation of this innovation and open access to public data. This is evidently already the case in the weather enterprise – a very good news story to tell.

Some in the public sector are worried about the emergence of observational data services in the private sector and the possibility that this might cause a breakdown in the current global arrangements whereby such data, paid for by national public investments, are shared free-of-charge via the WMO World Weather Watch. But with the risks come real opportunities for many more observations to be made. Private sector companies have indicated their support for WMO Resolution 40 and commitment to demonstrating the quality of their product as well as a desire to engage in a constructive way. To mitigate these risks, constructive and active engagement is needed between public and private sectors.

The weather forecasting role

Another area that needs more clarity is in the provision of information from operational NWP. The vast information stream from models can be used for the public weather forecast as well as for the tailored information needed for specific users. Public weather forecasts are designed to have wide utility, including to provide early warning of impending severe and hazardous weather. They are usually constructed from standardized sub-sets of the data output from NWP models. The tailored information needed by specific users can be constructed from these standardized data outputs using a variety of tools including post-processing/calibration, forecaster interpretation, and other value-adding techniques. But they can also be created by using non-standard data outputs to produce specific "forecasts" for particular uses/users.

NMHSs view it as crucial that they remain the single authoritative voice within their countries to warn the public regarding hazardous weather and for national security purposes. On the other hand, it is becoming clear that both NMHS and private companies are capable of creating operational global and regional NWP forecasts in-house. Private companies can and do tailor the information from NWP for a variety of business (and indeed public) customers. Private companies that run operational NWP models themselves would be able to produce both types of tailored information mentioned above. And for countries that lack the basic infrastructure there is the potential for non-national organizations, including private companies, to provide the public weather forecast also.

Complementarity

A market differentiation defining complementary roles may, therefore, be possible and desirable. Where possible, NMHSs would continue to provide the public and national contingency services with warnings and the private sector companies would provide business customers with tailored products. Again, constructive dialogue would seem essential to clarify these respective roles to at minimum prevent any confusion arising from multiple sources of weather forecasts.

However, it has to be recognized that duplication already exists regarding public weather forecasts as witnessed by the plethora of weather apps – the distinction between a forecast and a warning is perhaps lost on the public. It may be time for the WMO to consider a quality-assurance approach to inform the public of the inherent quality of the underlying forecast data in the various apps.

Regional diversity

The global framework of the weather enterprise belies large regional variations. Levels of public national investment in the weather enterprise are dramatically

different between countries as is the interplay between the public and private sectors. Even for countries with large public contributions to the weather enterprise, the regulatory environment governing the functioning of each NMHS, set by national governments, differs significantly.

On the other hand, many developing countries struggle to provide sufficient public funds to enable a national capability in weather forecasting. This means that there are opportunities for private companies, universities and NMHSs to operate in a trans-national fashion. It is important in such an environment that the basic national infrastructure, as an essential contribution to the global observing system, is established and maintained in all countries.

In conclusion

The weather enterprise is today a global public-private partnership and indeed some estimates suggest that it is around a 50:50 partnership. Dependencies between the public and private sectors mean that they cannot survive acting on their own. Innovation in observing and computing technology and the existence of private capital is enabling the private sector component of the weather enterprise to grow rapidly. Indeed, the domain of global operational NWP is also seen as within scope of the private sector. But this can only be successfully built on the public sector investment in research and development in weather science and in the global observing system.

What is needed urgently is a constructive dialogue between leaders across the public and private sectors to co-design these developments for the benefit of the weather enterprise as a whole. It will be most beneficial for both sectors if collaboration rather than competition is the norm. Of course there are issues to be addressed and the WMO is the right organization to galvanize the sectors for mutual benefit (see text-box for the outcomes of the WMO Executive Council special dialogue[7]).

The urgency to do this comes from the need to devise more accurate and reliable weather forecasts to be even more effective in saving lives and protecting infrastructure at a time of increasing vulnerability to weather hazards due to changing climate. There is a need to convene a PPP Summit of leaders across the public and private sectors to address key issues of mutual interest.

Next steps to enhance Cooperation between the Public and Private Sector

WMO will develop a Strategy for Cooperation between the Public and Private Sector for the next 15 years to elaborate on the following aspects:

1. Assess experience, good practices, opportunities and risks associated with private sector engagement;
2. To develop draft principles for private sector engagement based on the key issues;
3. To propose mechanisms and structures to foster dialogue and consultations, taking into consideration global, regional and national specifics;
4. To propose options for future governance of public-private partnerships and directions for development of WMO guidance to Members.

Acknowledgments

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References available in the online version.

[7] WMO Executive Council 68: EC-68/Doc.12(4) Public-Private Partnerships

Outcomes of COP21 and the IPCC

by Jonathan Lynn and Werani Zabula, IPCC

The Intergovernmental Panel on Climate Change (IPCC), which provides policymakers with scientific information about climate change, made a big contribution to the Paris Agreement to tackle global warming. The Agreement in turn has major implications for the work of the IPCC. This article examines these implications and what the IPCC is doing to help implement The Agreement.

What is the IPCC?

The IPCC was set up by the World Meteorological Organizations and the United Nations Environmental Programme (UNEP) to provide the world with a clear view of the state of knowledge on climate change and its potential environmental and social-economic impacts. To do this, the IPCC reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change and provides policymakers with an assessment of what is known and not known about climate change and what can be done about it.

It is a unique partnership between governments who are members of the IPCC and the scientific community who work on the assessments. An underlying principle of the Panel is that its work is policy relevant without being policy prescriptive.

IPCC and the UNFCCC

One of the most important indicators of the policy relevance of the work of the IPCC is the use of its reports in international climate negotiations like the Conference of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC). As stated on the UNFCCC website, the COP uses the information in IPCC reports as a baseline on the state of knowledge on climate change when making science based decisions.

Since science underpins the work of the Climate Change Convention, the IPCC works closely with UNFCCC's Subsidiary Body for Scientific and Technological Advice (SBSTA). With its most recent report, the Fifth Assessment Report (AR5), the IPCC presented its finding to SBSTA. The IPCC also took part in the Structured Expert Dialogue and Research Dialogue initiatives which provided the negotiators with an in-depth understanding of the scientific issues and contributed to their negotiations in the run up to the Paris Agreement.

IPCC and the Paris Agreement

The Paris Agreement reached at COP21 last December mentions the IPCC several times. The Agreement aims to reduce greenhouse gas emissions in order to limit the rise in global average temperature to well below 2°C above pre-industrial levels, with an effort to limit the increase to 1.5°C. It will to do this through measures set by each country – Nationally Determined Contributions (NDCs) – and reviewed regularly. Each Party shall regularly provide information on anthropogenic emissions by sources and removals by sinks of greenhouse gases, using methodologies accepted by the IPCC and agreed by the COP. As a result of this, the IPCC at its 43rd Session in April decided to refine and update these methodologies by May 2019 in order to provide a sound scientific basis for future international climate action especially under the Paris Agreement. Work on this is already underway and a decision on

the outline of a Methodology Report to supplement the current 2006 IPCC Guidelines for National Greenhouse Gas Inventories will be made at the 44th Session of the IPCC scheduled for 17–20 October.

In decision 1/CP.21 of the Paris Agreement, Parties invited the IPCC to provide by 2018, a Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. The 43rd Session of the IPCC Session accepted this invitation and work has started on the Special Report. The outline of the report will be approved at the Panel's 44th Session in October 2016. The Special Report will be finalized in September 2018 in time for the initial facilitative dialogue, which will be a first informal review under the global stocktake process.

The Parties also requested SBSTA to advise them on how IPCC assessments can inform the global stocktake of the implementation of the Paris Agreement. Under the Agreement, Parties are set to make an initial informal review of their collective efforts to reach their goals in 2018, and starting in 2023 they will hold a global stocktake every five years. Since the global stocktake will use the latest reports of the IPCC as one of its inputs, the IPCC also agreed to consider by 2018 how best to align its work during the Seventh Assessment Report (which will take place from 2023-2028) with the needs of the global stocktake process. During the UNFCCC summer meetings in May, a SBSTA-IPCC special event took place in Bonn, Germany, which allowed for an open exchange of views between Parties and representatives of the IPCC on how the Panel's Assessments can inform the global stocktake.

IPCC and the 22nd Conference of the Parties

During the COP22 meetings in Marrakesh, Morocco in November, the IPCC will host two side events. The first one, entitled "Refinement of the 2006 IPCC Guideline: Enhancing transparency in support of the Paris Agreement," will be held at lunch time on 7 November. This side event will present the approved outline of the methodology report to supplement IPCC's 2006 Guidelines.

On the evening of 14 November 2016, the IPCC will be presenting its work plan for the next 6 years and showing how the planned IPCC products support the implementation of the Paris Agreement. The side event is rightly titled "Responding to Paris: the IPCC's programme for the coming years". The event will be an opportunity to discuss the timing of the different products that the IPCC will produce during its Sixth Assessment Cycle. These include three Special Reports, a Methodology Report and the Sixth Assessment Report (AR6).

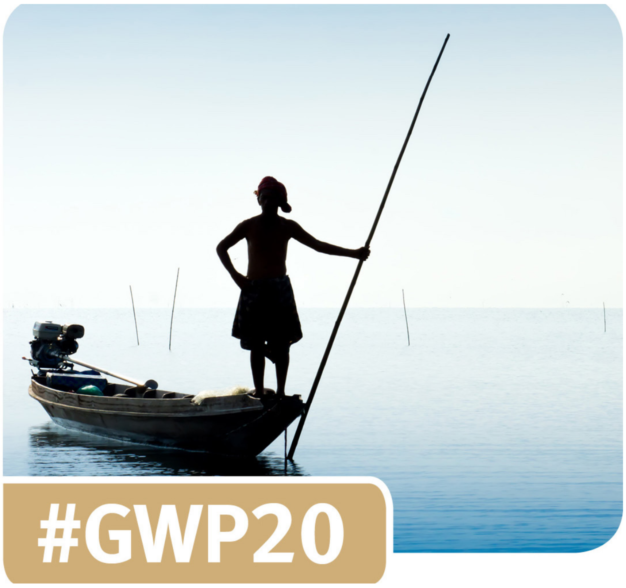
IPCC Chair Hoesung Lee speaking during the high level event of COP 21 in Paris, France on 7 December 2015

In addition to the Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, the IPCC will produce two more Special Reports in 2019. One will be on climate change and oceans and the cryosphere; and the other on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

The Working Group contributions to the AR6 will be delivered in 2021 and the AR6 Synthesis Report in the first half of 2022 well in time for the COP to use its findings during the first global stocktake set to take place in 2023.

20 Years of Impact – Working in Partnership on Water

by Steven Downey and Frederik Pischke[1]



One certainty about sustainable development is that it will not be possible without taking climate change into account. And if there is a certainty about climate change, it is that humanity will not adapt to it without taking into account water resources management. In September 2015 when 193 countries at the United Nations adopted the 2030 Agenda for Sustainable Development and its Sustainable Development Goals (SDGs) these two certainties so greatly influenced decision-making that goal #6 was dedicated to water. SDG #6 is not only about the urgent need for clean water and sanitation for everyone. It encompasses the full range of issues around managing water resources, including the work of the Global Water Partnership (GWP) for an integrated approach to water use by all economic sectors.

GWP began to support governments in applying a cross-sector approach to water resources management 20 years ago (1996), when the partnership was launched. In 2002, when GWP became an intergovernmental organization, the WMO was a founding member, expressing its solidarity with the GWP approach that came to be called Integrated Water Resources Management. Today GWP has 85 Country Water Partnerships and more than 3 000 institutional partners in 182 countries and remains committed to its initial approach to water resource management.

Implementing the cross-sector approach to water management

Typically, water investments are spread across many institutions and different levels of government. As a result, decisions are often fragmented and conflicting as water use may be covered by ministries such as agriculture, energy or commerce, that do not have water stewardship as their primary concern. This makes sustainable decisions unlikely, thus the need for an integrated, cross-sector approach to water resource management.

Through its multi-stakeholder partnership, GWP has advocated for, and facilitated the implementation of, Integrated Water Resources Management and Water Efficiency Plans in response to government commitments at the 2002 World Summit on Sustainable Development in Johannesburg. *Catalyzing Change*[2] and other GWP materials provide countries with the knowledge needed and actions required to meet the targets set at the Summit.

GWP further undertook a continent-wide programme to support 13 African countries in developing and implementing Integrated Water Resources Management

[1] Global Water Partnership

[2] www.gwp.org/en/ToolBox/PUBLICATIONS/Catalyzing-Change-Handbook1/

plans, which ended in 2008. One of the many lessons learned was that water resources management must be incorporated into national development processes in order to contribute effectively to sustainable development and poverty eradication. Another lesson, which became the basis for a subsequent programme, is that development is threatened unless climate resilience is built through better water management.

The subsequent GWP Water, Climate and Development Programme included the joint WMO and GWP Associated Programme on Flood Management (APFM) and Integrated Drought Management Programme (IDMP). The combined reach and expertise of the two organizations has facilitated implementation at state and community levels. The ten countries in Central and Eastern Europe that started to address the gaps in their approach to drought management through the Programme are already seeing clear benefits. The *Guidelines for Preparation of the Drought Management Plans*[3] and the *Guidelines on Natural Small Water Retention Measures*[4] have been a source of knowledge in this work.

GWP bridges the gap between what climate information producers provide and what policymakers, planners and other users, such as farmers, needs to manage water resources, and by so doing contributes to the Global Framework for Climate Services (GFCS). In Central America, for example, GWP trained meteorologists to use the standardized precipitation index (SPI), a common tool for monitoring drought. In 2015, the index became part of the climate forecasts shared with relevant government ministries. The next step is to develop a drought early warning system to strengthen regional capacity in monitoring droughts and to support decision-makers in related areas, especially agriculture, fisheries, water resources management, risk management and food security.

Another example is in an effort to improve climate resilience at the community level. In Burundi and Rwanda, GWP teamed up with stakeholders to implement a pilot project in the transboundary catchment area of Lake Cyohoha, located between the two countries. The project showcased the range of activities needed to bring about change: awareness-raising, stakeholder engagement, institutional capacity-building, and integration with government priorities. The project has improved living conditions and reduced vulnerability to climate change among the 30 000 catchment inhabitants through "no and low regret" interventions such as biogas facilities, water supply infrastructure and reforestation programmes.

Local communities and authorities, including the Minister of Water and Environment, joined hands to plant trees to protect the Lake Cyohoha buffer zone. The initiative aimed at sensitizing communities to own up and sustain initiatives to protect the Lake while stressing the importance of integrated water resources management.

Over the last 20 years, the GWP network has been instrumental in the development of 31 country-led policies, strategies and plans that integrate water security and climate resilience. Examples include the Zimbabwe National Climate Change Response Strategy, the Central Africa Regional Action Plan for Integrated Water Resource Management, and the Cameroon National Biodiversity Strategic Action Plan. As a result, millions of people have benefited from improved water security.

Inaction, the biggest risk

Big challenges remain, of course. But the biggest risk would be inaction. In 2013, GWP commissioned a task force of economists, led by Oxford University,

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3 www.gwp.org/Global/GWP-CEE_Files/IDMP-CEE/Drought-Guidelines-GWPCEE.pdf

4 www.droughtmanagement.info/literature/GWP-CEE_Guidelines_Natural_Small_Water_Retention_Measures_2015.pdf

to prepare a landmark study entitled *Securing Water, Sustaining Growth*, which was published in 2015. The study furnishes evidence that water insecurity costs the global economy some US$ 500 billion per year – and that figure does not take environmental impacts into account. The total drag on the world economy could be 1% or more of Global Domestic Product (GDP) if they were. For example, flood damage to urban properties alone is estimated at US$ 120 billion per year, while major droughts were found to reduce per capita GDP growth by half a percentage point. In particularly vulnerable economies, a 50% reduction in drought impacts could lead to a 20% increase in per capita GDP over a period of 30 years. Investing in water security would mitigate many of the related losses and promote long-term sustainable growth.

> ...water insecurity costs the global economy some US$ 500 billion per year – and that figure does not take environmental impacts into account.

High water and flooding in the streets in Steyr, Austria is an example of flood damage to urban properties that costs an estimated US$ 120 billion per year

GWP and the Organisation for Economic Co-operation and Development (OECD) incorporated the report findings into a policy statement and presented it to a high-level panel at the 7th World Water Forum in Korea in April 2015. The statement calls on governments to invest in water security, risk management, people and partnerships, and to pay special attention to social risks among poor and vulnerable communities.

Supporting Goal #6

The 2030 Agenda for Sustainable Development aims to eradicate poverty in one generation. Action must be prompt if this ambitious goal is to be achieved. Building on 20 years of experience and knowledge, GWP will support countries to achieve the SDGs through its Water Preparedness Facility. The Facility forms the basis for

building alliances with implementing partners, such as UN-Water, UNDP's Cap-Net programme, WMO and others.

The objective of the SDG Water Preparedness Facility is to provide practical support for 20 to 25 countries to implement SDG 6 on water and other water-related SDGs. The expected results include:

- Improving Policy, Financing and Monitoring: working collaboratively to ensure that national policy and planning frameworks are geared towards the SDGs; help countries understand and access finance for SDG implementation from multiple sources; collaboratively develop and put in place a robust global and national monitoring framework for water related targets;

- Improving Knowledge and Capacity: help countries to develop the skills to enable implementation of the water targets and develop knowledge on issues related to SDG 6 implementation; and

- Strengthening partnerships: broaden the GWP network to bring in actors from non-water sectors that substantially interact with water; share experiences across partnerships to expand SDG implementation.

The recent GWP Strategic Positioning Briefing Note outlines its ambitious plan to persuade leaders that integrated water governance is the foundation of food and energy security, poverty alleviation, social stability – and peace. GWP is committed to implementing the water-related SDGs and targets as the building blocks of social justice, economic prosperity and environmental integrity.

GWP is committed to implementing the water-related SDGs and targets as the building blocks of social justice, economic prosperity and environmental integrity.

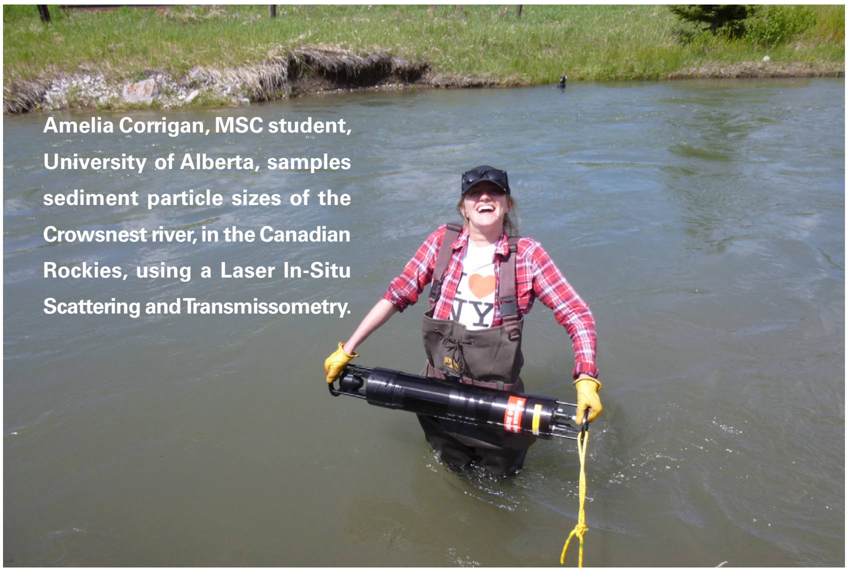
Photo Essay: Women in Meteorology

Louise Carroll (weather observer) releases a weather balloon on Macquarie Island research station in the sub-Antarctic.

Duncan Bullock

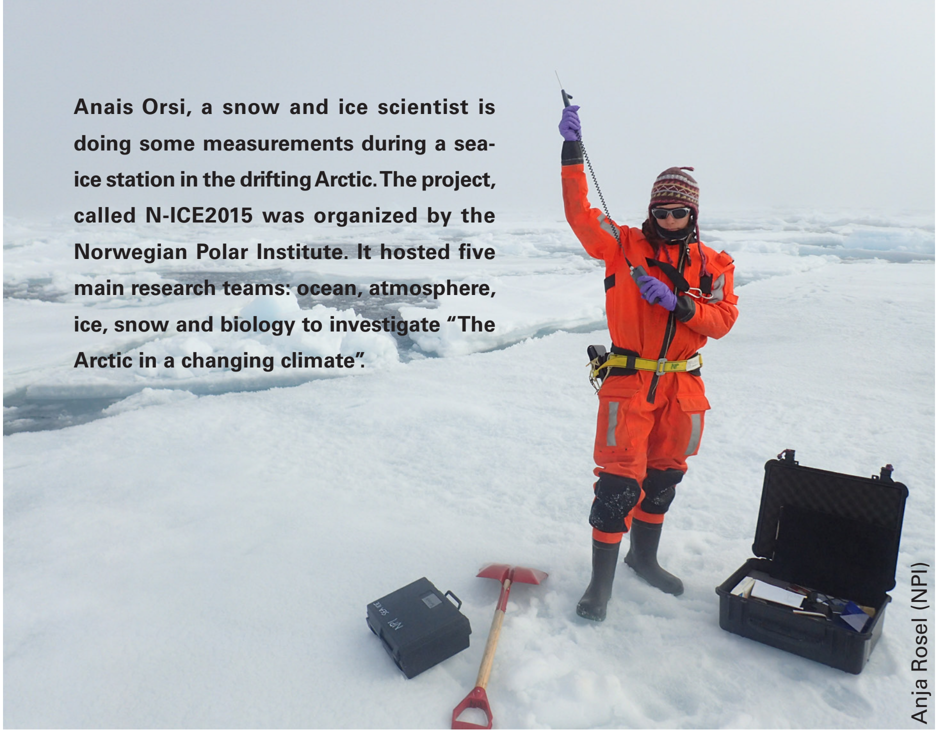
Air quality sampling at the Indonesian Agency for Meteorology, Climatology and Geophysics

Antonella Senese, a post-doc scientist at the Department of Earth Sciences of the University of Milan (UNIMI), Italy, replaces a wind sensor on the Presena Glacier (Italian Alps).



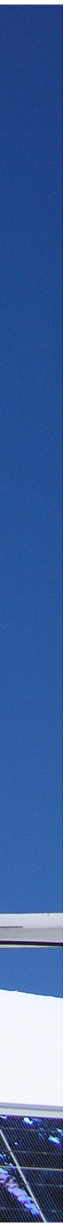
Amelia Corrigan, MSC student, University of Alberta, samples sediment particle sizes of the Crowsnest river, in the Canadian Rockies, using a Laser In-Situ Scattering and Transmissometry.

Claudia Riedl changing measurement equipment in the drill holes of the permafrost project Sonnblick observatory, Austria. (ZAMG)

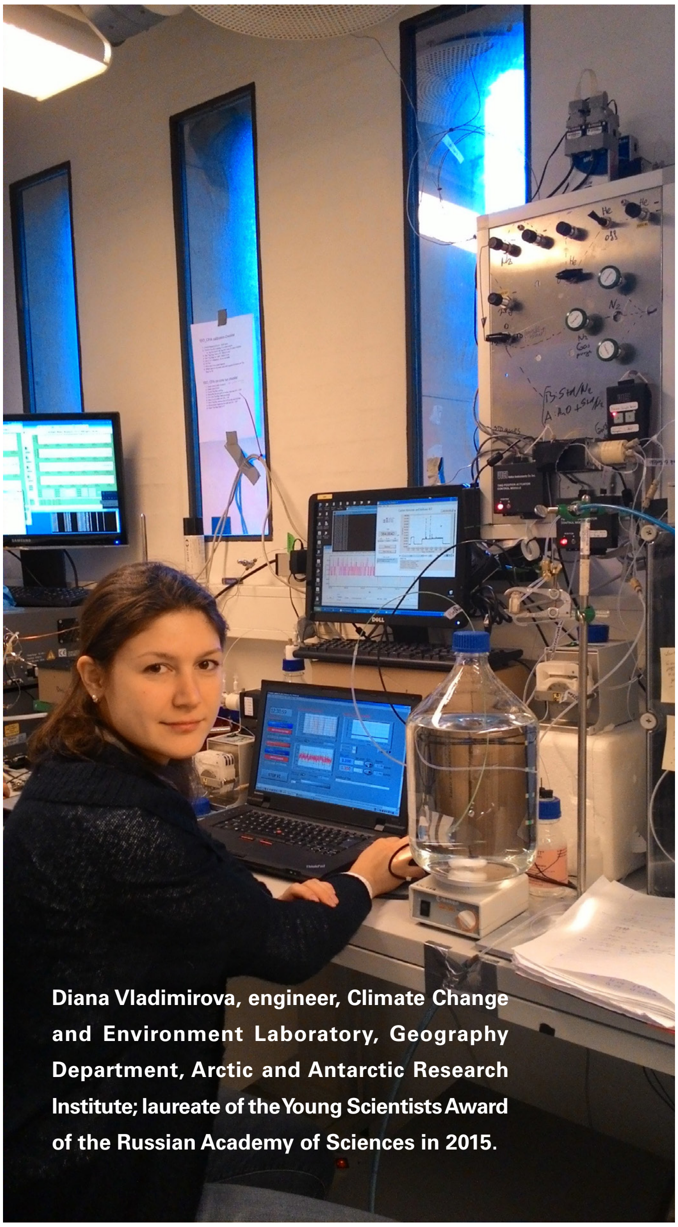


Anais Orsi, a snow and ice scientist is doing some measurements during a sea-ice station in the drifting Arctic. The project, called N-ICE2015 was organized by the Norwegian Polar Institute. It hosted five main research teams: ocean, atmosphere, ice, snow and biology to investigate "The Arctic in a changing climate".

Anja Rosel (NPI)



A meteorologist from Zimbabwe's Meteorological Service taking part in a cloud seeding operation.



Diana Vladimirova, engineer, Climate Change and Environment Laboratory, Geography Department, Arctic and Antarctic Research Institute; laureate of the Young Scientists Award of the Russian Academy of Sciences in 2015.

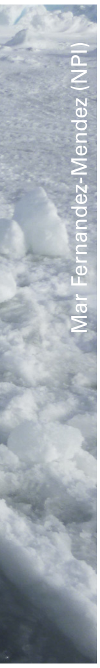
AEROMET Engineers at the meteorological enclosure at Lagos airport, Nigeria (NIMET)

Biologist Mar Fernandez-Mendez is ready to deploy an experiment under the sea ice during the Norwegian N-ICE2015 expedition in the Arctic in 2015

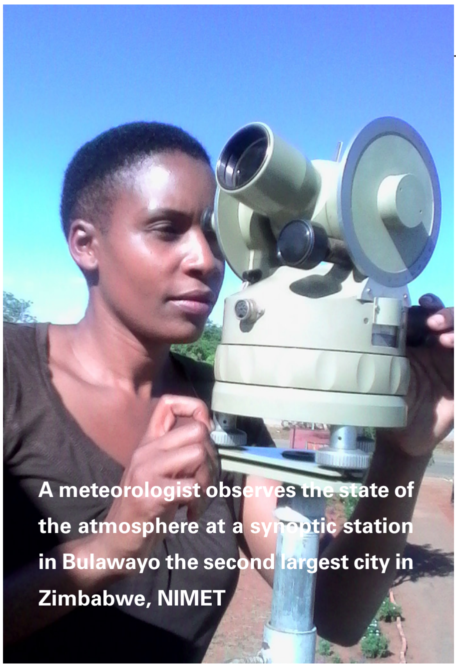
Elizabeth Lewis, a hydrometric technologist from the Meteorological Service of Canada, servicing a Water Survey gauge on the Ruggles River at the outlet of Lake Hazen on Ellesmere Island in June 2015

Tatyana Strelkova in action at a meteorological station 2 300m above sea level during the Sochi 2015 Winter Olympics

Ms. Sigourney Joyette engages in a practical infiltration exercise at the Caribbean Institute for Meteorology & Hydrology



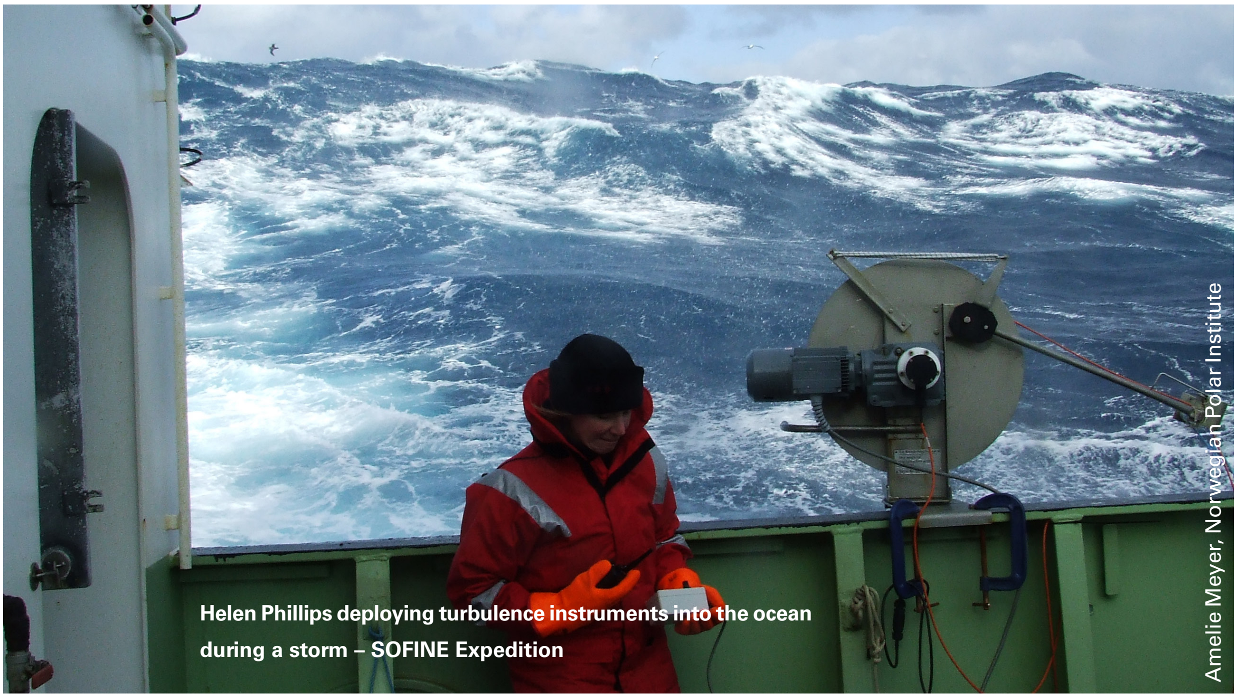
Mar Fernandez-Mendez (NPI)



A meteorologist observes the state of the atmosphere at a synoptic station in Bulawayo the second largest city in Zimbabwe, NIMET

Fram Strait Arctic expedition (Roshydromet)

Fred Lemire



Helen Phillips deploying turbulence instruments into the ocean during a storm – SOFINE Expedition

Amelie Meyer, Norwegian Polar Institute

Dr. Kathrin Höppner, an Air Chemist at the German Research Station “Neumayer III”, Queen Maud Land, Antarctica, as part of the 2012 winter crew.

US National Weather Service Incident Meteorologist Pam Szatanek on a helicopter going to a fire site

WMO Virtual Laboratory for Meteorological Satellite Education and Training

By James F. Purdom[1], Volker Gärtner[2], Maja Kuna-Parrish[3] and the WMO Secretariat[4]

High costs and relatively low usage are major concerns for operational meteorological satellite systems. In the early 1990s, Tillman Mohr, then Director General of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), made a rough calculation that the operational cost of the constellation of meteorological satellites was in the order of US$ 2 million per day. However, a WMO survey conducted around the same time determined that many of its Members were not able to access and use satellite data and products in real time and were, thus, not able to reap the benefits of this major investment.

The WMO Virtual Laboratory for Meteorological Satellite Education and Training (VLab), which celebrates its 20th anniversary this year, has gone a long way in remedying this situation. VLAB is today challenged to assist WMO Members with a new generation of satellites with enhanced observation capabilities that will become operational in the 2015-2021 timeframe.

Training concept defined

WMO was the main international provider of class-room-based training on the use of satellites data and products until the mid 1990s. However, the reach of these was limited, approximately 20 to 30 people were trained per year. Even advanced countries were experiencing difficulties in developing and maintaining the skills and expertise of staff in using traditional and new data and products such as those from geostationary satellites being launched by China, EUMETSAT, Japan and the United States of America (U.S.). In addition, training material and resources were only available in hard copy format and were expensive to produce and distribute.

In the 1990s, the WMO Executive Council (EC) Panel of Experts on Satellites, led by Mr Mohr, studied options to resolve these issues. Their final report in 1993 recommended that the Coordination Group of Meteorological Satellites (CGMS), representing the satellite operators, and WMO, representing the specialized regional training centres[5], collaborate on a joint education and training initiative. Mr Donald Hinsman (then Chief of the WMO Satellite Activities Office) and to Mr James Purdom (then Chair of the WMO Commission for Basic Systems Open Programme Area Group on Integrated Observing Systems) were tasked with finding a practical solution that would engage a large number of Members.

Subsequently, in 1995, the WMO Regional Training Centre in Costa Rica hosted a course on the Utilization of Satellite Data and Products at the University of Costa Rica in San Jose, which came up with the answer. The basic concept was to use the Internet to gather expert trainers around the globe to better support Members in their use of satellite data and products. The course participants and lecturers were enthusiastic that this

1 Retired from the National Environmental Satellite, Data, and Information Service of the U.S. National Oceanic and Atmospheric Administration (NOAA)

2 Retired from EUMETSAT

3 EUMETSAT

4 Jeff Wilson (Education and Training Office) and Luciane Veeck (Vlab)

5 Later renamed Centres of Excellence (CoEs)

VLMG-3 in Boulder, Colorado, June 2007

Front row (left to right): Volker Gaertner, Juan Ceballos, Andy Kwarteng, Daniel Barrera. Middle row: HansPeter Roesli, Richard Francis, Jeff Wilson, Bernadette Connell, Anthony Mostek. Back row: Amadou Garba, James Purdom.

would lead to more, and better trained, users and justify the huge investments into satellite systems.

The concept was further refined and, in December 2000, China's Nanjing Institute of Meteorology (now Nanjing University of Science and Technology) hosted the first VLab training event. There, Bernadette Connell from the U.S. Cooperative Institute for Research in the Atmosphere (CIRA) used VisitView to broadcast her talk from Nanjing to the rest of the world.

The first meeting of the VLab Management Group (VLMG-1) in May 2001 further developed its operating plan, strategy and timelines. The VLab co-chairs, Richard Francis (EUMETSAT) and Jeff Wilson (then with Australian Bureau of Meteorology Training Centre), were charged with driving the concept forward. Following which, the first Internet-based global weather discussion took place at the Asia Pacific Satellite Applications Training Seminar in Melbourne, Australia, in May 2002 with input from presenters in the U.S. and Europe. Amongst others, Ray Zehr from CIRA presented four interactive lectures from Fort Collins to audiences in Melbourne and other regional training centres, confirming the viability of remote interactive, questions-and-answers training presentations.

VLMG-2, in December 2003, proposed the launch of monthly weather discussions and high profile training events (HPTEs) that continue to this day. It also developed the specifications for a VLab work station as a lack of equipment, software and training resources was hindering participants from training colleagues upon their return home. The idea was to seek funding so laptops could be provided to all participants. In 2005, WMO, through CIRA and a grant from the U.S. (NOAA) National Environmental Satellite, Data, and Information Service, was able to loan out laptops, complete with training materials, to all attendees of a training event in Costa Rica.

VLab infrastructure

In addition to the standard information technology available in most countries, VLab introduced new tools such as VisitView, SABA Centra, GotoMeeting and WebEx to enable interactive training in the Centres of Excellence and in the National Meteorological and Hydrological Services (NMHS). Their capability, efficiency and cost-effectiveness enabled VLab to function and Centres of Excellence to conduct global and regional training events. The VLab maintains close links with the WMO Education and Training Office, which assists both groups in meeting the needs of their target audiences.

Two key developments from 2006 to 2009 helped ensure that VLab would deliver on its promise. A technical support officer was appointed to coordinate and assist in the organization of online events and VLMG actions, this thanks to long-term collaborative funding from CGMS satellite operators via the WMO VLab Trust Fund. A VLab home page was developed where all relevant documentation and training materials are accessible. The site serves as a platform for collaboration and networking, providing links to the individual web pages of contributing agencies.

The VLab Network: Satellite operators and Centres of Excellence

Eight satellite operators

- Chinese Meteorological Administration (CMA
- Argentinian National Space Activities Commission (CONAE)
- EUMETSAT
- Brazilian National Institute of Space Research (INPE)
- Japan Meteorological Agency (JMA)
- Korea Meteorological Administration (KMA)
- National Oceanic and Atmospheric Administration (NOAA)
- Roshydromet

The Centres of Excellence

- Argentina (Buenos Aires and Cordoba)
- Australia (Melbourne)
- Barbados (Bridgetown)
- Brazil (Cachoeira Paulista)
- China (Beijing and Nanjing)
- Costa Rica (San Jose)
- Kenya (Nairobi)
- Morocco (Casablanca)
- Niger (Niamey)
- Oman (Muscat)
- Republic of Korea (Gwanghyewon)
- the Russian Federation (Moscow and St Petersburg
- South Africa (Pretoria)

Training events

Each Centre of Excellence is responsible for conducting training activities and usually supports one or more Regional Focus Group, representing the NMHSs in the region. From 2010 to 2014, over 50 classroom and virtual training events were organized annually. All regions benefited and courses were provided in all the official languages of the United Nations plus Portuguese. These included regular online weather briefings, event weeks, regional training and virtual round tables. The increase in online training activities has, in turn, increased the number of participants all over the world.

VLab has also provided education and training in other areas of relevance to Members. For example, a five-language virtual round table on the implementation of the aeronautical meteorological competencies received 212 connections from 87 countries.

VLab has demonstrated that a network of enthusiastic people can offer effective, innovative and very cost-efficient training, through sharing and synergetic mobilization of national resources.

Future perspectives

VLab continues to evolve, in order to meet its goal to improve weather, climate and water related environmental services by enabling Members to use satellite data and products. It has attained its twofold objective: better exploitation of data from the space-based global observing system and the sharing of knowledge, experiences, methods and tools related to satellite data, especially in support of Members that have limited resources. VLab has demonstrated that a network of enthusiastic people can offer effective, innovative and very cost-efficient training, through sharing and synergetic mobilization of national resources. Its success helped to inform the proposal for a WMO Global Campus.

Global VLab network (yellow boxes indicate funding satellite agencies). Connecting lines link VLab Centres of Excellence with their supporting satellite operators.

The continued collaboration of VLab with other international training and education programs in meteorology is essential for further success. The coming years will see intensified cooperation with partner organizations such as the European Virtual Organisation for Meteorological Training (EUMETCAL), the EUMETSAT-sponsored international training project (EUMETRAIN), CIRA and the U.S. COMET Training Program, the international CALMet group and the WMO Training and Education Office. The VLMG will also further build on its existing partnerships and explore new ones in order to ensure the synergetic optimization of global training efforts during times of limited resources. There is an increasing expectation that more Open Educational Resources (OER) will be created and shared within the community of meteorological trainers and that VLab will contribute to WMO Global Campus activities.

Satellite data and products contribute to weather, climate and water services and to all the priority areas identified by the Seventeenth World Meteorological Congress in May 2015. Thus, the VLab has a growing role to play, especially in view of the challenges that a new generation of satellites with will bring in the coming years. We encourage our readers to read the article that follows this one on the new Himawari-8 satellite network and the solutions implement for NMHS to access and use its data.

The HimawariCast Project: Bringing the power of new satellite data to the Asia-Pacific region

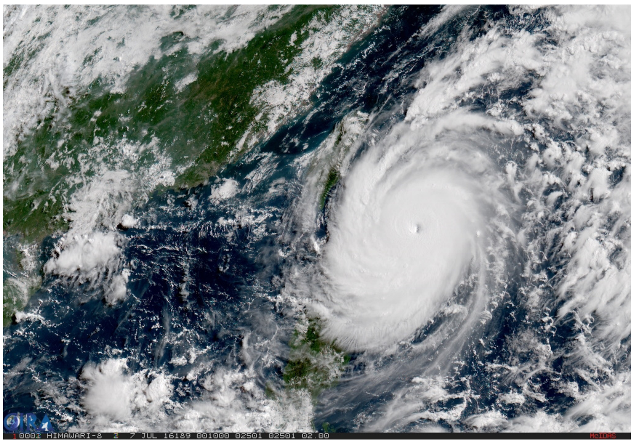
by WMO Secretariat[1]

At 05:16 UTC on 7 October 2014, the Japanese satellite Himawari-8 atop an H-IIA rocket took off from the Yoshinobu Launch Complex Pad 1 at the Tanegashima Space Centre in Japan. The launch was flawless and the satellite arrived a few weeks later at its final geostationary orbiting position 36 000 km above the equator at 140.5°E, just north of Papua New Guinea in the Western Pacific Ocean. It was the first of a new generation of satellites that would start operations in the 2015-2021 timeframe. These new meteorological satellites have enhanced observation capability that will bring benefits, but also challenges for the National Meteorological and Hydrological Services (NMHSs). WMO and the Japan Meteorological Agency joined forces on the HimawariCast Project in order to assist them.

Benefits of satellite imagery

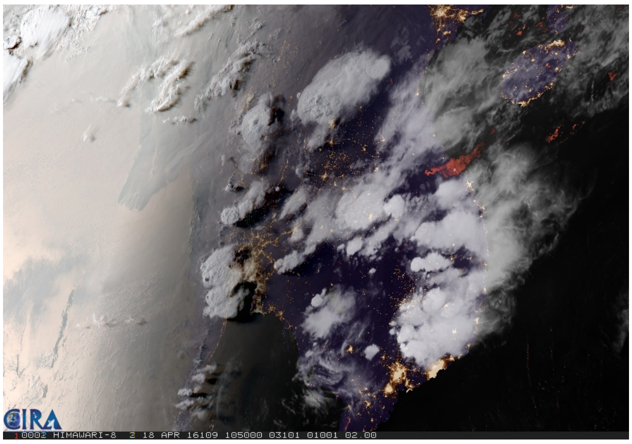
Geostationary meteorological satellites provide image data for large areas of the Earth at high frequency, and are vital tool for observing the development of weather systems from space. They are useful for monitoring rapidly developing weather systems like tropical cyclones, extra-tropical storms, severe convective systems, volcanic ash clouds, and sand and dust storms. In the Asia-Pacific region, typhoons and tropical cyclones are life-threatening meteorological hazards. All NMHSs continuously strive to improve their early warning systems to better monitor and detect them.

[1] Ayse Altunoglu, Mikael Rattenborg, Kuniyuki Shida, Ryuji Yamada, DRA Department; Stephan Bojinski, Space Programme, OBS Department



Geostationary satellite images are a complement to ground-based precipitation radar systems for monitoring of the onset of severe convection. In fact, observations from geostationary satellites give earlier warning of the development of severe convection, because strong vertical motions in clouds become visible in satellite images around 15-30 minutes before the onset of precipitation. Geostationary satellites also offer an alternative in areas of the world where weather radars are absent or poorly maintained.

Generally, data acquired from Low-Earth orbiting satellites provide the most vital input to Numerical Weather Prediction (NWP) models for global and regional forecasting. However technological and scientific developments over the last 25 years have made it possible for geostationary image data to be transformed into quantitative products that also have positive impact on NWP models and specifically provide information for areas where other observations are sparse, like oceans and deserts.



China, EUMETSAT (the European Organisation for the Exploitation of Meteorological Satellites), India, Japan, Republic of Korea, Russian Federation and United States of America (U.S.) maintain geostationary satellite programmes positioned above the equator in what is called the "geostationary ring". They form an optimised global system, supervised by satellite agencies that work together in the Coordination Group for Meteorological Satellites (CGMS) and the WMO Space Programme, which standardizes processing and distribution of data to serve global users, in particular WMO Members.

The challenges

The replacement of the existing global system by a new generation of geostationary satellites started with the Himawari-8 launch. With its enhanced observation capability of 16 bands (channels), Himawari-8 is expected to improve the performance of NMHSs in the Asia-Pacific region in a variety of fields, including weather forecasting, climate monitoring, disaster risk reduction and transportation safety.

With the previous generation satellite, MTSAT-2, due to be taken out of service at the end of 2015, forecasters would depend fully on the data from Himawari-8 from that time on. That left very little time to get NMHSs on board for Himawari-8. Preparation and training for the processing and use of Himawari-8 data across the region would be on a tight schedule. But the bigger issue was the volume of data generated by Himwari-8: around 50 times that of MTSAT-2. How could the NMHSs access and use the massive increase in the data disseminated to them?

The HimawariCast Solution

JMA wanted to ensure that the Asia-Pacific NMHSs were ready to use the image data from the new satellite under its operation. The original data plan was to use an internet cloud service. But JMA quickly recognized that the massive data volumes and the limited Internet bandwidth available in large parts of the Asia-Pacific region would make that solution impracticable for some NMHSs.

JMA decided to complement Internet access with a satellite-based distribution system, using commercial telecommunications satellite and low-cost DVB-S reception technology. The system, modelled on the highly successful EUMETCast system implemented by EUMETSAT in 2003, was named HimawariCast. It would provide a subset of Himawari-8 image data, equivalent to that disseminated directly from the MTSAT-2.

The WMO-JMA project

A typical HimawariCast reception system is composed of low-cost, off-the-shelf components with a moderately sized (2.4 m) reception antenna. Even so, many NMHSs, especially the smaller ones, could not stretch tight budgets further to cover these costs. Therefore, JMA and WMO decided to initiate and fund a project to install HimawariCast receiving and processing systems in the NMHSs of 14 countries: Bangladesh, Cambodia, Federated States of Micronesia, Kiribati, Mongolia, Myanmar, Nepal, Palau, Papua New Guinea, Samoa, Thailand, Tonga, Tuvalu and Viet Nam.

To guide the project, the WMO Commission for Basic Systems (CBS) together with the Coordination Group for Meteorological Satellites (CGMS) developed best practices for achieving satellite user readiness. The WMO Development and Regional Activities Department and the Space Programme, together with JMA and project partners, were responsible for the final technical specifications of the systems, for the selection of the supplier and for overseeing the testing and deployment of the reception systems.

WMO selected Oriental Electronics, Inc. (ORI) as the supplier in April 2015 and planning of the factory

testing, installation and acceptance started. ORI also performed site visits to all recipient NMHSs, to confirm the suitability of the locations where the systems were to be installed and to identify issues that could affect their installation and operation. These revealed eminent construction of a new monorail transportation system in Dhaka, Bangladesh, that would impact the Project and the need for coordination with planned relocations of NMHS offices in Mongolia, Palau, Tonga and Viet Nam. However, the main concerns related to integration of the HimawariCast with existing systems and the need to provide forecasters in other locations with access to HimawariCast system products.

The systems would consist of a satellite data reception antenna (2.4 m in diameter), a computer for data acquisition and a separate computer for product generation and visualisation.

Time was a critical factor: that same Spring, HimawariCast had started routine dissemination of MTSAT-2 data. In July 2015, JMA declared Himawari-8 operational, after which the old and the new distribution systems continued in parallel. However, MTSAT-2 data would only continue until 4 December 2015. After that date, the satellite would no longer be able to maintain its nominal position, and for NMHSs to use its data: it was crucial that the new HimawariCast systems be fully operational by then to avoid a gap in the provision of satellite data for the NMHSs.

After the site visits, Factory Acceptance testing were conducted at the ORI premises in Kyoto, combined whenever possible with technical training, to allow NHMS personnel to familiarize themselves with the systems.

The strong partnerships and coordination between WMO, NMHSs, JMA and ORI yielded great results. Nine countries now have the HimawariCast system in operational use. The remaining five will have them by early 2017. In addition to the technical training provided by ORI, JMA has been carrying out expert visits to the recipient NMHSs to conduct seminars to maximize the benefits they can derive from Himawari-8 data. So far, the feedback has been very positive.

The success of the HimawariCast Project is in addressing the challenges in an end-to-end manner by providing near-real-time access to data via satellite broadcast, facilitating the acquisition and processing of data, and ensuring that NMHS staff, both engineers/technicians and forecasters, are fully trained on the new systems. As pointed out the by WMO Secretary-General Petteri Taalas, "The joint efforts by WMO and JMA to facilitate the reception and use of new generation satellite data can be a model for WMO support for other regions in coming years."

Capacity development is crucial for a successful introduction of new satellite systems in the WMO regions. WMO and JMA will assist all recipient NMHS with the sustainable operation of HimawariCast systems for three years after the expiry of the 2-year warranty

period for the systems. In addition, WMO and its partners will support the participation of NMHS representatives in the annual Asia-Oceania Meteorological Satellite Users Conference, associated training events and meetings of regional satellite user requirements groups. This will help to sustain the capacity developed in the NMHSs through the HimawariCast project.

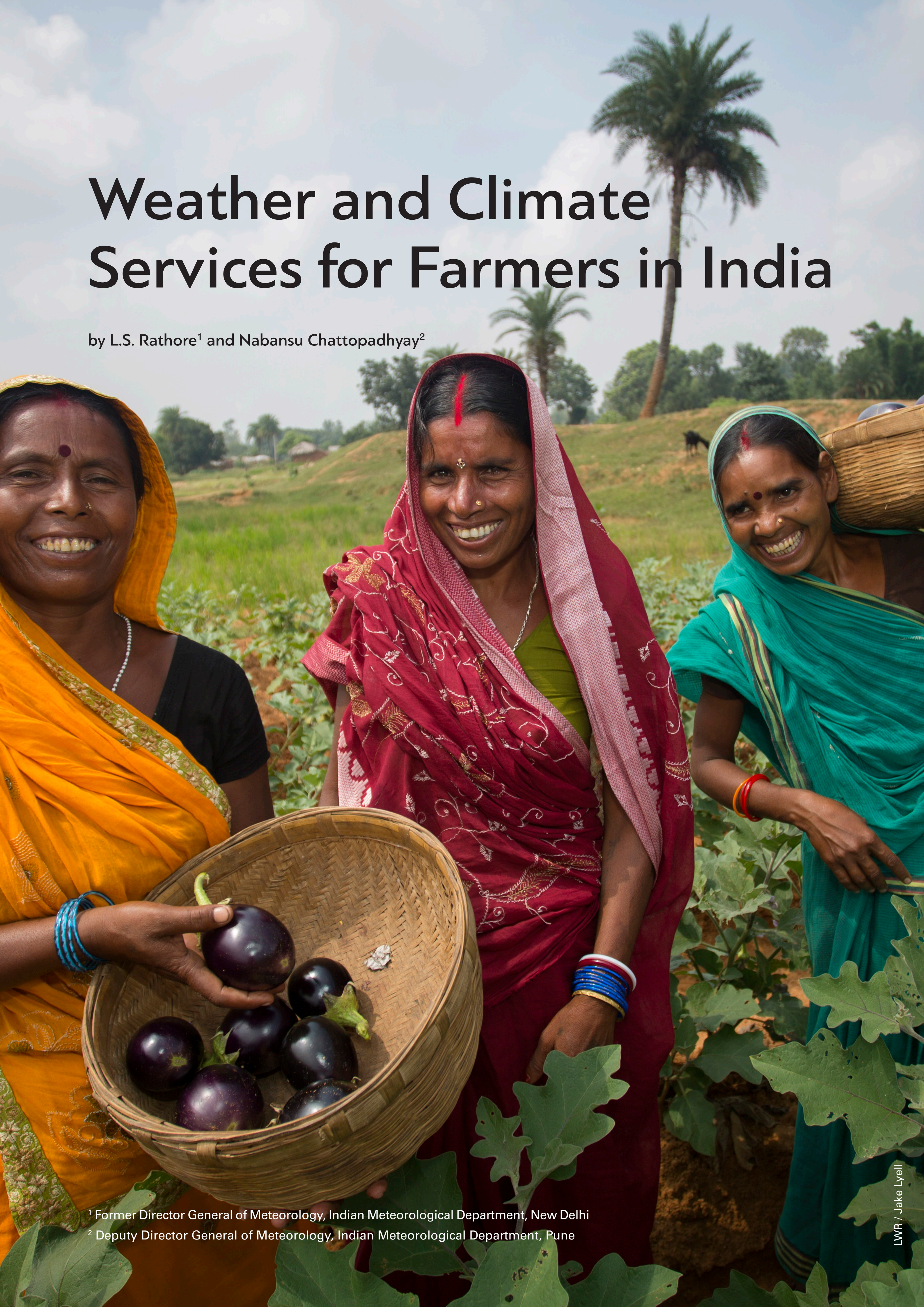
The joint efforts by WMO and JMA to facilitate the reception and use of new generation satellite data can be a model for WMO support for other regions in coming years.

"I am proud that we have a new world class meteorological satellite data receiving system. The system can detect various severe events, including volcanic ash which is detrimental for aircraft," said Mr Samuel Maiha, Director of the National Weather Service of Papua New Guinea.

Former JMA Director-General and Japan's Permanent Representative to WMO, Mr Noritake Nishide stated with pride, "I am convinced that the new systems installed in countries through this project will further improve capability in early detection of, and responses to, severe weather events of recipient countries."

Weather and Climate Services for Farmers in India

by L.S. Rathore[1] and Nabansu Chattopadhyay[2]



[1] Former Director General of Meteorology, Indian Meteorological Department, New Delhi
[2] Deputy Director General of Meteorology, Indian Meteorological Department, Pune

The management of weather and climate risks in agriculture has become an important issue due to climate change. The Intergovernmental Panel on Climate Change (IPCC) has highlighted multiple climate risks for agriculture and food security as well as the potential of improved weather and climate early warning systems to assist farmers. Wise use of weather and climate information can help to make better-informed policy, institutional and community decisions that reduce related risks and enhance opportunities, improve the efficient use of limited resources and increase crop, livestock and fisheries production. National Meteorological and Hydrological Services (NMHSs) have an important role to play in providing this weather and climate information to farmers, big and small.

However, NMHSs will need realignment, new resources and training in order to provide location and crop specific actionable weather and climate services and products that link in available technologies, best practices and go the last mile to reach all farmers. The Agromet Advisory Services of the India Meteorological Department (IMD) in the Ministry of Earth Sciences is a small step in this direction, aimed at "weatherproofing" farm production.

Agromet Advisory Services

The sources of weather and climate-related risks in agriculture are numerous and diverse: limited water resources, drought, desertification, land degradation, erosion, hail, flooding, early frosts and many more. Effective weather and climate information and advisory services can inform the decision-making of farmers and improve their management of related agricultural risks. Such services can help develop sustainable and economically viable agricultural systems, improve production and quality, reduce losses and risks, decrease costs, increase efficiency in the use of water, labour and energy, conserve natural resources, and decrease pollution by agricultural chemicals or other agents that contribute to the degradation of the environment. Thus, the importance of the Agromet Advisory Services that have now been established at district levels in India. These Services meet the real-time needs of farmers and contribute to weather-based crop/livestock management strategies and operations dedicated to enhancing crop production and food security. They can make a tremendous difference in agricultural production by assisting farmers in taking the advantage of benevolent weather and in minimizing the adverse impact of malevolent weather.

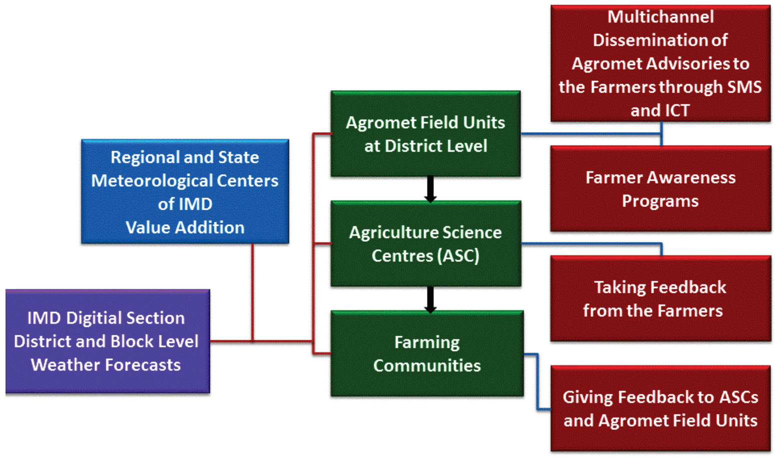
Putting the structure in place

IMD began regular weather services for farmers in 1945 in the form of a "Farmers' Weather Bulletin" and broadcasts through All India Radio in regional languages. In 1971, on the recommendation of the National Commission on Agriculture (NCA), it launched Agrometeorological Advisory Services (AAS), a comprehensive tool tailored to farmers' need. Then in 1975-1976, the U.S. National Aeronautics and Space Administration (NASA), conducted a Satellite Instructional & Television Experiment (SITE) with IMD and agricultural agencies that led to the production of crop specific weather-based agronomic advisories for different regions of the country. These integrated Agromet Advisory Services were further developed in 2007 and have steadily been improved since.

Today, IMD is implementing operational agrometeorological schemes across the country under a five-tier structure:

1. Top-level policy planning body in Delhi
2. Execution by the National Agromet Service headquarters in Pune
3. Coordination and monitoring by State Agromet Centres
4. Definition of the agro-meteorological zone
5. District or local level extension and training for input management advisory service

This structure includes State Agricultural Universities, Institutes of Indian Council of Agricultural Research and Indian Institutes of Technology. Without it, the district Agromet Advisory Services would not be sustainable.



Overview of Operational Agromet Advisory Services in India (ICT-Information and Communication Technologies)

NWP: Numerical Weather Product
IVRS: Interactive Voice Response System
KVKs: Krishi Vigyan Kendras

Production and dissemination

The primary need of a farmer is a location-specific and quantified weather forecast. IMD started by issuing from June 2008 quantitative district level weather forecasts – for rainfall, maximum and minimum temperatures, wind speed and direction, relative humidity and cloudiness – with up to 5 days advance warning and a weekly cumulative rainfall forecast. These products were sent twice a week along with other value added information to 130 AgroMet Field Units (AMFUs) for preparation of district level advisories.

The application of weather forecasts to generate crop advisories requires the definition of a spatial domain of validity and a temporal range as well as accuracy. At the district level, such are prepared containing past weather, forecast for 5 days ahead and a weather-based agrometeorological advisory that includes pest and disease information. The phenological stages of plant development are included in crop specific advisories to offer farmers guidance on cultural practices. All of the information is geared to help farmers maximize output and avert crop damage or loss. The Agromet Advisory Services also has an end-user group feedback mechanism to help the district level forecasters to tailor their services further.

The analysis and decision support information, for example, include information on how to manage pests when the forecast is for relative humidity, rising or falling temperatures or high or low winds; on how to manage irrigation through rainfall and various temperature forecasts; on how to protect crop from thermal stress when the forecast is for extreme temperature conditions, etc. It also helps farmers anticipate and plan for chemical applications, irrigation scheduling, disease and pest outbreaks and many more weather related agriculture-specific operations from cultivar selection to dates of sowing, planting, transplanting, intercultural operations, harvesting and post-harvest operations. In a recent survey conducted by the National Council of Applied Economic Research (NCAER), 93% of farmers responding agreed that numerical weather prediction were reliable, and asserting that they used the information in making decisions during different farming stages, from sowing to harvesting.

Such actionable weather information is consistently being delivered to farmers and productivity reports have shown significant increases in yields and with it food availability and incomes. A study has demonstrated that the Agromet Advisory Services has decreased cultivation costs overall by up to 25% for the studied crops. Initial results in some cases had shown increased costs of up to 10%, but this was more than offset by consequent rise in net returns of up to 83%. The crops that benefited most are paddy, wheat, pearl millet, and fruits and vegetables. The economic benefit has been estimated at US$ 7.575 billion per year and is extrapolated to rise to US$ 32 billion if the entire farming community in the country were to use Agromet Advisory Services in their agricultural activities.

Outreach to users

Agromet Advisory Services use three dissemination channels – mass media, group awareness campaigns and individual contacts – in order to reach more farmers. Some 19 million farmers are currently subscribed to the SMS advisories, but there is still a need for greater dissemination and to convince farmers of the sustainability of the positive impacts observed in the long term.

The group awareness campaigns are strengthening use of the services in farming communities and helping farmers to be more self-reliant in dealing with weather and climate issues that affect agricultural production. They are also permitting farmers to adapt better by improving their planning skills and management decision-making. A participatory, cross-disciplinary approach is taken to deliver climate and weather information and enhance awareness in these user groups.

IMD, state agricultural universities, Institutes of the Indian Council of Agricultural Research (ICAR) and the Indian Institute of Technology, working with local non-governmental organizations (NGOs) and other stakeholders, have jointly organized these group awareness campaigns in different parts of the country. Farmers receive informative brochures and pamphlets outlining weather-based farming guidelines; information on crop management practices in the district; about pests and diseases, severe weather conditions, crops that can be grown under stress conditions and contingency plans; and on the District Agromet Bulletin – all in local languages. Five plastic rain gauges are distributed to the most progressive farmers participating in the campaign in order to improve the relationship between providers of the advisories and the users and to develop a local, or village level, rain-measuring network. The rain gauges engage farmers in the observation of weather data that contribute to the preparation of the Agromet Advisory Services. Such outreach campaigns are organized in farmers' club meeting, during scientific field trips, farmers' field schools, etc.

Future plans

To further improve the relevance of these services, local-level Agromet Advisory Services have been proposed. High-resolution weather forecasts at local level will be used to develop this service. A pilot study has been carried out in selected locations in Maharashtra for the last three years. For each, IMD has generated 5-day weather forecast – for rainfall, maximum and minimum temperature, cloud cover, maximum and minimum relative humidity, wind speed and direction – using numerical weather prediction models at resolution of 25 km2 as well as 9 km2. The accuracy of these forecasts is approximately 70%. They are used to develop crop-specific and location-specific Agromet Advisory Services. Substantial increases in productivity for cereals, oil seeds and vegetables were observed in the pilot locations. These local-level forecasts have shown incremental benefits of up to 13% over district-based advisories. The weather forecast and warnings have enhanced livelihood security for the rural community in the pilot region.

There is still a long way to go. Agricultural production farmers' incomes can be further increased by reducing their losses and distress. It is challenging task for government, IMD as well as all the other stakeholders. IMD has set itself the challenge of further enhancing the accuracy of weather forecasts and to make the Agromet Advisory Services more useful and demand-driven by farmers. It will also venture into generating high-resolution medium range weather forecast and advisories that address livestock, poultry and fisheries issues.

A priority for IMD and WMO is to continue to promote Agromet Advisory Services in South Asia countries. The benefits to farmers and the contribution to food security and national economic development are measurable. The return on investment is manyfold for governments that can put effective, tailored agrometeological services in places.

Climate change impacts on aviation: An interview with Herbert Puempel

by WMO Secretariat

Efforts to reduce fuel burn and thus carbon dioxide (CO_2) emissions in aviation over the past four decades have been impressive. Operational measures in line with new air traffic management systems, as well as new technological concepts, all have the potential to continue reducing these CO_2 emissions. The Commission for Aeronautical Meteorology (CAeM) supports aviation stakeholders in their efforts to operate under changing climate conditions.

At its July 2014 session, CAeM, which was partly held in conjunction with the Meteorology Divisional Meeting of the International Civil Aviation Organization (ICAO), decided to establish an expert team to tackle some of the challenges that the aviation industry is facing related to atmospheric science and climate. The ICAO Global Air Navigation Plan and Aviation System Block Upgrades provided a 15 -year forward vision of the global air traffic management system aimed at helping the industry cope with the pressing challenges of growth and related environmental effects. The meteorological and climatologic research communities can support this vision by providing their best possible estimates of potential climate change impacts. This information would enable aviation stakeholders to make informed decisions. While ICAO addresses relevant mitigation measures to reduce emissions by the sector, WMO will support the long-term adaptation strategies of aviation stakeholders.

Herbert Puempel, the Chairperson of the CAeM Expert Team on Science, Aviation and Climate, has been the WMO representative on the ICAO Committee on Aviation Environmental Protection (CAEP) since 2000. His explanations of the potential impact of climate change on aviation operations have been instrumental in raising aviation stakeholders' interest in the related risks for the air transport sector. In this interview, Mr Puempel gives us a perspective of what flying through changed atmospheric conditions could look like in the near future.

Have challenges related to climate change been identified for the aviation industry?

The question of climate change impacts on aviation was addressed in the light of the Fourth (2007) and Fifth (2014) Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC). The aim was to identify impacts on aviation as a significant part of the transport sector. But there was a need to go beyond the interpretation of the "general" results of the two Assessment Reports, and look for specific scientific and user issues to be addressed in dedicated studies. Such studies are being carried out by several authors and we can now distinguish the impacts that will be caused by large-scale phenomena as well as small- to micro-scale effects.

What are the consequences of the large-scale phenomena related to overall temperature rise?

The scientific case for the effects of higher surface temperatures on aviation has been established and rests on a firm understanding of the physical processes involved in driving up these temperatures. The expected higher temperature maxima, coupled in some regions to higher values of specific humidity could have severe consequences on take-off performance at airports at high-altitudes or with short runways, limiting payload or fuel uptake.

These effects will require more detailed analyses for different regions, but will be a major concern for elevated airports in subtropical regions. The established method of scheduling long-haul departures for the cooler evening and night hours in some regions (the Middle East, and Central and Southern American high-altitude airports) will be further affected by reduced overnight cooling where high cloud cover, partially caused by long-lived contrails, is often present. In these cases, the warming effect of contrail-related cirrus clouds, which reduce radiative cooling at night, may have to be considered as an additional problem. This would reduce the already limited hours of operation even further in some regions.

For large-scale phenomena, what are the risks to air transport resulting from sea-level rise?

Linked to the higher temperatures, the consequential rise in sea level (through increased melting of ice caps and glaciers and thermal expansion of the oceans) is fairly well understood and documented. In regions with strong monsoons, tropical storms, sea-level rise and storm surges linked to more intense extratropical cyclones will threaten the viability of airports at coastal locations unless protective measures are taken. These effects are likely to be exacerbated in those regions by very intense precipitation linked to the storms. The intense precipitation can lead to flooding where rainfall runoff hits storm tides head-on, for example, the extreme floods that occurred in Myanmar during Tropical Storm Nargis. Effective planning of new airports in such regions requires hydrological, climatologic and technical expertise.

Is the aviation sector sensitive to global climate events such as El Niño and what adaptation measures could be put in place?

An in-depth analysis of the El Niño Southern Oscillation (ENSO) from the latest generation of climate models appears to support evidence from paleo-climatologic studies that point to an increase in the severity of El Niño. This trend may be visible in the 2015/2016 El Niño episode. Such high-amplitude El Niño effects will affect many regions of the world by exacerbating extreme droughts and heat waves. All these extreme situations will have strong negative impacts on all forms of transport, including aviation.

However, an understanding of the role of seasonal, inter-annual and decadal variations, such as ENSO, the North Atlantic Oscillation and other recurring phenomena, will require significantly more research efforts. Given the overwhelming amount of data resulting from climate model predictions, the initial approach to understanding future climate states was the analysis of a new quasi-equilibrium state predicted for the end of the 21st century, when climate would have settled at a warmer level in line with the increased CO_2. This new equilibrium state was described in latitudinal and regional means of temperature and precipitation over extended periods of time to isolate, sometimes, conflicting signals. However, many climate model predictions exhibit noticeable biases in some regions and parameters, for example, in the Equatorial Pacific Ocean temperatures, when compared to the current climate.

Adaptation measures need to address future mean state, and local and regional extremes likely to occur over the next decade(s). Such extremes may already be exhibiting typical conditions that we only expected to become regular features by the end of the century.

To provide robust scientific advice to stakeholders, the scientific community will need to address typical scenarios and try to describe impacts linked to

those scenarios. As an example, we may consider the emerging evidence of a sequence of high-amplitude, low wave atmospheric flow regimes in none El Niño years. For example, over the East Atlantic and Europe, these regimes have led to paradoxical occurrence of intense snowfall and low winter temperatures over the east coast of North America and large areas of Europe. This evidence was contrasted by a significant northward displacement of the westerly jets with very mild temperatures during the extreme El Niño years, which are probably closer to what the earlier, average-based predictions gave (high rainfall and strong winds over northern latitudes, and drought in the Mediterranean region). The preponderance of extended periods of quasi-stationary, large-amplitude planetary waves may persist, even in such years.

What about the potential impacts of smaller scale local phenomena, which affect flight safety?

Scientific research into future impacts of climate change on aviation encounters a problem in that many high-impact weather phenomena are linked to space and time scales far below those resolved by current forecast models. This problem is even more pronounced when using much coarser climate models, so that intelligent ways of downscaling, statistical post-processing and advanced methods of conceptual models would be needed to derive at least statistically reliable results for small- to micro-scale phenomena. This relates to high-impact weather phenomena such as convection and related effects ranging from low-level wind shear to hail and lightning strikes, clear-air turbulence (CAT) and mountain-wave turbulence, as well as turbulence near thunderstorm tops, icing and low-level wind shear, and low visibility and ceiling.

Improving our physical understanding of the generation of small-scale rotational movements in the atmosphere that play a part in reducing vertical wind shear – experienced as turbulence of varying intensities by crew and passengers – can help. For example, although CAT occurs on a micro-scale, our physical understanding tells us that the wind shear that generates it is driven by much larger scales. It is, therefore, potentially resolvable by the current generation of weather and climate models. More basic scientific research is needed to improve our understanding of these small-scale effects. This will require better atmospheric observations and operational data from aircraft (for example, for turbulence).[1]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Another area of research is in the changing behaviour of atmospheric jet streams as a response to climate change. The mid-latitude jet stream in each hemisphere is created and sustained by the temperature difference between the cold polar regions and the warm tropics. Climate models, satellite observations and physical theory all suggest that this temperature difference is changing in a complicated manner. It is decreasing at ground level because of polar warming, but it is increasing at flight cruising levels because of lower stratospheric cooling. One possibility is that changes in the prevailing jet stream wind patterns may modify optimal flight routes, journey times and fuel consumption. Another possibility is that increased shear within the jet streams at cruising levels may reduce the stability of the atmosphere and increase the likelihood of CAT breaking out.

Is there any research linking other weather aviation hazards, such as icing or sand/duststorms, in the context of climate change?

Airframe icing is traditionally seen as a problem for general aviation and, more specifically, for commuter aviation where there is limited engine power and rudi-

[1] Research on the CAT regime changes with conclusive results has been conducted by Paul Williams and Manoj Joshi (www.met.rdg.ac.uk/~williams/publications/nclimate1866.pdf)

mentary anti-icing devices. It nevertheless needs to be better understood in order to predict future scenarios. The presence of large supercooled droplets at a temperature range between –4 and –14 °C depends on a number of conditions. These include the availability of large amounts of water vapour, typically meso-scale bands of intense updrafts and a limited concentration of suitable aerosols acting as condensation nuclei, favouring the formation of large supercooled droplets.

The general warming trend and increase of moisture in some latitude bands, with a more active dynamic of the flow, all point to an increased chance of occurrences of conditions favourable to icing. They also lead to an upward extension of the upper limit of icing layers due to the higher temperatures.

High-altitude icing is caused by ingestion of a high density of icicles at very low temperatures (below –50 °C) in the vicinity of convective cloud tops with ice contents in excess of 5 g/m^3 of air. It is likely to increase with more intense cumulonimbus clouds and a rise of the tropopause due to the higher temperature and moisture of tropical air masses. The most energy-efficient modern (lean-burn) aviation engines appear to be more susceptible to these events than older, robust but thirstier turbines.

The likely increase in the occurrence and intensity of sand- and duststorms, caused by longer drought periods and potentially stronger winds in subtropical latitudes, will require a thorough analysis of the impacts on safety and regularity of flights. There is emerging evidence that the drive to higher engine efficiency (not least in order to reduce specific fuel consumption!) has pushed the operating temperatures in the combustion chambers of the most modern engines towards temperatures in excess of 1 600 °C. At these temperatures, the silicates contained in typical sand- and duststorms when sucked into the engine would melt and, thus, in a way similar to the volcanic ash, affect the performance and maintenance requirements.

Should the air transport sector consider climate change related risk management?

Aviation is exposed to weather phenomena not only on the ground, but also at levels up to the higher troposphere and lower stratosphere. It probably has the strongest tradition of prioritizing safety in the transport industry and is thus a prime candidate for developing sound and balanced risk management.

Aviation is probably the only reliable means of disaster response and relief in cases of large-scale disasters. For example, it will be unrealistic to maintain or repair hundreds or thousands of kilometres of roads or rail connections across areas affected by flooding, landslides, fires or storms in order to bring relief and aid to those affected. Adaptation measures and risk management, therefore, need to pay particular attention to the hardening of aviation infrastructure to ensure a robust and sustainable relief mechanism.

How does CAeM and the aviation community plan to turn insights into actionable guidance?

International organizations such as ICAO or the European Aviation Safety Agency need to develop guidance material and best practice models to support risk management. These should involve all stakeholders, from operators, pilots, airport managers and manufacturers to governments and national safety regulators. A multidisciplinary effort by scientists and operational and safety experts could contribute to the drafting of such guidance material together with operational and safety experts. It will be important for the guidance material to be regularly revised and updated to reflect evolving and changing climate statistics.

The wider community, including stakeholders such as ICAO-CAEP, Eurocontrol, the airports council and aircraft and equipment manufacturers, has been in close contact over recent months and years. There is a growing consensus that a multidisciplinary workshop leading to guidance for adaptation should be held in the near future.

Observing Water Vapour

By Ed Dlugokencky[1], Sander Houweling[2], Ruud Dirksen[3], Marc Schröder[4], Dale Hurst[1,5], Piers Forster[6], and WMO Secretariat[7]

Those who question the importance of climate change sometimes claim that reducing carbon dioxide (CO_2) emissions into the atmosphere will have a very limited effect, because water vapour is the most dominant greenhouse gas. If that is the case, they wonder why bother so much about CO_2 and other greenhouse gases? Observations by the WMO Global Atmosphere Watch programme have helped to investigate this in some detail.

Some atmospheric gases, such as water vapour and CO_2, absorb and re-emit infrared energy from the atmosphere down to the Earth's surface. This process, the greenhouse effect, leads to a mean surface temperature that is 33 °C greater than it would be in its absence. If it were not for the greenhouse gas effect, Earth's average temperature would be a chilly -18 °C. However, is the non-condensable or long-lived greenhouse gases – mainly CO_2, but also methane (CH_4), nitrous oxide (N_2O) and halocarbons (CFCs, HCFCs, HFCs) – that act as the drivers of the greenhouse effect. Water vapour and clouds act as fast feedbacks – that is to say that water vapour responds rapidly to changes in temperature, through evaporation, condensation and precipitation.

1 U.S. National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory

2 Netherlands Institute for Space Research (SRON)

3 Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN) Lead Centre, Deutscher Wetterdienst (DWD)

4 Deutscher Wetterdienst (DWD)

5 Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado

6 School of Earth and Environment, University of Leeds

7 Oksana Tarasova, Chief, and Geir Braathen, Senior Scientific Officer, Global Atmosphere Watch

This strong water vapour feedback means that for a scenario considering a doubling of the CO_2 concentration from pre-industrial conditions, water vapour and clouds globally lead to an increase in thermal energy that is about three times that of the long-lived greenhouse gases. Therefore, measured in the ability to trap the heat emanating from the Earth's surface, water vapour and clouds are the largest contributors to warming. The amount of water vapour in the atmosphere is a direct response to the amount of CO_2 and the other long-lived greenhouse gases, increasing as they do.

It is impossible for us to control directly the amount of water vapour in the atmosphere since water is found everywhere on our planet – it covers 71% of Earth's surface. To limit the amount of water vapour in the atmosphere and control Earth's temperature, we must limit the greenhouse gases that we can, in practice, do something about: CO_2 and the other long-lived greenhouse gases.

GAW observes water vapour as it is an important atmospheric constituent through the role it plays in the climate system as a potent greenhouse gas and as a source for clouds. Water vapour is also important as a chemical compound, both in the troposphere as a source of the hydroxyl radical, the most important oxidant in the troposphere, and in the stratosphere where it has an influence on ozone depletion, especially in the Polar Regions.

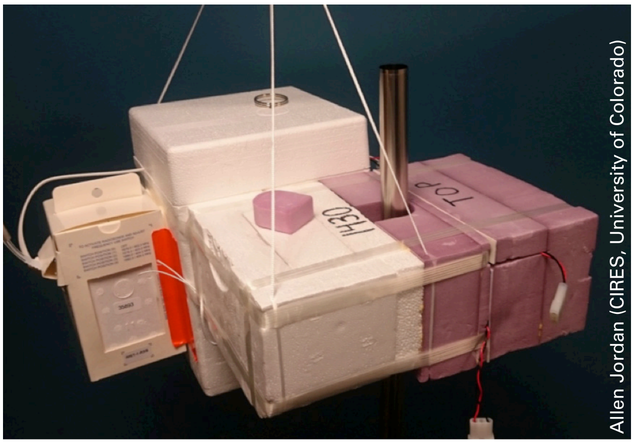
Measurement of water vapour

Atmospheric water vapour can be measured using a wide range of techniques and observational platforms. These observations are primarily used for numerical weather prediction, monitoring and research into climate and atmospheric chemistry. Water vapour is measured in situ by balloon- and aircraft-based

instruments, and remotely by satellite- and ground-based sensors.

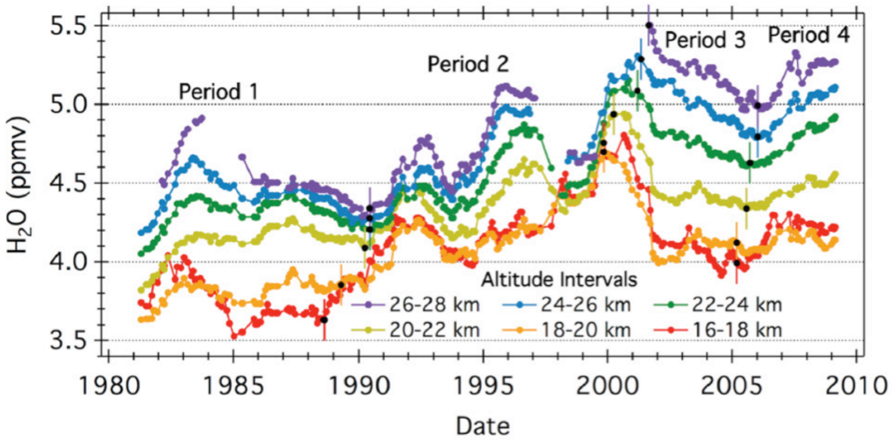
The different techniques for measuring water vapour include the use of:

- Passive microwave sensors installed on polar orbiting platforms;
- Infrared sensors, which constitute the longest satellite record of water vapour profiling and sounding instruments;
- Ultraviolet/visible/near-infrared imagers (daytime retrieval methods that use two channels and provide high spatial resolution (~ 1 km));
- Limb sounding, the technique of sounding various layers of the atmosphere by observation along a tangent ray that does not intersect the Earth's surface;
- Radiosondes, a commonly used instrument for in situ sounding that provides high-quality profiles of relative humidity (among other variables) at a still unmatched vertical resolution of approximately 5 metres – on a global scale about 1 000 radiosondes are launched each day. The humidity sensors on radiosondes give good-quality humidity data throughout most of the troposphere, however, important corrections must be applied to their humidity measurements in the upper troposphere and stratosphere;
- Balloon-borne frost point hygrometers that use a cooled mirror, whose temperature is carefully controlled at the frost point temperature;
- Ground-based instruments, which allow for semi-continuous probing of the air mass over a fixed location; and
- Various long-range commercial aircraft equipped with vapour sensors.



Balloon-borne sounding payload consisting of a NOAA frost point hygrometer (FPH, front), an electrochemical concentration cell (ECC) ozonesonde (rear) and an InterMet radiosonde (left). The thin stainless steel air inlet tube extends out the top of the FPH. A similar tube is fixed to the bottom of the FPH before launch.

Emrys Hall (CIRES, University of Colorado) prepares to launch a balloon carrying a NOAA FPH, an ECC ozonesonde and a radiosonde from the Marshall Field Site in Boulder, Colorado.



Stratospheric water vapour trends over Boulder, Colorado, show a 30-year net increase in stratospheric water vapour. From Hurst et al., 2011

Trends in observed atmospheric water vapour are hampered by inhomogeneities in data records, which occur when measurement programmes are discontinued because of, for example, the limited lifespans of satellite missions or insufficiently documented or understood changes in instrumentation. Combining records from different instruments that do not agree with one another is also a problem. One example is the offset between records from the HALOE and MLS satellite instruments. Nevertheless, observations show a steady increase of the total water vapour column as well as a 30-year net increase in stratospheric water vapour.

Water vapour in climate models

During the latter half of the twentieth century the amount of water vapour in the stratosphere showed a net increasing trend, but since 2000 there have been periods of both increasing and decreasing abundance (Nedoluha et al., 2013). A comprehensive understanding of all the mechanisms driving changes in stratospheric water vapour is currently lacking. Most of the transport of gases from the troposphere to the stratosphere happens through the tropical tropopause. Due to the low temperatures in this region of the atmosphere, the air gets freeze-dried and very little water enters the stratosphere. In fact, an important source of stratospheric water vapour is the oxidation of methane transported up from the troposphere. Future warming due to climate change and increasing concentrations of methane are both expected to lead to more water vapour in the stratosphere.

Increases in water vapour in the upper troposphere and lower stratosphere (UTLS) lead to radiative cooling at these levels and induce warming at the surface. Recent analyses suggest that warming at the Earth's surface may be sensitive to sub- parts per million (ppm) by volume changes in water vapour in the lower stratosphere. Research has found that a 10% decrease in stratospheric water vapour between 2000 and 2009 acted to slow the rate of increase in global surface temperature over this time period by about 25% compared to that which would have occurred due only to CO_2 and other greenhouse gases.[8] More limited data suggest that stratospheric water vapour probably increased between 1980 and 2000, which would have enhanced the decadal rate of surface warming during the 1990s by about 30% as compared to estimates neglecting this change. These findings show that stratospheric water vapour is an important driver of decadal global surface climate change.

In the absence of global three-dimensional observations of water vapour, global reanalysis products are often used to validate numerical model simulations. Two extensively used reanalysis data sets are the NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA), its newest release MERRA2, and European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Reanalyses.

8 Solomon, S., K. H. Rosenlof, R. Portmann, J. Daniel, S. Davis, T. Sanford, and G.-K. Plattner (2010), Contributions of stratospheric water vapour to decadal changes in the rate of global warming, Science, 327, 1219–1223, doi:10.1126/science.1182488.

A recent study showed that reanalysis data on high-altitude atmospheric water vapour, critical for the greenhouse effect, are not as accurate as previously thought. Water vapour data for the UTLS region from these reanalysis data sets have been compared to water vapour data from the Microwave Limb Sounder (MLS) on the AURA satellite. These satellite data have not been used in the production of these reanalysis, so they represent an independent data set well suited for validation. The study found that the reanalyses differed quite a lot from the MLS observations, overestimating the annual global mean water vapour in the upper troposphere by about 150%. Vertically, water vapour transport across the tropical tropopause (16–20 km) in the reanalyses is faster by up to ~86% compared to MLS observations. In the tropical lower stratosphere (21–25 km), the mean vertical transport from ECMWF is 168% faster than the MLS estimate, while MERRA and MERRA2 have vertical transport velocities within 10% of MLS values. Horizontally at 100 hectopascal (hPa), both MLS observations and reanalyses show faster poleward transport in the Northern Hemisphere than in the Southern Hemisphere. Compared to MLS observations, the water vapour horizontal transport for both MERRA and MERRA2 is 106% faster in the Northern Hemisphere but about 42–45% slower in the Southern Hemisphere. ECMWF horizontal transport is 16% faster than MLS observations in both hemispheres.

To add complexity to these discrepancies it should also be mentioned that water vapour data from MLS show dry biases of 10-20% in the tropical upper troposphere compared to frost point hygrometers launched on weather balloons from Hilo, Hawaii, and San José, Costa Rica (Dale Hurst, 2016). The MLS dry biases may slightly reduce the wet biases in the MERRA and ERA Interim reanalyses with respect to MLS.

These large discrepancies between different types of observational data, and between observations and reanalysis results, demonstrate significant uncertainties in the measurements as well as our lack of understanding of the transport and dehydration processes in the UTLS region. They also show that there is a great need for more and better observations of water vapour in this region. As mentioned in the section on measurements, the current observational systems are hampered by various shortcomings, such as the limited lifetimes of satellite missions and a sparse spatiotemporal distribution of balloon- and ground-based measurements; for example, there is only one site in the world (Boulder, Colorado) where there is a 30+ year time series of balloon measurements of water vapour in the UTLS region.

The models that are used to predict future climate use reanalysis data to verify that the current climate is modelled correctly. The lack of accurate water vapour data in the important UTLS region will therefore limit the ability of these models to predict future climate.

Water vapour as a chemical compound

In addition to acting as a greenhouse gas and as a source of clouds, water molecules also take part in chemical reactions in the atmosphere. Water vapour, together with ozone, is an important source for the formation of the highly reactive hydroxyl radical (OH). The OH radical is the most important oxidant in the lower atmosphere, providing the dominant sink for many greenhouse gases (e.g., CH_4, hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs)) and pollutants (e.g., CO and non-methane hydrocarbons). In clean air, the OH radical is formed through this pair of chemical reactions:

$$\mathbf{O_3 + n\ (l<340nm) \rightarrow O_2 + O(^1D)}$$
$$\mathbf{O(^1D) + H_2O \rightarrow 2OH}$$

The abundance of OH in the atmosphere depends on the amounts of ozone and water vapour. OH production also depends on the amount of overhead ozone as this determines the amount of short-wave radiation needed to crack the ozone molecule.

Whereas the troposphere is quite moist, the stratosphere is very dry, typically with water vapour mixing ratios ≤ 5 ppm. This means that usually there are no clouds in the stratosphere. However, if temperatures drop below-78°C a special type of water and nitric acid ($HNO_3 \bullet 3H_2O$) ice clouds can form. On the surfaces of the ice particles, chemical reactions occur that convert innocuous chlorine reservoir compounds (hydrochloric acid, HCl and chlorine nitrate, $ClONO_2$) to reactive forms (chlorine monoxide, ClO) that destroy ozone.

Increasing concentrations of water vapour together with decreasing temperatures in the stratosphere – also a

consequence of climate change – will give rise to more of these clouds and that will lead to more severe ozone depletion as long as the concentration of ozone depleting gases remains high.

Mother-of-pearl clouds in the stratosphere, about 20-25 km above the ground, form in lee-waves when strong westerly winds blow over the Norwegian mountains. The colours are caused by diffraction around the ice particles that make up these clouds. Despite their beauty they forebode ozone destruction through the conversion of passive halogen compounds into active species that destroy ozone.

Challenges in observing water vapour

The distribution of water vapour in the upper troposphere and the stratosphere is not very well known due to a paucity of observations in this region of the atmosphere. The global distribution of water vapour in the upper troposphere and the stratosphere is not very well known due to a paucity of high vertical resolution observations in this region of the atmosphere. In some cases there are also significant discrepancies between satellite data, frost point hygrometer data and meteorological reanalyses. More accurate data with better geographical coverage is needed. The observed temporal trends in stratospheric water vapour are poorly understood and this demonstrates our lack of understanding of how water vapour enters the stratosphere. These are areas that GAW will address in the future.

References available in the online version.

Contributions to Climate Science of the Coupled Model Intercomparison Project

by David Carlson[1] and Veronika Eyring[2]

The World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP) serves as a fundamental basis for international climate research. The process represents a remarkable technical and scientific coordination effort across dozens of climate modelling centres, involving some 1 000 or more researchers. A sequence of CMIP phases has underpinned and enabled a parallel sequence of Intergovernmental Panel on Climate Change (IPCC) Assessment Reports. The Fifth Assessment Report openly acknowledges a heavy reliance on CMIP phase 5. This brief overview of the design, intended capabilities and progress of the current sixth phase of CMIP (CMIP6) will demonstrate how it contributes to climate science.[3]

Motivation and benefits

Although model intercomparison projects now seem standard, the concept first arose when atmospheric modelling centres around the world started running coupled ocean and atmosphere models for climate. The need to share and intercompare outputs of those models was quickly recognized. But the tasks were easier said than done: a persistent organized set of protocols and mechanisms had to be defined along with a process to develop and support the coordination itself and the necessary intercomparison tools. In response, the WCRP Working Group on Coupled Modelling initiated CMIP. Early support from the Program for Climate Model Diagnosis and Intercomparison[4] (PCMDI) allowed CMIP to develop formats and standards and to establish effective mechanisms for model output availability.

Since 1995, CMIP has supported modelling centres and a broad range of model developers and users in the fundamental analysis and comparison of state-of-the-art climate model experiments under common protocols. While providing a useful and accessible basis for formal external assessments by IPCC and others, CMIP has, from the start, demonstrated two parallel benefits within the climate research community:

- Progress in the technical developments of the models themselves, fostered by exchange and intercomparison, and accompanied by agreed formats for exchange and metrics for intercomparisons;
- Ability to explore, in a systematic way through model diagnostics, ensemble means or careful cross-comparisons, specific scientific aspects of the climate system, from clouds to deep ocean circulation and the carbon cycle.

[1] Director, World Climate Research Programme, jointly sponsored by the Intergovernmental Oceanic Commission (IOC) of UNESCO (United Nations Educational, Scientific and Cultural Organization), ICSU (International Council for Science) and WMO

[2] Deutsches Zentrum für Luft- und Raumfahrt

[3] Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organisation by Eyring et al. (2015)

[4] United States Department of Energy (DOE)

CMIP processes deliberately foster the sharing of hardware and software expertize and exchanges between model users and the research community. They have the additional valuable impacts of minimizing duplication of effort and reducing operational and computational resource demands. This is much appreciated by individual centres, as well as the collective community, in a resource-constrained environment.

CMIP6 Challenges

The need for CMIP and the challenges facing, in particular, CMIP6 have grown. More centres run more versions of more models, which are increasingly complex. A modern Earth system model might now have full atmospheric chemistry, active land processes – including vegetation growth and decay – and an interactive carbon cycle on land and in the ocean. It remains very challenging to run Earth system models with all amendments at highest resolution, but the list of necessary and desired model outputs for climate-related decision-making has grown enormously while basic resolution has improved.

Some configurations of CMIP6 models will run at global resolutions of 25 km, which is better than the regional resolutions of only a few years ago. Running these models requires enormous computational resources, while archiving, documenting, subsetting, supporting and distributing the terabytes (and increasingly petabytes) of model output challenges the capacity and creativity of the biggest data centres and fastest data networks.

In designing CMIP6, the CMIP Panel – an oversight group of international scientists – undertook a rigorous assessment of past performance and future needs. It listened carefully to customers, in this case, modelling centres and research users. Based on prior CMIP phases, particularly the increment from CMIP3 to CMIP5, it assessed which strategies and practices had aided or limited substantial progress in model skill and scientific understanding. From this consultation, the Panel defined five design goals for CMIP6:

- To facilitate relationships between and intercomparisons among various Model Intercomparison Projects within CMIP6 and to ensure consistency across CMIP phases;
- To enable the research community to provide modelling centres with a science-based priority outline of CMIP6 preferred activities;
- To allow modelling groups to implement self-determined development schedules and research experiments uncoupled from, but still relevant to, a single IPCC deadline;
- To strengthen overall Model Intercomparison Project activities by embedding them within a coherent scientific framework, leading to an enhanced collective outcome; and
- To achieve all of the above through an open and inclusive process.

The CMIP6 design as it evolves, and as implemented to date, achieves these goals through fundamental changes in process and procedure and by adopting the WCRP Grand Science Challenges[5] as an encompassing scientific framework.

Continuous and flexible operations

To avoid alternating haste and delay in the lead-up to a fixed deadline, CMIP6 allows modelling centres to implement improved model versions and to run various CMIP experiments as ready and as convenient. They can do so as long as they also complete and submit the Diagnosis, Evaluation, and Characterization of Klima experiments (DECK) and the CMIP6 historical simulation according to guidelines, as certification of their CMIP capabilities and intents and as "entry cards" to CMIP6.

For CMIP6, historical forcing datasets – including emissions and concentrations of greenhouse gases, land use changes, solar and stratospheric (volcanic aerosol, ozone) variations – became available in April 2016. This will allow modelling centres to start running CMIP6 entry card experiments very soon.

Forcing datasets for future climate projections will become available by the end of 2016 from the Integrated Assessment Modelling (IAM) community, allowing clim-

5 www.wcrp-climate.org/grand-challenges

Members of the CMIP Panel

- Veronika Eyring (Chair, Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre))
- Sandrine Bony (Centre national de la recherche scientifique, (National Centre for Scientific Research), France)
- Jerry Meehl (National Center for Atmospheric Research, U.S.)
- Catherine Senior (MetOffice, United Kingdom of Great Britain and Northern Ireland)
- Bjorn Stevens (Max-Planck-Institute for Meteorology, Germany)
- Ron Stouffer (Geophysical Fluid Dynamics Laboratory, U.S.)
- Karl Taylor (Program for Climate Model Diagnosis and Intercomparison, U.S.)

ate projection experiments to start at that point. The majority of the CMIP6-endorsed Model Intercomparison experiments will occur during the period 2017–2018. Research based on analysis of the CMIP6 output will start to emerge in 2018–2020, in time to contribute to the IPCC Sixth Assessment Report.

Consistent and persistent model protocols

DECK and the CMIP6 historical simulation extend from the sound basis of prior CMIP phases. They are also very likely to represent exactly the experiments that most modelling groups use, or will use, to test and evaluate their newest model versions. Note that for the purpose of CMIP6, future climate began in 2015. We expect that the protocols for DECK and the CMIP historical simulation will remain quite consistent for future CMIP phases. In this way, rather than imposing performance or computational barriers, DECK and the historical simulation encourage consistency among models and across phases.

Improved standards and documentation

The push for improved standards and documentation arises internally due to the growing complexity of the models and externally in recognition that an increasing number of users outside the climate modelling community want access to CMIP data. CMIP works closely with the WCRP Working Group on Coupled Modelling Infrastructure Panel to establish and promulgate requirements, formats and specifications for output products, model and simulation documentation, and archival and access systems. These guidelines and standards, coupled with the long-term viability of the overall CMIP process, have allowed and encouraged the parallel evolution of data and evaluation infrastructure. One new effort will facilitate the execution of accepted analysis packages whenever an archive site registers a new CMIP product.

Routine use of these tools and diagnosis patterns will greatly facilitate systematic model evaluations as part of subsequent assessments. The CMIP standards and guidelines have also enabled a substantial data assembly effort, focused on gathering and converting observations and reanalysis products into accessible and CMIP-like formats for use in model evaluation. Both of these model evaluation efforts will broaden and accelerate during CMIP6. Fundamentally, these community-based CMIP tools and data sources encourage progress on model development and on scientific exploration.

Deliberate science focus

In the face of the increasing complexity of individual models, more versions running at more modelling centres and the share number of Model Intercomparison Projects within and outside of CMIP, the CMIP Panel wanted to ensure the dual roles of CMIP: to advance model development and to facilitate and advance climate research.

In evaluating more than 30 Model Intercomparison Projects proposed for CMIP6, the Panel considered the relevance of each to the three fundamental science questions of CMIP6:

- How does the Earth system respond to forcing?
- What are the origins and consequences of systematic model biases?

- How can we assess future climate changes given climate variability, predictability and uncertainties in scenarios?

These questions serve as the model improvement basis for seven WCRP Grand Science Challenges. The Panel merged, adjusted and revised the 30 proposals to come up with a “final” list of 21 CMIP6-endorsed Model Intercomparison Projects. All of these earned a commitment from 10 or more modelling centres, which committed to run all the top priority (tier 1) experiments specified by the Model Intercomparison Project and to produce all requested diagnostic outputs and information.

This convergence of Model Intercomparison Project goals with modelling centre commitments did not occur automatically or spontaneously. It is a clear signal that the CMIP process does, and will continue to, focus on highly relevant science questions extracted from, and contributing to, the WCRP Grand Science Challenges. Obviously, the Model Intercomparison Projects tailored their goals and requests to expected model capabilities and capacities, but through this process, modelling centres participated directly in designing the scientific focus and size of CMIP6.

To gain endorsement, and to help CMIP6 and the modelling centres set priorities and monitor progress, all of the Model Intercomparison Projects specify top priority tier 1 activities. Most also contain longer lists of optional and encouraged experiments. Working together with the IAM community, CMIP6 will specify Shared Socioeconomic Pathways with close (and quantitative) connection to the Representative Concentration Pathways of CMIP5. CMIP6 also takes a deliberate step towards improved communication with the assessments, adaptation and services communities through the establishment of a vulnerability, impacts and adaptation, and a climate services advisory board.

Available computing resources do not meet the full expected analytical and experimental desires of CMIP6. WCRP hopes that an orderly CMIP process encourages efficiency but also stimulates additional interest and resources. Circa 2011, Jerry Meehl of NCAR (National Center for Atmospheric Research) wrote that CMIP5 represented “the most ambitious coordinated multi-model climate change experiment ever attempted.” Today, the breadth and ambition of CMIP6 offers an extraordinary new standard of multidisciplinary climate science and a new level of coordination challenges.

Summary

CMIP6 envisions and encourages a consistent and persistent set of core activities, enhanced tools and mechanisms for access and analysis, and a simultaneously broad but focused scientific impact. It sets a notable example for inclusivity, for transparency and for open access of its information and products. It functions almost entirely through coordination, collaboration and cooperation. Although the meteorological community understands global (atmospheric) models and rapid exchange of high-quality data and model outputs, the CMIP endeavour almost certainly exceeds numerical weather prediction in complexity and data volumes.

Most of the coordination and collaboration occurs through the volunteered time of climate researchers. We know of no other community of models, modellers and researchers in the worlds of physics, medicine, economics, energy or weaponry, that puts such a large effort into intercomparison and exchange and which sustains such a remarkable effort through community motivation.

The CMIP response deserves appreciation and admiration within the scientific community. The breadth and ambition of CMIP6 offer an extraordinary new standard of multidisciplinary climate science and a new level of coordination challenges. As attention turns increasingly to the impacts of a changing climate, the CMIP process and products will represent one of society’s most important sources of robust and reliable climate information.

References available in the online version.

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WMO at COP22

Visit the WMO Climate Science and Information Booth 6 at the One U.N. Exhibit

Date	Time	Title	Place
7 November	13:15-14:45	Refinement of 2006 IPCC Guidelines	Mediterranean Room
7 November	**15:00-16:30**	**Urgencies in Fundamental Climate Research following the Paris Agreement**	**Mediterranean Room**
8 November	10:00-18:00	EarthInfo Day	To be announced
8 November	10:00-11:30	Climate Observations in Africa: Challenges and Opportunities	African Pavilion, room 2
8 November	18:30-20:00	Sustainable industrialization and International transport	Austral Room
8 November	To be announced	Press Conference: Release of 5-year climate statement 2011-2015	To be announced
9 November	13.15-14:45	Oceans: Science based solutions for achieving adaptation and mitigation goals	Mediterranean Room
9 November	18:30-20:00	Hydro-Climate Services for All	Mediterranean Room
11 November	13:15-14:45	Science for informed mitigation and adaptation choices	Austral Room
14 November	13:15-14:45	Community-level adaptation practices to reduce disaster risk, build resilience and end poverty	Arabian Room
14 November	To be announced	Press Conference: Release of provisional statement on the status of the climate in 2016	To be announced
15 November	11:30-13:00	Urban Development as a Catalyst of Climate Action	Pacific Room
15 November	13:15-14:45	Building capacity for 2030 Agenda through climate action solutions for regional implementation	Bering room
15 November	18:30-20:00	Good health and wellbeing ONE-UN side event on “Climate and Health”	Pacific Room
15 November	18:30-20:00	Delivering the Paris Promise – Making Climate Finance Matter in Marrakech	Austral Room
16 November	13:15-14:45	CREWS – Early Warning System for Climate Resilience	French Pavilion
16 November	13:15-14:45	Zero hunger under a changing climate	Pacific Room
17 November	18:30-20:00	Meeting the 2°C challenge: Nexus of Innovation and Clean Energy	Mediterranean Room

World Meteorological Organization

7 bis, avenue de la Paix - Case postale 2300 - CH-1211 Geneva 2 - Switzerland
Tel.: +41 (0) 22 730 81 11 - Fax: +41 (0) 22 730 81 81
E-mail: wmo@wmo.int - Website: www.public.wmo.int

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