Final Scientific Report for DE-SC 0004956:

Detection and Attribution: New Frontiers and Applications

PI: Claudia Tebaldi

Task 1.1 Regional D&A

ST 1.1.1 Regional D&A with CMIP5 models

Most of regional detection and attribution literature assessed by the IPCC AR5 WGI report in its chapter on D&A (Bindoff et al. 2013) are published by **IDAG members**. Studies by IDAG members within and after AR5 have covered many aspects of regional D&A for variables other than average temperatures and precipitation. Examples are extreme temperatures in China and other parts of the world (Wen et al., 2013, Min et al. 2013, Zwiers et al. 2011, Morak et al. 2013); total and extreme precipitation, especially in high latitudes (Zhang et al. 2013, Wan et al. 2014); summer heat in Eastern China (Sun et al., 2014); extreme temperatures in China (Wen et al., 2013); seasonal precipitation over land-areas (Polson et al., 2013). Extreme events over New Zealand were attributed by Harrington et al., (2014) and Dean et al., (2013), whose work required the development of innovative methodologies that make use of important large-scale predictors of extreme events that are well simulated by CMIP5 generation models

In the IPCC AR5 WG2 report, regional detection and attribution plots were produced by **D. Stone** for a number of the regional chapters, comparing simulations of CMIP5 models driven by both anthropogenic and natural drivers, simulations of CMIP5 models driven with natural drivers only, simulations under projected changes in drivers, and historical estimates from a number of observational products. The production of these plots was explained in Diffenbaugh et alii (2014), while they appeared in the chapters on Africa (Niang et alii 2014), Asia (Hijioka et alii 2014), the oceans (Hoegh-Guldberg et alii 2014), South America, and North America, as well as global versions in the WGII Technical Summary (Field et alii 2014a) and Summary for Policymakers (Field et alii 2014b). **D. Stone** was also responsible for the discussion of observed, detected, and attributed climate changes in African regions in the African chapter (Niang et alii 2014).

More methodological or "big picture" studies continued to be carried out as well. Much detection and attribution work carried out by IDAG and others has assumed linear additivity of the responses, that is the sum of responses of the climate system to individual radiative drivers is the same as the response to the sum of the radiative drivers. **Shiogama** et alii (2012) evaluated this assumption at global and continental scales using the uniquely large arrays of single-forcing simulations conducted with the MIROC3 model, finding no evidence for violation under past conditions but that it may be violated for the precipitation response in future decades. Santer et al. (2012) successfully tested the robustness of results of D&A on atmospheric temperatures to a range of uncertainties (observational and model-related). Ribes et al. (2015) worked on identifying an optimal experimental design to recommend single forcing simulations in order to maximize the signal-to-noise in the D&A analyses. DelSole (2012) applies a form of discriminant analysis to identify the "most detectable components" of a climate model. This technique identifies the time-dependent climate change signal that maximizes average detectability. The technique was applied to determine the most detectable components in the CMIP3 models of precipitation over land. No single pattern of the five-year mean July-September precipitation over land could be detected in all models, indicating that the forced response of precipitation is not robust across the climate models. This technique appears to be a significant advancement in detection capabilities, as previous attempts to identify forced precipitation patterns were restricted to zonal averages within certain latitudinal bands.

ST 1.1.2 Regional D&A using RCM experiments and new statistical approaches

Several studies used output from Regional Climate models nested into Global Climate models to test model performance against observations, for example regarding extreme seasonal precipitation trends (Wehner, 2013) finding some improvement in the ability to simulate extreme rainfall by higher resolution RCMs. Knutson et al., (2013) used dynamical downscaling to assess projections of hurricane activity into the 21st Century.
More strictly D&A work was performed over the European domain, and its implications in terms of communication and adaptation policies was assessed: the "consistency" method originally proposed by Bhend and von Stoch (2008; 2009) was modified and the results showed that recently observed warming over the Mediterranean region has very likely an anthropogenic origin and thus will likely continue *(*Barkhordarian et al., 2012a*)*. The consistency analysis of surface specific humidity (q) indicates that the large-scale component (spatial-mean) of anthropogenic signal has a detectable and dominant influence in the observed record of q *(*Barkhordarian et al., 2012b*)*. This may imply that the observed upward trends of temperature and specific humidity serve as an illustration of plausible future expected change in the Mediterranean region, allowing for a better communication of the societal challenges to meet in the future.

In contrast, the expectation of future precipitation change is different from the observed trends. The analysis clearly shows that projections of future regional precipitation change, an important factor for the estimation of future agricultural and hydrological resources, are not consistent with observed recent change *(*Barkhordarian et al., 2013*).* The analysis of large-scale circulation patterns, in terms of mean and extreme sea-level pressure and Geopotential height at 500hPa, confirms the inconsistency detected for precipitation *(*Barkhordarian A., 2012c*).* This significant shortcomings in the understanding of recent observed changes of precipitation complicate communication for future expected changes in the Mediterranean *(*Barkhordarian et al., 2013*).*

ST 1.1.3 Interpretation of regional variability over the last Millennium in Europe and North America

A paper by Neukom et al. (2014) analyzed the inter- hemispheric temperature variability over the past millennium.

ST 1.1.4 Disaggregating influences affecting the regional response

Global and regional temperature extremes were analyzed with and without the influence of internal modes of variability in order to better identify the external component of observed changes (Kim et al., 2015).

Work on Arctic land temperature changes was able to distinguish the influence of greenhouse gases from other anthropogenic forcings, aerosols in particular. Nature Climate Change wrote this up as a research highlight (Najafi et al., 2015). Christidis et al. (2012 and 2014) analyzed the distribution of annual mean temperatures and warm extremes under forced and unforced conditions. Sun et al. (2014) was able to identify and separate the effects of rban heat islands on regional warm extremes over China.

Morgenstern et al. (2014) disaggregated
influences affecting the regional response into "direct" vs "indirect" .The paper for the first time demonstrates that the effects of greenhouse gases on the Southern Annular Mode (an important dynamical feature of the Southern Hemisphere) are significant but reduced by the indirect effects of greenhouse gases on ozone depletion. This has important consequences for the way in which all detection and attribution experiments must be undertaken if one wants to isolate the most important forcings of the climate system on regional scales.

The Global Teleconnection Operator approach developed in Li, Forest, and Barsugli (2012) was used to explore specific attribution of regional climate changes to sea surface temperature changes during the 1950-2000 period. The results are sensitive to the estimated internal variability in the regional climate for a specific location with higher variability estimate identified in mid-latitudes compared with tropical latitudes (Li et al., 2012; Hoffman et al., 2014; Tsai et al., 2014; Li and Forest, 2014). This work main message is that attribution of the component of regional climate change due to SST changes remains a challenge requiring significantly larger ensembles to address the signal to noise concerns. The method was applied to dust source emissions (Hoffman et al., 2014), regional climate over large river basins (Tsai et al., 2014), and the variability of the North Atlantic Oscillation and Pacific North America patterns (Li and Forest, 2014). In all cases, the key regions of ocean basins can be identified as driving regional climate although the fraction of variance explained by these signals indicates additional investigations are required beyond the teleconnection mechanisms. The sensitivities of non-local regional climate to SST changes (or variability) provides a regionalized approach to understanding the forcing/response paradigm The circulation changes associated with changes in SST patterns also implies a state dependence of local feedbacks that requires further investigation.

Task 1.2 Extremes

Extreme events continue to be an area of interest for many IDAG members. Besides attribution of individual events (Task 1.3) several studies have addressed the detection of extremes in general, and the uncertainties in their projections. New high resolution simulations provided insight into how well attribution statements based on coarse resolution models can be transferred to real world events happening on smaller scales (Angelil et al., 2014). A new method was developed to spatially aggregate extreme events into a probability density function, in order to detect changes in extremes that would not be significant on the grid point level (Fischer and Knutti, 2014). These studies showed that trends in hot and wet extremes are detectable already today, are consistent between models and observations, and can be projected remarkably consistently with global models (Fischer et al. 2013, Fischer and Knutti, 2014). If extreme temperature is combined with humidity, the uncertainties are further reduced (Fischer and Knutti, 2012). This points towards the potential to use combined indices for both attribution and for constraining future projections.

Other, more traditional work, continued to identify the human component in several global and regional definitions of temperature extremes (Min et al., 2013; Kim et al. 2015). Wuebbles et al. (2014) draws a big picture of sever weather in the United States. Stone et al. (2013) detects anthropogenic influence on local temperature extremes. Hegerl analyzed with coworkers in her group and IDAG changes in mean and intense precipitation, showing that the human fingerprint of precipitation change is beginning to emerge (Polson et al., 2013a,b) and published a review paper on the changing watercycle in press with BAMs.

ST 1.2.1 Methodological work

Wehner (2014) tested the consistency of the recent behavior in temperature extremes during the hiatus with human-induced warming. Holbrook et al. (2014) focused on cross-scale interactions from decadal variability on extreme events.

ST 1.2.2 Analysis of specific phenomena

Many studies focused on particular seasonal-scale or annual scale phenomena, besides single events: Irish et al., (2014) unraveled the effects of sea level rise and warming since 1900 on hurricane Katrina. Kunkel et al. (2013) analyzed trends in other types of severe storms than tropical cyclones while Knutson et al. (2014a) analyzed extremes of seasonal and annual precipitation from storms in 2013. Knutson et al., (2014b) focused on the warm anomalies in Australia and the Western tropical Pacific during 2013. Christidis et al., 2013 conducted an attribution study for the heavy rainfall over eastern Australia that fell in March 2012.

Much more work is being conducted over Australia, given the extreme nature of climate anomalies over that continent in the last years. King et al., 2013, 2014; Lewis et al. 2013, 2014; Karoly et al., 2014; Lewis and Karoly, 2014a,b; it generally detects anthropogenic influences on temperature extremes, less significant influences on precipitation patterns and events.

Task 1.3 Probabilistic Attribution

The research area of event attribution has garnered strength within the IDAG membership, with many members busy developing and testing methodologies to assess the contribution of anthropogenic forcings on specific (extreme) events.

Methodological work together with analysis of specific events is taking place.

ST 1.3.1 Developing theory

Angelil et al., 2014 tested the sensitivity of attribution statement to spatial and temporal scales of aggregation, finding that results were mostly sensitive to the latter rather than the former for temperature, the opposite for precipitation. Pall et al. (2014) is a review paper of methods employed in this type of analysis.

ST 1.3.2 How to minimize selection bias

Angelil et alii (2014a) examined the degree to which event attribution conclusions, estimated from very large ensembles of a high resolution climate model, vary spatially within South Africa. It was found that while estimates of attributable probability for temperature events may often be considered valid within smaller and neighboring spatial domains, it appears that estimates for heavy daily precipitation events may be sensitive to the spatial definition of the event. Angelil et alii (2014b) examined how event attribution conclusions vary globally as a function of spatial and temporal scales. It was found that attributable risk tends to be more sensitive to the temporal than spatial scale of the event, increasing as event duration increases. Globally, correlations between attribution statements at different spatial scales are very strong for temperature extremes and moderate for heavy precipitation extremes.

The Weather Risk Attribution Forecast (http://www.csag.uct.ac.za/~daithi/forecast) has now generated several years of forecasts and hindcasts of the degree to which anthropogenic greenhouse gas emissions have influenced the chance of unusual monthly weather over pre-defined regions of the world. Aggregated conclusions are not sensitive on the climate model, but in the case of unusual precipitation months do vary strongly across the world.

ST 1.3.3 Ensemble modeling and approaches based on statistical modeling of observations

IDAG has been working with the International CLIVAR Climate of the 20th Century Plus (C20C+) Project in the development and implementation of their Detection and Attribution project (Folland et alii 2014). The project is producing a climate modelling data set targeted for understanding historical changes in weather extremes and the role of anthropogenic emissions. This is running atmospheric modelling experiments following the Pall et alii (2011) design, running a large ensemble of simulations under observed radiative and ocean boundary conditions and under counterfactual estimates of what those boundary conditions might have been in the absence of anthropogenic emissions. The project is being undertaken with at least half a dozen climate models, each covering at least a decade with large ensembles, and using a number of estimate of the attributable ocean warming.

Stone et alii (2013b) examined whether attribution statements in a recent paper were in fact supported by the observational data used in that paper. It was found that while observed trends in Western European summer extremes were supportive of a conclusion of an anthropogenic warming influence, the observed trends in Western Russian and in Texan summer temperatures were not. The study illustrated the difference in inferring regional warming conclusions from global versus regional data, and the potential bias that could result from using global data.

Christidis et al. (2014) presented a method for fast-track attribution assessments based on pre-computed odds of warm extremes from a large ensemble of historical or natural only simulations.

ST 1.3.4 Comparison of methodologies

Stott et alii (2013) presented a review and assessment of the current status of the investigation of the role of anthropogenic emissions in specific extreme weather events. This position paper included a discussion of current challenges including the different conceptual frameworks under which "event attribution" is currently conducted, as well as possible pathways toward dealing with these challenges. Lewis, S. C. and D. J. Karoly (2014) tested the model-dependence of attribution statements specific to Australian extreme heat.

Task 1.4 Extending D&A conceptual framework to impact studies

D. Stone contributed to the detection and attribution assessment of the impacts of observed climate changes globally (Cramer et alii 2014, Field et alii 2014a, Field et alii 2014b) and over Africa (Niang et alii 2014) undertaken in the IPCC's Fifth Assessment Report (AR5). Assessment of the detection and attribution of impacts in the AR5 was an activity distributed across sectoral and regional chapters, integrated within Cramer et alii (2014). This distributed activity required a consistent cross-disciplinary framework which was formulated in Stone et alii (2013) and elaborated in Hansen et alii (2013) and Hansen et alii (2015). A particular challenge was the treatment of the impacts of extremes. This was conducted within a risk-based framework which compared the relative importance of long-term trends in various climatological and non-climatological contributors to risk as proposed in Huggel et alii (2014), implemented in the AR5 in Cramer et alii (2014).

Wolski et alii (2014) examined the role of anthropogenic greenhouse gas emissions on the chance of high seasonal flooding in the Okavango Delta, Botswana. It was found that changes to precipitation, that were uncertain across methods and models, were unimportant in comparison to the descreasing chance driven by warming, which was consistent across methods and models.

Mueller et al. (2014) looks at changes in growing season length due to anthropogenic influences and Lobell and Tebaldi (2014) demonstrates that anthropogenic climate change is changing the risk of significant slowdowns in the production of two important crops, maize and wheat, at the global scale.

Task 2.1 Use of CMIP5 results and new datasets for updating D&A studies

ST 2.1.1 CMIP5 output

The availability of the Coupled Model Intercomparison Project Phase 5 (CMIP5) triggered a large number of studies in various areas that are relevant to detection and attribution. These included analysis of the uncertainty and robustness of the emerging climate change signal (Knutti and Sedlacek, 2012, Sedlacek et al., 2014), a new analysis of the relationship and interdependence of different models in the ensemble (Knutti et al. 2013), studies on the interpretation ensembles of opportunity like CMIP5 (Sanderson and Knutti, 2012), and studies on the role of natural variability and its contribution to past and future changes.

The first main conclusions are that the robust changes seen in earlier models are still very similar in the new models, and consistent with the changes attributed to human influence. However, the spread across models in CMIP5 has not decreased compared to CMIP5, despite substantial model development, better observations, and higher computational capacities. The interpretation is that considering more processes in Earth System models can in fact increase the uncertainty for projections, highlighting the role of observations and attribution studies in constraining parameters and projections in those models (Knutti and Sedlacek, 2012, Sedlacek et al., 2014).

The second conclusion is that the interpretation of ensembles of opportunity is still challenging, because models share ideas and code and are highly dependent (Knutti et al. 2013), and as a result the interpretation of the ensemble in a statistical sense in challenging (Sanderson and Knutti, 2012).

A third area that got a lot of attention recently is the role of natural variability, partly related to the reduced warming trend globally since about 1998. A new method was developed to study attribution based on the combined evidence of warming in the ocean and atmosphere, and comparing it to natural variability (Sedlacek and Knutti, 2012). Earlier studies on the emerging climate signal for temperature (Mahlstein et al. 2011) were updated for precipitation (Mahlstein et al. 2012), and methodological differences were clarified (Hawkins et al., 2014). The role of natural variability is more important than most people appreciate for the local grid point scale. Local trends for the future could be near zero in a few places for several decades (Deser et al. 2012). These recent studies are consistent with the dominant human influence on large scale warming, but highlight the role of variability on small scales

Fyfe et al. (2013) examined the consistency of CMIP5 models with the observed warming hiatus, finding that under the paradigm of exchangeability the pause in warming is still consistent with the ensemble behavior. Kharin et al., (2013) documented the new CMIP5 output projections with regard to temperature and precipitation extremes, while Knutson et al. (2013) compared the multi-model output to observed regional surface temperature trends. Lewis and Karoly (2014) assessed the accuracy of the forced responses from the Australian Community Climate and Earth System Simulator (ACCESS) version 1.3 in its CMIP5 historical experiments. Within the new phase of CMIP5/IPCC IDAG members collaborated on communicating detection and attribution results, including uncertainties and statistical challenges, based on the new CMIP5 experiments and reported in the IPCC AR5 detection and attribution chapter (Bindoff et al., 2013; Hegerl and Stott, 2014; Hegerl and Russon, 2011; Hegerl et al., 2011; Zwiers et al., 2011)

ST 2.1.2 New observational datasets

Frame and Stone (2013) examined the detection and attribution problem from a forecast perspective. In 1990, the IPCC's First Assessment Report effectively made a prediction of climate change over the next 20 years. Using CMIP3 unforced simulations, Frame and Stone (2013) found that observed climate change over those 20 years was consistent with that prediction but would have been inconsistent with a prediction of no-change.

Gallant et al. (2014) updated the Climate Extreme Index to compute current trends in the US, while Wan et al. (2014) used an updated and quality controlled observational dataset of high-latitude precipitation amounts to attribute recent trends to human influence. Westra et al. (2013) studied changes in precipitation extremes based on station data, examining whether changes are linked to warming; they exploited the block maximum approach of Extreme Value Analysis and used global mean temperature anomalies as a covariate; using the fitted EVA models, a sensitivity of extreme precip to warming of ~7%/K, consistent with Clausius-Clapeyron, was estimated. Donat et al. (2013) updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century producing a new version of the HadEX dataset, HadEX2. Wan et al. (2013) tested the robustness of D&A results on precipitation mean and variability of changes in data coverage.

ST 2.1.3 Perfect model approach for testing probabilistic attribution

An energy balance model has been used to predict a PDF of equilibrium climate sensitivity and the transient climate response for a 20 member ensemble of the NCAR/NSF/DOE model CESM (Huber at al. 2014). In general the value of such methods was confirmed, but the results are sensitive to the time period of the observations (i.e., data from CESM in this case), and in particular to the uncertainties that are assumed for the constraints. If those are small, the structural limitations of the energy balance approach become limiting (e.g., how natural variability is treated, see below), and the result can be an overconfident but biased probabilistic estimate of climate sensitivity, the transient climate response and therefore future warming.

ST 2.1.4 Constraining ECS and TR

The method of subtask 2.1.3 was also used to the estimate the effect of natural internal climate variability on the constrained PDFs of climate sensitivity and the transient climate response (Huber et al. 2014). The contribution of variability is not negligible, and can shift the mode of the PDF by half a degree C or more. This highlights the fact that short observational record (where the variability is small compared to the trend) are not suitable to infer climate system properties, to evaluate trends in models, or to constrain future projections.

In an effort to test the consistency of ranges for radiative forcing, climate sensitivity and recent warming and ocean heat uptake, inferred in various chapters of the IPCC report, a large group of authors derived new estimates of climate sensitivity and the transient response from the most reliable datasets (Otto et al., 2013).

To produce an observed record of surface warming and ocean heat uptake without variability turns out to be challenging. For the surface warming, the effect of ENSO for example is well understood, but the ocean integrates the surface signal and removing variability in the ocean is much more difficult, and limited by a short observational record to calibrate any statistical regression model. A direct estimate of climate sensitivity from a noise reduced record is therefore difficult, but the recent warming hiatus provides an opportunity to better understand the natural variability component. A new method was developed to estimate the contribution of variability originating from the tropical Pacific to the global surface temperature, by picking and aggregating control run segments that had a similar ENSO evolution (Huber and Knutti, 2014). Combined with an estimated contribution of solar forcing,

and the effect of stratospheric background aerosol forcing not accounted for in CMIP5, the authors showed that the simulated and observed warming over the past two decades is consistent, and there is no evidence that the CMIP5 models as a whole are significantly overestimating climate sensitivity or the transient climate response.
Recent claims that the observed warming implies a low climate sensitivity were analyzed in more detail, and the implications on required emission reductions were quantified (Rogelj et al., 2014). This was the most downloaded perspective in Environmental Research Letters in 2014.

For estimating the distributions of climate system properties including equilibrium climate sensitivity (ECS), transient climate response (TCR), ocean heat uptake properties, and net global radiative forcing, Libardoni and Forest (2011, 2013) examined the sensitivity of the distributions to using multiple surface temperature climate records. The central estimates and the ranges for ECS and TCR are significantly impacted by using different data records by about 1ºC for the lower bound and median and greater than 2 ºC for the upper bound. The interpolation and averaging methods used by each group (GISS, NCDC, and HadCRU) for estimating the temperatures on the 5ºx5º grid for the globe contribute to the uncertainties in the southern hemisphere, primarily in the oceans, and impact the spatial patterns used to constrain the climate system properties within the single model context used by Libardoni and Forest (2013).

ST 2.1.5 Limitations in forcing/feedback concepts

Recent studies emphasize that some of the basic assumptions that are underlying detection and attribution are only valid within some ranges of forcing and response, and exploring those limitations is therefore key. These include the fact that the feedbacks may depend on the timescale and state of the climate, the forcing type and the forcing magnitude. As a consequence, patterns of change cannot be assumed to perfectly scale with the magnitude of the forcing, and may not add up linearly. Two studies explored the difference between greenhouse gas and solar forcing, the additivity, and scalability of the response and find that the above assumptions are difficult to justify for solar forcing (Schaller et al. 2013, 2014). Further studies on various types of models are underway to better quantify those effects.

ST 2.1.6 Carbon cycle metrics

The concept of cumulative carbon, i.e. the linearity between global temperature and total carbon emitted, has been one of the key results of the IPCC Working Group 1 report (highlighted in the summary for policymakers IPCC 2013, Fig. SPM.10), and the synthesis report, based largely on the work by IDAG authors (Knutti, Allen, Gillett). The concept is now well established and prominently featured in high ranked journals (Friedlingstein et al., 2014). Some of the recent work and insight is only now being written up (Knutti and Rogelj, 2015), and a special issue in Environmental Research Letters on the concept of cumulative carbon is being produced in 2015.

ST2.1.7 Detection of mitigation
Tebaldi and Friedlingstein (2014), Delayed detection of climate mitigation benefits due to climate inertia and variability, looks at the time of emergence of a significant differences between the trajectories of RCP2.6 and two higher RCPs, 4.5 and 8.5 in order to characterize how long it would take for global and regional temperatures to be significantly different under a strong mitigation scenario than they would be under a scenario with increasing CO2 emissions. For global mean surface temperature, the median detection time of mitigation is about 25–30 y after RCP2.6 emissions depart from the higher emission trajectories. This translates into detection of a mitigation signal by 2035 or 2045, depending on whether the comparison is with RCP8.5 or RCP4.5, respectively. The detection of climate benefits of emission mitigation occurs later at regional scales, with a median detection time between 30 and 45 years after emission paths separate. Requiring a 95% confidence level induces a delay of several decades, bringing detection time toward the end of the 21st century.

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