# 20. THE ROLE OF CLIMATE CHANGE IN THE TWO-DAY EXTREME RAINFALL IN GOLDEN BAY, NEW ZEALAND, DECEMBER 2011

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*Introduction.* In December 2011, a torrent of water fell from the sky in Golden Bay and Nelson, overwhelming local streams and inundating the landscape with mud and debris. Barren scars of earth littered the hillsides of the region, a testimony to the power of the event (see Supplementary figures). The culprit was a low-pressure weather system that transported moist air directly from the subtropics to New Zealand (Fig. 20.1a and Supplementary animation). When this "atmospheric river" collided with the coastal hills of Golden Bay and Nelson, the rainfall amounts were staggering—in the township of Takaka 453 mm was recorded in just 24 hours and 674 mm in 48 hours. This greatly exceeds any previous record at this site, and from the available observations, it has been estimated that the 48-hour total is a one in 500-year event. The event was also the largest 48-hour accumulation ever recorded in an urban area in New Zealand.

Strikingly, the rain fell predominantly on coastal hills within 2 km–5 km of the coast (all <500 m elevation), such that none of the major rivers with headwaters in the mountains reached extreme flood levels. Such high rainfall in coastal areas is damaging, predominantly because of higher population density. The event was unusual due to its rare combination of high humidity in the lower atmosphere accompanied by only moderate winds (Doyle and Harvey 2012). A stationary high east of New Zealand also played a key role in slowing the progress of the deep low.

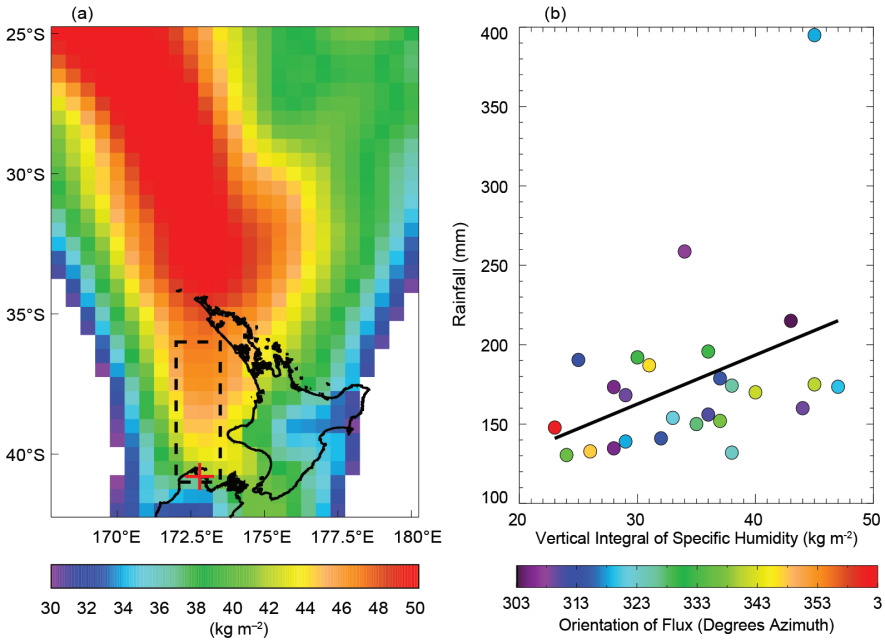


**Fig. 20.1. Observations of the Dec 2011 Golden Bay and Nelson extreme rainfall event. (a) Vertical integral of the specific humidity (kg m$^{-2}$) for 14 Dec 2011 from the ERA-Interim reanalysis. The location of the Takaka rain gauge is indicated by the red cross, while the dashed lines indicate the box over which the large-scale fields were averaged. (b) Vertical integral of the specific humidity (kg m$^{-2}$) from ERA-Interim averaged for the box in (a) plotted against all daily rainfall amounts (09:00 to 09:00 NZST) measured at Takaka that exceeded 130 mm for the period 1979–2012. Colors indicate the orientation of the vertical integral of the moisture flux. Note that the Dec 2011 event lies in the top right of the figure.**

*Was this event influenced by climate change?* Pall et al. (2011) have recently demonstrated how the risk of a monthly scale flooding event in England and Wales changed due to the emission of anthropogenic greenhouse gases (GHGs). However, it is difficult to apply their techniques to the short duration rainfall events that are typical of flooding in New Zealand, largely because of the higher spatial and temporal variability involved.

Here it is suggested that progress might be made on this question by using a methodology that is capable of identifying all occurrences of the synoptic situation matching the Golden Bay/Nelson event within large ensembles of climate-model simulations that alternatively exclude and include the impact of GHGs. If the observed precipitation distribution for these events is well simulated by the model for the past climate, then any change in the rainfall distribution due to GHGs can be considered.

A formal attribution based on precipitation requires a large ensemble from a regional climate model capable of resolving the fine structure of atmospheric rivers, and this is an objective of the Australia/New Zealand "weatherathome" experiment (http://www.weatherathome.net). As a first step, this paper tests the proposed methodology in a simplified manner by considering the daily data available from the Coupled Model Intercomparison Project 5 (CMIP5) archive of global climate models (Taylor et al. 2012). Our analysis relies on the relationship between rainfall extremes at midlatitudes and the large-scale moisture fluxes associated with atmospheric rivers (Junker et al. 2008; Ralph and Dettinger 2012). Here we derive the relationship between the large-scale circulation and Golden Bay extreme rainfall events using station observations and moisture fluxes from the ERA-Interim reanalyses (Dee et al. 2011). We then apply these constraints to the CMIP5 models and consider the impact on the humidity available for precipitation.

*Observations of rainfall and moisture*. In Fig. 20.1b, all observations are 09:00 New Zealand Standard Time (NZST) 24-hour rainfall accumulations, which have exceeded 130 mm in Takaka (1979–2012). This corresponds to all observations at or above the 99.8th percentile of the rainfall distribution, an arbitrary threshold for an extreme. For each of these 26 events, the vertical integral of the meridional and zonal moisture fluxes from ERA-Interim were used to calculate an orientation and magnitude for the integrated moisture flux averaged over the dashed box shown in Fig. 20.1a. The direction of origin for the moisture fluxes (Fig. 20.1b, colors) lies in a narrow range of angles between north and northwest. This is a direct consequence of the topography that surrounds this location.

The vertical integral of specific humidity derived from ERA-Interim, and averaged over the same area, is plotted against the extreme precipitation amounts in Fig. 20.1b. Rainfall extremes are hypothesized to increase with the availability of moisture (Allen and Ingram 2002; Trenberth et al. 2003), and the moderate positive correlation in this very small sample of observations suggests some support for this conclusion. The observations also suggest that high moisture flux magnitudes are a prerequisite for extreme precipitation (not shown), but there is no similar linear relationship between moisture fluxes and extreme precipitation (not shown).

Altogether, this analysis suggests that an angle constraint on moisture flux direction, combined with a minimum magnitude of moisture flux and specific humidity, may be used to define large-scale synoptic conditions that are a prerequisite for rainfall extremes at this location. Thresholds used for the integrated specific humidity and moisture flux are the minimum values observed for Takaka extreme events, 23 kg $m^{-2}$ and 400 kg $m^{-1}$ $s^{-1}$ respectively. However, these basic criteria overpredict extreme precipitation: for 1979–2012 ERA-Interim has 315 events that match the criteria while only 26 extreme events (>130 mm $day^{-1}$) are observed at Takaka.

*Is there evidence from global climate models that the total moisture available for this event has changed as a result of GHG emissions?* Daily pressure, humidity, and wind fields were acquired from the CMIP5 archive for climate models providing historical simulations (1950–2005) that included all natural and anthropogenic forcings (ALL) as well as matching simulations that included only natural forcings (NAT). The only four climate models that met these criteria were BNU-ESM, GFDL-ESM2M, IPSL-CM5A-LR, and IPSL-CM5A-MR (see PCMDI 2013 and links therein for model descriptions). From these, the vertical integrals of moisture flux and specific humidity were calculated for the dashed box in Fig. 20.1a. Potential extreme rainfall events were identified using the constraints for moisture flux and humidity described previously. The number of events that match these synoptic criteria for a Takaka rainfall extreme in the ALL simulations range from 469 to 738, which can be compared to an estimate of 525 from ERA-Interim for a period of 55 years. This suggests the models do a reasonable

job of reproducing the frequency of these synoptic conditions. All four models show an increase in the number of events for the ALL simulations compared to the NAT, with a range of 8% to 32%. In all cases, this is dominated by an increase in the number of events that exceed the moisture thresholds, rather than because of changes in the occurrence of synoptic lows. This gives confidence that these increases in the ALL simulations are a thermodynamic response to the emission of GHGs.

Figure 20.2 shows the percentage change in the vertically integrated specific humidity for these events for ALL relative to NAT. The plot is created by calculating the quantiles for the smaller number of events in the NAT simulations (a percentile for every value) and then interpolating the events in the ALL simulations onto these percentiles. While all four model distributions are noisy at this scale, there is a consistent trend for the models to increase the specific humidity, particularly in the high tail of the distribution. To calculate the change at the actual value of the Takaka event, we reduce this noise by averaging over the 16 quantile values centered on 45 kg m$^{-2}$. All four models increase the integrated specific humidity in the ALL simulations relative to the NAT, with a range of 1.3%–5.4% and an average of 3.6%.

It is hypothesized that rainfall extremes should increase with global warming, primarily as the availability of moisture in the atmosphere increases by about 7% per degree of warming following the Clausius-Clapeyron constraint. For this particular event, the integrated specific humidity increases from NAT to ALL by an average 6% per degree of warming (range of 2%–10%), where the change in temperature is calculated over a region covering both Golden Bay and the moisture source region for the event. For mid-latitudes, the increase in precipitation expected to have occurred may be somewhat more or less than these changes in moisture due to the way vertical winds and the vertical temperature structure change locally (O'Gorman and Schneider 2009; Pall et al. 2007).

*Conclusions.* This analysis indicates that the total moisture available for precipitation in the Golden Bay/Nelson extreme rainfall event of December 2011 was 1%–5% higher as a result of the emission of anthropogenic greenhouse gases. Theory and observations imply that this should have led to increased precipitation for this location. This analysis also found that the number of synoptic events with enough moisture to cause extreme rainfall in Takaka has increased, which indicates there may have been an elevated risk of this type of event. In this study, no attempt has been made to adequately assess the uncertainty on these results. A much larger ensemble of a higher resolution model, such as in the "weatherathome" experiment, is required for formal attribution statements about precipitation extremes.

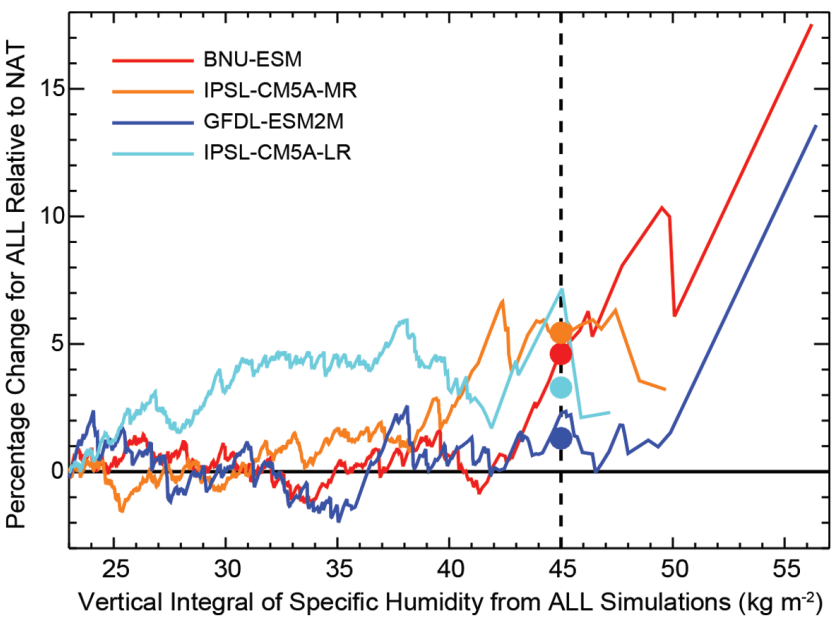


**Fig. 20.2. Percentage change in the vertical integral of specific humidity for an ALL simulation relative to a NAT simulation for each of four CMIP5 models over the period 1950–2005. This is shown plotted against the values of the vertical integral of specific humidity for the ALL simulations, such that the value for the Golden Bay/Nelson event (45 kg m$^{-2}$) calculated from ERA-Interim can be shown by the dashed line. The colored dots are the respective values for the change in vertical integral of specific humidity when 16 quantile values are averaged about the value of the Golden Bay/Nelson event. In the case of IPSL-CM5A-LR, there are only two points above 45 kg m$^{-2}$ available for the calculation.**