Implications of a decrease in the precipitation area - Supporting Material

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Statistics on the precipitation area

This is a document is intended as the supporting material for the paper with the title 'Implications of a decrease in the precipitation area'. It is meant to provide a record like a lab note-book, to enhance the possibility of replication and provide details about the analysis. It provides openness and transparency, and is not mean to be a 'well-structured' document.

Getting the data

The TRMM data was downloaded (February 2017) from NASA data portals https://disc2.gesdisc.eosdis.nasa.gov/data/TRMM_L3/TRMM_3B42_Daily.7/ using he instructions provided in https://disc.sci.gsfc.nasa.gov/recipes/?q=recipes/How-to-Download-Data-Files-from-HTTP-Service-with-wget and https://disc2.gesdisc.eosdis.nasa.gov/data/TRMM_L3/TRMM_3B42_Daily.7/doc/TRMM_Readme_v3.pdf. It is necessary to create a user account and set up user details/cookies as descibed in the intructions. The code presented here was written for Linux, and it is uncertain whether it works for Windows machines. It maybe will work on iOS. The data volumes are large and require some time and space for a complete download

Satellite data - the Tropical Rain Measurement Mission (TRMM)

Download the daily TRMM data (~16Gb and takes time) on a Linux platform (using a terminal and bash-scripts).

```
## Retrieving the data:
## https://disc2.gesdisc.eosdis.nasa.gov/data/TRMM_L3/TRMM_3B42_Daily.7/
## See this web page for how to download the files.
## https://disc.sci.gsfc.nasa.gov/recipes/?q=recipes/How-to-Download-Data-Files-from-HTTP-Service-with-
## https://disc2.gesdisc.eosdis.nasa.gov/data/TRMM_L3/TRMM_3B42_Daily.7/doc/TRMM_Readme_v3.pdf

## Script for downloading thr TRMM data
#!/bin/bash
mkdir TRMM
cd TRMM
for year in {1998..2016}
do
  for month in {1..12}
  do
  wget --load-cookies ~/.urs_cookies --save-cookies ~/.urs_cookies --keep-session-cookies
       -r -c -nH -nd -np -A nc4
       "https://disc2.gesdisc.eosdis.nasa.gov/data/TRMM_L3/TRMM_3B42_Daily.7/$year/$month"
  done
done
```

Independent reanalysis - ERAINT

The ERAINT data were downloaded from http://apps.ecmwf.int/datasets/data/interim-full-moda/levtype=sfc/ (Monthly means of daily means as well as daily accumultated precipitation) as netCDF and renamed `ERAINT_t2m.nc` (2-meter temperature), `ERAINT_Qs.nc` (surface moisture flux), and `ERAINT_Q-columntotal.nc` (total column water). The daily precipitation was downloaded in multiple files due to large data volumes: `ERAINT_24hr_precip*.nc`. The unit of the precipitation was 'm' (it is assumed it was m/day).

The following lines of code were the contents of the script `totprecip.jnl` implemnted by PMEL Ferret:

```
use $1
set reg/y=50S:50
CANCEL LIST/HEAD
let TotP = TP[x=@din,y=@din]
let pre001 IF TP GT 0.0001 then 1 else 0
let Ap001 = pre001[x=@din,y=@din]
let pre01 IF TP GT 0.001 then 1 else 0
let Ap01 = pre01[x=@din,y=@din]
let pre1 IF TP GT 0.01 then 1 else 0
let Ap1 = pre1[x=@din,y=@din]
let pre0 IF TP LT -9999 then 0 else 1
let TotA=pre0[x=@din,y=@din]
!save/append/clobber/file=totprecip.nc TotP,Ap01,Ap1,TotA
list/append/file=totprecip.txt TotP, Ap001,Ap01,Ap1,TotA
cancel data ($1)
cancel memory
! Earth's area = 5.111859e+14 m^2
```

The Ferret script was run through bash jobs:

```
#!/bin/bash
for f in ERAINT_24hr-precip*.nc; do
  echo $f
  /home/rasmusb/ferret/bin/ferret -gif -script ~/Downloads/totprecip.jnl $f
done
```

The use of MERRA-2 was also attempted, but without success. The right data (daily precipitation) was hard to find, and a search on the web site gave numerous hits with all sorts of precipitation results but not for 24-hr precipitation on a daily basis through the reanalysis interval. A Google search did not give any useful tips.

Preparing indices from the data

This section shows how indeces stored in the `preciparea` package were derived, such as `data("Parea")`.

TRMM

The TRMM netCDF files were unfortunately not stored with CF convention and a time dimension, and it was unclear how common netCDf processing tools like `ncra` could be applied to estimate the monthly means. Instead, the monthly data were aggrigated from the daily ones in the R-environment and the R-package `preciparea` (which was time-consuming).

The following command line were used to prepare the daily indicex describing the precipitation area $A_P = \int_A H(x - x_0)da$, where H is the Heaviside function, x is the precipitation, and x_0 is a precipitation threshold, where $H(x) = 1 \; \forall \; x \geq x_0$ and $H(x) = 0 \; \forall \; x < x_0$. The index A_P was estimated through the `retrievemodis` function and stored in the object `Parea` (short for precipitation area):

```
## TRMM: daily data
retrievemodis() -> Parea
save(Parea,file='Parea.rda')
## data("Parea")
```

It was convenient to also include a number of other indices in `Parea` while estimating A_P, and the object also was designed to hold additional information such as the precipitation area over land and oceans respectively in addition to the precipitation intensity (wet-day mean precipitation) and total precipitation amount $P_{tot} = \int_A P da$ where P is the precipitation. The total precipitation can also be written as $P_{tot} = A_P \overline{P}$.

```
attr(Parea,'longname')
#[1] "Precipitation area"              "Precipitation area over ocean"   "Precipitation area over land"
#[4] "wet-day mean preciptation"       "total precipitation"             "total precipitation over ocea
#[7] "total precipitation over land"   "number of valid data"
```

Quality check:

Repeat the calculations with NOAA/Pacific Marine Environment Lab (PMEL) Ferret:

```
use $1
set reg/y=50S:50
CANCEL LIST/HEAD
let precip = precipitation
let TP = precip[x=@din,y=@din]
let pre IF precip GT 1 then 1 else 0
let A = pre[x=@din,y=@din]
!save/append/clobber/file=totprecip.nc TP,A
list/append/file=totprecip.txt TP,A
cancel data ($1)
cancel memory
```

The bash-script `ferretjobs.sh` was used to carry out the ferret jobs:

```
## Ferret script to estimate the total precipitation and the area
## Rasmus.Benestad@physics.org
#!/bin/bash

for f in 3B42*.nc4; do
  echo $f
  /usr/local/ferret/bin/ferret -gif -script ~/TRMM/totprecip.jnl $f
done
```

The job was implemented by typing the command:

```
./ferretjobs.sh
```

The results were then read in R and compared with the calculations done in R:

The data looks like

```
I / *:     104515.  8493.
I / *:     97743.  8408.
I / *:     98213.  8205.
I / *:     90036.  8106.
...
```

The format of the output means that Ferret did not make use of the metadata (coordinate units etc) for properly estimating the area and the total precipitation. The output from Ferret was then reformatted in R:

```r
library(preciparea)
```

```
## Loading required package: ncdf4

## Loading required package: zoo

##
## Attaching package: 'zoo'

## The following objects are masked from 'package:base':
##
##     as.Date, as.Date.numeric

## Loading required package: esd

##
## Attaching package: 'esd'

## The following object is masked from 'package:base':
##
##     subset.matrix
```

```r
tp.in <- read.table('~/TRMM/totprecip.txt')
pta <- cbind(tp.in$V4,tp.in$V5)
tpa.day <- zoo(pta,order.by=seq(from=as.Date('1998-01-01'),by='day',
                                          length.out=length(pta[,1])))
names(tpa.day) <- c('tot.precip','precip.area')
```

Repeating the analysis on monthly mean precipitation

A quality check was applied to the *monthly* TRMM data

```r
## May have to run this several times with different values for yr1
## and having restarted R - there seems to be a memory leak in ncdf4.
TRMM2monthly()
## Processing for data("Parea.month")
```

The monthly TRMM files were also concatinated into one file using NCO so that the monthly data derived from daily A_P could be compared with monthly data estimated from monthly mean precipitation:

```
ncrcat trmm-precip*.nc trmm-precip-mon.nc
```

```r
## Only the precipitation area - not total precipitation
monthP2area(x0=4.5) -> Parea.month
```

Quality check:

Repeat the calculations with PMEL Ferret:

```
use trmm-precip-mon.nc
set reg/y=50S:50
CANCEL LIST/HEAD
let TP = precip[x=@din,y=@din]
let pre IF precip GT 4.5 then 1 else 0
let A = pre[x=@din,y=@din]
save/clobber/file=totprecip.nc TP,A
list/clobber/file=totprecip.txt TP,A
```

The results were then read in R and reformatted:

```r
tp.in <- read.table('~/TRMM-monthly/totprecip.txt')
pta <- cbind(tp.in$V5,tp.in$V6)
tpa.mon <- zoo(pta,order.by=seq(from=as.Date('1998-01-01'),by='month',
                                           length.out=length(pta[,1])))
names(tpa.mon) <- c('tot.precip','precip.area')
```

ERAINT

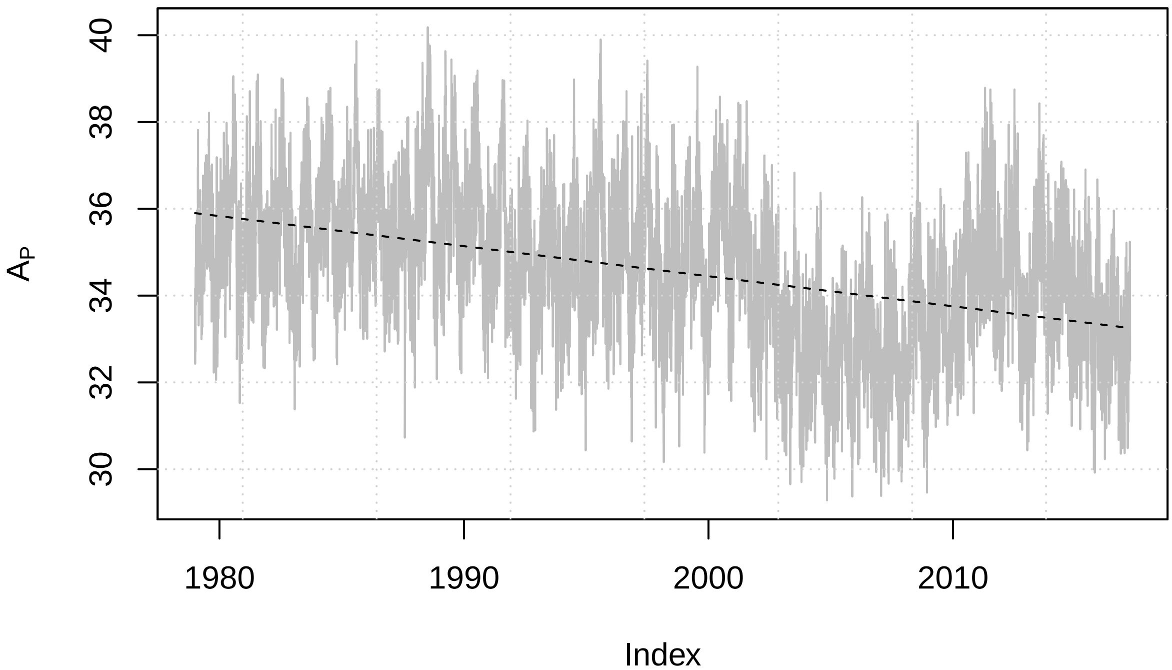
Supporting analyses included ERAINT-based indices describing the global rate of evaporation $Q_s = \int_A E da$, total atmospherc water, and the area with precipitation A_P.

```r
## ERAINT
tp.in <- read.table('~/Downloads/totprecip.txt')
pta <- cbind(tp.in$V5,tp.in$V6,tp.in$V7,tp.in$V8,tp.in$V9)
n <- length(pta[,1])
PTA <- pta[seq(1,(n-1),by=2),] + pta[seq(2,n,by=2),]

tpa.eraint <- zoo(PTA,order.by=seq(from=as.Date('1979-01-01'),by='day',
                                   length.out=length(PTA[,1])))
names(tpa.eraint) <- c('tot.precip','area.P.gt.0.1mm','area.P.gt.1mm','area.P.gt.10mm','tot.area')
save(tpa.eraint,file='tpa.eraint.rda')
```

ERAINT also suggest a decreasing A_p, from 36% to about 33%. This is roughly consistent with the TRMM data, but the total area estimated for ERAINT was estiamted to be $7.8 \times 10^8 km^2$ whereas the area of the earth is $5.1 \times 10^8 km^2$.

S1 Total precipitation area from ERAINT

```r
data(tpa.eraint)
plot(100*tpa.eraint[,2]/tpa.eraint[,5],col='grey',ylab=expression(A[P]))
grid()
lines(trend(100*tpa.eraint[,2]/tpa.eraint[,5]),lty=2)
```



Other quantities from ERAINT include the rate of evaportation and the total columnt water: $H_2O = \int_A qda$ where q is the water mass in the entire air column.

```
## Aggregated instantaneous surface moisture fluxes (evaporation)
moistflux() -> Qs
## data("Qs")

## Total atmospheric column water
columnH2O() -> H2O
## data("H2=")
```

Furthermore, the total precipitation was also estimated from ERAINT for comparing with TRMM.

```
#ERAINT: units in m/s
prtot.eraint <- globalsum('~/Downloads/ERAINT_precip.nc')
## The data is stored as the daily mean precipitation for 00:00-12:00hr and 12:00-24:00hr bacthes
mm <- as.character(month(prtot.eraint))
mm[nchar(mm)==1] <- paste('0',mm[nchar(mm)==1],sep='')
yyyymm <- paste(year(prtot.eraint),mm,'01',sep='-')
prtot.eraint <- aggregate(prtot.eraint,yyyymm,mean)*1000  # Unsure about 'mean' or 'sum'
index(prtot.eraint) <- as.Date(index(prtot.eraint))
prtot.eraint <- prtot.eraint*1e3# units in mm rather than m
attr(prtot.eraint,'unit') <- rep('tons',3)
save(prtot.eraint,file='prtot.eraint.rda')
```

The units of ERAINT precipitation is m and when aggregated using 'sum' the value is close to twice that of the TRMM data and twice the daily evaporation. The data comes with two values per month - it's not clear whether the both values are daily averages or 12-hour accumulated values.

Ferret script:

```
use ERAINT_precip.nc
set reg/y=50S:50N
CANCEL LIST/HEAD
let totpre = TP[x=@din,y=@din]
```

```
let pre IF TP GT 0.005 then 1 else 0
let A = pre[x=@din,y=@din]
list/clobber/file=totmonprecip.txt totpre,A
```

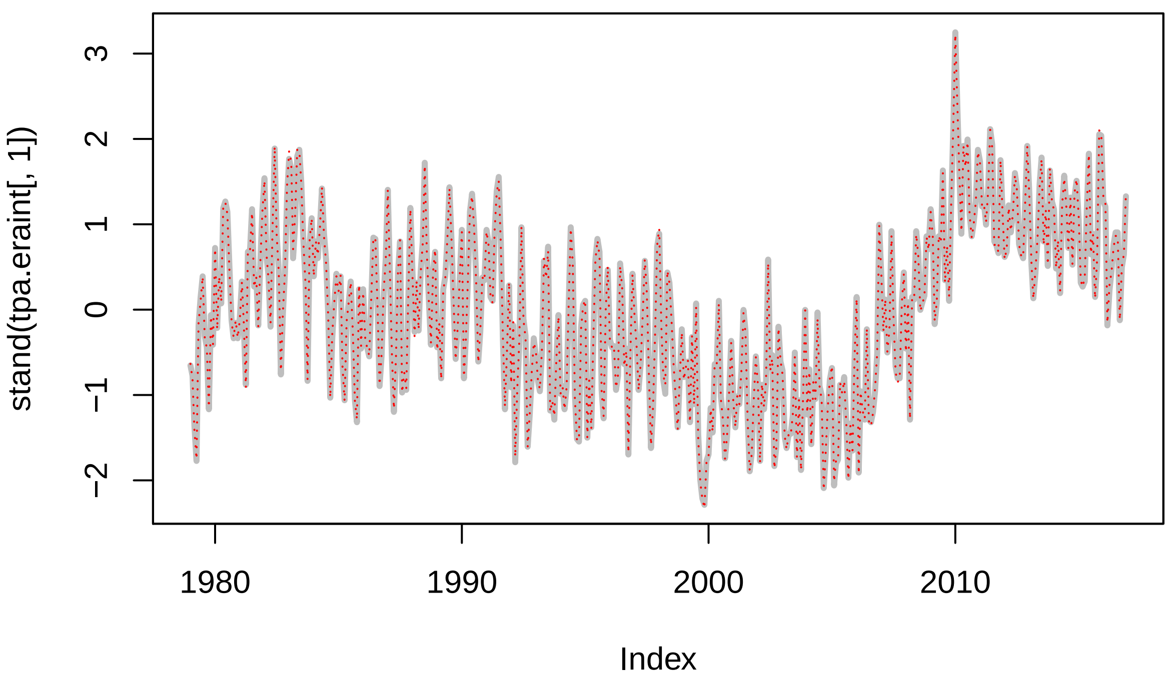
The estimation of the global rate of evaporation from ERAINT was also carried out in Ferret:

```
use ERAINT_Qs.nc
let Qs = IE[x=@din,y=@din]*86.4
CANCEL LIST/HEAD
list/file=qs.txt qs
```

```
## TYhe ERAINT data were stored in a devious format:
#01-JAN-1979 00:00 /   1:  1.259E+12  1.504E+14
#01-JAN-1979 12:00 /   2:  1.278E+12  1.557E+14
#01-FEB-1979 00:00 /   3:  1.254E+12  1.573E+14
#01-FEB-1979 12:00 /   4:  1.275E+12  1.640E+14
tp.in <- read.table('~/Downloads/totmonprecip.txt')
pta <- cbind(tp.in$V5,tp.in$V6)
n <- length(pta[,1])
PTA <- pta[seq(1,(n-1),by=2),] + pta[seq(2,n,by=2),]
names(PTA) <- c('tot.precip','precip.area')
tpa.eraint <- zoo(PTA,order.by=seq(from=as.Date('1979-01-01'),by='month',
                                    length.out=length(PTA[,1])))
```

S2 Check: Comparison of total precipitation amount from ERAINT based on Ferret and the R-package esd

```
data("prtot.eraint")
# Compare with the calculations done in R:
plot(stand(tpa.eraint[,1]),lwd=3,col='grey')                        # From PMEL Ferret
lines(stand(prtot.eraint[,1]),col='red',lty=3)    # From R
```



```r
print(mean(tpa.eraint[,1])*0.5)
```

```
## [1] 1.290099e+12
```

```r
print(mean(prtot.eraint[,1]))
```

```
## [1] 1.300211e+12
```

A comparisons verified the consistency of the calulations in R and with Ferret, albeit with different units (not shown)

CMIP 5 simulations

Estimate monthly aggregated precipitation area from the RCP4.5 CMIP5 experiment. These are only crude indices since the spatial resolution varies from model to model and the grid boxes represent an area average of the rainfall while the rain in reality only falls over a fraction of the area.

```r
PareaCMIP() -> Parea.cmip5
```

The data for the analysis is provided in the R-package `preciparea`

```r
data(Parea)
data(Parea.month)          # Only precipitation area
data(Parea.eraint.month)  # Only precipitation area
data(prtot.eraint)
```

Some basic statistics such as the mean area of precipitation (km^2), wet-day mean precipitation (mm/day) and total precipitation (Ktons) estimated for the 50S-50N according to the TRMM data (`nv` is the number of valid data points):

```r
colMeans(Parea)
```

```
##       A.precip A.precip.marine   A.precip.land              mu
##   9.263687e+07    7.078492e+07    2.154263e+07    1.217305e+01
##          P.tot        P.marine          P.land              nv
##   1.137030e+09    8.763201e+08    2.589023e+08    5.759642e+05
```

The figures in the main paper:

The figures are not shown here, but the code for producing them are lsted for greater transparency.

Figure 1

```r
Fig1()
```

Figure 2

```r
Fig2()
```

Figure 3

```
Fig3()
```

Figure 4

```
Fig4()
```

Other estimates

```
t1 <- start(Parea)
t2 <- end(Parea)
A.p <- window(trend(Parea[,1]),start=t1,end=t2)

## Lower-Upper range
print(range(Parea[,1]))
```

```
## [1]  75357829 112288335
```

```
## P-value for trend analysis
print(trend.pval(Parea[,1]))
```

```
##  trend.pvalue
## 5.921477e-254
```

```
## Trend: min and max
print(range(A.p))
```

```
## [1] 89276558 95997176
```

```
## Change in percentage
print(100*diff(range(A.p))/max(A.p))
```

```
## [1] 7.000849
```

```
## Trend as percentage of the total area:
print(round(100*range(A.p)/attr(Parea,'total area'),2))
```

```
## [1] 22.96 24.69
```

Table GCM and mean precipitation area

Check how the mean precipitation area in (1000km)^2 varies wih the GCM and spatial resolution:

```
data(Parea.cmip5)
y <- colMeans(Parea.cmip5)*1.e-6
names(y) <- attr(Parea.cmip5,'model_id')
print(y)
```

```
##      ACCESS1-0      ACCESS1.3     bcc-csm1-1   bcc-csm1-1-m          CCSM4
##      114.47292      114.11887       99.80467      105.41772      117.96891
##          CCSM4          CCSM4          CCSM4          CCSM4     CESM1-CAM5
##      117.99934      117.94483      118.08124      117.92007      125.26258
##     CESM1-CAM5       CNRM-CM5  CSIRO-Mk3-6-0  CSIRO-Mk3-6-0  CSIRO-Mk3-6-0
```

```
##      125.48309      134.56997      103.59292      103.58252      103.61078
##  CSIRO-Mk3-6-0  CSIRO-Mk3-6-0  CSIRO-Mk3-6-0       EC-EARTH       EC-EARTH
##      103.52044      103.49940      103.55699      118.07293      117.95375
##       EC-EARTH       EC-EARTH       EC-EARTH      FGOALS_g2        FIO-ESM
##      117.94951      118.12942      117.83714      110.69197      114.92459
##        FIO-ESM      GFDL-ESM2G     GFDL-ESM2M    GISS-E2-H-CC      GISS-E2-R
##      114.93279      109.56792      108.71557      121.82228      122.83289
##      GISS-E2-R      GISS-E2-R      GISS-E2-R      GISS-E2-R      GISS-E2-R
##      122.83012      122.76569      123.71191      123.78483      123.75834
##      GISS-E2-R      GISS-E2-R      GISS-E2-R      GISS-E2-R   GISS-E2-R-CC
##      125.03421      125.12128      125.06882      125.21202      122.79296
##     HadGEM2-AO     HadGEM2-CC     HadGEM2-ES     HadGEM2-ES         inmcm4
##      115.24538      114.77601      114.76813      114.66049      128.25190
##    IPSL-CM5A-LR   IPSL-CM5A-LR   IPSL-CM5A-LR   IPSL-CM5A-MR         MIROC5
##      102.33452      102.37673      102.35315      104.87125      127.02375
##      MIROC-ESM      MPI-ESM-LR     MPI-ESM-LR     MPI-ESM-MR     MPI-ESM-MR
##      112.66080      114.18791      113.99439      116.55495      116.52032
##      MRI-CGCM3      NorESM1-M     NorESM1-ME         MIROC5         MIROC5
##      112.91478      109.08905      108.85142      127.47700      127.01134
##         MIROC5 MIROC-ESM-CHEM     MPI-ESM-LR     MPI-ESM-MR      MRI-CGCM3
##      127.02375      111.91312      114.18791      116.52032      112.91478
##      NorESM1-M     NorESM1-ME
##      109.08905      108.85142
```

Test to see if there is a systematic dependency on the model spatial resolution.

```
## ANOVA to analyse potential systematic relationship between model resolution and mean precipitation a
data("IPCC.AR5.Table.9.A.1") ## From the esd-package

nm1 <- tolower(gsub('.','',gsub('-','',IPCC.AR5.Table.9.A.1$Model.Name),fixed=TRUE))
nm2 <- tolower(gsub('.','',gsub('-','',attr(Parea.cmip5,'model_id')),fixed=TRUE))
##x <- IPCC.AR5.Table.9.A.1$Horizontal.Grid[charmatch(nm2,nm1)]
x <- cmipgcmresolution()[charmatch(nm2,nm1)]
rbind(IPCC.AR5.Table.9.A.1$Model.Name,as.character(IPCC.AR5.Table.9.A.1$Horizontal.Grid),x)
```

```
## Warning in rbind(IPCC.AR5.Table.9.A.1$Model.Name,
## as.character(IPCC.AR5.Table.9.A.1$Horizontal.Grid), : number of columns of
## result is not a multiple of vector length (arg 1)
```

```
##   [,1]          [,2]          [,3]          [,4]             [,5]
##   "ACCESS1.0"   "ACCESS1.3"   "BCC-CSM1.1"  "BCC-CSM1.1(m)" "BNU-ESM"
##   "192x145 N96" "192x145 N96" "T42 T42L26"  "T106"           "T42"
## x "1.875"       "1.875"       "2.8"         NA               "0.9"
##   [,6]     [,7]      [,8]           [,9]           [,10]
##   "CanCM4" "CanESM2" "CCSM4"        "CESM1(BGC)"   "CESM1(CAM5)"
##   "T63"    "T63"     "0.9x1.25 deg" "0.9x1.25 deg" "0.9x1.25 deg"
## x "0.9"    "0.9"     "0.9"          "0.9"          NA
##   [,11]                [,12]          [,13]
##   "CESM1(CAM5.1.FV2)" "CESM1(WACCM)" "CESM1(FASTCHEM)"
##   "1.9x2.0 deg"       "1.9x2.5 deg"  "0.9x1.25 deg"
## x NA                  "0.95"         "1.875"
##   [,14]                   [,15]                    [,16]
##   "CMCC-CESM"             "CMCC-CM"                "CMCC-CMS"
##   "3.75x3.75 deg (T31)"  "0.75x0.75 deg (T159)"  "1.875x1.875 deg (T63)"
## x "1.875"                 "1.875"                  "1.875"
##   [,17]        [,18]
```

```
##   "CNRM-CM51" "CSIRO-Mk3.6.0"
##   "TL127"     "1.875x1.875 deg (T63)"
## x "1.875"     "1.875"
##   [,19]
##   "EC-EARTH"
##   "1.125 deg longitudinal spacing, Gaussian grid T159L62"
## x "1.125"
##   [,20]               [,21]                  [,22]
##   "FGOALS-g2"         "FGOALS-s2"            "FIO-ESM v1.0"
##   "2.8125x2.8125 deg" "R42 (2.81x1.66 deg)" "T42"
## x "1.125"             "1.125"                "1.125"
##   [,23]                                       [,24]
##   "GFDL-CM2.1"                                "GFDL-CM3"
##   "2.5 deg longitude, 2 deg latitude M45L24" "200 km C48L48"
## x "1.125"                                     NA
##   [,25]
##   "GFDL-ESM2G"
##   "2.5 deg longitude, 2 deg latitude M45L24"
## x "2.8"
##   [,26]
##   "GFDL-ESM2M"
##   "2.5 deg longitude, 2 deg latitude M45L24"
## x "2.8"
##   [,27]
##   "GFDL-HIRAM-C180"
##   "Averaged cell size: 50x50 km. C180L32"
## x "2.5"
##   [,28]
##   "GFDL-HIRAM-C360"
##   "Averaged cell size: 25x25 km. C360L32"
## x "2.5"
##   [,29]                               [,30]
##   "GISS-E2-H"                         "GISS-E2-H-CC"
##   "2 deg latitudex2.5 deg longitude" "Nominally 1 deg"
## x "1"                                 "2"
##   [,31]                               [,32]
##   "GISS-E2-R"                         "GISS-E2-R-CC"
##   "2 deg latitudex2.5 deg longitude" "Nominally 1 deg"
## x "2"                                 "2"
##   [,33]                 [,34]
##   "HadCM3"              "HadGEM2-AO"
##   "N48L19 3.75x2.5 deg" "1.875 deg in longitudex1.25 deg in latitude N96"
## x "2"                   "2"
##   [,35]
##   "HadGEM2-CC"
##   "1.875 deg in longitudex1.25 degin latitude N96"
## x "2"
##   [,36]
##   "HadGEM2-ES"
##   "1.875 deg in longitudex1.25 deg in latitude N96"
## x "2"
##   [,37]
##   "INM-CM4"
##   "2x1.5 deg in longitude and latitude latitude-longitude"
```

```
## x "2"
##   [,38]
##   "IPSL-CM5A-LR"
##   "96x95 equivalent to 1.9x3.75 deg LMDZ96x 95"
## x "2"
##   [,39]
##   "IPSL-CM5A-MR"
##   "144x143 equivalent to 1.25x2.5 deg LMDZ144x143"
## x "2"
##   [,40]                                          [,41]
##   "IPSL-CM5B-LR"                                 "MIROC4h"
##   "96x95 equivalent to 1.9x3.75 deg LMDZ96x95" "0.5625x0.5625 deg T213"
## x "1"                                            "1.875"
##   [,42]                    [,43]
##   "MIROC5"                 "MIROC-ESM"
##   "1.40625x1.40625 deg T85" "2.8125x2.8125 deg T42"
## x "1.875"                  "1.875"
##   [,44]                  [,45]         [,46]         [,47]
##   "MIROC-ESM-CHEM"       "MPI-ESM-LR"  "MPI-ESM-MR"  "MPI-ESM-P"
##   "2.8125x2.8125 deg T42" "1.8 deg T63" "1.8 deg T63" "1.8 deg T63"
## x "1.875"                "2"           "1.9"         "1.9"
##   [,48]          [,49]            [,50]            [,51]
##   "MRI-AGCM3.2H"  "MRI-AGCM3.2S"   "MRI-CGCM3"      "MRI-ESM1"
##   "640x320 TL319" "1920x960 TL959" "320x160 TL159" "TL159(320x160)"
## x "1.9"          "1.25"           "1.4"            "2.8"
##   [,52]         [,53]
##   "NCEP-CFSv2"  "NorESM1-M"
##   "0.9375 T126" "Finite Volume 1.9 deg latitude, 2.5 deg longitude"
## x "1.875"       "1.875"
##   [,54]                                                [,55]
##   "NorESM1-ME"                                         "ACCESS1.0"
##   "Finite Volume 1.9 deg, latitude, 2.5 deg longitude" "192x145 N96"
## x "1.875"                                              "1.875"
##   [,56]         [,57]        [,58]            [,59]     [,60]    [,61]
##   "ACCESS1.3"   "BCC-CSM1.1" "BCC-CSM1.1(m)" "BNU-ESM" "CanCM4" "CanESM2"
##   "192x145 N96" "T42 T42L26" "T106"          "T42"     "T63"    "T63"
## x "1.125"       "1.9"        "1.9"           "1.4"     "1.4"    "1.4"
##   [,62]          [,63]          [,64]          [,65]
##   "CCSM4"        "CESM1(BGC)"   "CESM1(CAM5)"  "CESM1(CAM5.1.FV2)"
##   "0.9x1.25 deg" "0.9x1.25 deg" "0.9x1.25 deg" "1.9x2.0 deg"
## x "2.8"          "1.875"        "1.875"        "1.125"
##   [,66]          [,67]
##   "CESM1(WACCM)" "CESM1(FASTCHEM)"
##   "1.9x2.5 deg"  "0.9x1.25 deg"
## x "1.9"          "1.9"
```

```r
resbias <- data.frame(y=y,x=x)
print(summary(lm(y ~ x, data=resbias)))
```

```
##
## Call:
## lm(formula = y ~ x, data = resbias)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
```

```
## -13.1622  -5.7248  -0.5667   6.3921  15.0818
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  124.095      3.436  36.117   <2e-16 ***
## x             -4.849      1.884  -2.573   0.0125 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 7.681 on 61 degrees of freedom
##   (4 observations deleted due to missingness)
## Multiple R-squared:  0.09793,    Adjusted R-squared:  0.08314
## F-statistic: 6.622 on 1 and 61 DF,  p-value: 0.01252
```

The results from the ANOVA suggests that there is a tendency for smaller mean precipitation area for models with higher resolution since the regression coefficient x is negative. The relationship is statistically significant at the 5%-level. One issue is that different spatial resolution may mean different values, as they reflect area mean values for the grid box. This may also influence the analysis as a constant threshold value x_0 for all these models may select precipitation events differently for models with high and low spatial resolution, unless the regridding of the models has taken the area-mean into account.

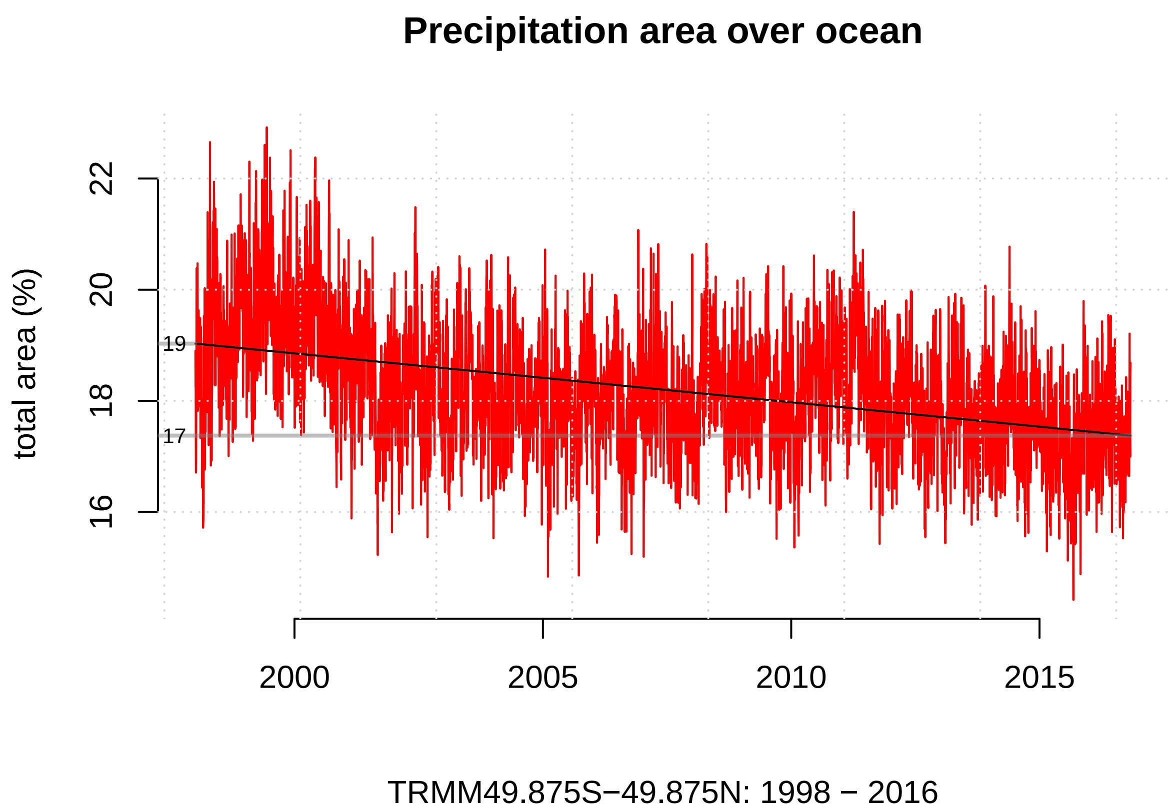
The resolution in this case was derived from a table of model details from the IPCC AR5, and the data here had all been regridded to the same spatial grid in the KNMI Climate Explorer https://climexp.knmi.nl/.

Supporting material and additional analysis

Rainfall area over ocean

The precipitation area over ocean was esimated by masking out all land/contentent grid boxes. This index is the second in the `Parea` object:

```
timeseries(Parea,is=2)
```




```r
print(trend.coef(Parea[,2]))
```

```
## trend.coefficients
##          -9357.147
```

```r
print(trend.pval(Parea[,2]))
```

```
##  trend.pvalue
## 2.290628e-306
```

```r
print(range(window(trend(Parea[,2]),start=t1,end=t2)))
```

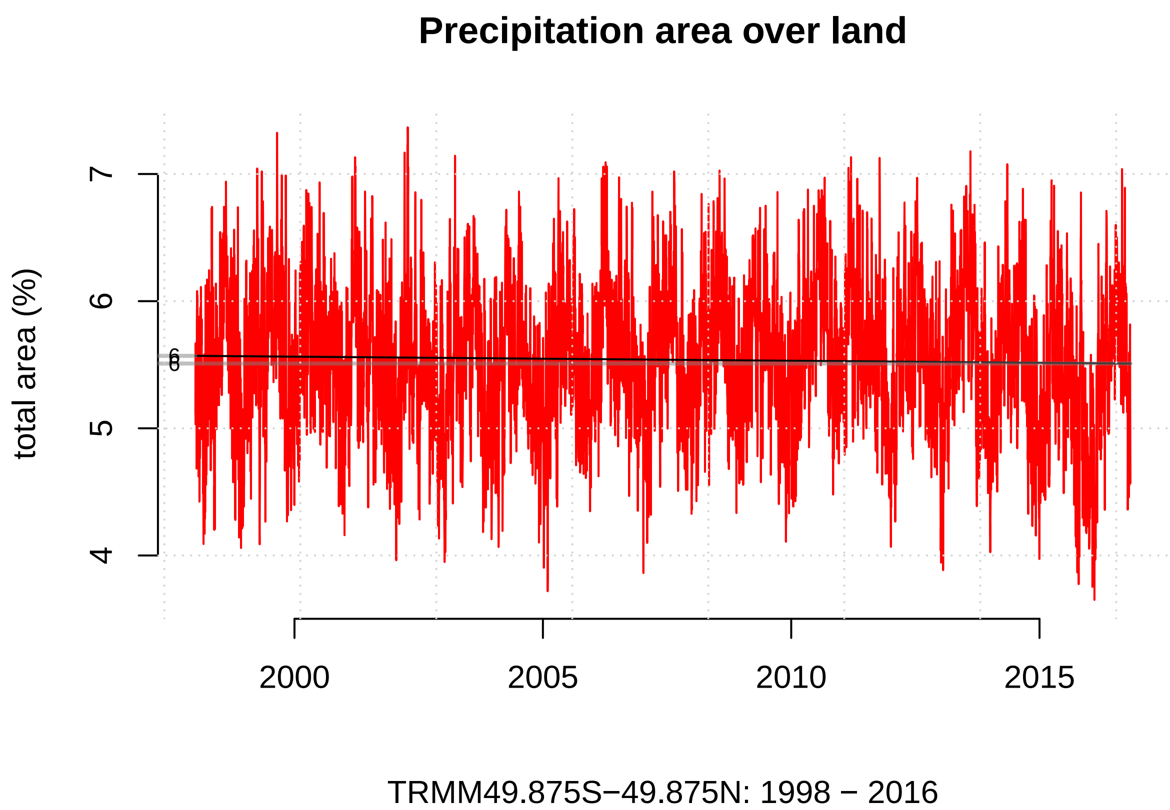
```
## [1] 67567460 74002370
```

There was a clear decrease in A_P over the oceans.

Rainfall area over land

Consequently, the rainfall area over land was estimated by masking all ocean grid points:

```r
timeseries(Parea,is=3)
```




```
print(trend.coef(Parea[,3]))
```

```
## trend.coefficients
##          -342.3229
```

```
print(trend.pval(Parea[,3]))
```

```
## trend.pvalue
##   0.01099293
```

```
print(range(window(trend(Parea[,3]),start=t1,end=t2)))
```

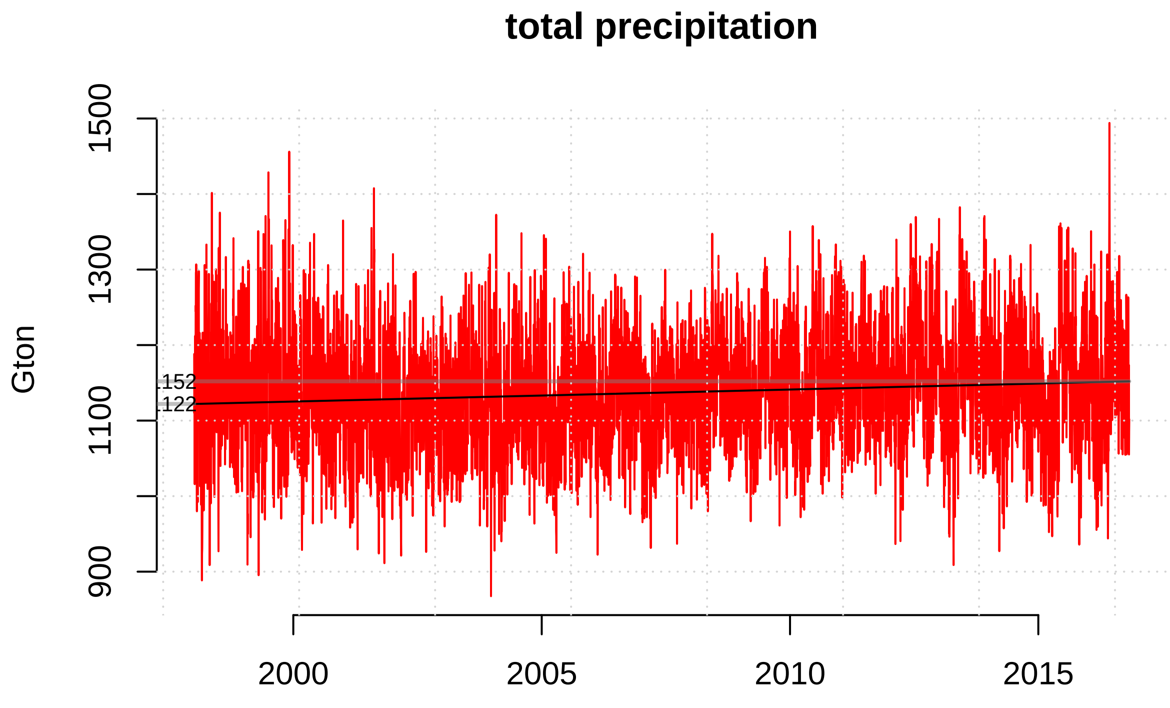
```
## [1] 21424919 21660334
```

The total rain area over land is minor compared to the rain area over the oceans. Furthermore, the trend is much weaker and not statistically significant at the 5%-level. There is a more pronounced annual cycle in A_P over land than over the oceans, which may be related to monsoon-type systems.

Total precipitation from the TRMM data

The 50S-50N total precipitation amount was estimated by summing up all grid boxes with rainfall for each day:

```r
timeseries(Parea,is=5,denominator=1e6,ylab='Gton')
```



TRMM49.875S−49.875N: 1998 − 2016

```r
## Lower-Upper range
print(range(Parea[,5])/1.0e6)
```

```
## [1]  867.5472 1494.0877
```

```r
## Check period
print(c(start(Parea),end(Parea)))
```

```
## [1] "1998-01-02" "2016-10-31"
```

```r
## P-value for trend analysis
print(trend.coef(Parea[,5]))
```

```
## trend.coefficients
##           43549.14
```

```r
print(trend.pval(Parea[,5]))
```

```
## trend.pvalue
## 1.892162e-21
```

```r
## Trend: min and max: ocean and land
print(range(window(trend(Parea[,5]),start=t1,end=t2)/1e6))
```

```
## [1] 1122.055 1152.004
```

```r
## Trend: min and max: ocean
print(trend.coef(Parea[,6]))
```

```
## trend.coefficients
```

```
##           56412.37
```

```
print(trend.pval(Parea[,6]))
```

```
## trend.pvalue
## 3.568926e-37
```

```
print(range(window(trend(Parea[,6]),start=t1,end=t2)/1e6))
```

```
## [1] 856.9228 895.7175
```

```
## Trend: min and max: land
print(trend.coef(Parea[,7]))
```

```
## trend.coefficients
##          -15638.72
```

```
print(trend.pval(Parea[,7]))
```

```
## trend.pvalue
## 3.291038e-12
```

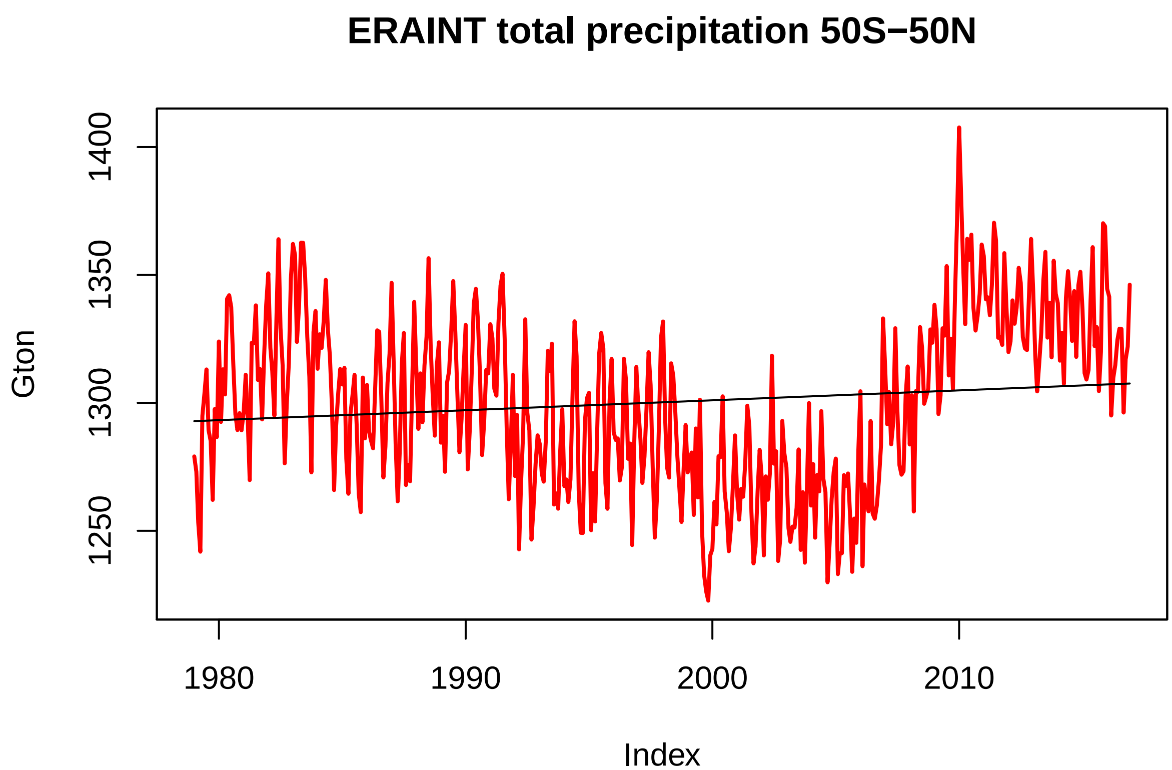
```
print(range(window(trend(Parea[,7]),start=t1,end=t2)/1e6))
```

```
## [1] 253.5249 264.2797
```

The total daily volume of rainfall between 50S–50N exhibits a wide range of daily fluctuations between 868 – 1494 Gton, but there is no strong long-term trend. An increasing trend is seen in the plot from 1120 – 1150 Gton.

S3 The total precipitation from ERAINT:

```
## ERAINT
plot(prtot.eraint[,1]/1e9,ylab='Gton',main='ERAINT total precipitation 50S-50N',col='red',lwd=2)
lines(trend(prtot.eraint[,1]/1e9))
```




```
## Trend: min and max
print(trend.coef(prtot.eraint[,1]))
```

```
## trend.coefficients
##          323304576
```

```
print(trend.pval(prtot.eraint[,1]))
```

```
## trend.pvalue
##  0.006275298
```

```
print(range(window(trend(prtot.eraint[,1]),start=t1,end=t2)/1e9))
```

```
## [1] 1300.261 1307.501
```

Compare the total precipitation between 50S–50N with the rest of the globe:

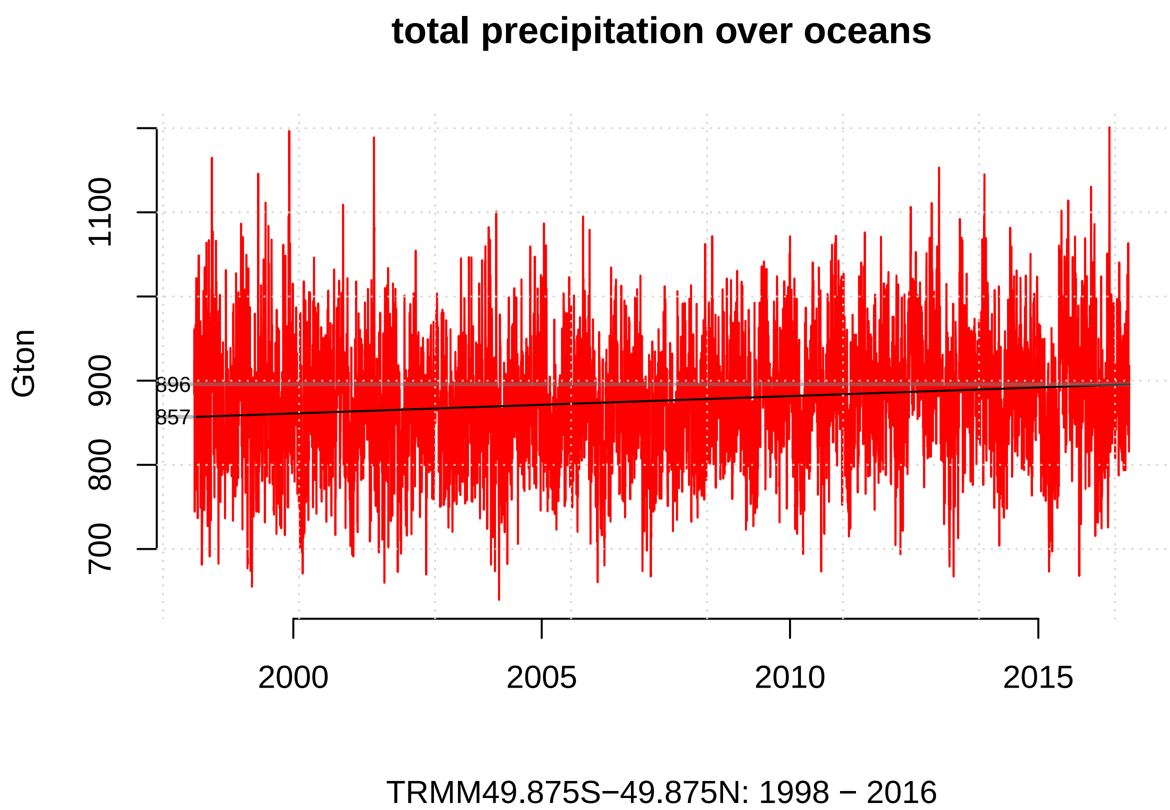
```
print(colMeans(prtot.eraint)/1.0e9)
```

```
##  X.50s50n  X.90s50s  X.50n90n
## 1300.2108  115.9212  106.9426
```

Rainfall amount over ocean

This index can be split into the total rainfall amount over the oceans by masking out the land grid boxes:

```
## The units are mm*km^2 -> 1000m^3 -> million kg or 1000 tons (1 Kton).
timeseries(Parea,is=6,denominator=1e6,ylab='Gton')
```



The contribution to the total precipitation from the oceans exhibits a slightly more pronounced increasing trend than the total oceans+land amounts do.

The fraction of earth's area between 50S–50N is $\int 2\pi a \cos(\phi) a d\phi / 4\pi a^2 = [\sin(\phi_2) - \sin(\phi_1)]/2$ where $\phi = \pm\pi * 50/180$.

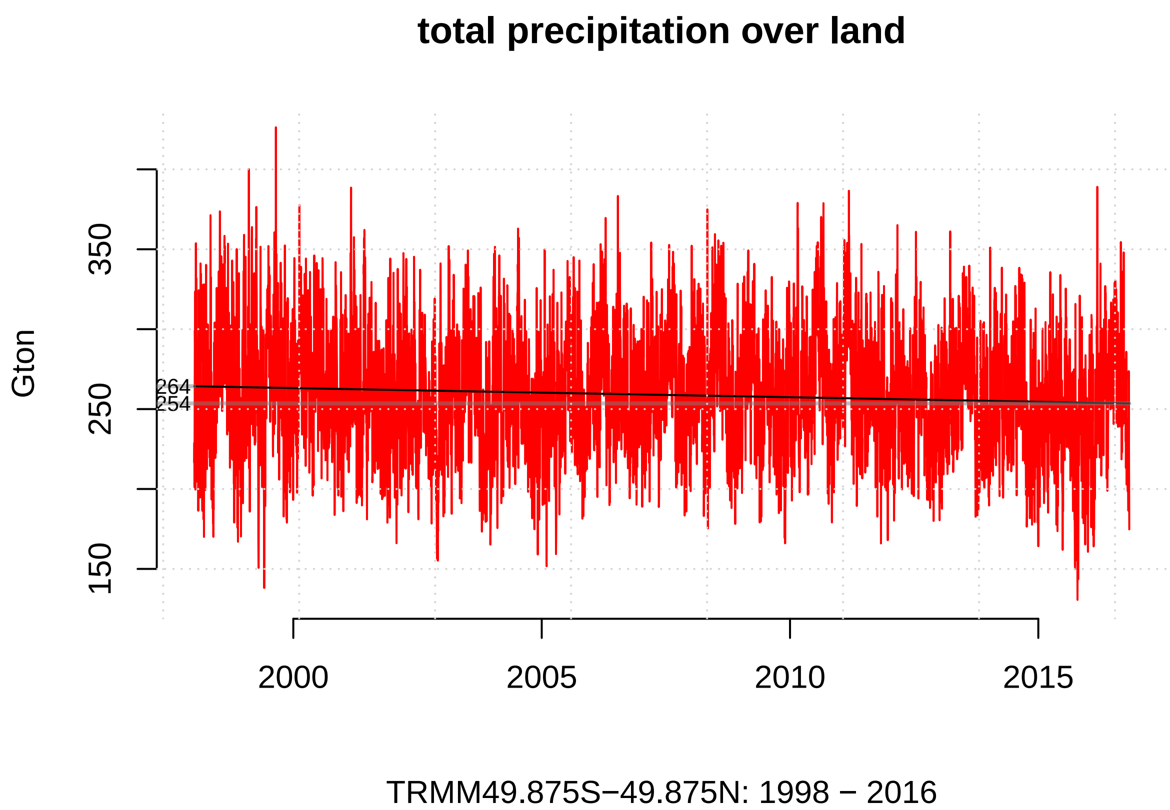
```
print(paste(round(100*sin(pi*50/180)),"% of earth's surface area is between 50S-50N"))
```

```
## [1] "77 % of earth's surface area is between 50S-50N"
```

Rainfall amount over land

The corresponding index for the total land precipitation is

```
timeseries(Parea,is=7,denominator=1.0e6,ylab='Gton')
```

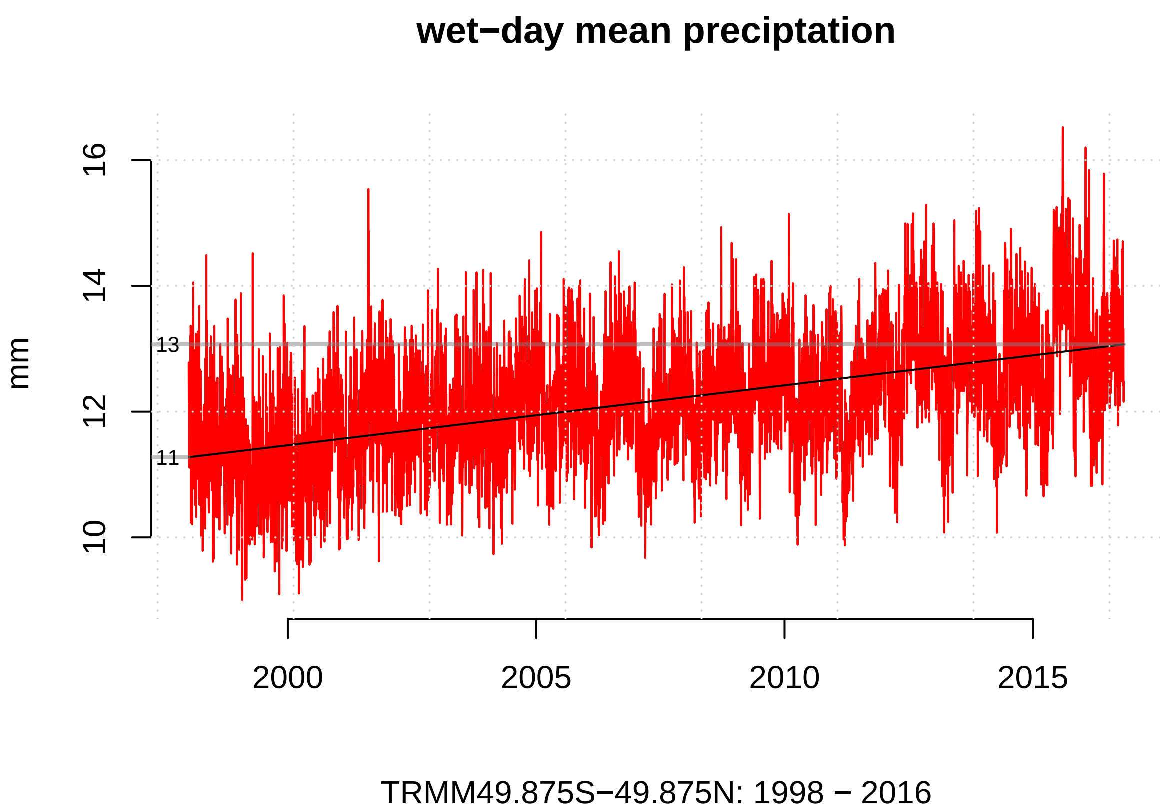


The TRMM data suggests a declining trend in the total precipitation amount land in contrast to the precipitation over ocean and the sum oceans+land.

Precipitation intensity from TRMM

The rain intensity $\overline{P}$ can be estimated by taking the average of all grid boxes with rain for each day:

```
timeseries(Parea,is=4,denominator=1)
```




```
## Trend: min and max
print(trend.coef(Parea[,4]))
```

```
## trend.coefficients
##         0.00260986
```

```
print(trend.pval(Parea[,4]))
```

```
## trend.pvalue
##            0
```

```
print(round(range(window(trend(Parea[,4]),start=t1,end=t2)),2))
```

```
## [1] 11.28 13.07
```

The graph reveals an increasing trend in $\overline{P}$, and the trend analysis is applied to a long series of daily values which makes it statistical significant at the 5%-level (p-value $\approx 10^{-21}$).

A combination of a declining rainfall area over time with increasing precipitation amount is consistent with an increasing precipitation intensity: $P = \overline{P} * A_P$.

Check - covariation with the global mean temperature?

Assess the scaling relation between observed precipitation area and the global mean temperature through regression analysis ($A_P = \beta_0 + \beta_1 T + \eta$) where regression coefficient β_1 describes the slope (rate of change in A_P with the global mean temperature) and β_0 the zero-intersect and η being a noise-term.

```
require(esd)
hc4 <- HadCRUT4()
## The precipitation area:
```

```r
XY <- merge(annual(hc4),annual(Parea[,1]),all=FALSE)
cal <- data.frame(x=coredata(XY[,1]),y=coredata(XY[,2]))
pax <- lm(y ~x, data=cal)
print(summary(pax))
```

```
##
## Call:
## lm(formula = y ~ x, data = cal)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -1701949  -891677  -534321   653273  3390757
##
## Coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept) 101275339    1488911  68.020  < 2e-16 ***
## x           -17168097    2868290  -5.985 1.48e-05 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 1503000 on 17 degrees of freedom
## Multiple R-squared:  0.6782, Adjusted R-squared:  0.6593
## F-statistic: 35.83 on 1 and 17 DF,  p-value: 1.476e-05
```

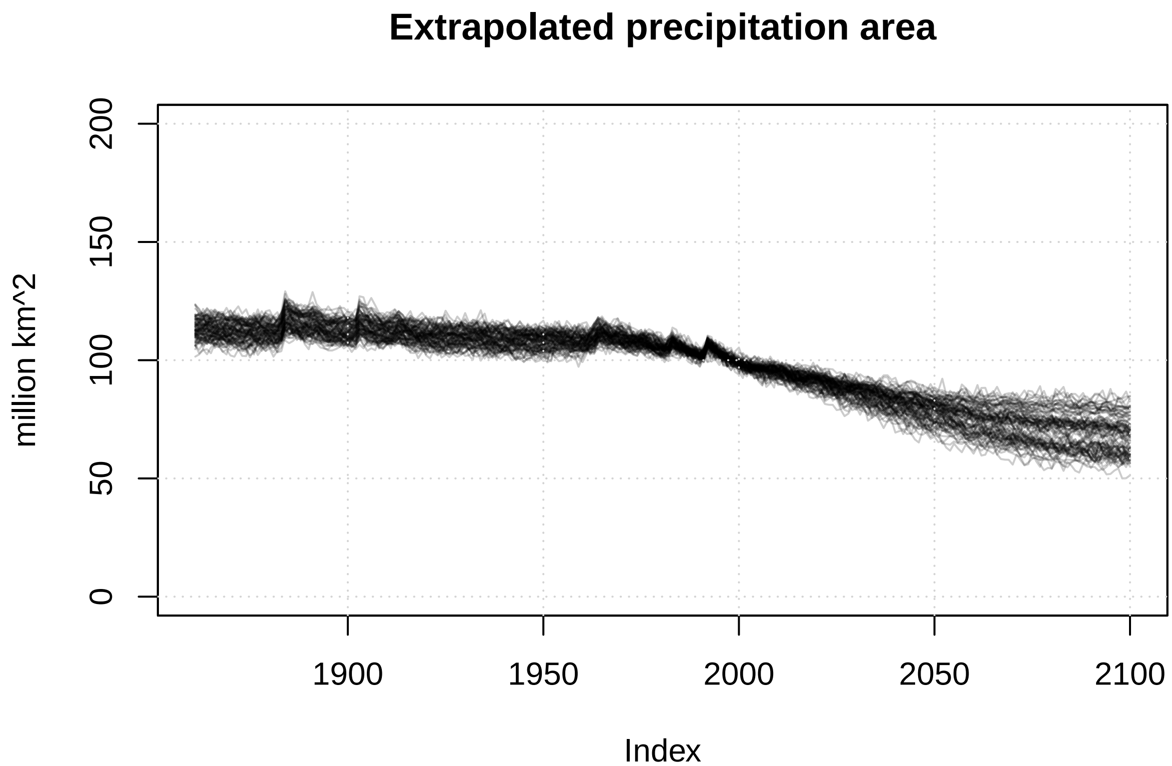
```r
## Total precipitation:
XY <- merge(annual(hc4),annual(Parea[,5]),all=FALSE)
cal <- data.frame(x=coredata(XY[,1]),y=coredata(XY[,2]))
print(summary(lm(y ~x, data=cal)))
```

```
##
## Call:
## lm(formula = y ~ x, data = cal)
##
## Residuals:
##       Min        1Q    Median        3Q       Max
## -19875870 -15521846   2807379   8336656  27657399
##
## Coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept) 1.130e+09  1.464e+07  77.180   <2e-16 ***
## x           1.364e+07  2.821e+07   0.484    0.635
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 14790000 on 17 degrees of freedom
## Multiple R-squared:  0.01357,    Adjusted R-squared:  -0.04445
## F-statistic: 0.2339 on 1 and 17 DF,  p-value: 0.6348
```

An ANOVA on the TRMM annual mean values indicates strong covariance between the global mean temperature and the precipitation area, with R^2 of 0.6 and a negative regression coefficient $\beta_1 = -17 \times 10^6 km^2$/degree K. (statistically sign. at the 0.1%-level). A similar analysis for the total precipitation suggests little covariance.

S4 Naive extrapolation for future daily A_P based on global mean temperature change

```
data("global.t2m.cmip5")
Pacmip5 <- global.t2m.cmip5
for (i in 1:dim(global.t2m.cmip5)[2]) {
  pre <- data.frame(x=coredata(global.t2m.cmip5[,i]))
  coredata(Pacmip5)[,i] <- predict(pax,newdata=pre)
}
plot(Pacmip5*1.0e-6,plot.type='single',main='Extrapolated precipitation area',
     ylab='million km^2',ylim=c(0,200),col=rgb(0,0,0,0.2))
grid()
```




```
print(100*(mean(window(Pacmip5,start=2079,end=2099)) - mean(window(Pacmip5,start=1998,end=2016))) /mean
```

```
## [1] -27.25385
```

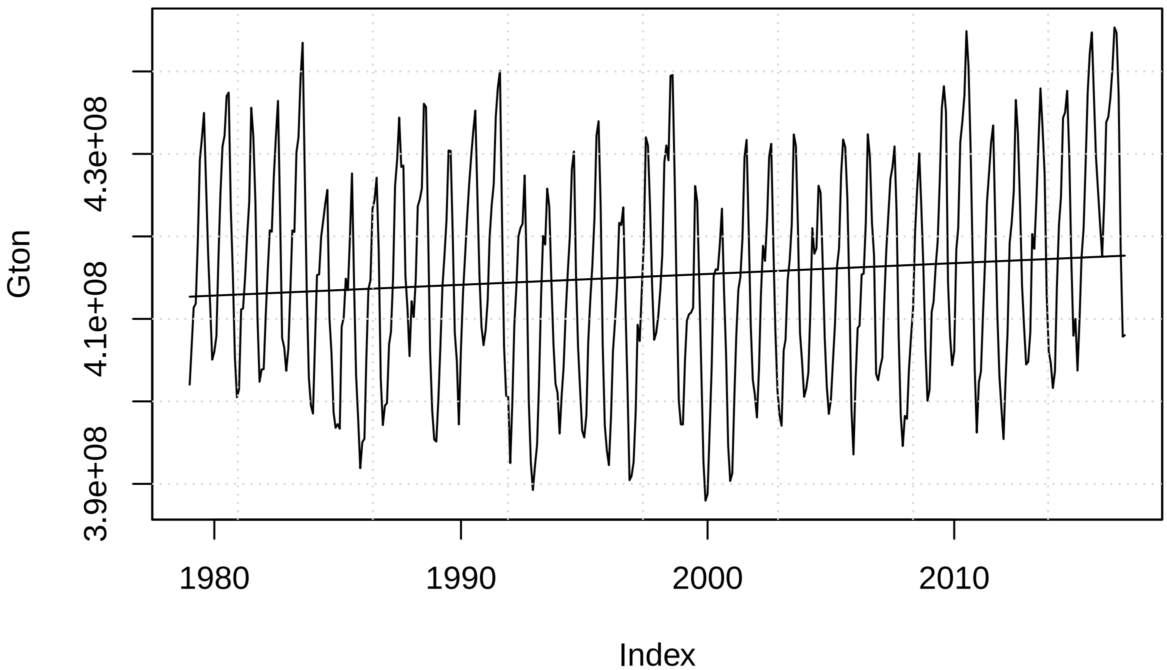
A naive extrapolation assuming that (a) the regression analysis between the global mean temperature and precipitation area captures a true dependency and (b) that this dependency is stationary and holds in the future suggests a reduction in A_P from near 110 million km^2 in the 20th century to 75 million km^2 by 2100. The CMIP5 ensemble mean suggests around a 28% decrese in A_P.

S5 Total atmospheric water content from ERAINT

The total 50S-50N atmospheric water content was estimated from the ERAINT reanalysis

```
data(H2O)
plot(H2O[,1]/1e9,ylab='Gton')
## The 50S-50N water content is much higher than for the high latitude regions
## "kg km**-2" agregated (sum) over the area
```

```r
lines(trend(H2O[,1]/1e9))
grid()
```




```r
## Trend: min and max
print(trend.coef(H2O[,1]))
```

```
## trend.coefficients
##       1.093271e+14
```

```r
print(trend.pval(H2O[,1]))
```

```
## trend.pvalue
##   0.01614728
```

```r
print(range(window(trend(H2O[,1]),start=t1,end=t2)/1e9))
```

```
## [1] 415195890 417642699
```

```r
print(c(start(H2O),end(H2O)))
```

```
## [1] "1979-01-01" "2016-12-01"
```

```r
colMeans(H2O)/1e9 ## Gtons
```

```
##  X.50s50n  X.90s50s  X.50n90n
## 415179004  14569584  20829813
```

The total atmospheric water exhibits weak long-term changes according to the ERAINT reanalysis and shows a hint of an increase over time.

The surface moisture flux Q_s from ERAINT is the same as evaporation E_s and the declining trends (negative numbers) indicates an increased evaporation over time. This is consistent with increased P_{tot} in the TRMM data. Negative values indicate flux out of the oceans.

S6 Global evaporation from ERAINT

```
data(Qs)
plot(annual(Qs,FUN='mean'),ylab='Gton')
## The 50S-50N moisture flux is much higher than for the high latitude regions
## Units are mm/day  * km^2 which is equivalent to 1000m^3/day or kilo-tons/day
lines(trend(annual(Qs,FUN='mean')))
grid()
```


```
## Giga-tons/day - divide by 1e6

## Trend: min and max
print(trend.coef(Qs[,1]))
```

```
## trend.coefficients
##          -1.830651
```

```
print(trend.pval(Qs[,1]))
```

```
## trend.pvalue
## 1.345195e-32
```

```
print(range(window(trend(Qs[,1]),start=t1,end=t2)))
```

```
## [1] -1508.758 -1467.762
```

```
print(c(start(Qs),end(Qs)))
```

```
## [1] "1979-01-01" "2016-12-01"
```

```
mean(Qs)
```

```
## [1] -1467.479
```

Previous estimates of global precipitation flux

Table 1 in Zektser et al (1993) http://www.sciencedirect.com/science/article/pii/0022169493901829

```
## Example in the text: evaporation
print(294*128) ## km^3/year - should be 38,000 km^3 according to the article
```

```
## [1] 37632
```

```
## As kg/day: 1 km^3 = 1.oe9 tons = 1 Gton.
print(294*128/365.25)
```

```
## [1] 103.0308
```

```
## Precipitation over land
print(paste('Precipitation: 834 mm/year=',round(834*128/365.25),'Gton/day'))
```

```
## [1] "Precipitation: 834 mm/year= 292 Gton/day"
```

Estimate of the global mean precipitation from Kiel and Trenberth: 2.46 – 2.90 mm/day http://journals.ametsoc.org/doi/pdf/10.1175/1520-0477%281997%29078%3C0197%3AEAGMEB%3E2.0.CO%3B2

```
print(paste('2.46mm/day =',round(2.46*1.0e-3 * 4*pi*6378000^2*1.0e-9),'Gton/day'))
```

```
## [1] "2.46mm/day = 1258 Gton/day"
```

```
print(paste('2.46mm/day =',round(2.90*1.0e-3 * 4*pi*6378000^2*1.0e-9),'Gton/day'))
```

```
## [1] "2.46mm/day = 1482 Gton/day"
```

Legates (1995): 2.6 to 3.1 mm/day http://onlinelibrary.wiley.com/doi/10.1002/joc.3370150302/full

```
print(paste('2.6mm/day =',round(2.6*1.0e-3 * 4*pi*6378000^2*1.0e-9),'Gton/day'))
```

```
## [1] "2.6mm/day = 1329 Gton/day"
```

```
print(paste('3.1mm/day =',round(3.1*1.0e-3 * 4*pi*6378000^2*1.0e-9),'Gton/day'))
```

```
## [1] "3.1mm/day = 1585 Gton/day"
```

S7 Test the correlation between the precipitation area and galactic cosmic rays

Compare the cosmic rays from Climax with the precipitation area

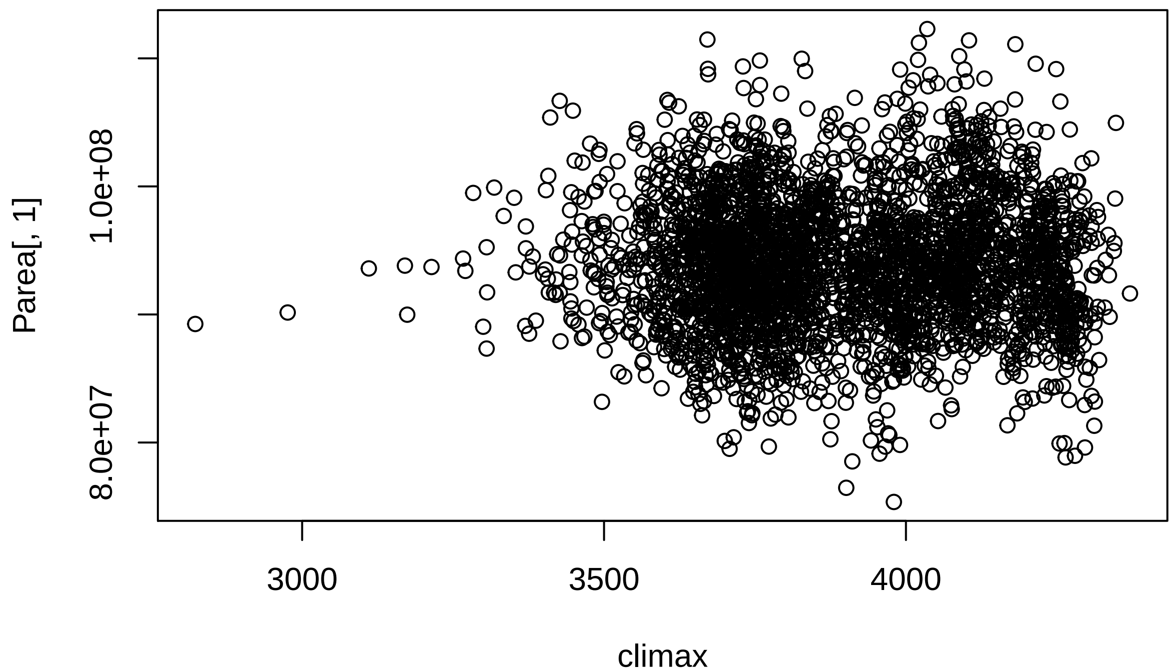
```
require(replicationDemos)
```

```
## Loading required package: replicationDemos

## Loading required package: waveslim

##
## waveslim: Wavelet Method for 1/2/3D Signals (version = 1.7.5)

## Loading required package: lmtest

## Loading required package: deSolve
```

```
data(gcr)
t <- paste(substr(gcr$Date,7,10),substr(gcr$Date,1,2),substr(gcr$Date,4,5),sep='-')
climax <- zoo(as.numeric(as.character(gcr$Climax)),order.by=as.Date(t))
```

```
## Warning in zoo(as.numeric(as.character(gcr$Climax)), order.by =
## as.Date(t)): NAs introduced by coercion
```

```r
plot(climax,Parea[,1])
```




```r
gcrpa <- merge(climax,Parea[,1],all=FALSE)
ok <- is.finite(gcrpa[,1]) & is.finite(gcrpa[,2])
print(cor.test(gcrpa[ok,1],gcrpa[ok,2]))
```

```
##
##  Pearson's product-moment correlation
##
## data:  gcrpa[ok, 1] and gcrpa[ok, 2]
## t = 0.41268, df = 3157, p-value = 0.6799
## alternative hypothesis: true correlation is not equal to 0
## 95 percent confidence interval:
##  -0.02753667  0.04220784
## sample estimates:
##         cor
## 0.007344513
```

Estimate of the portion of the vertical energy flow due to convection from the total precipitation

The precipitation was assumed to be a by-product of moist convection with an energy content equivalent to the release of latent heat of evaporation PL_E:

$f_{conv} = \frac{PL_e}{\pi a^2 (1-A) S_0}$

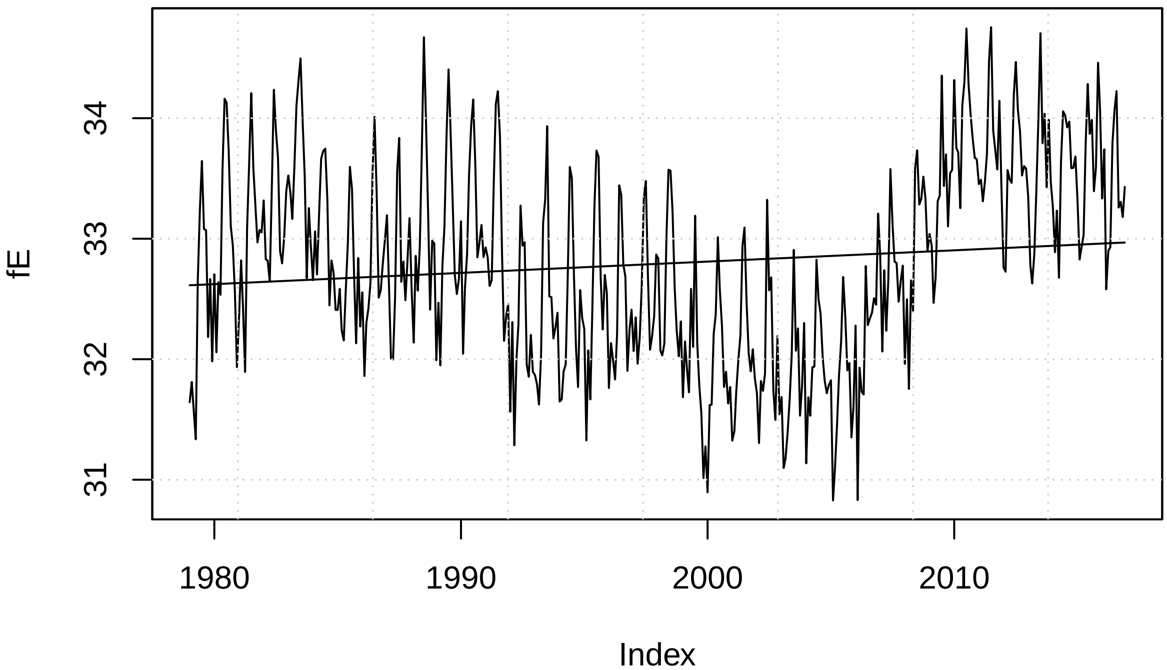
```r
a <- 6378000 # Earth's area (m)
A = 0.3 # The albedo
S0 <- 1361 # The Solar constant (W/m²)
Le <- 2264.76 * 1000 # Latent heat of evaporation (https://en.wikipedia.org/wiki/Latent_heat) J/kg
tot.E <- pi * a^2 * (1-A) * S0 * 24 * 3600 # Energy over 24 hrs
P <- sum(colMeans(prtot.eraint))*1000
```

```
frac.E <- P*Le/tot.E * 100
print(paste('Convection is responsible for ',round(frac.E,2),'percent of the vertical heat flow'))
```

```
## [1] "Convection is responsible for  32.79 percent of the vertical heat flow"
```

S8 Trend anlysis of the proportionn of vertical energy flow being connected to convection

```
fE <- (prtot.eraint[,1]+prtot.eraint[,2]+prtot.eraint[,3])*Le*100000/tot.E
plot(fE)
grid()
lines(trend(fE))
```




```
prop <- window(trend(fE),start=t1,end=t2)
print(round(c(prop[1],prop[length(prop)]),1))
```

```
## 1998-02-01 2016-10-01
##       32.8       33.0
```

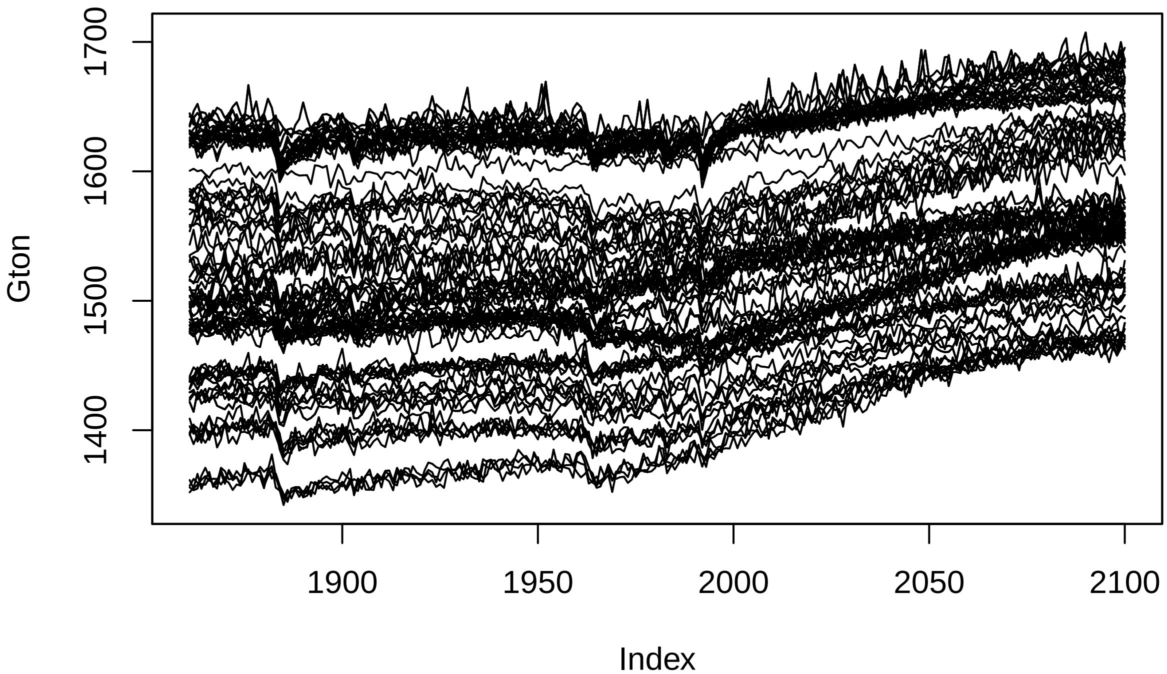
For the TRMM data:

```
y <- window(trend(Parea[,5]),start=t1,end=t2)
print(paste('Percentage energy flow associated with convection',round(c(y[1],y[length(y)])*Le*1e6/tot.E*
```

```
## [1] "Percentage energy flow associated with convection 24 %"
## [2] "Percentage energy flow associated with convection 25 %"
```

S9 Estimate the globally summed precipitation from CMIP5:

```
data(ptot.cmip)
plot(zoo(ptot.cmip)/1e6,plot.type='single',ylab='Gton')
```




```
pclim <- colMeans(window(ptot.cmip,start=1980,end=2009))/1e6  # mean total precipitation
print(summary(pclim*Le/tot.E * 100))
```

```
##      Min.   1st Qu.    Median      Mean   3rd Qu.      Max.
## 2.983e-11 3.142e-11 3.270e-11 3.273e-11 3.406e-11 3.530e-11
```

```
print(summary(pclim))   # In gigatons
```

```
##    Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
##    1386    1459    1519    1520    1582    1640
```

```
Ptrends <- apply(window(ptot.cmip,start=2000,end=2100)/1e6,2,trend.coef)
print(summary(Ptrends))
```

```
##    Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
##   1.409   4.486   5.087   5.619   7.536   9.090
```

```
Ftrends <- apply(100*window(ptot.cmip,start=2000,end=2100)*Le*1e6/tot.E,2,trend.coef)
## Change in percent of energy flow connected with convection between 2000 and 2100
print(summary(Ftrends*10))
```

```
##    Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
##  0.3034  0.9658  1.0952  1.2097  1.6225  1.9570
```

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The PMEL/NOAA software ferret http://ferret.pmel.noaa.gov/Ferret/ and David Pierce's ncview were used to check and verify the netCDF files and the calculations. The function `globalsum` and ferret indicated similar results for the monthly mean precipitation totals.