Aerosol-cloud-interactions

Jim Haywood

Are aerosol second indirect effects important in climate and NWP?

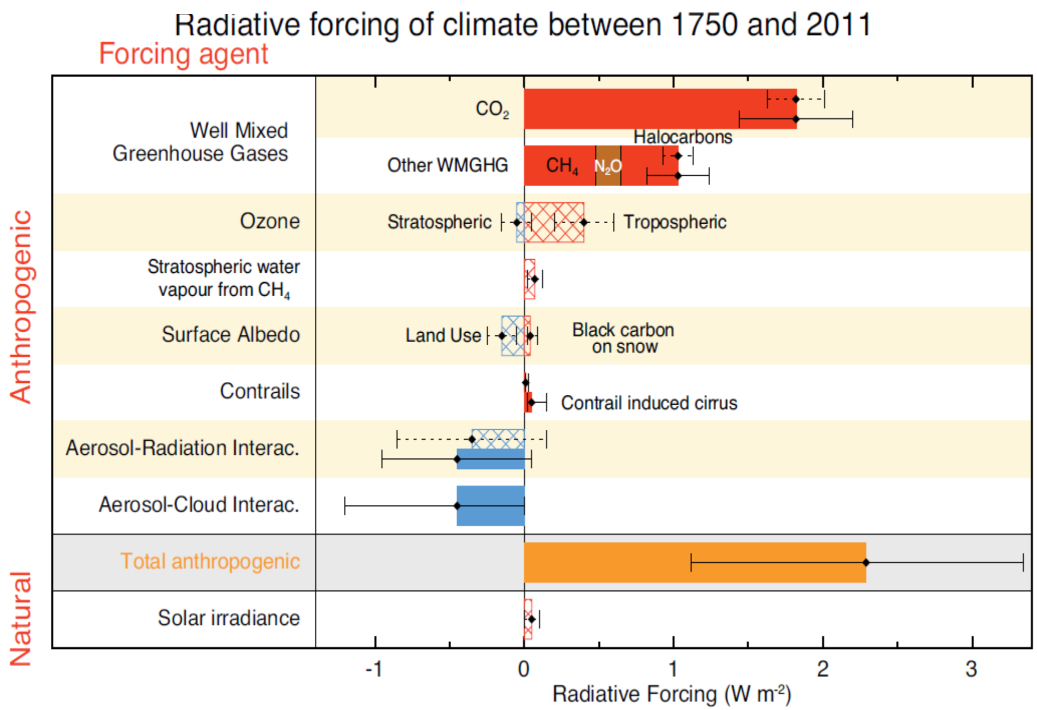
Generally I've stuck to direct effects:-

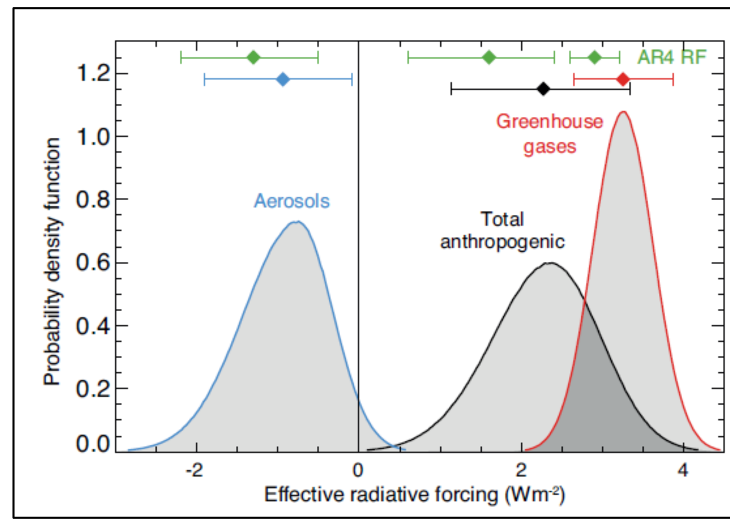
- Haywood, J.M., et al., The impact of volcanic eruptions in the period 2000-2013 on global mean temperature trends evaluated in the HadGEM2-ES climate model, *Atmos. Sci. Letts*, DOI: 10.1002/asl2.471, 2014.
- Haywood, J.M., et al., Asymmetric forcing from stratospheric aerosols impacts Sahelian drought, *Nature Climate Change, 3, 7, 660-665,* doi: 10.1038/NCLIMATE1857, 2013.
- Haywood, J. M., et al., The roles of aerosol, water vapor and cloud in future global dimming/brightening, *J. Geophys. Res.*, 116, D20203, doi:10.1029/2011JD016000, 2011.
- Haywood, J.M., et al., Prediction of visibility and aerosol within the operational Met Office Unified Model. Part: validation of model performance using observational data, *Q. J. R. Meteorol. Soc.* 134: 1817–1832, DOI: 10.1002/qj.275, 2008.
- Haywood, J.M, et al., Can desert dust explain the outgoing longwave radiation anomaly over the Sahara during July 2003? *J. Geophys. Res*., 110, D05105, doi:10.1029/2004JD005232, 2005.

A new offering on indirect effects:-

- **Malavelle, F.**, J.M. Haywood, et al., Strong constraints on aerosol-cloud interactions from volcanic eruptions, Nature, 546, 485–491,doi:10.1038/nature22974, 2017.

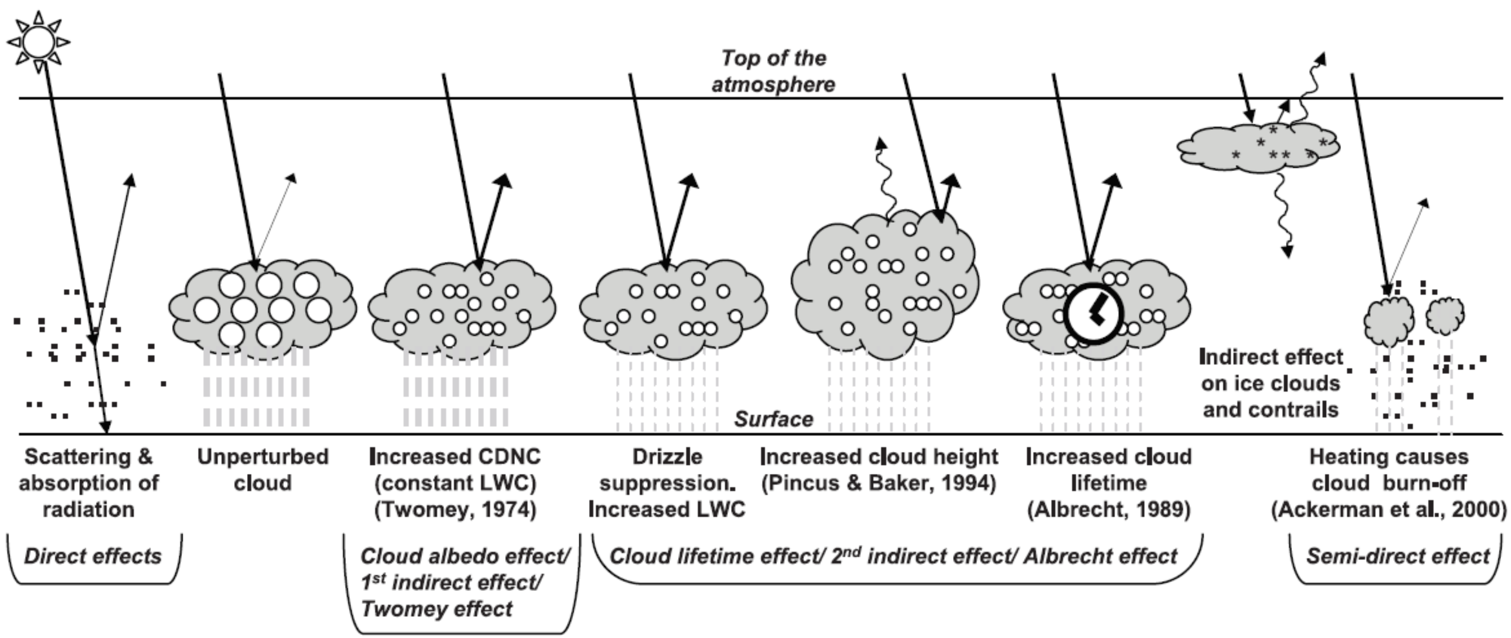
Aerosol-cloud-interactions





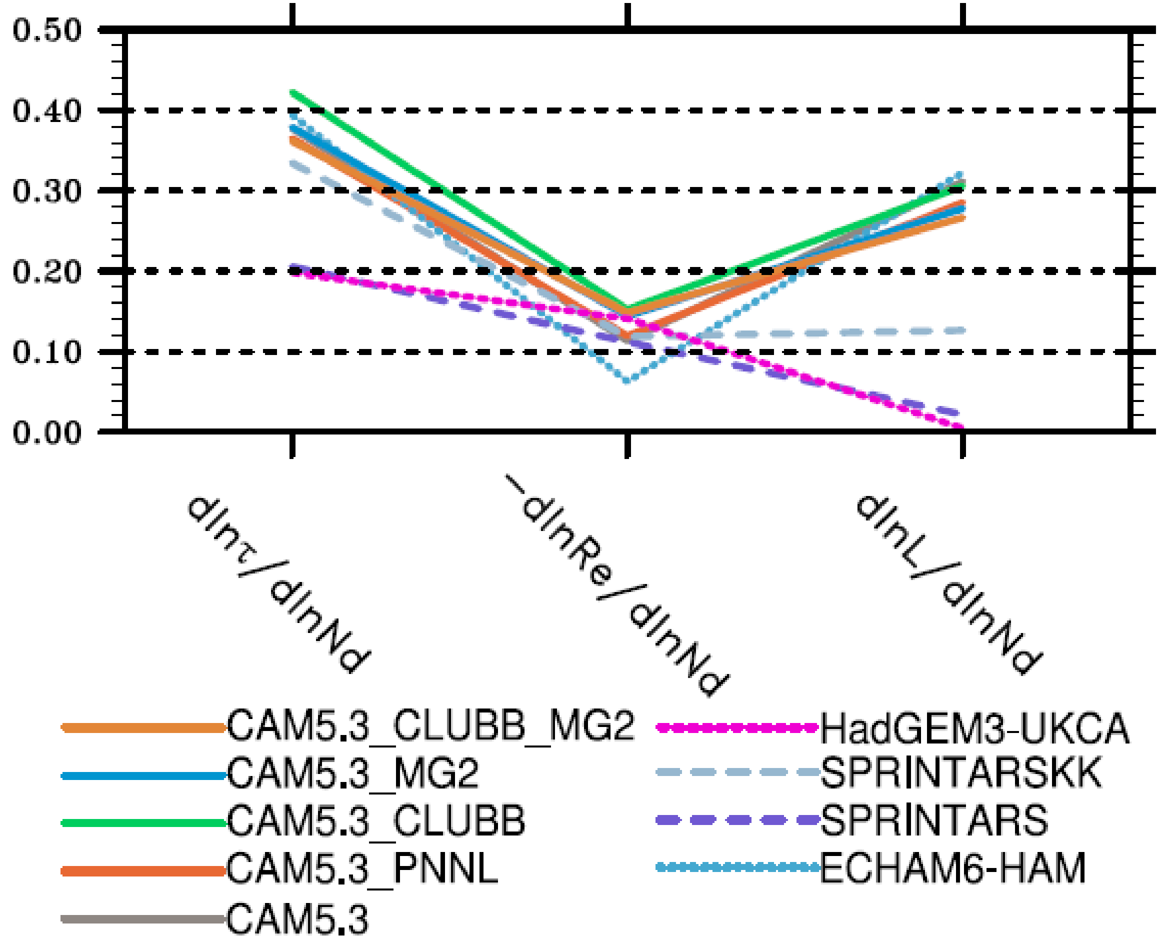
- **Aerosol-cloud-interactions: ACI continue to be the leading uncertainty in climate forcing.**
- **Models diverge strongly in the 2nd indirect effects**

Aerosols MAY influence clouds in a variety of ways



Many studies show that 2nd indirect effects may either enhance (positive feedback), reduce (negative feedback) or have little impact on the initial perturbation to the cloud effective radius.

ACI 2nd indirect effects in climate models tends to fall in two camps: i) big enhancement, ii) no enhancement of 1st indirect effect



Ghan et al, PNAS, 2016

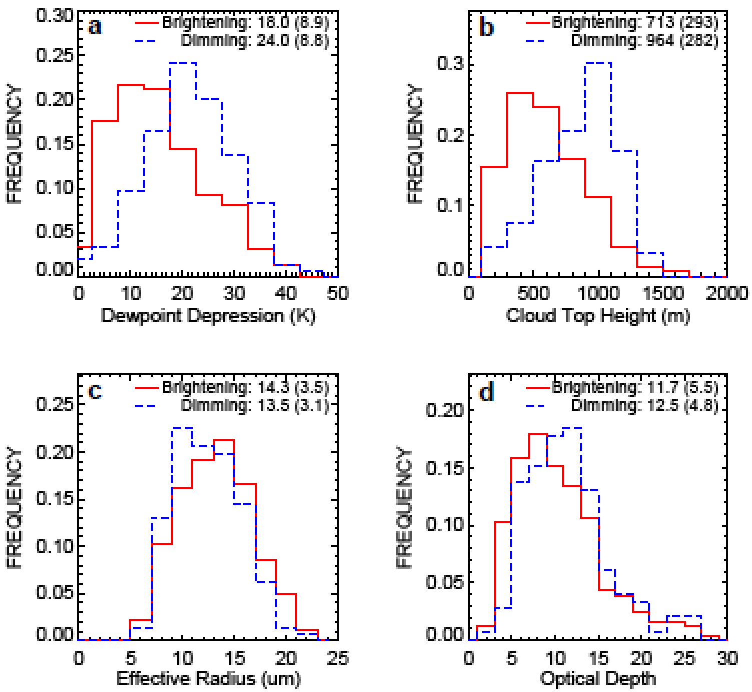
Setting the scene

The ‘poster boy’ for aerosol-cloud-interactions for the last couple of decades has been the observation of ship-tracks

Setting the scene

The problems:-

- Ship-tracks are very small scale phenomena.
- Observational studies have shown a change in the cloud effective radius, but the liquid water path can go up or down.



Chen et al., Atmos. Chem. Phys., 12, 8223–8235, 2012, analysed 589 individual ship-tracks and found "the sign (increase or decrease) and magnitude of the albedo response in ship tracks depends on the mesoscale cloud structure, the free tropospheric humidity, and cloud top height."

- GCMs have a very coarse resolution
- Ship-tracks can be modelled in large eddy simulation and cloud resolving models, but not GCMs

Holuhraun fissure eruption:

Up to 100ktSO2/day

Up to x10 emission rate from all of 28 European countries put together

Sustained for ~ 6 months

Images courtesy of Anja Schmidt

If we can’t detect/model the impact on clouds then the impact is not important.

Met Office
Hadley Centre

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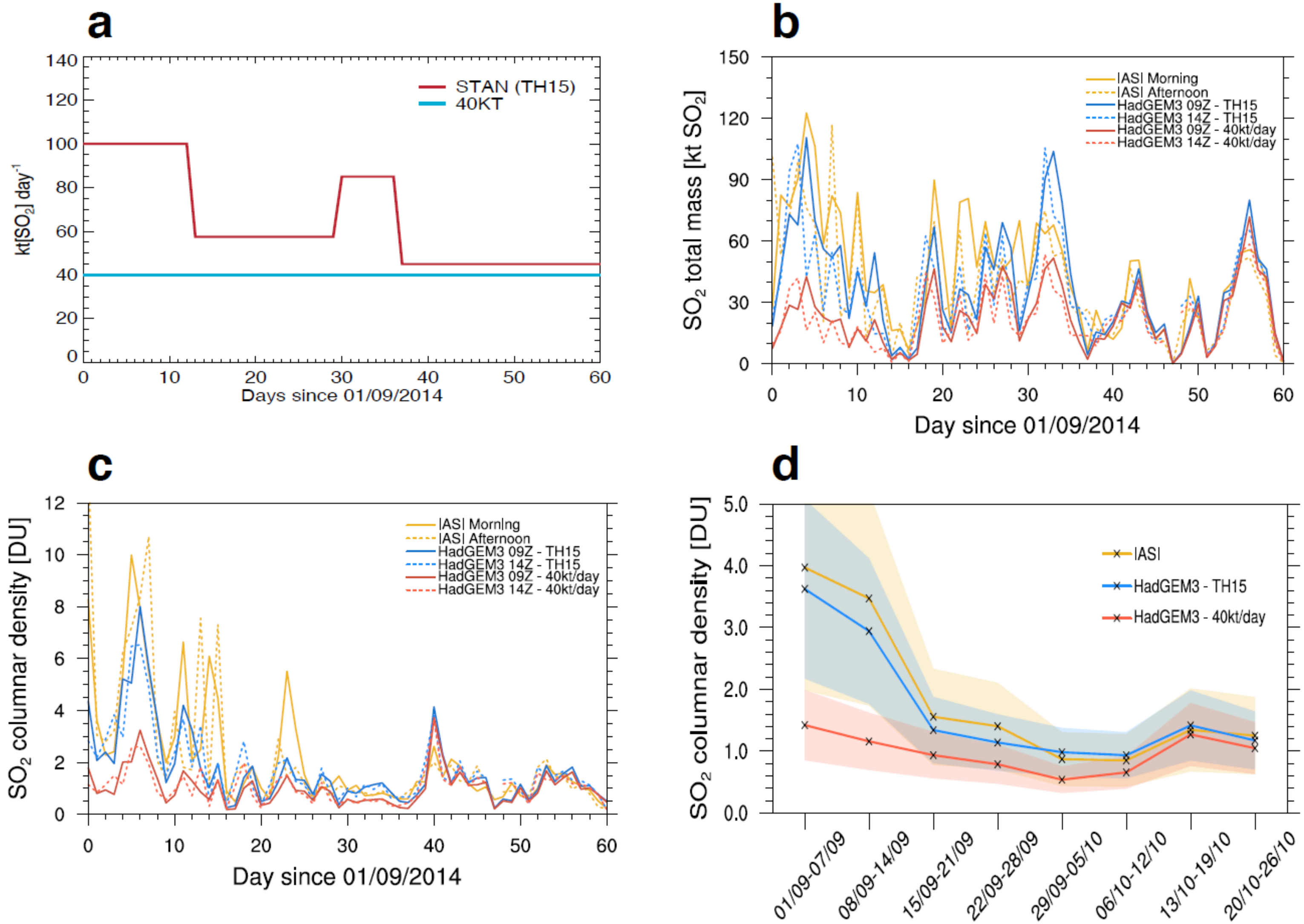
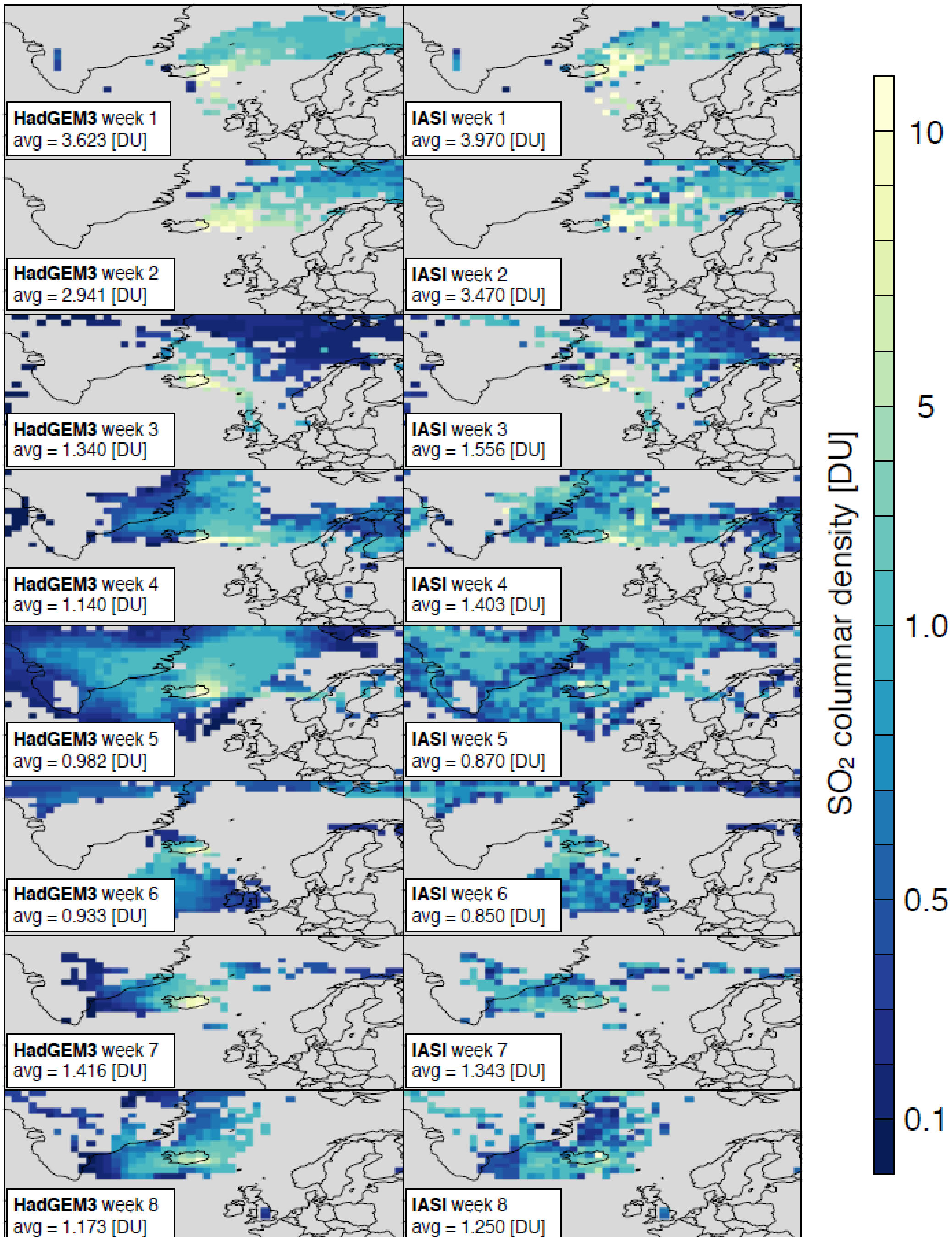
Assessment of emission rates

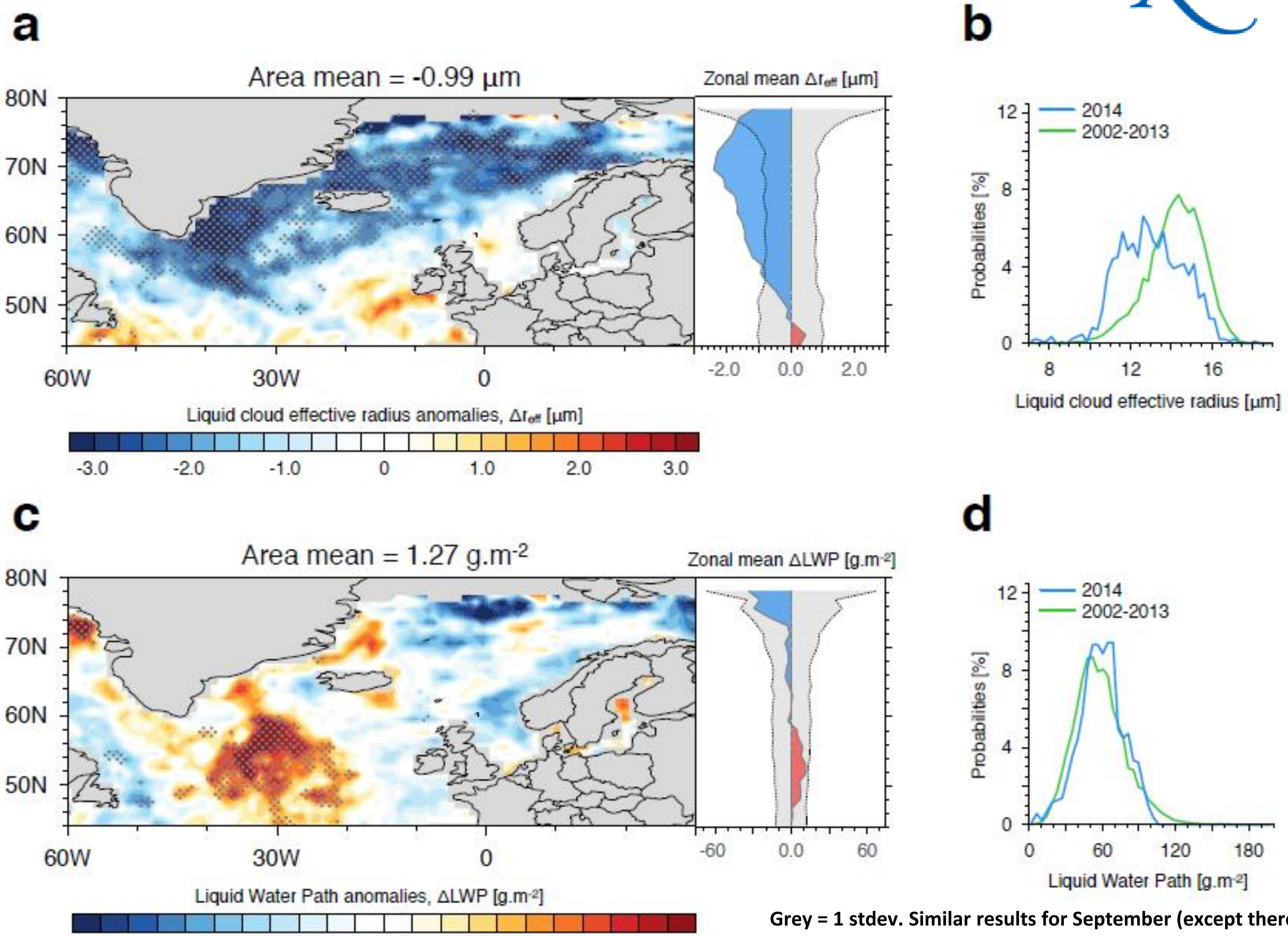


Malavelle et al (2017):-

- Nudged version of proto-HadGEM3 to replicate the meteorology.
- 2-moment UKCA aerosol scheme.
- Empirical relationship between degassed sulphur and TiO_2/FeO ratios and lava production derived from Icelandic basaltic flood lava eruptions
- IASI retrievals of SO2
- MODIS Collection 5 for cloud (Aqua as TERRA has drift from sensor degradation).
- Untangles the impacts of meteorology
- Allows proper assessment of statistical significance
- Allows us to accept/reject results from GCMs

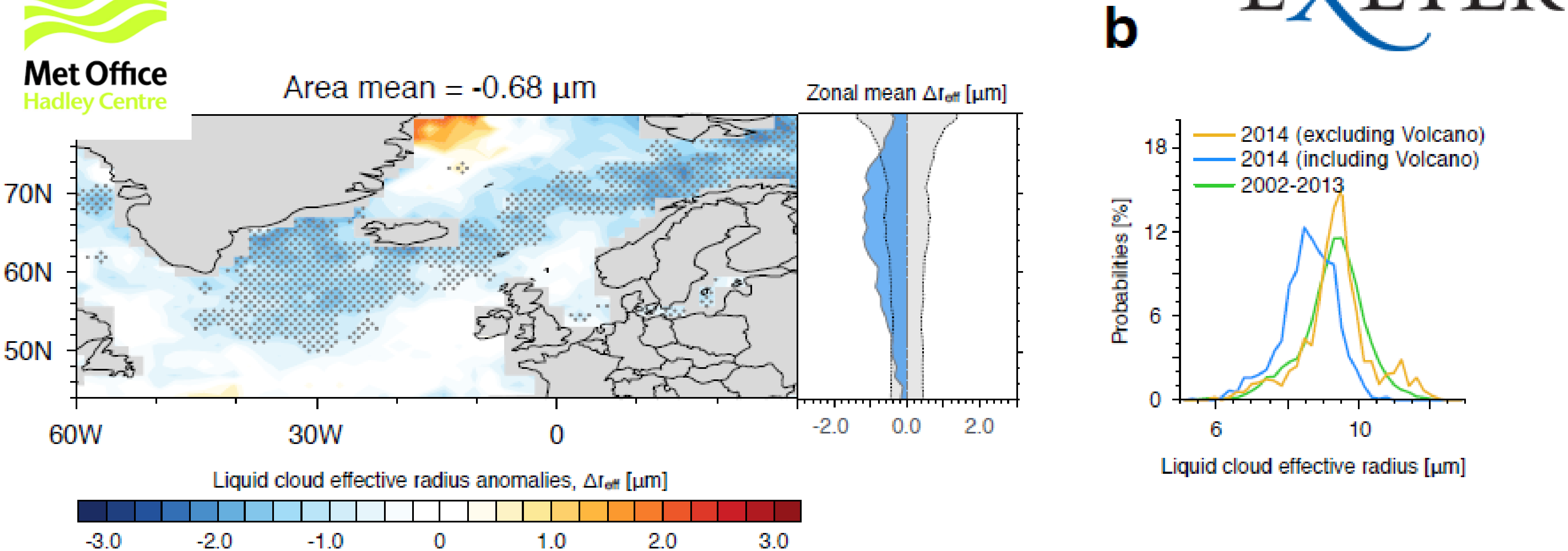


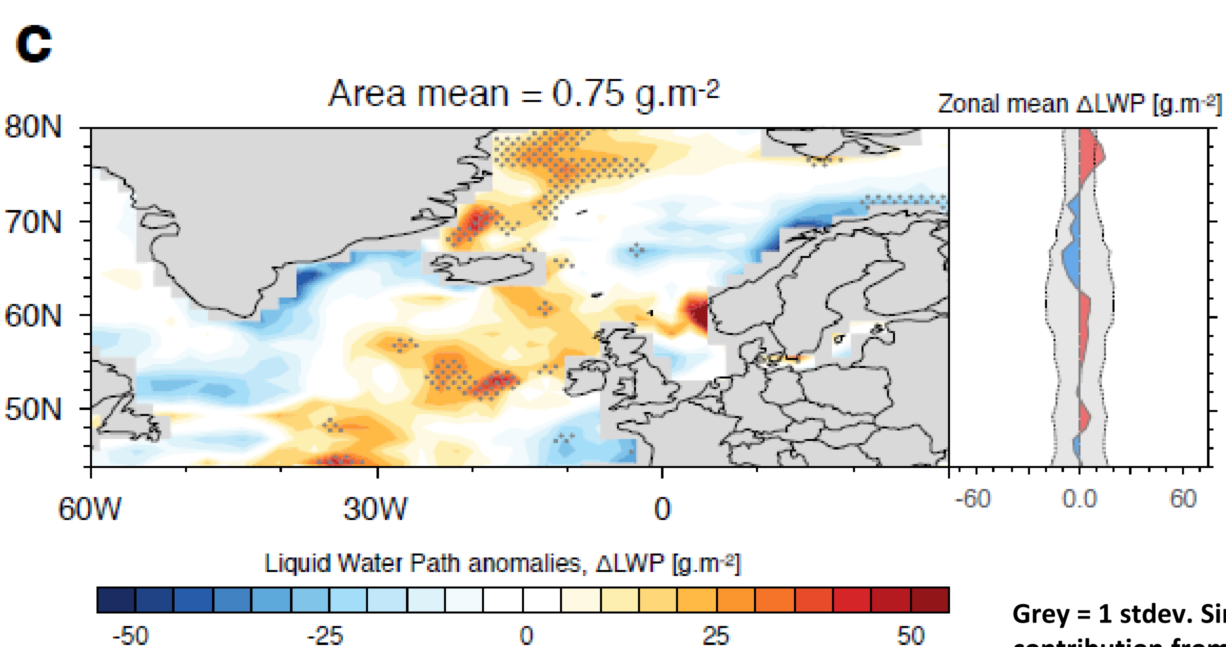
AQUA MODIS - October 2014

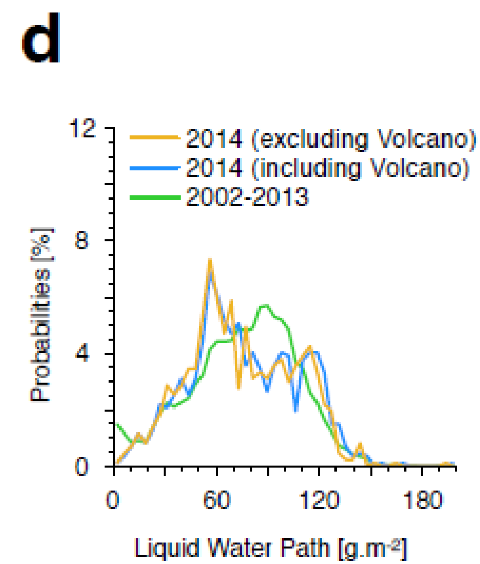


Grey = 1 stdev. Similar results for September (except there is some contribution from continental pollution to south of the region)

HadGEM3-UKCA - October 2014

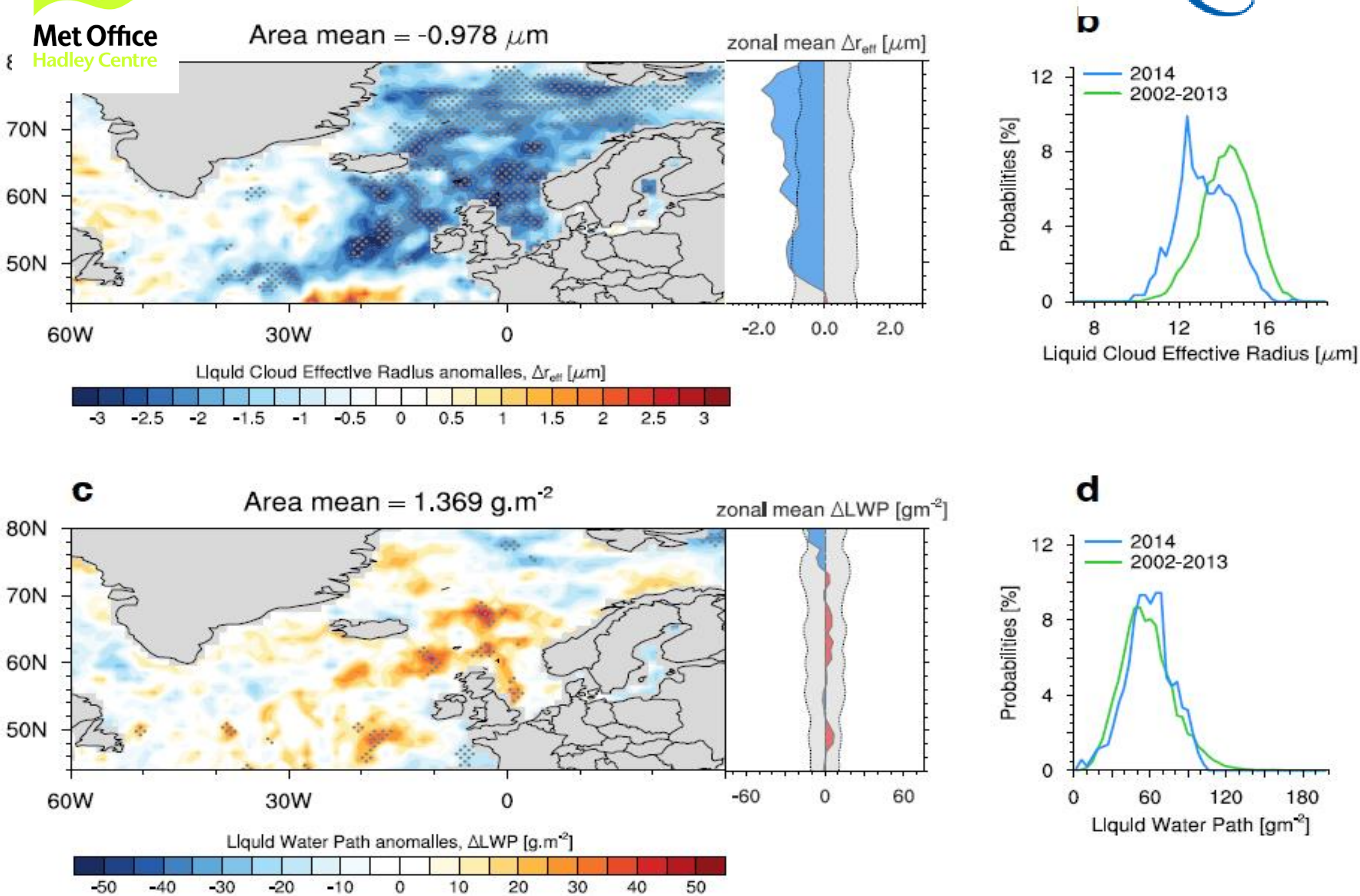




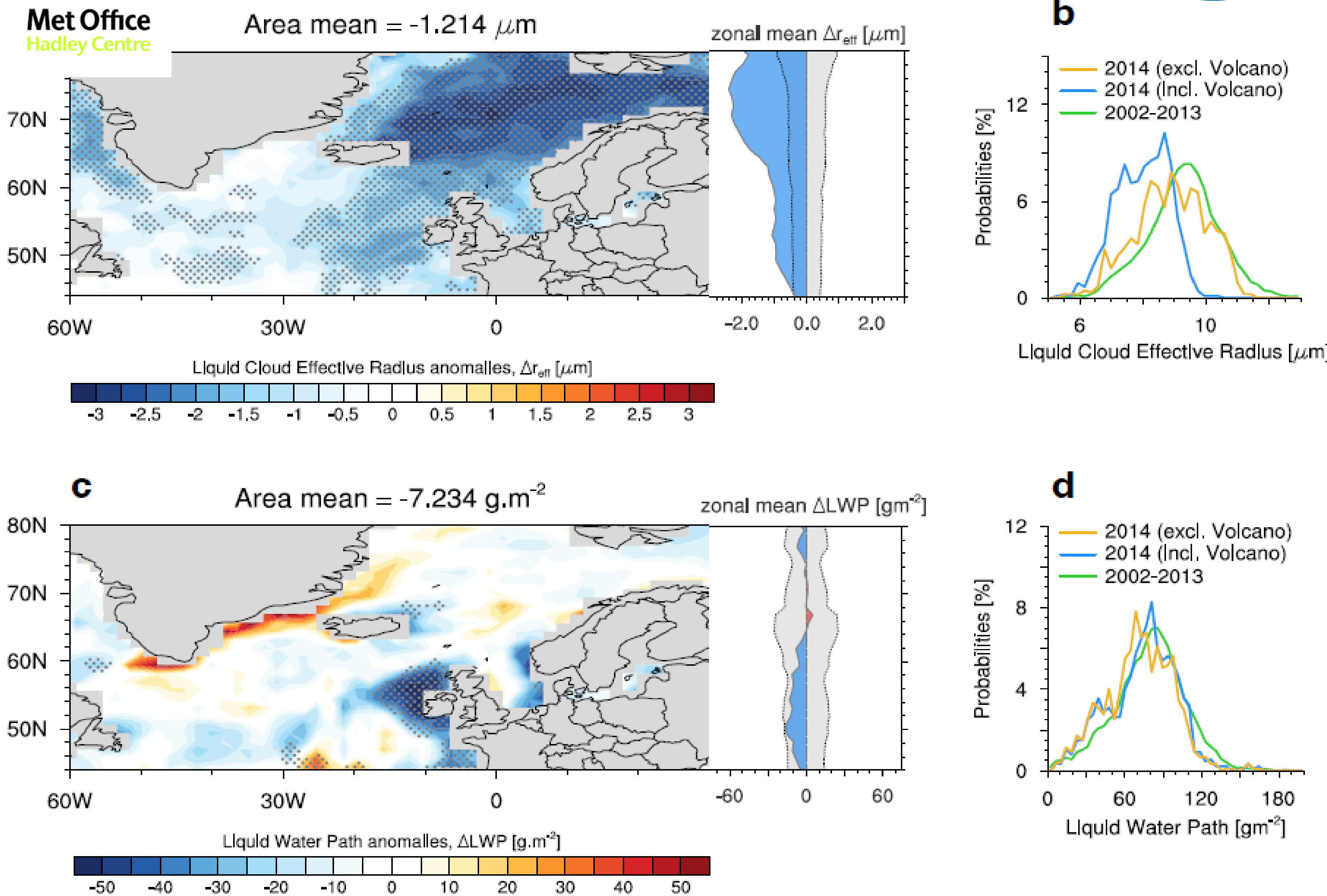


Grey = 1 stdev. Similar results for September (except there is some contribution from continental pollution to south of the region)

AQUA MODIS - September 2014



HadGEM3-UKCA - September 2014



A word on untangling the impacts of meteorology

1. Nudged with eruption (2014) – Nudged without eruption (2014)

$$\frac{\partial r_{eff}}{\partial a}\delta a$$

2. Nudged with eruption (2014)– Nudged without eruption (2002-2013)

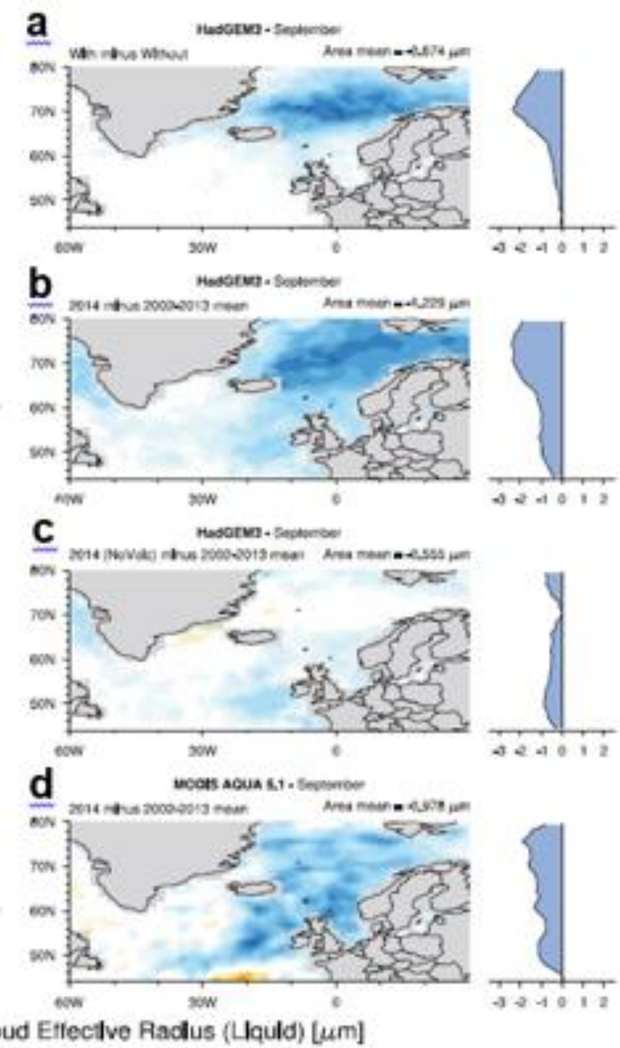
$$\frac{\partial r_{eff}}{\partial m}\delta m + \frac{\partial r_{eff}}{\partial a}\delta a$$

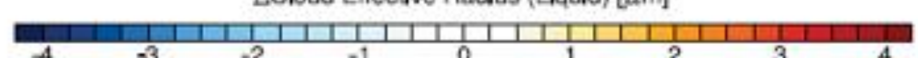
3. Nudged with eruption (2014) – Nudged without eruption (2014)

$$\frac{\partial r_{eff}}{\partial m}\delta m$$

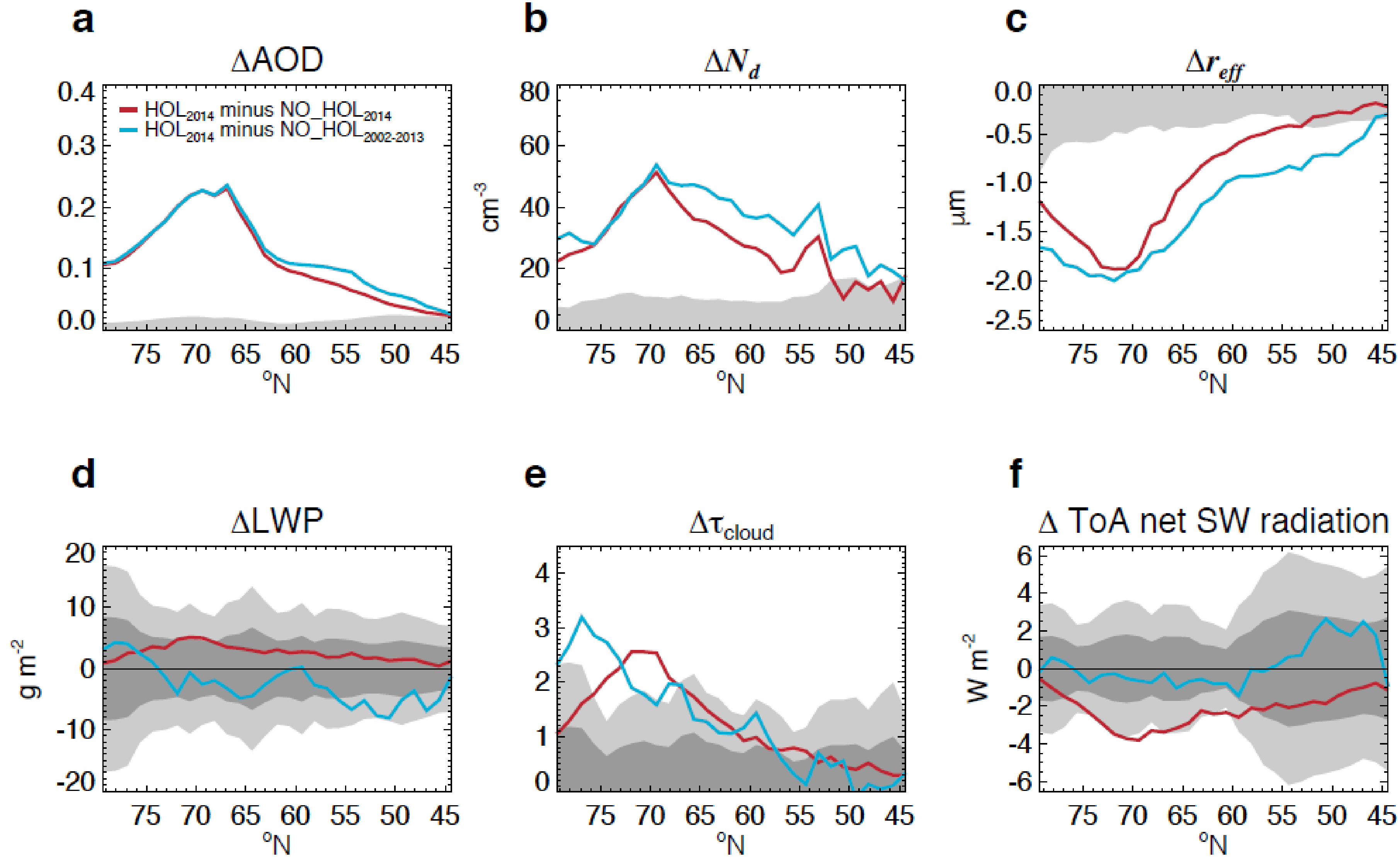
4. Obs with eruption (2014) – Obs without eruption (2002-2013)

$$\frac{\partial r_{eff}}{\partial m}\delta m + \frac{\partial r_{eff}}{\partial a}\delta a$$





Assessment of statistical significant is pretty straightforward as we can use the results from 2002-2013 to build up a picture of variability in both the satellite observations and the models. These are from the models:-



Dark grey = 1 stdev. Sept & Oct

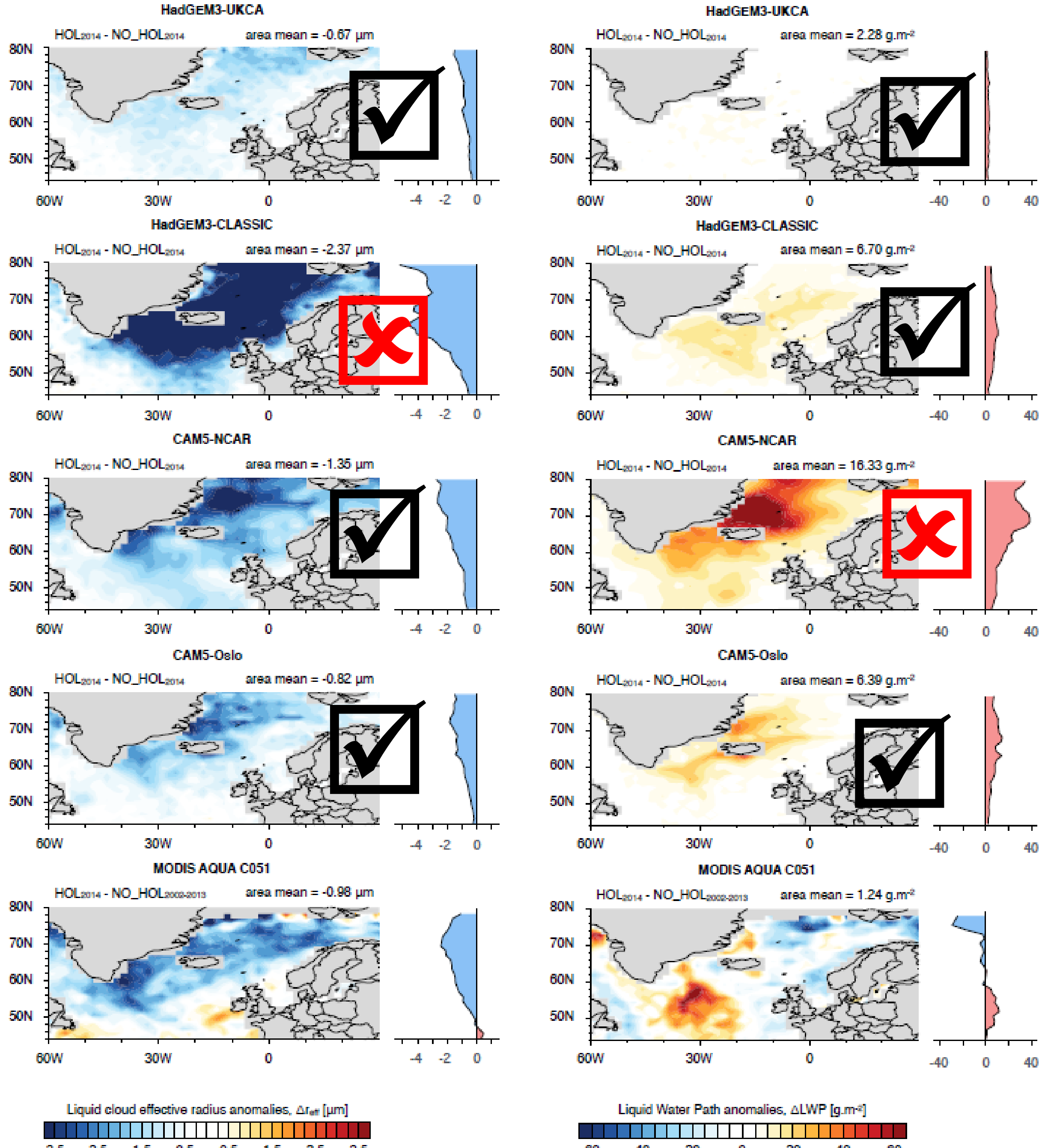
HadGEM3-UKCA:

HadGEM3-CLASSIC

CAM5.4:

CAM5-Oslo:

MODIS:



More detail on precipitation – more relevant for NWP

Impacts on precipitation over during September/ October are very unremarkable.........

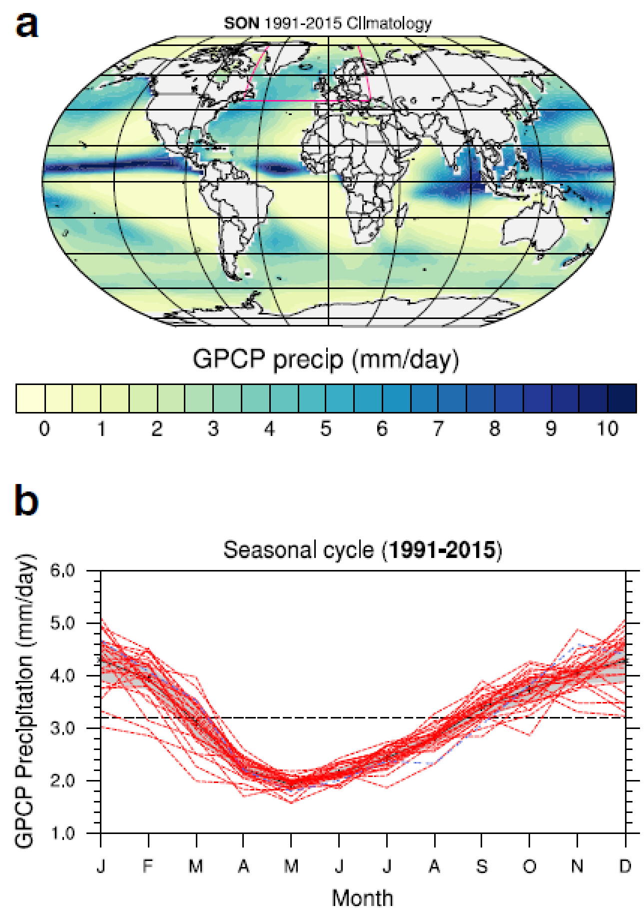


Figure S10.1. The climatology of surface precipitation from GPCP. The precipitation rate (in mm/day) shown as a) September-October-November (SON) seasonal average for the 1991-2015 period, and b) the corresponding seasonal cycle derived for the region in the vicinity of Holuhraun (45°N-80°N; 60°E-30°W). The long term (1991-2015) mean seasonal cycle is represented by the black line. The red dashed lines represent the seasonal cycle for each individual year. 2014 is highlighted in blue.

The precipitation is actually the most average October in the satellite record........

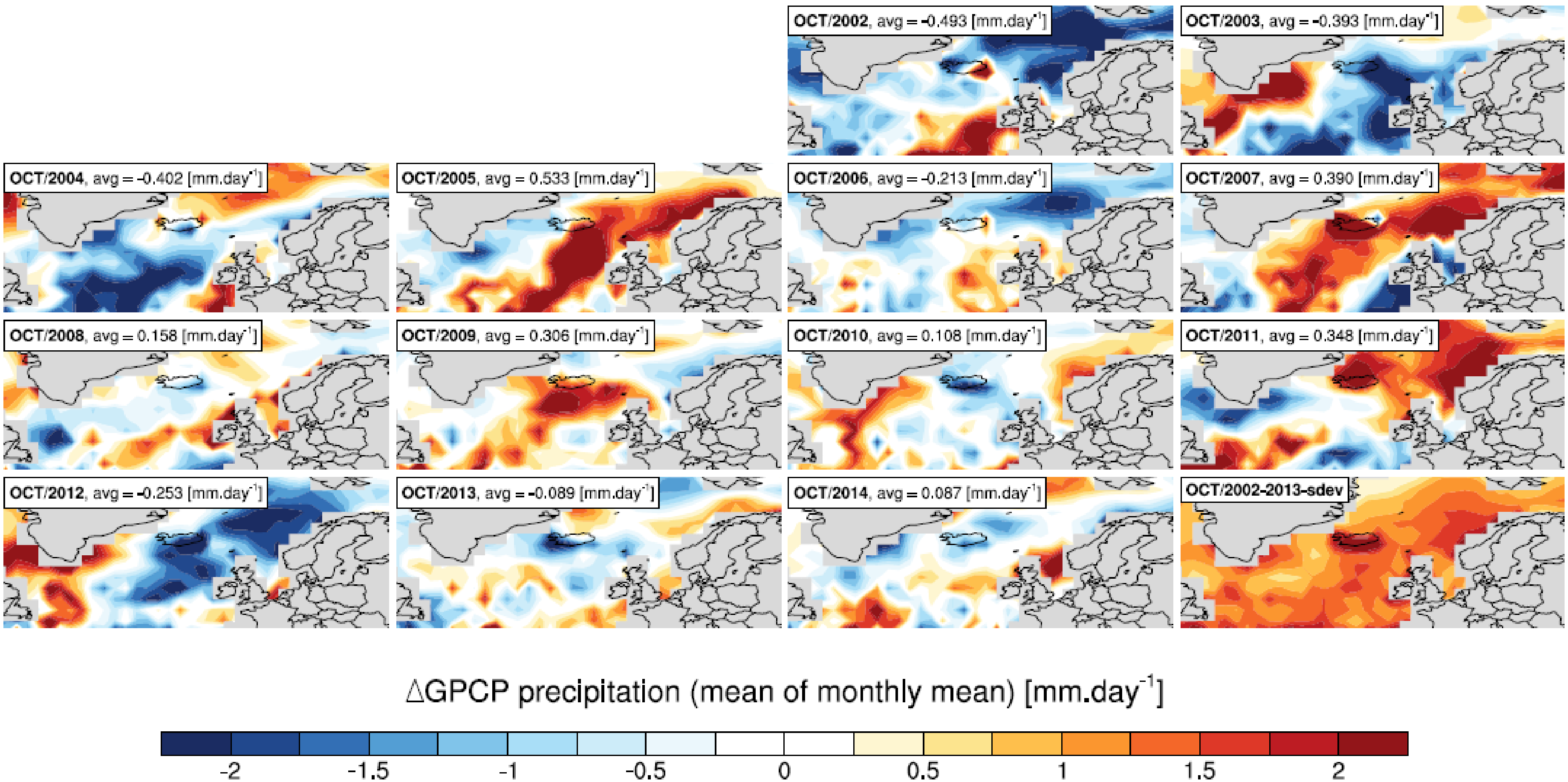


Figure S10.3. The precipitation rate anomalies during October months from GPCP. *The precipitation rate anomalies are shown from 2002 to 2014 period (in mm/day) with their associated zonal mean (continued). The anomalies are calculated with regard to the 2002-2013 climatology. The grey shading represents the standard deviation from the 2002-2013 period. The last panel shows the precipitation rate standard deviation (sdev) calculated for the 2002-2013 period. In the first 13 panels, 'avg' represents the average anomalies.*

Unlike the change in effective radius that is very obvious in the observations ....

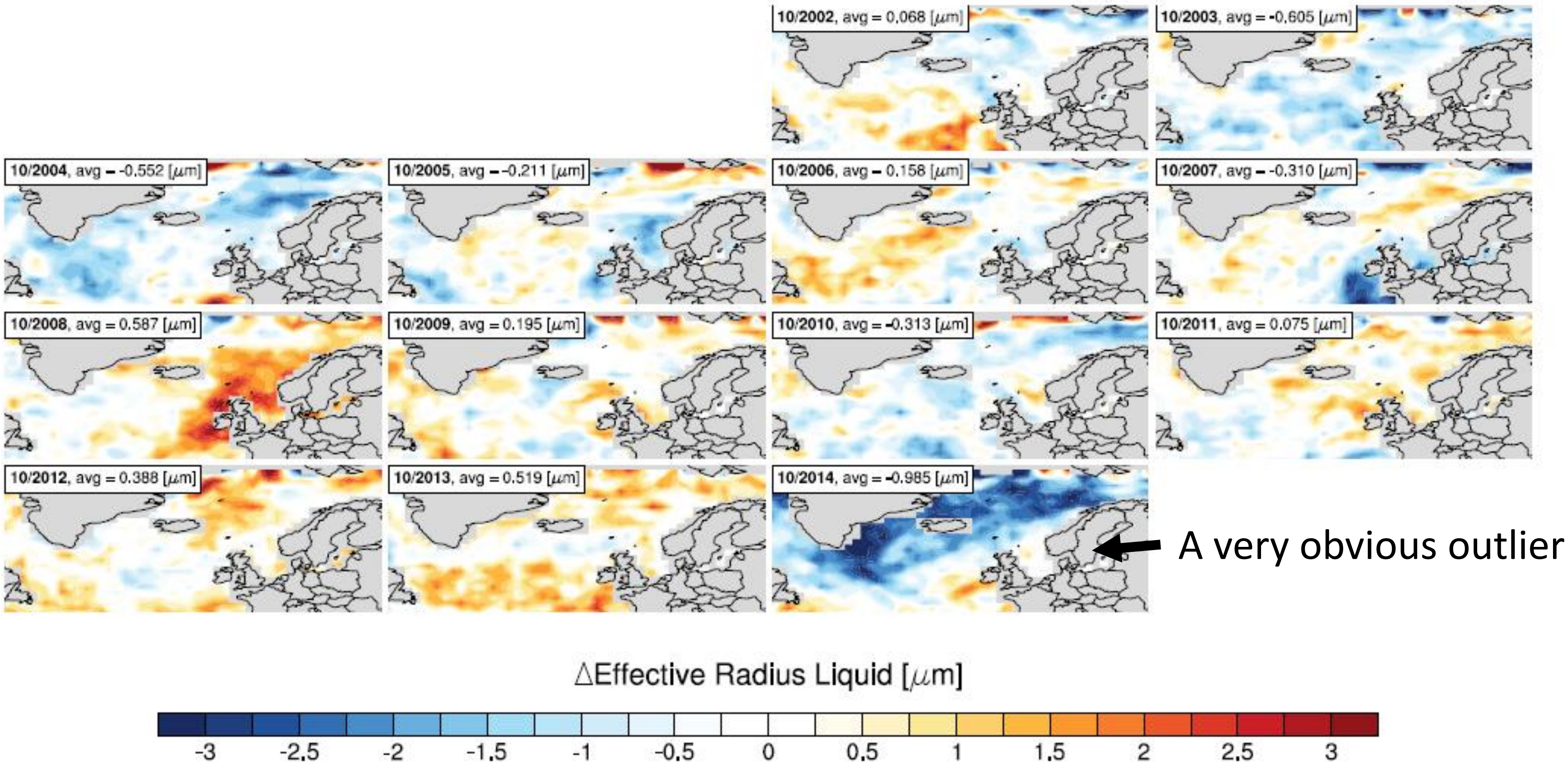


Figure S4.2. The effective radius anomalies during October months from MODIS. Showing Δr_{eff} for each individual October month derived as the difference in annual monthly mean from the multi-year (2002-2013) October mean. In each case 'avg' represents the average anomalies.

Met Office
Hadley Centre

The precipitation is actually the most average October in the satellite record……..

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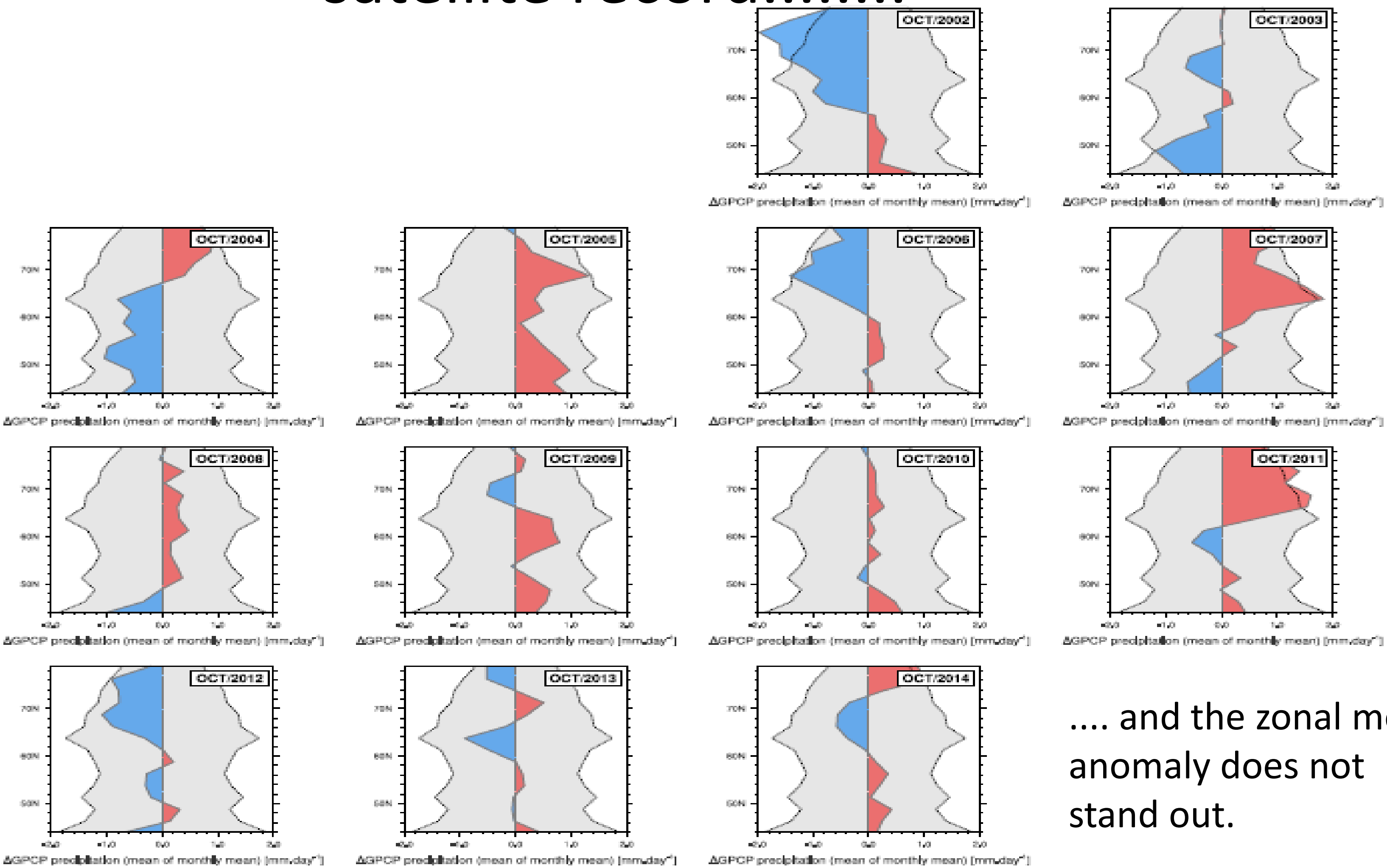
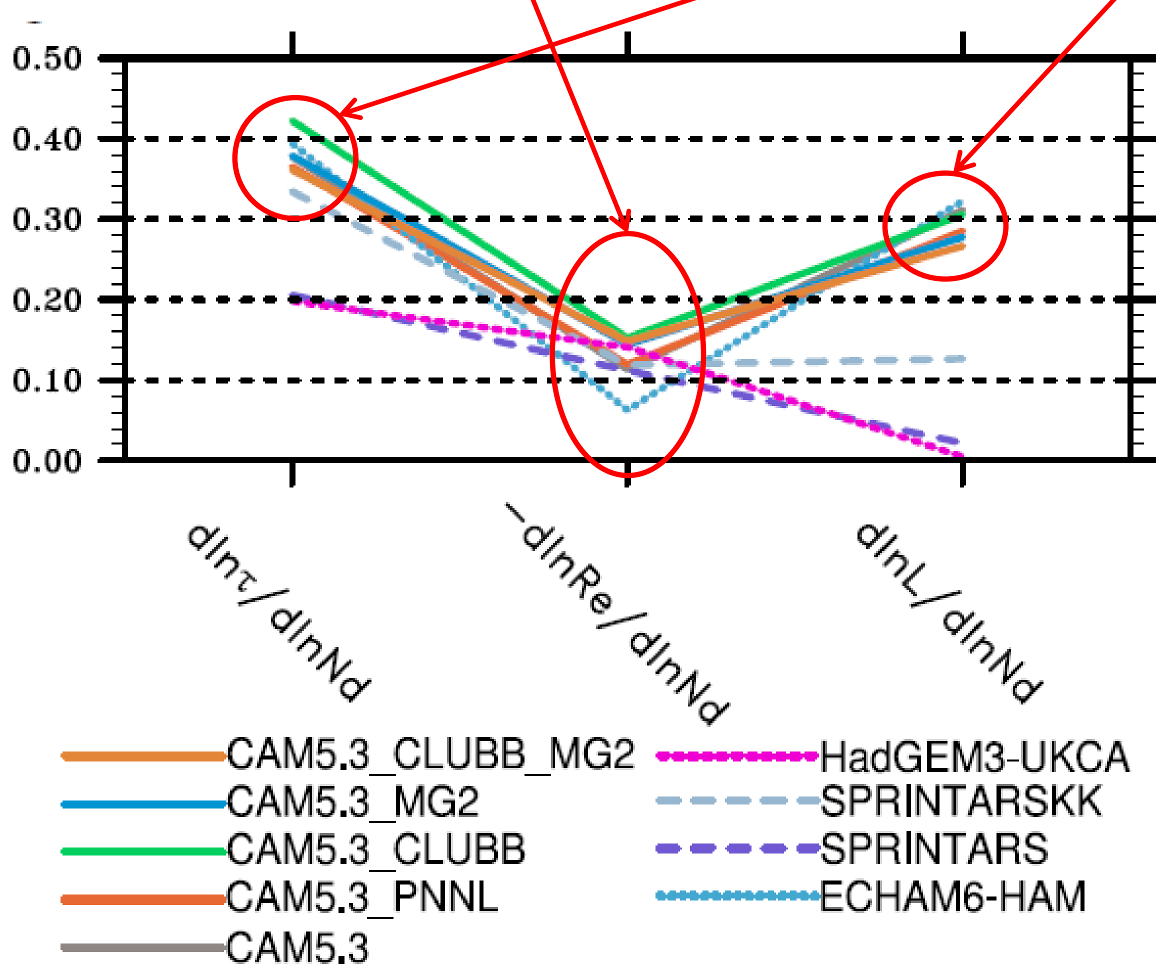


…. and the zonal mean anomaly does not stand out.

There are some big implications for the believability of ACI in climate models

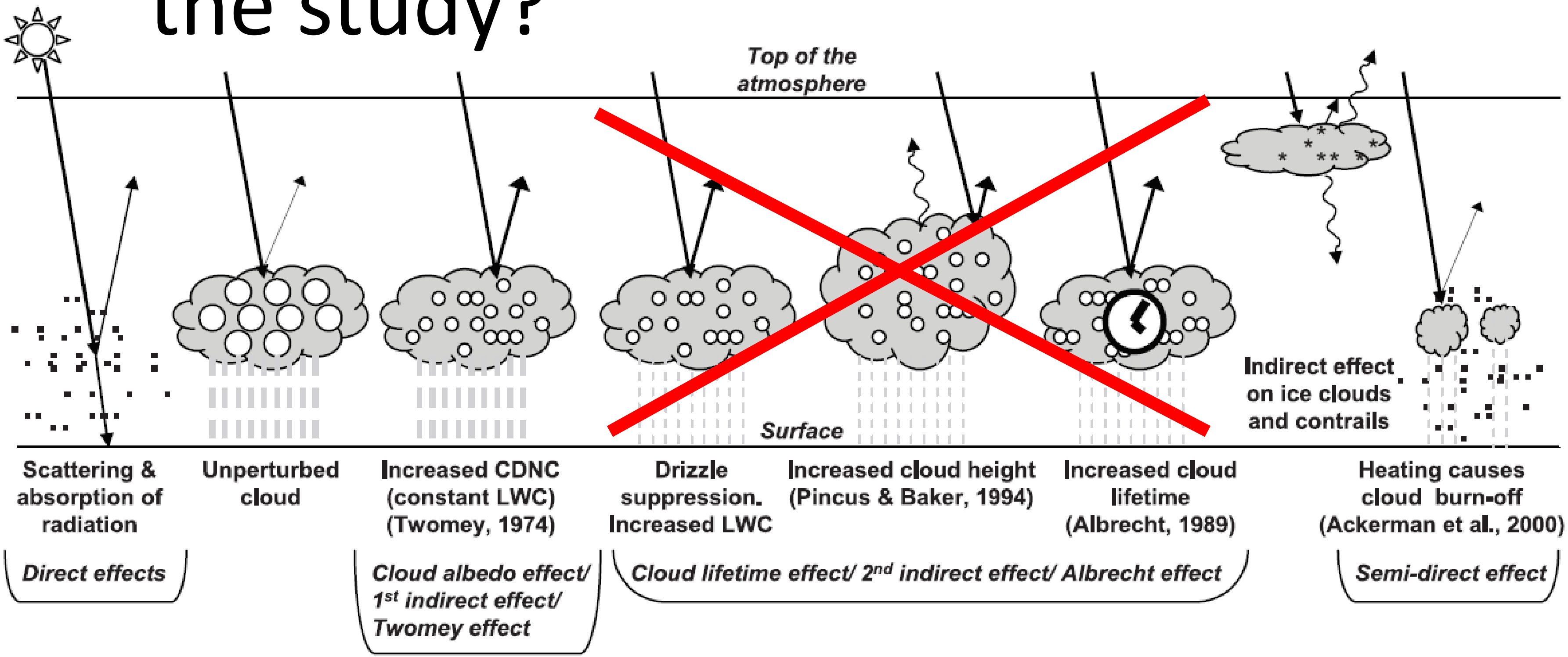
These models are all OK

These models are all wrong



Ghan et al, PNAS, 2016

What can we conclude from the study?



- A massive plume (1/3 of global emission rate!) was emitted from Iceland in 2014
- The emissions clearly perturbs cloud effective radius
- The radiative forcing was a modest -0.2Wm^{-2} during Sept/Oct 2014
- The radiative forcing could be *2.9 (June) *2.3 (Sc region) * 1.5 (pre-industrial) = -2Wm^{-2}
- The emission have no detectable net influence on cloud liquid water
- The emissions have no detectable net influence on precipitation
- SOME models are accurate, some are not ....

Additional Material

Cloud regime analysis – update to ISCCP: Lazarus Oreopolis et al. (2016)

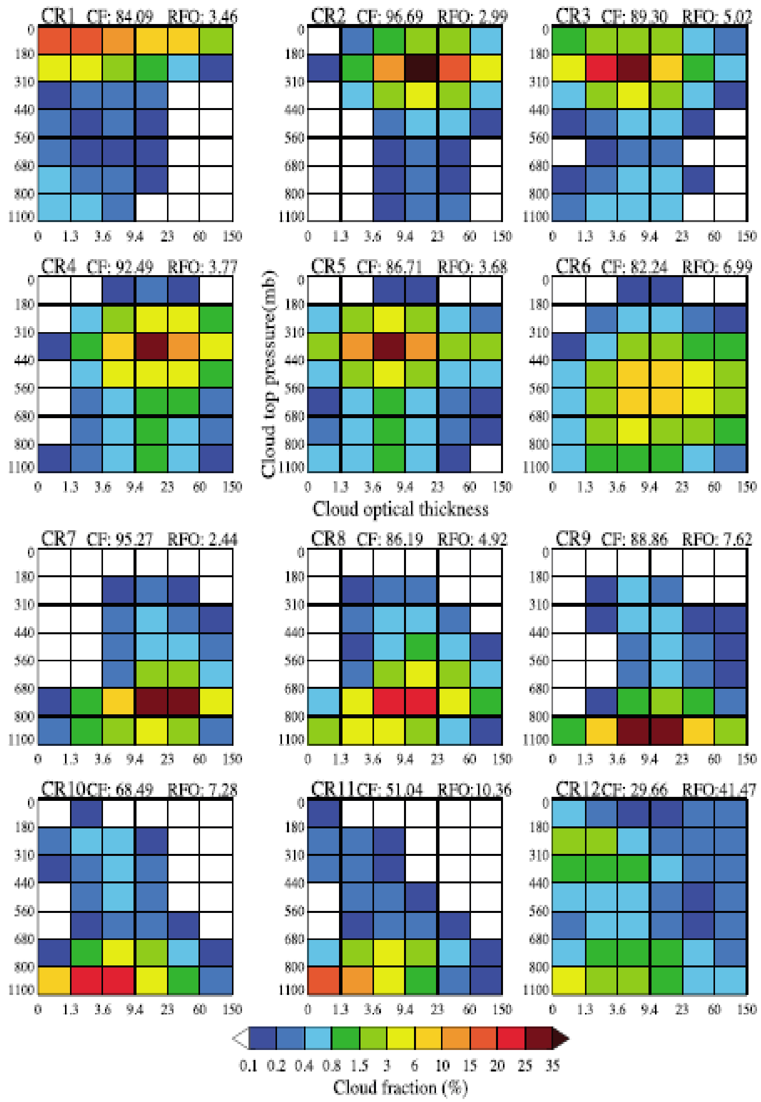


Figure 1. Centroids (mean histograms) of the 12 cloud regimes (CRs) derived from clustering analysis on 12 years of MODIS C6 Aqua-Terra p_c-τ joint daily histograms at a resolution of 1°. Additional information included in each panel is the mean global cloud fraction CF and relative frequency of occurrence (RFO) of each CR.

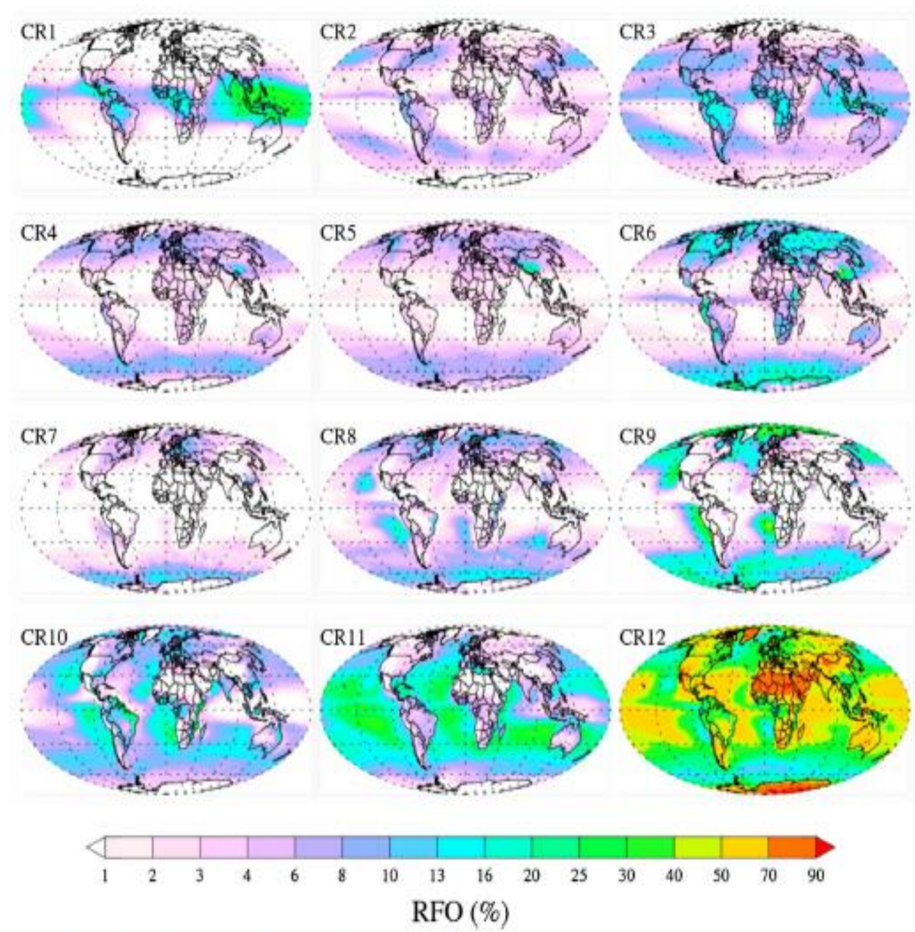


Figure 2. The geographical multiannual mean RFO of each of the 12 MODIS C6 CRs.

We are far from examining a meteorological special case – the area consists of a mix of all cloud types

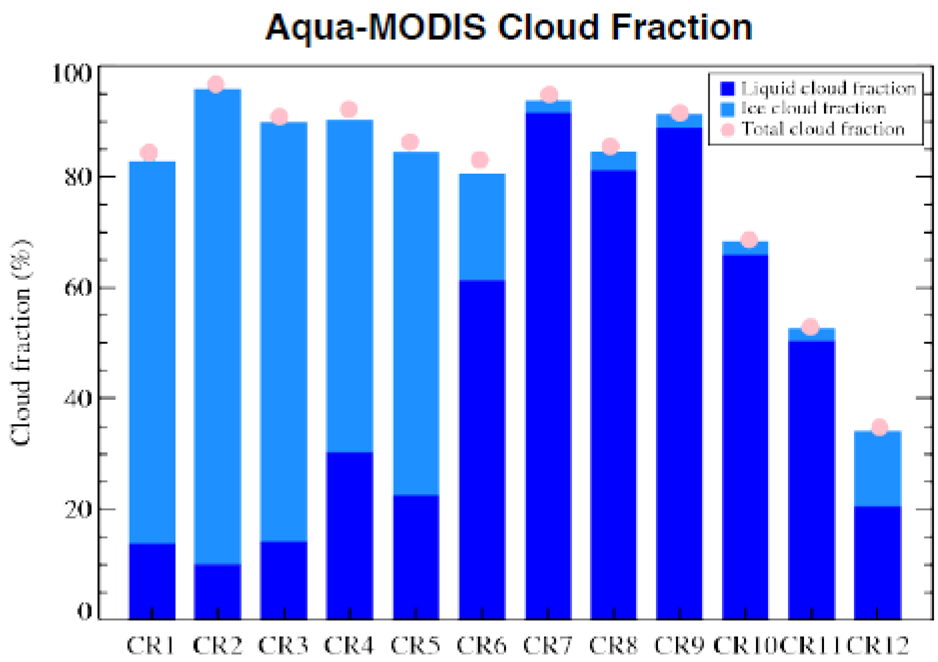


Figure S13.1. The cloud fraction from the different cloud regimes. *The Cloud Regime analysis is derived in the region 44°N-80°N, 60°W-30°E using MODIS AQUA data from 2002-2014 for the September-October months.*

Kilauea

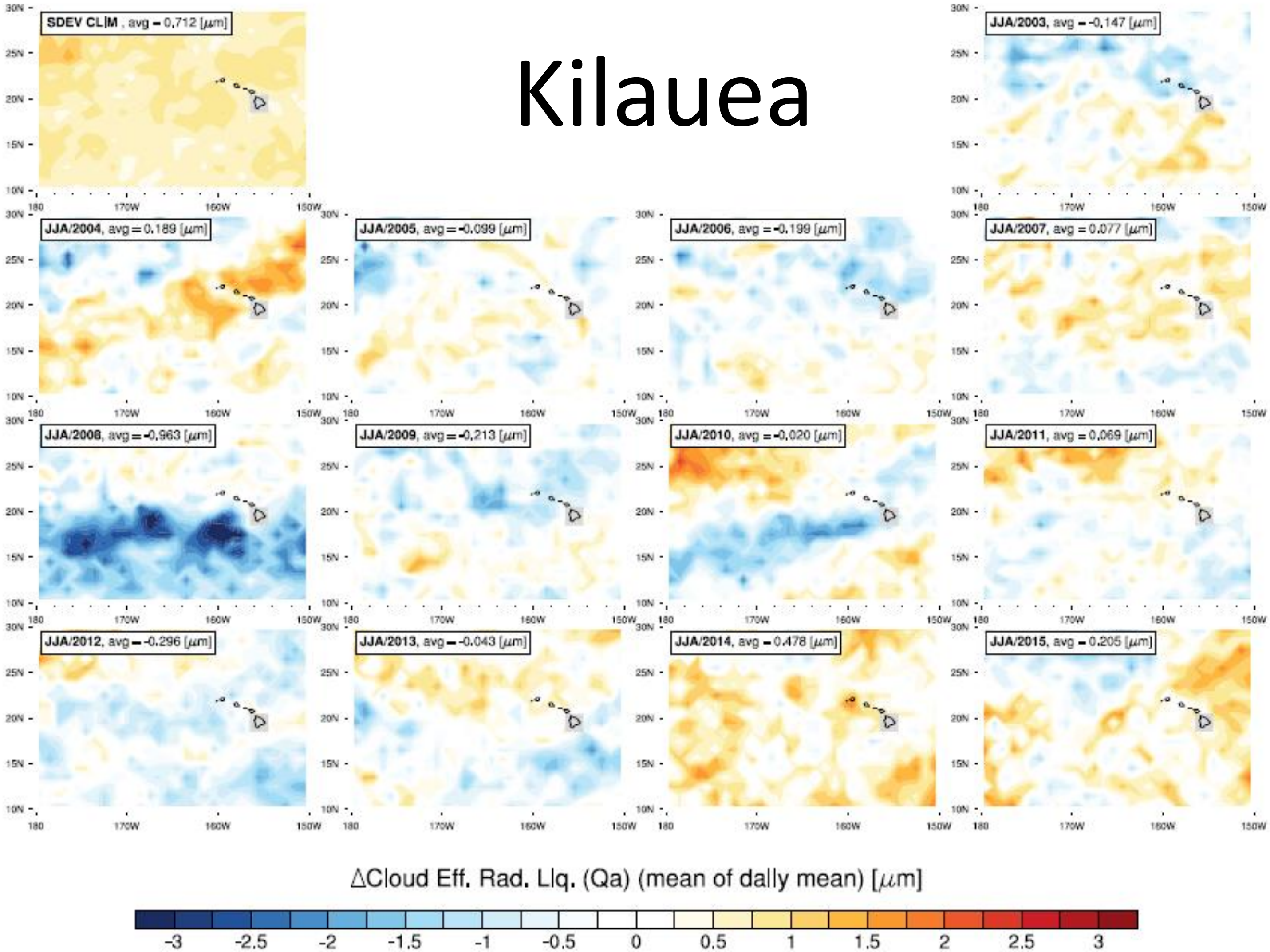


***Figure S14.1. The effective radius anomalies during the June-August (JJA) season from MODIS.** Showing Δr_{eff} (in μm) and associated zonal mean (continued). Anomalies for each individual JJA season are derived as the difference in annual JJA mean from the 2003-2015 (excluding 2008) JJA mean. The grey shading in the zonal mean represent the standard deviation over the 2003-2015 period.*

Kilauea

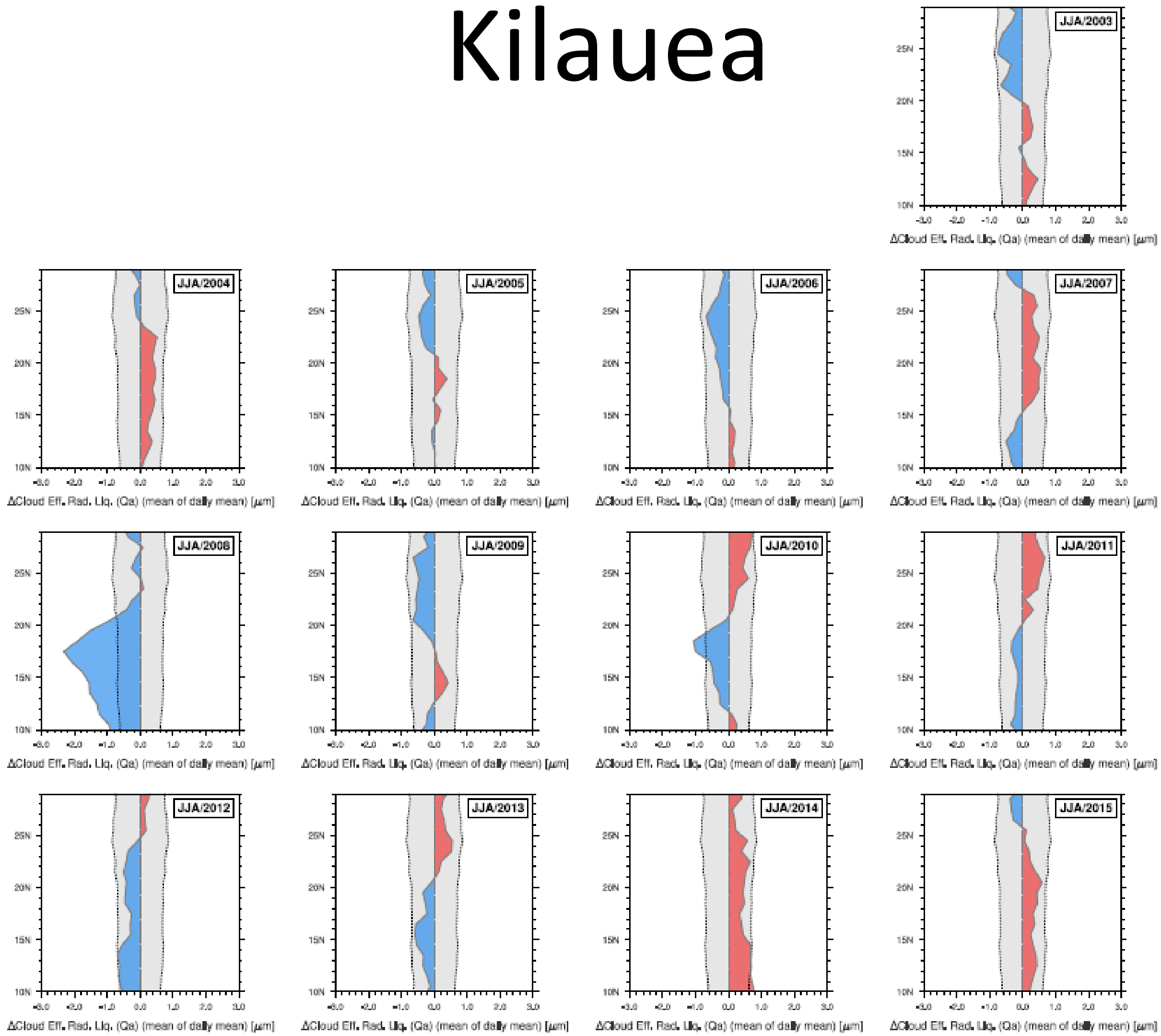


Figure S14.1. continued

Grey envelope = 1 stdev

Kilauea

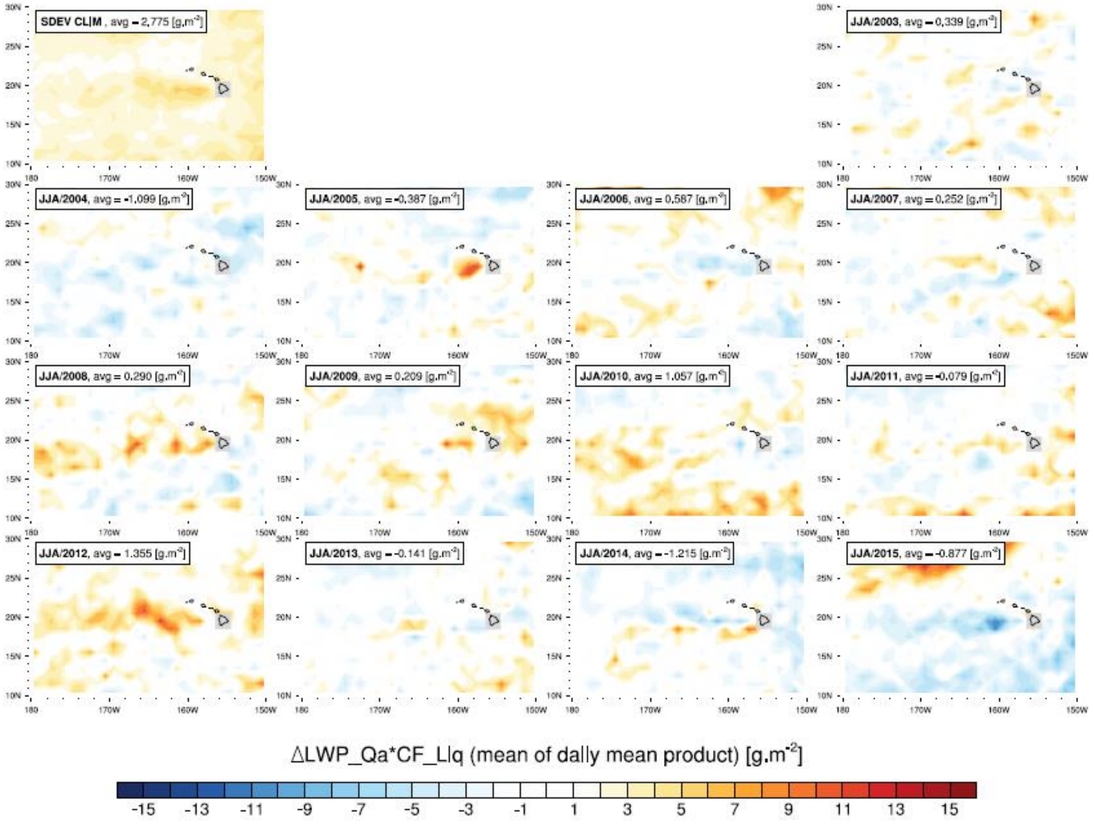
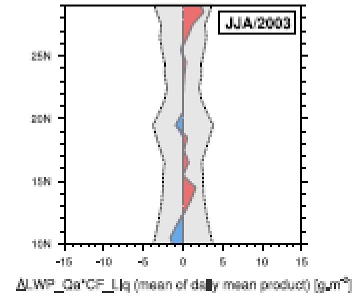


Figure S14.2. The liquid water path anomalies during the June-August (JJA) season from MODIS. *Showing ΔN_d (in cm^{-3}) and associated zonal mean (continued). Anomalies for each individual JJA season are derived as the difference in annual JJA mean from the 2003-2015 (excluding 2008) JJA mean. The grey shading in the zonal mean represent the standard deviation over the 2003-2015 period.*

Kilauea



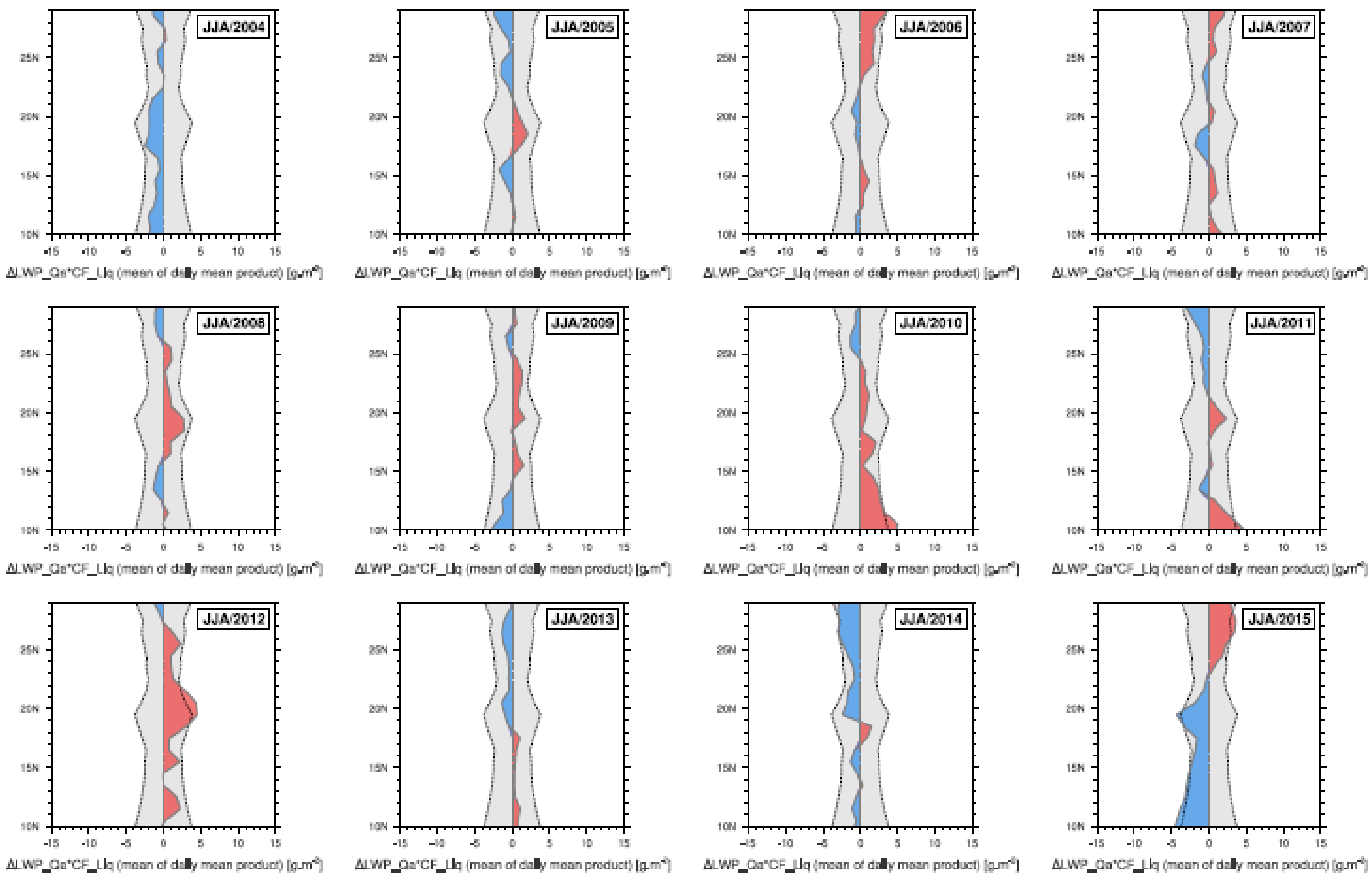
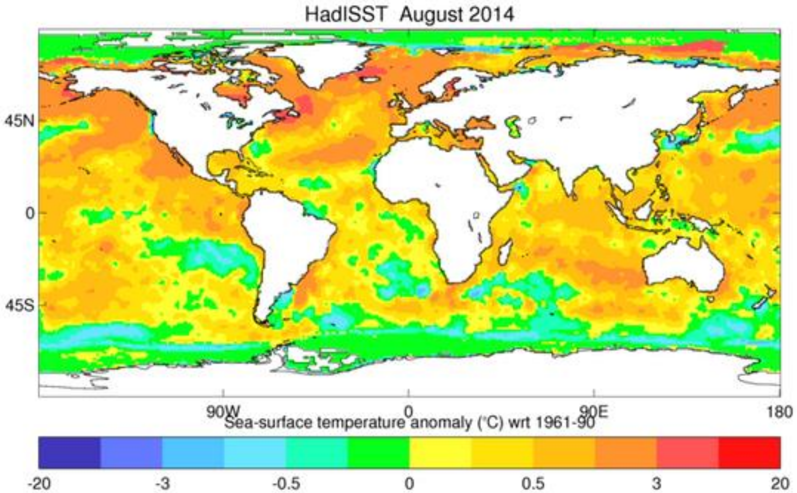
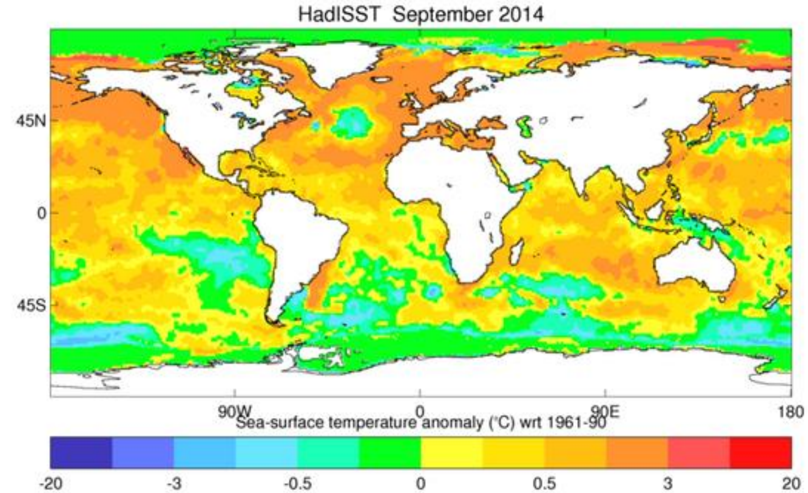
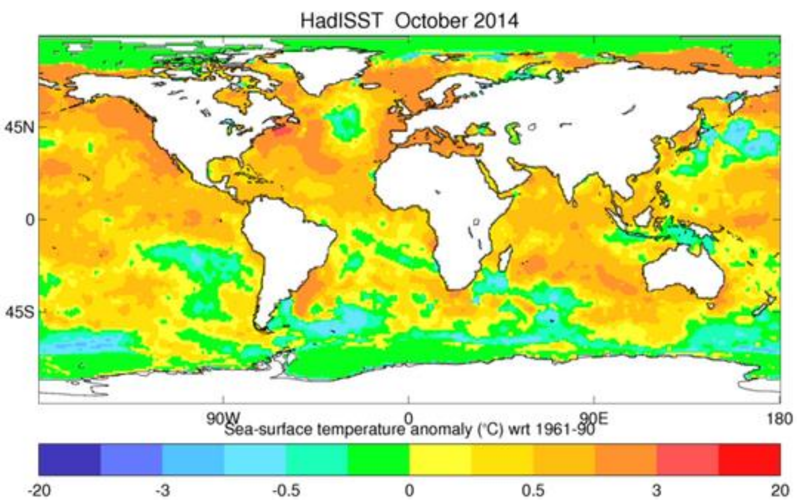


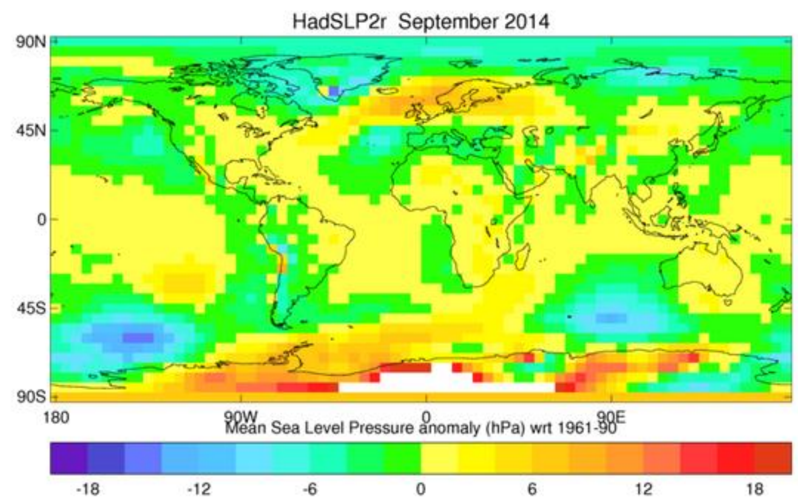
Figure S14.2. continued

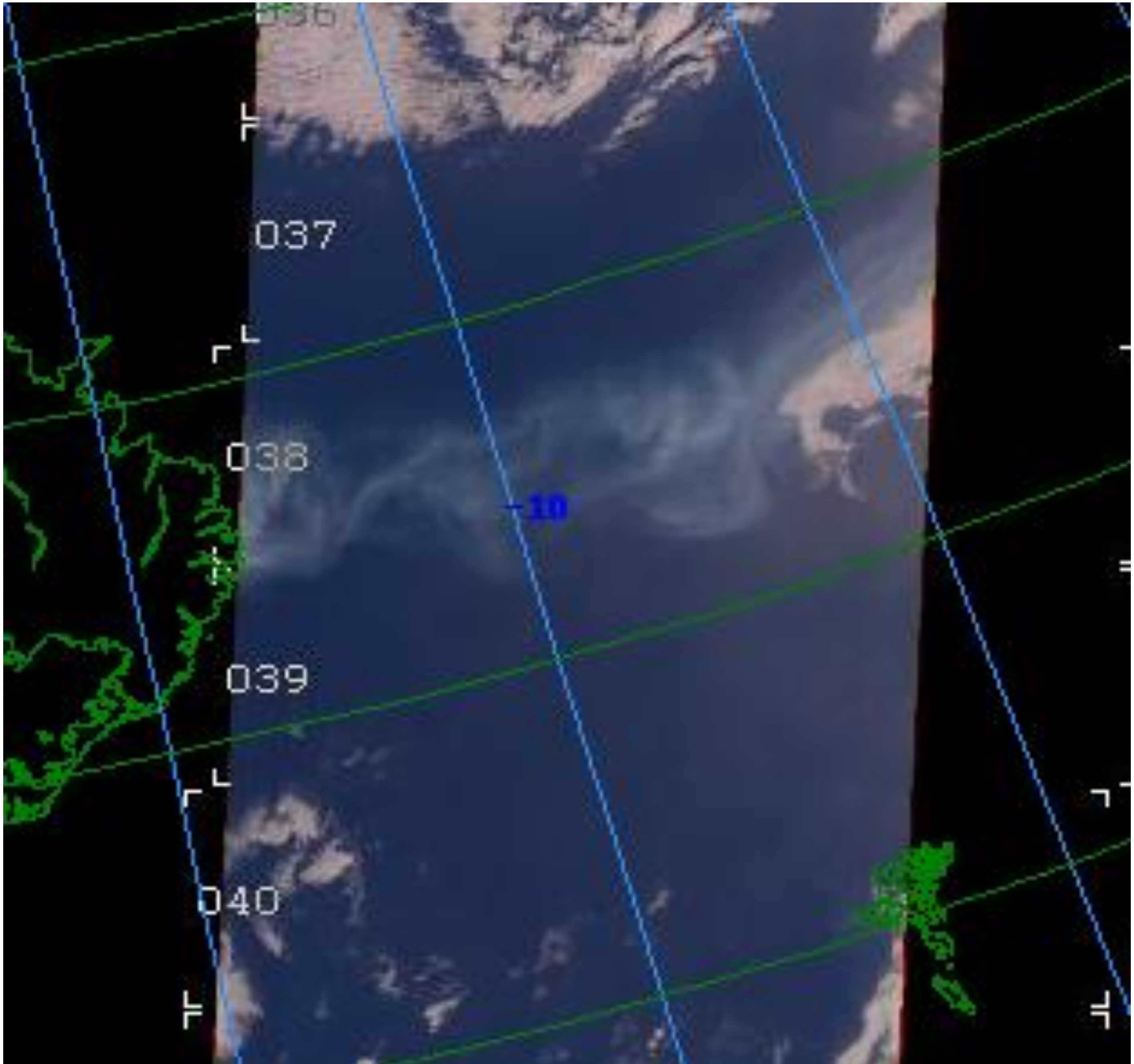
Grey envelope = 1 stdev


HadISST August 2014
45N
0
45S
90W
0
90E
180
Sea-surface temperature anomaly (°C) wrt 1961-90
-20
-3
-0.5
0
0.5
3
20


HadISST September 2014
45N
0
45S
90W
0
90E
180
Sea-surface temperature anomaly (°C) wrt 1961-90
-20
-3
-0.5
0
0.5
3
20


HadISST October 2014
45N
0
45S
90W
0
90E
180
Sea-surface temperature anomaly (°C) wrt 1961-90
-20
-3
-0.5
0
0.5
3
20

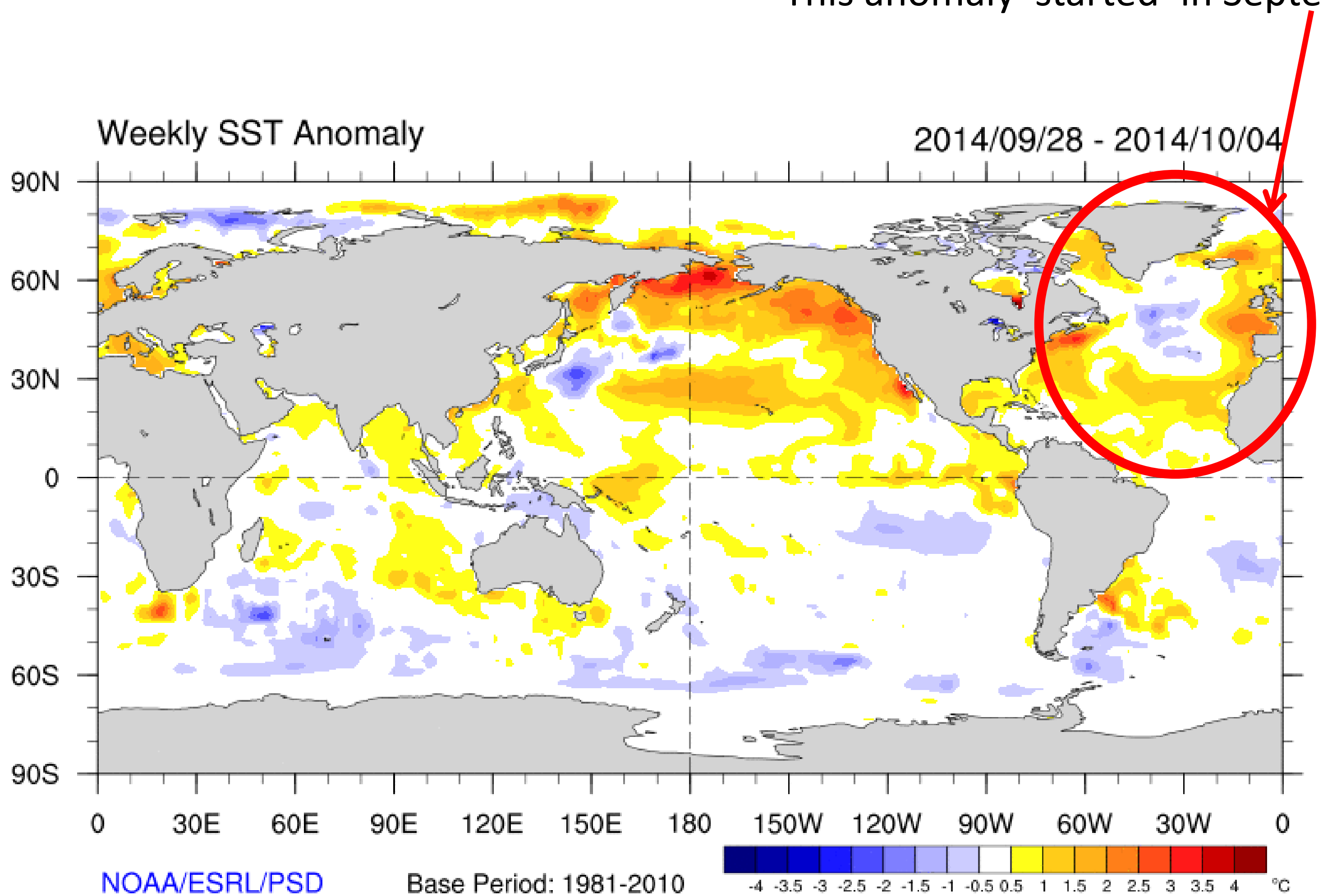

HadSLP2r September 2014
90N
45N
0
45S
90S
180
90W
0
90E
Mean Sea Level Pressure anomaly (hPa) wrt 1961-90
-18
-12
-6
0
6
12
18



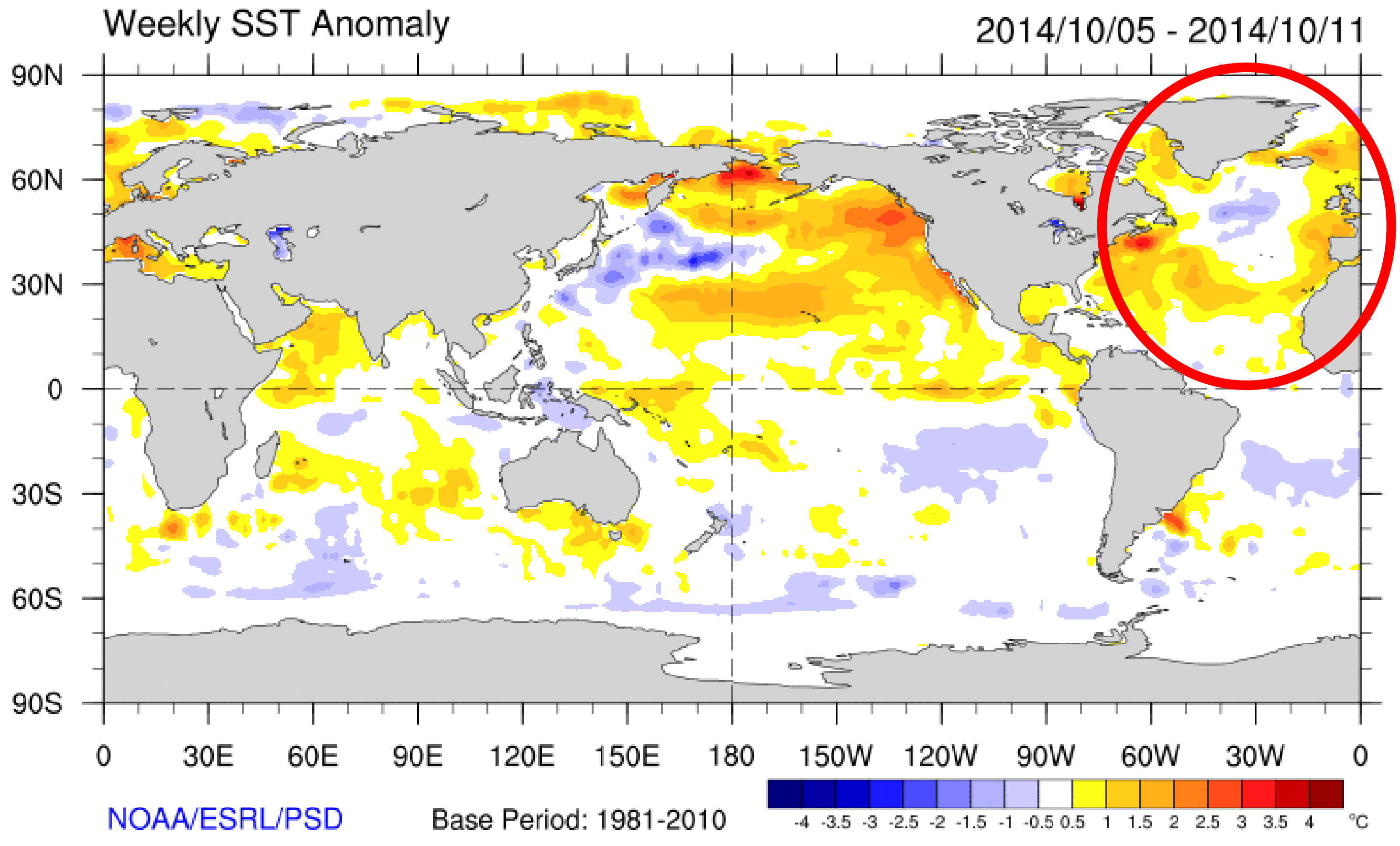
037
038
-10
039
040

Jim Haywood, Andy Jones, Florent Malavelle, Richard Allan

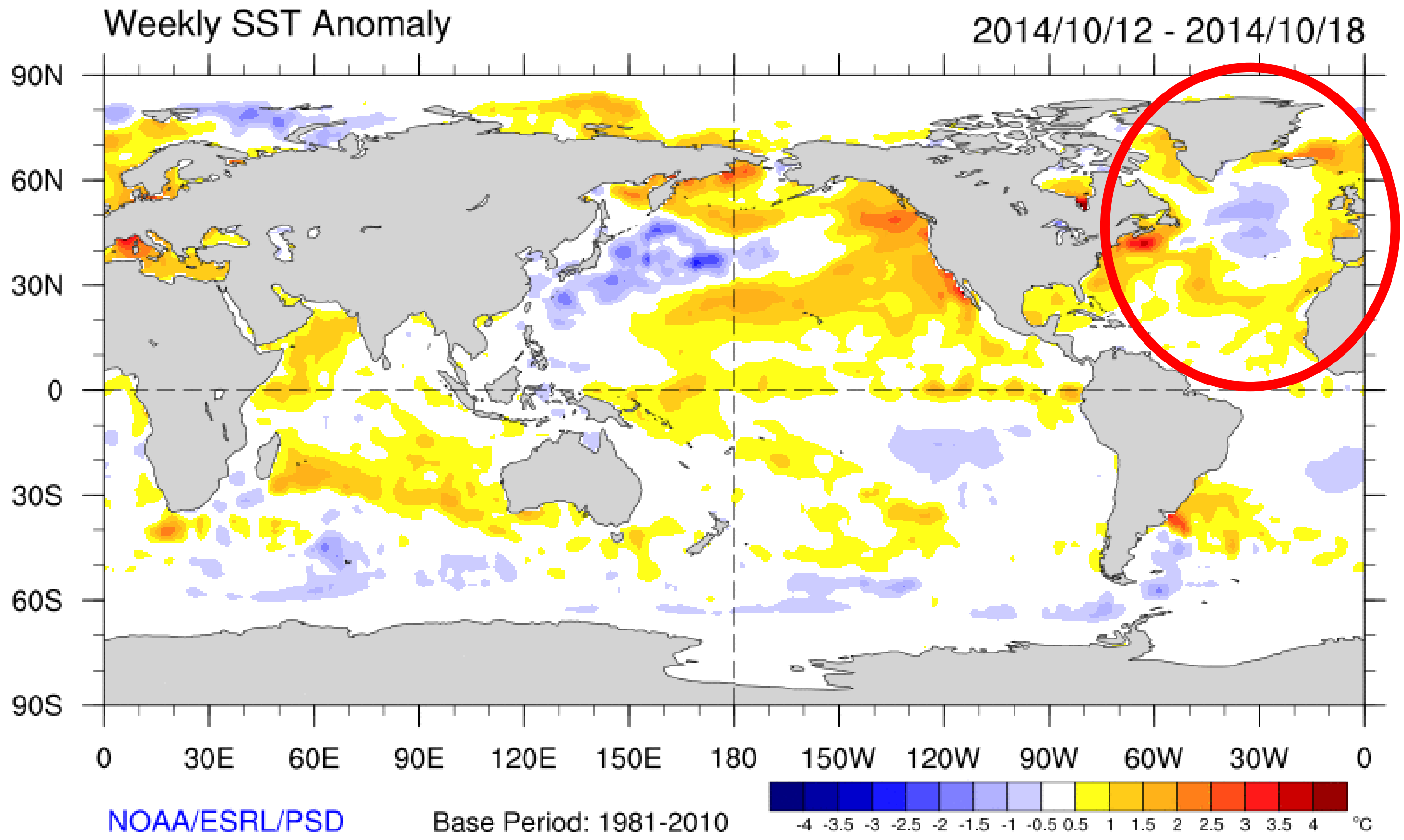
This anomaly 'started' in September

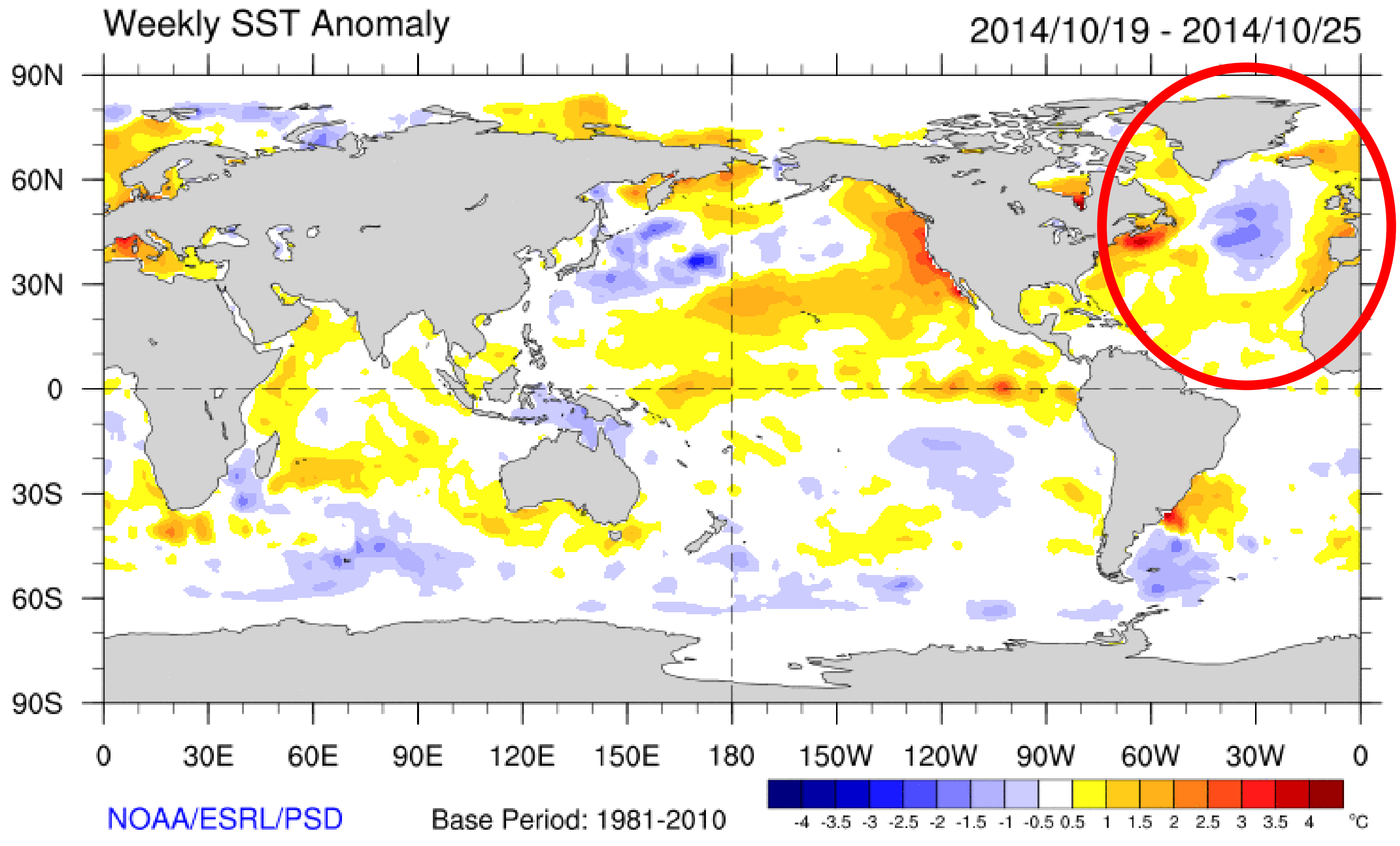


(I can only go back a year on this website....)

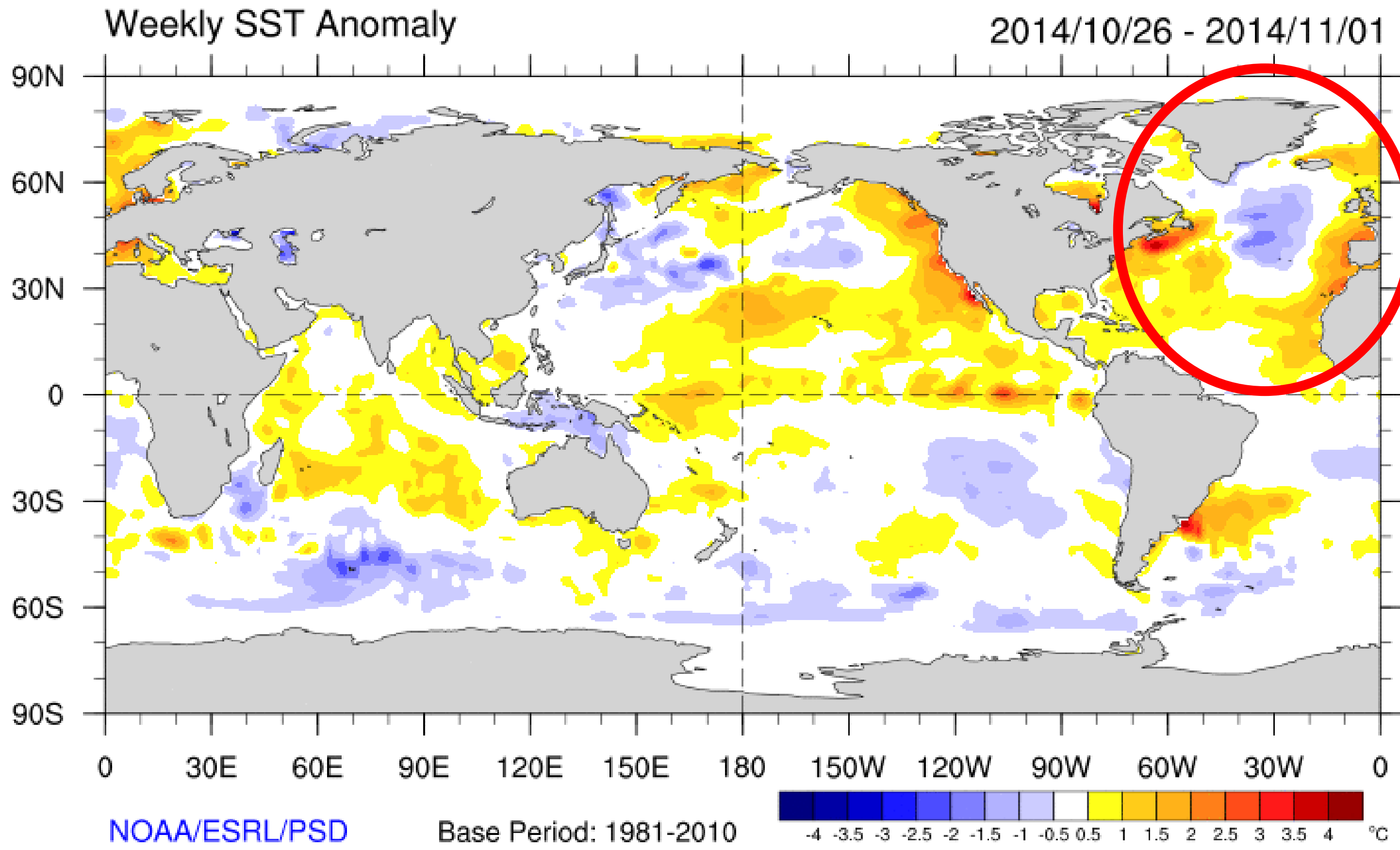


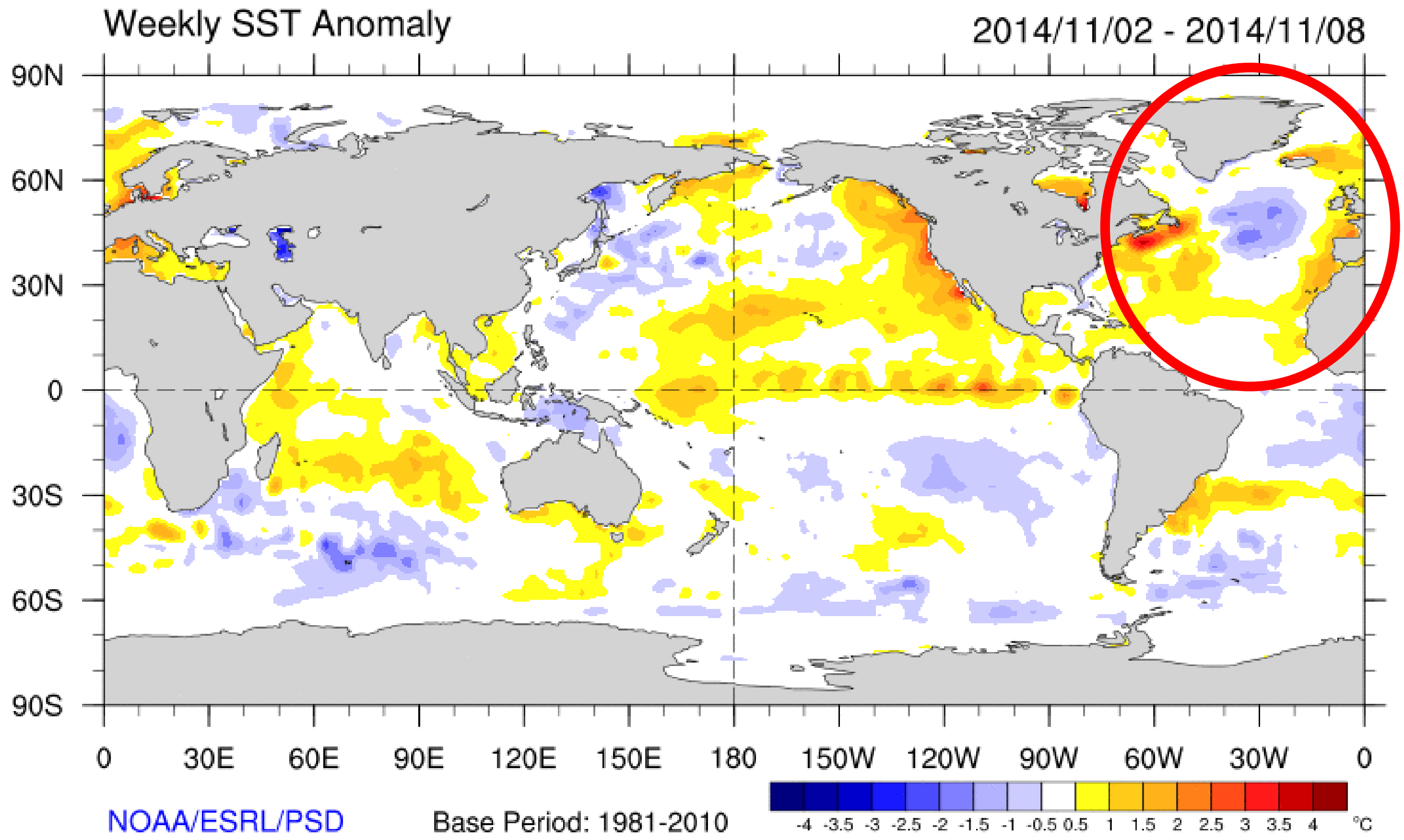
Weekly SST Anomaly
2014/10/05 - 2014/10/11
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
NOAA/ESRL/PSD
Base Period: 1981-2010
-4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5 0.5 1 1.5 2 2.5 3 3.5 4
°C

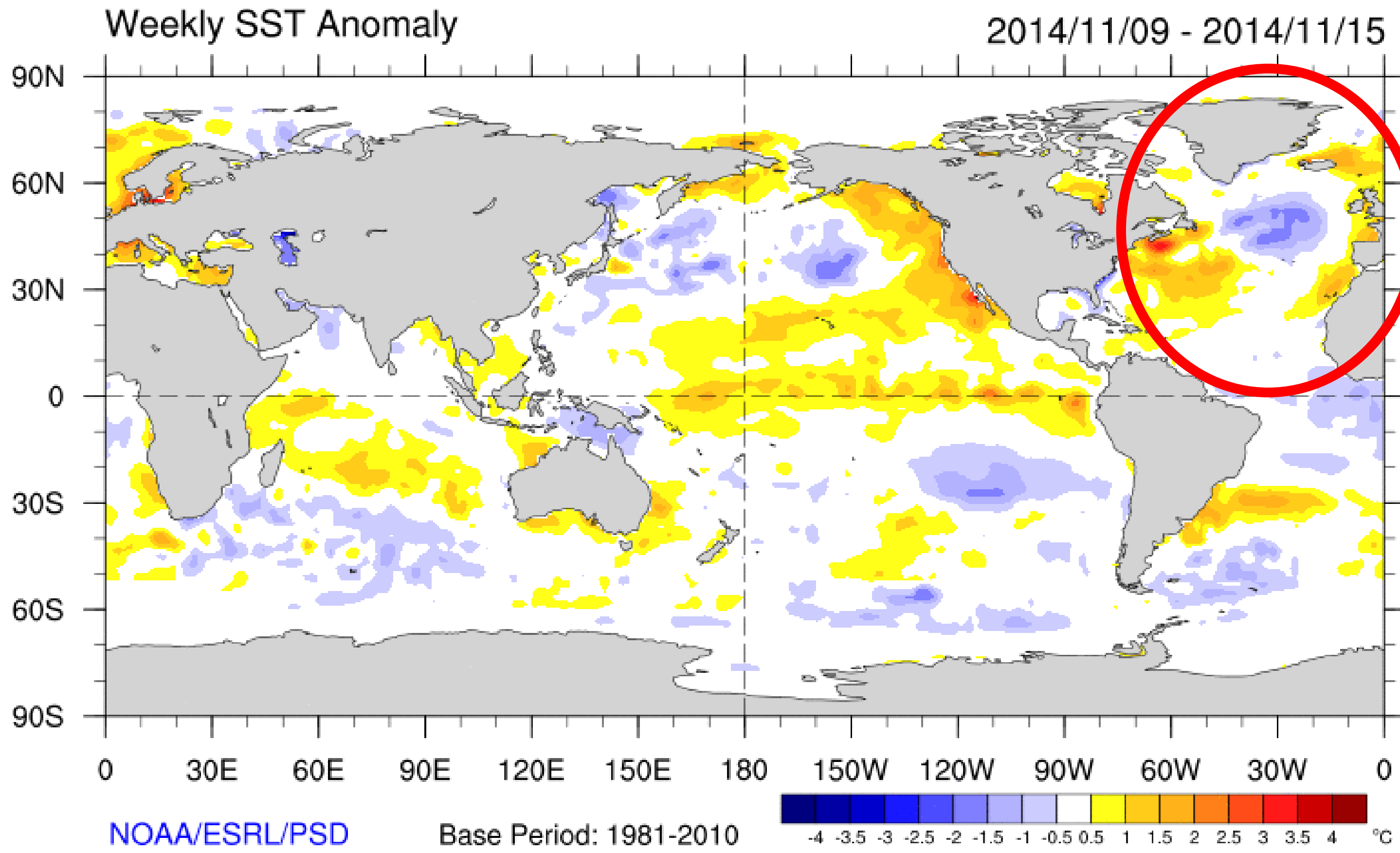

Weekly SST Anomaly
2014/10/12 - 2014/10/18
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
NOAA/ESRL/PSD
Base Period: 1981-2010
-4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5 0.5 1 1.5 2 2.5 3 3.5 4
°C

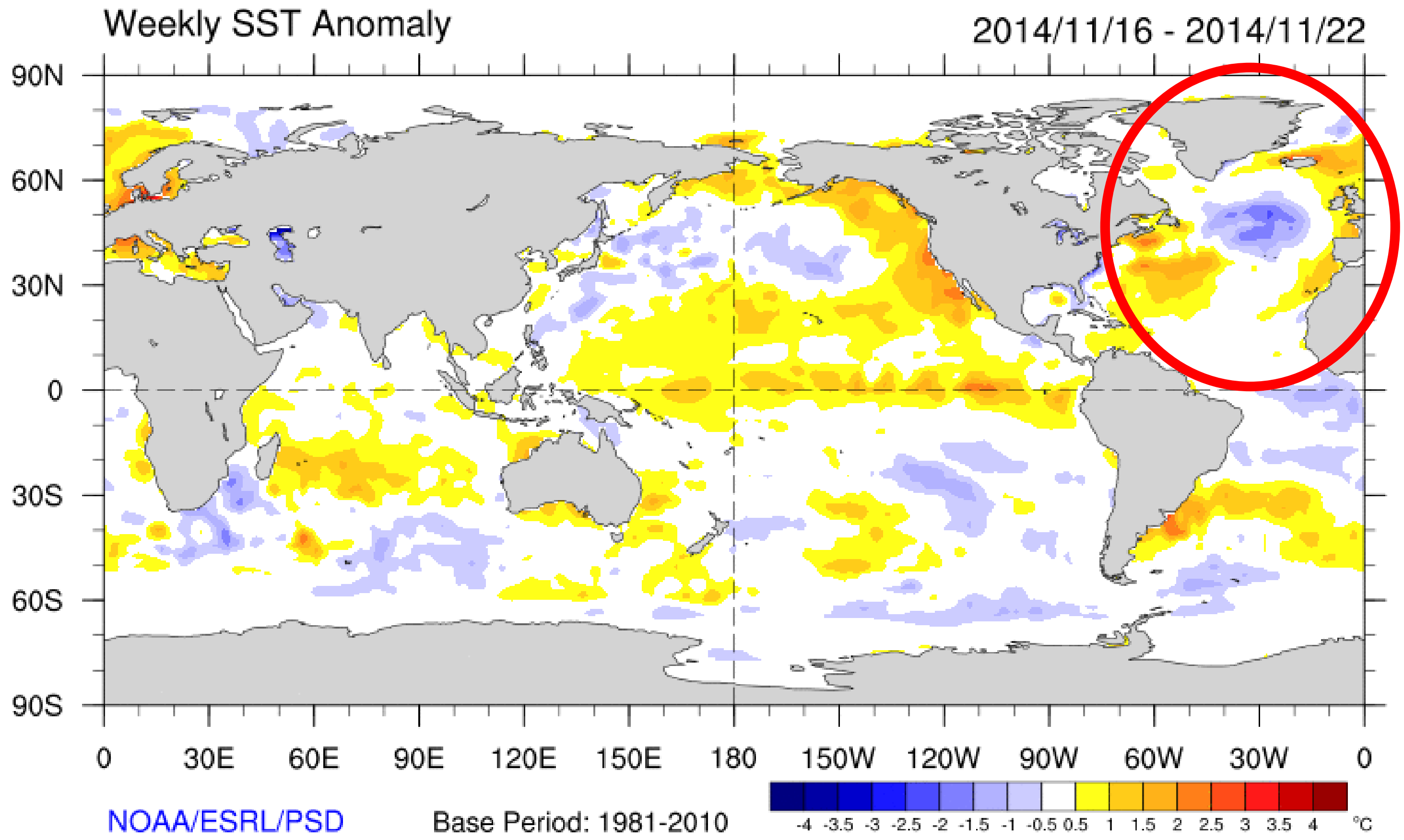


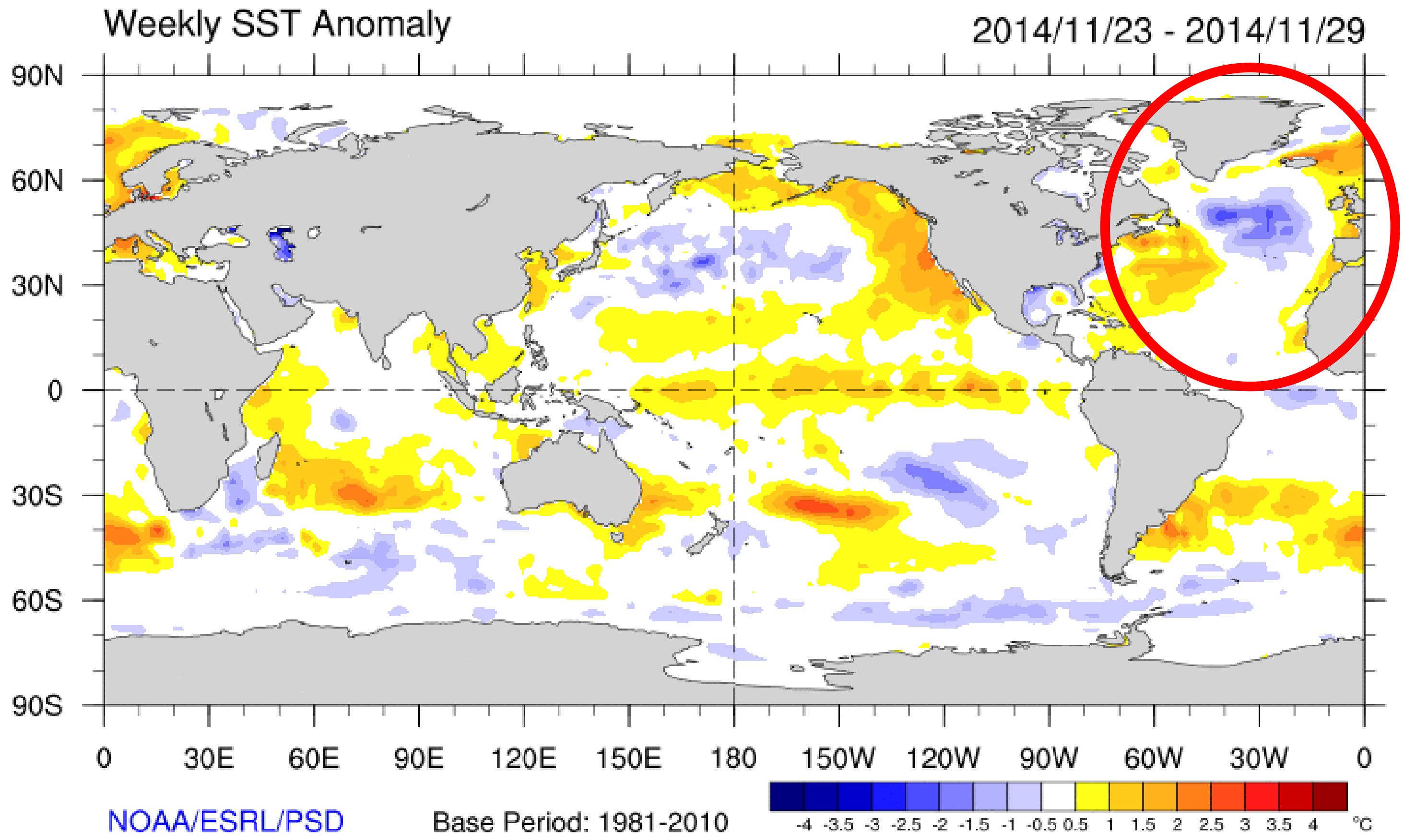
Weekly SST Anomaly
2014/10/19 - 2014/10/25
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
NOAA/ESRL/PSD
Base Period: 1981-2010
-4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5 0.5 1 1.5 2 2.5 3 3.5 4
°C

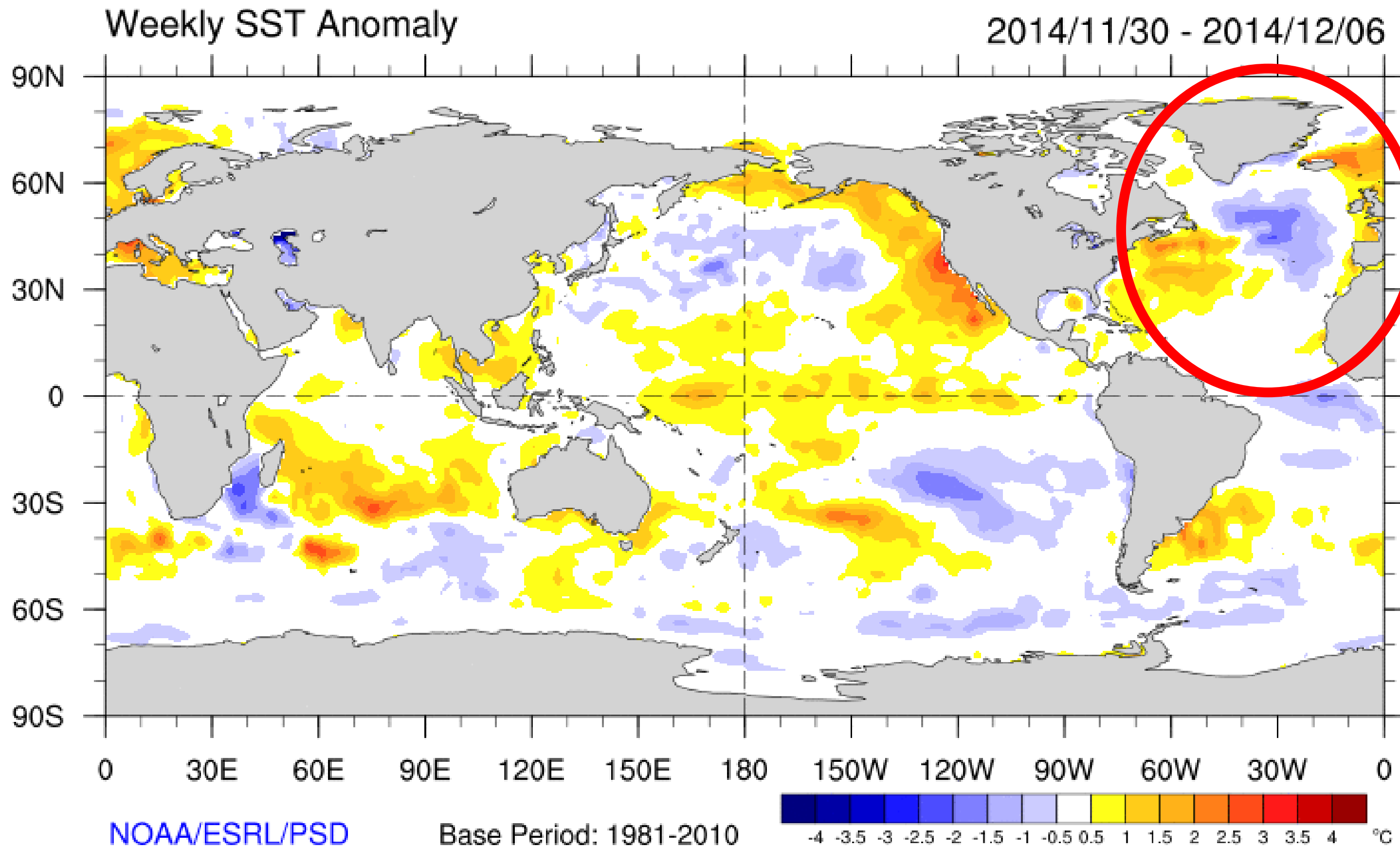

Weekly SST Anomaly
2014/10/26 - 2014/11/01
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
NOAA/ESRL/PSD
Base Period: 1981-2010
-4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5 0.5 1 1.5 2 2.5 3 3.5 4
°C

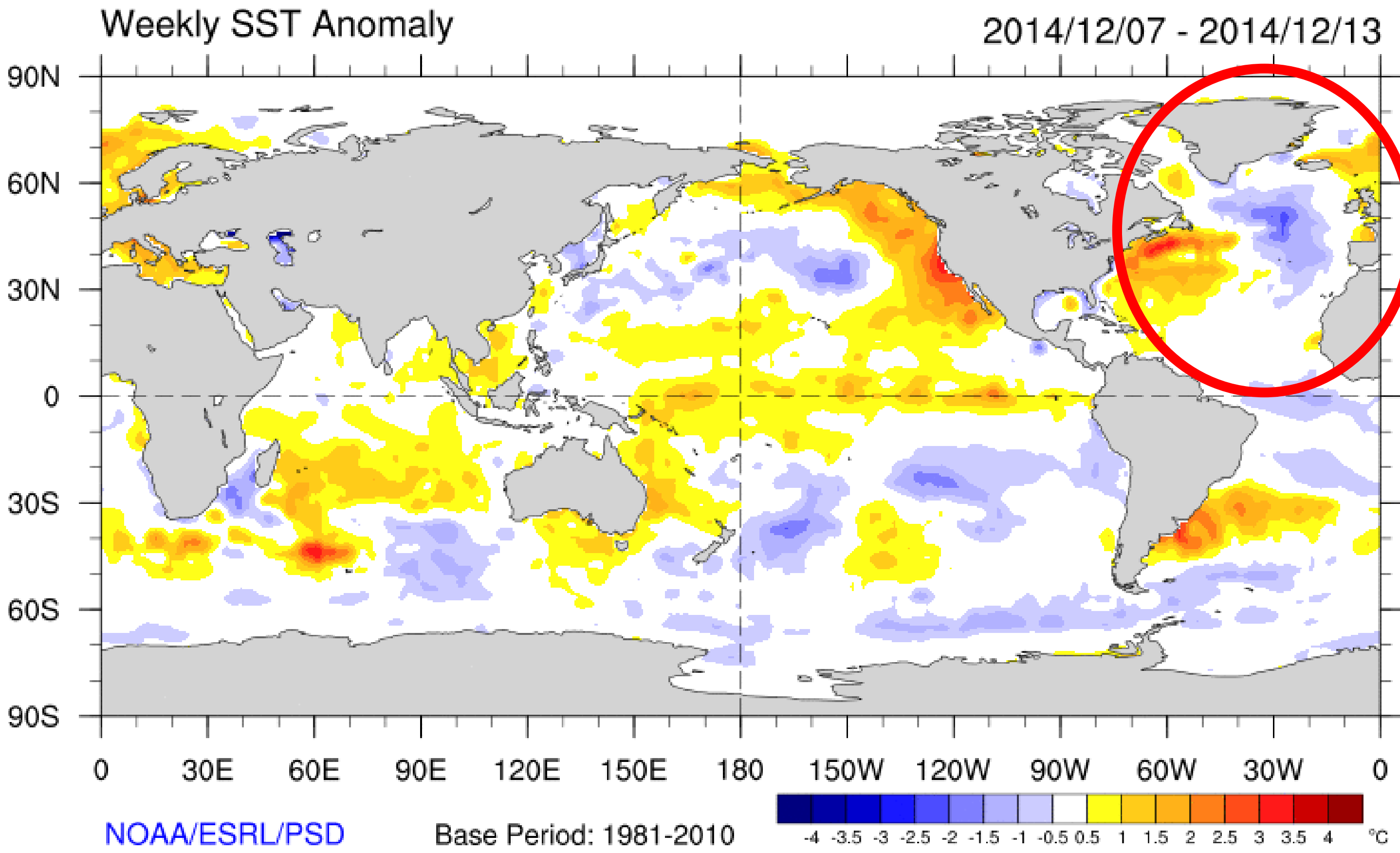

Weekly SST Anomaly
2014/11/02 - 2014/11/08
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
NOAA/ESRL/PSD
Base Period: 1981-2010
-4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5 0.5 1 1.5 2 2.5 3 3.5 4
°C


Weekly SST Anomaly
2014/11/09 - 2014/11/15
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
NOAA/ESRL/PSD
Base Period: 1981-2010
-4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5 0.5 1 1.5 2 2.5 3 3.5 4
°C


Weekly SST Anomaly
2014/11/16 - 2014/11/22
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
NOAA/ESRL/PSD
Base Period: 1981-2010
-4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5 0.5 1 1.5 2 2.5 3 3.5 4
°C

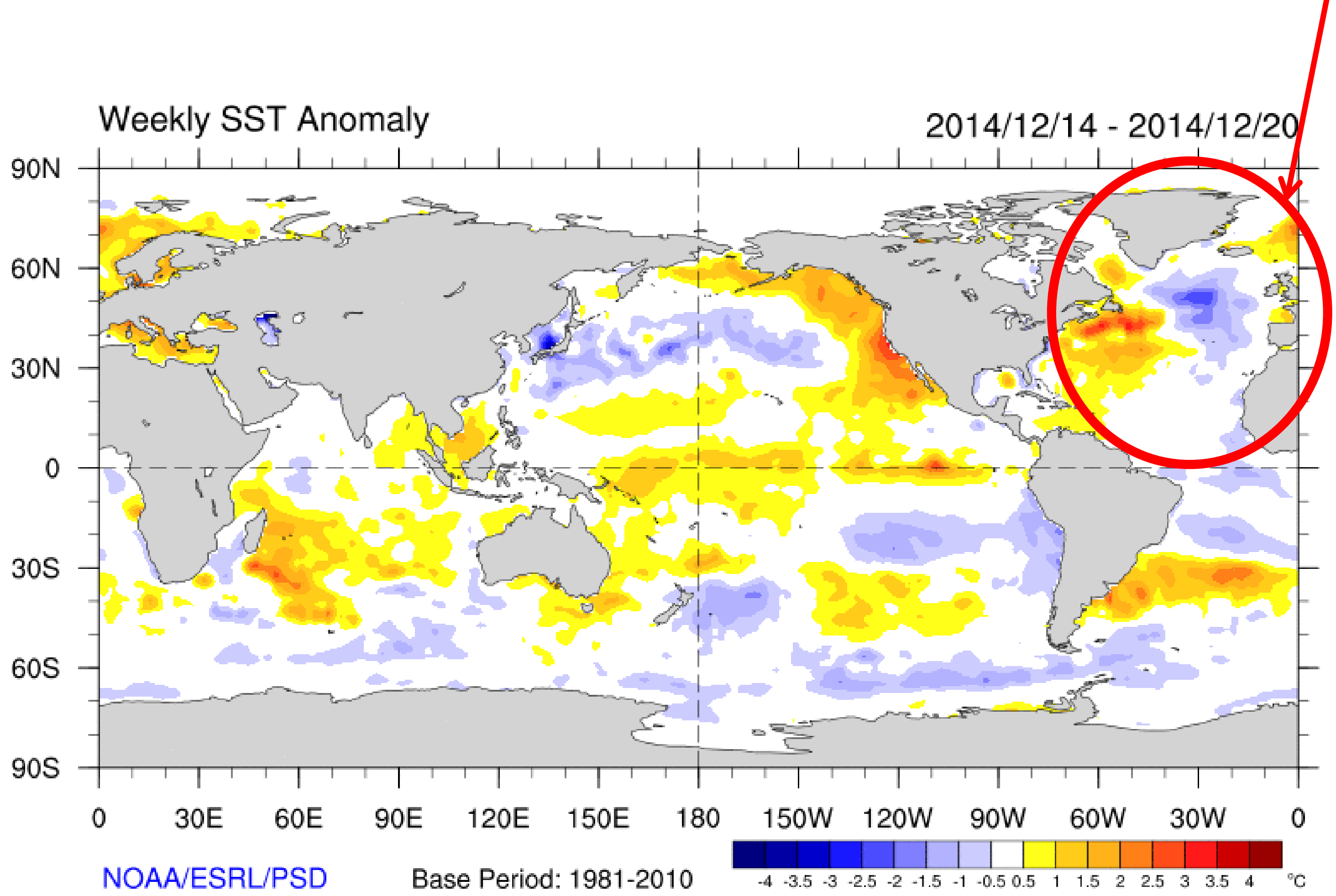

Weekly SST Anomaly
2014/11/23 - 2014/11/29
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
NOAA/ESRL/PSD
Base Period: 1981-2010
-4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5 0.5 1 1.5 2 2.5 3 3.5 4
°C


Weekly SST Anomaly
2014/11/30 - 2014/12/06
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
NOAA/ESRL/PSD
Base Period: 1981-2010
-4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5 0.5 1 1.5 2 2.5 3 3.5 4
°C



Weekly SST Anomaly
2014/12/07 - 2014/12/13
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
NOAA/ESRL/PSD
Base Period: 1981-2010
-4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5 0.5 1 1.5 2 2.5 3 3.5 4
°C

Anomaly grows and maintains its position



External influence?

- Holuhraun eruption started at end of August 2014 and emitted on average ~40ktSO_2/day (x4 times the emission rate from Europe).
- Eruption was maintained at this average rate through until March 2015
- Total emissions ~ x2 the annual emissions from Europe
- Should be large detectable aerosol effects?
- Should influence the amount of radiation at the sea-surface?
- Should cool the north Atlantic?
- Simulations runs for Sept and Oct 2014 nudged to meteorology.......

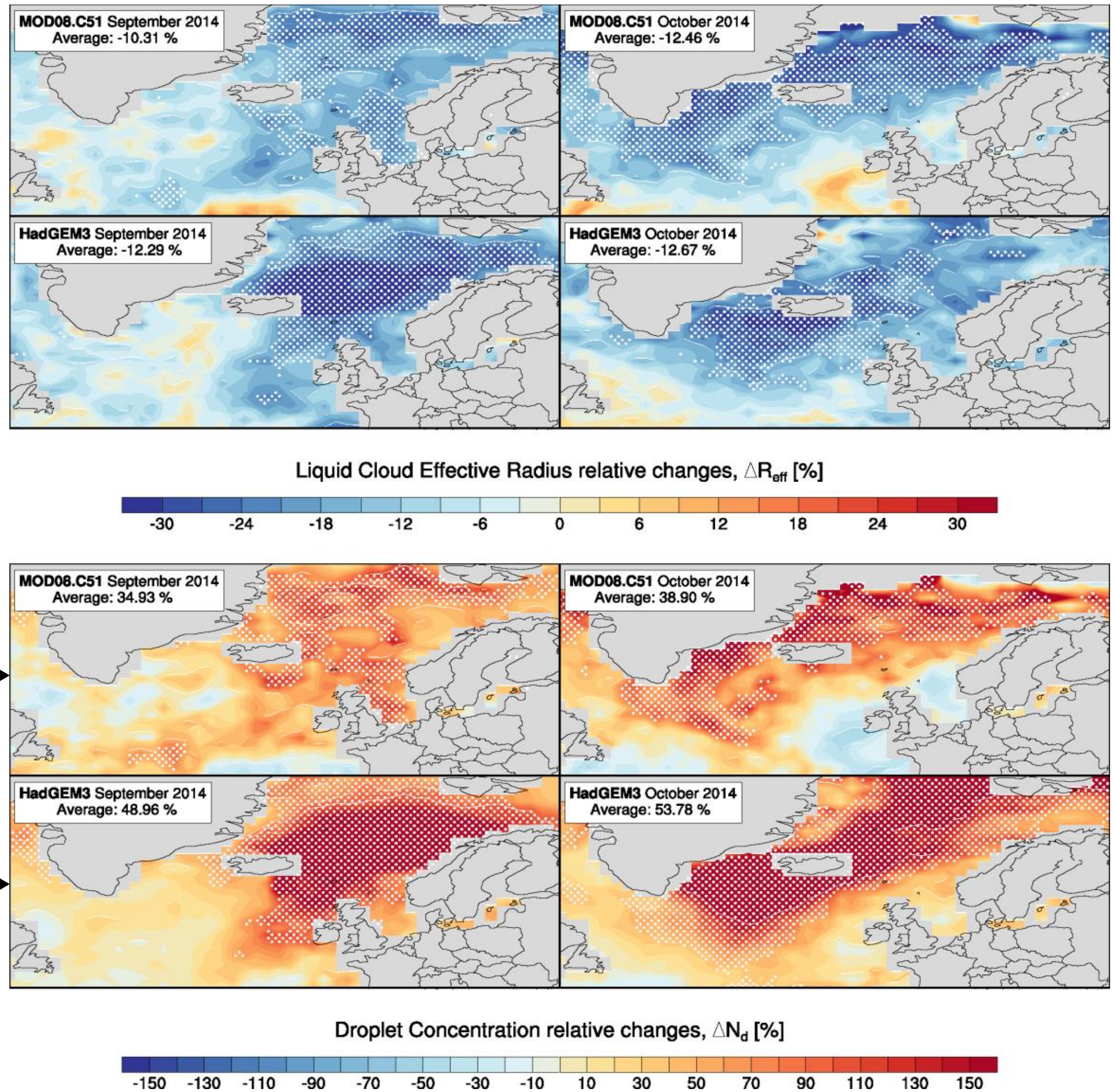
Should be a large detectable indirect effect?

MODIS →

HadGEM3 →

MODIS →

HadGEM3 →



Anomalies calculated as $2014-\overline{2000-2013}$

Stippling: significant at **95%!**

Wow! Model is in excellent agreement with obs.......

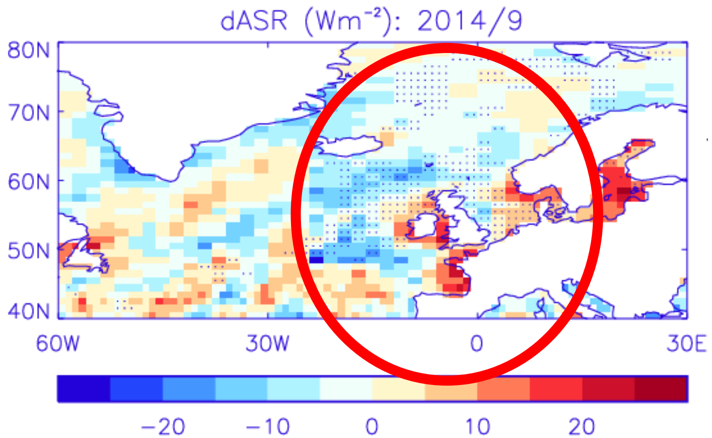
We can model aerosol indirect effect to within far better than the factor of 2 from recent IPCC reports

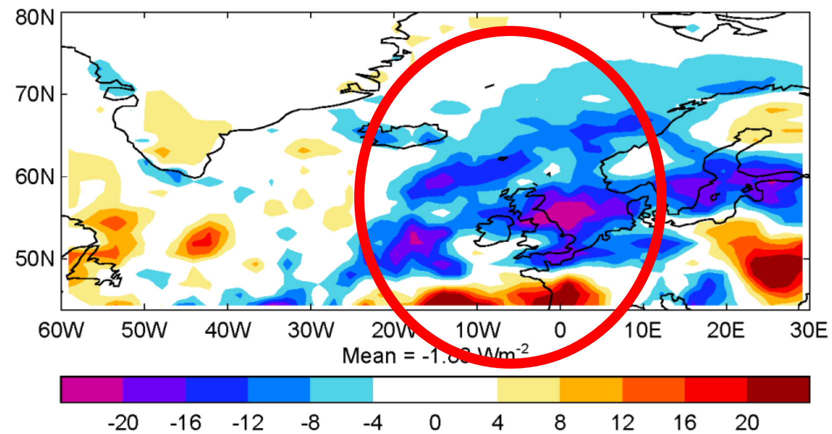
Should influence the amount of radiation at the sea-surface?

Observations from CERES

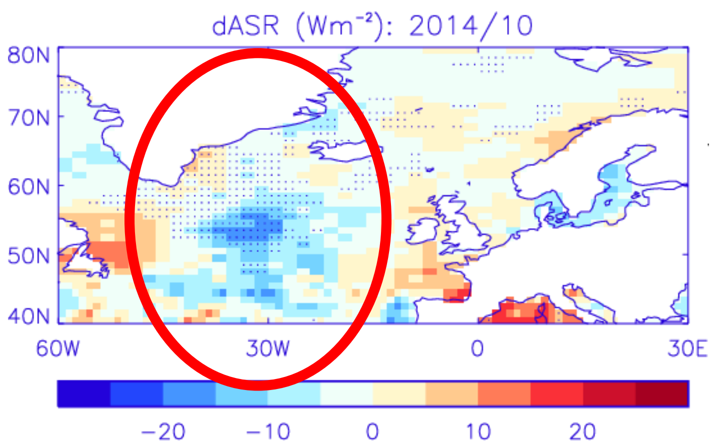
Model has a reasonable attempt

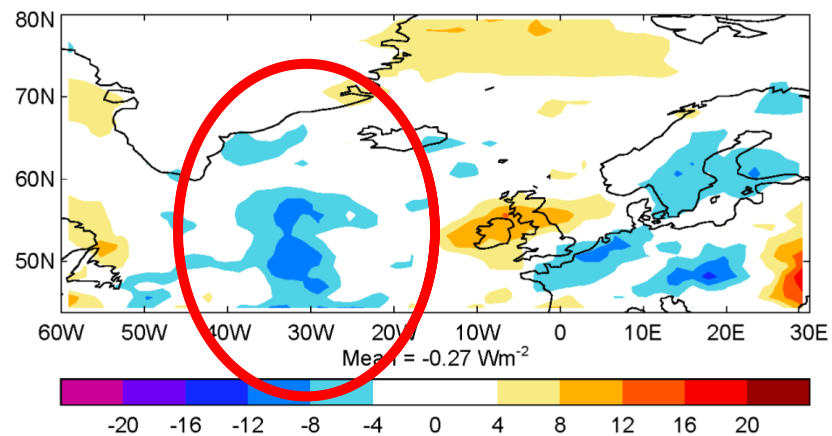
Sept





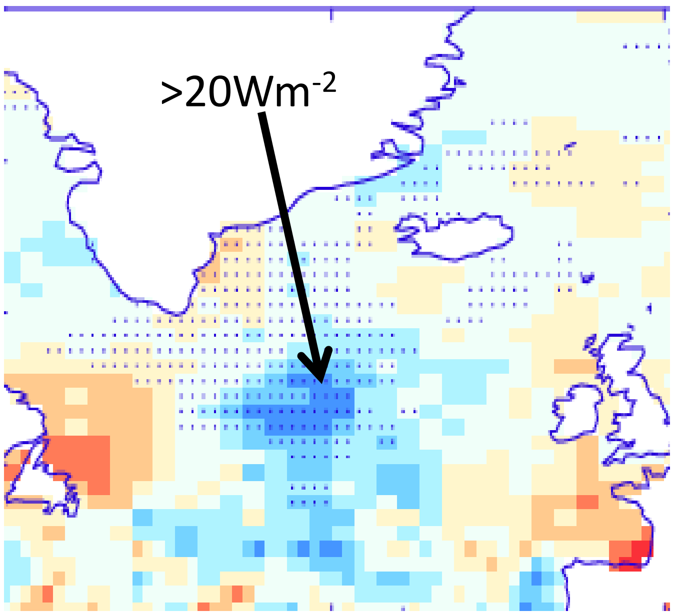
Oct



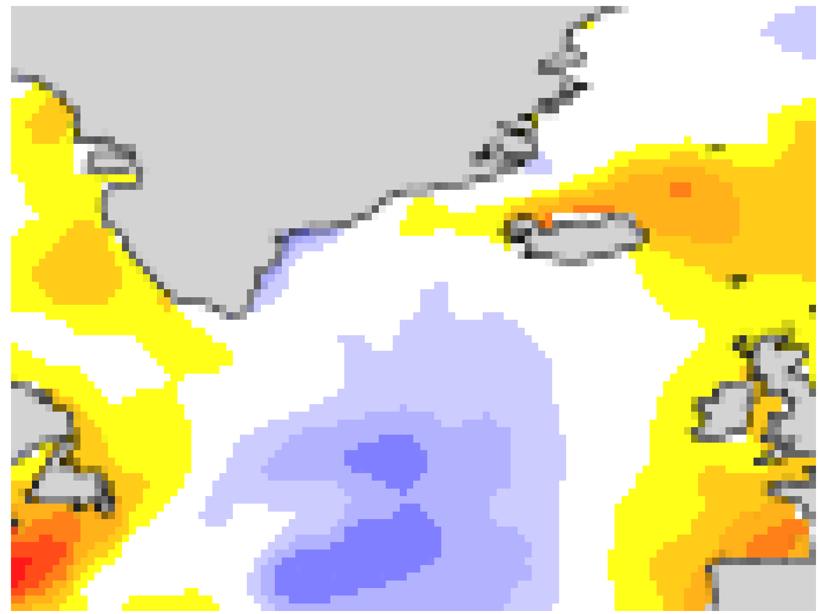


So the CERES and the HadGEM3 simulations show a significant perturbation to SW surface radiation and a similar pattern (assuming that the ToA and surface perturbations are the same – reasonable for scattering processes).

Co-incidence?



Oct surface SW anomaly....



Mid-Oct SST anomaly....

...... Probably a coincidence, but worth investigating?

Many caveats

- Will 20Wm^{-2} sustained surface forcing trigger a cooling of N Atlantic?
- Model seems a little less than observations.
- It could be that most of the signal seen in the spatial pattern is due to natural variability in meteorology
- You'd need a free-running model and a lot of simulations........