A clearer view of cloudy skies:

Understanding systematic cloud and radiation errors in the ECMWF global model

6th WGNE Workshop on Systematic Errors in Weather and Climate Models, 31 Oct – Nov 4 2022, ECMWF

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With thanks to ECMWF colleagues

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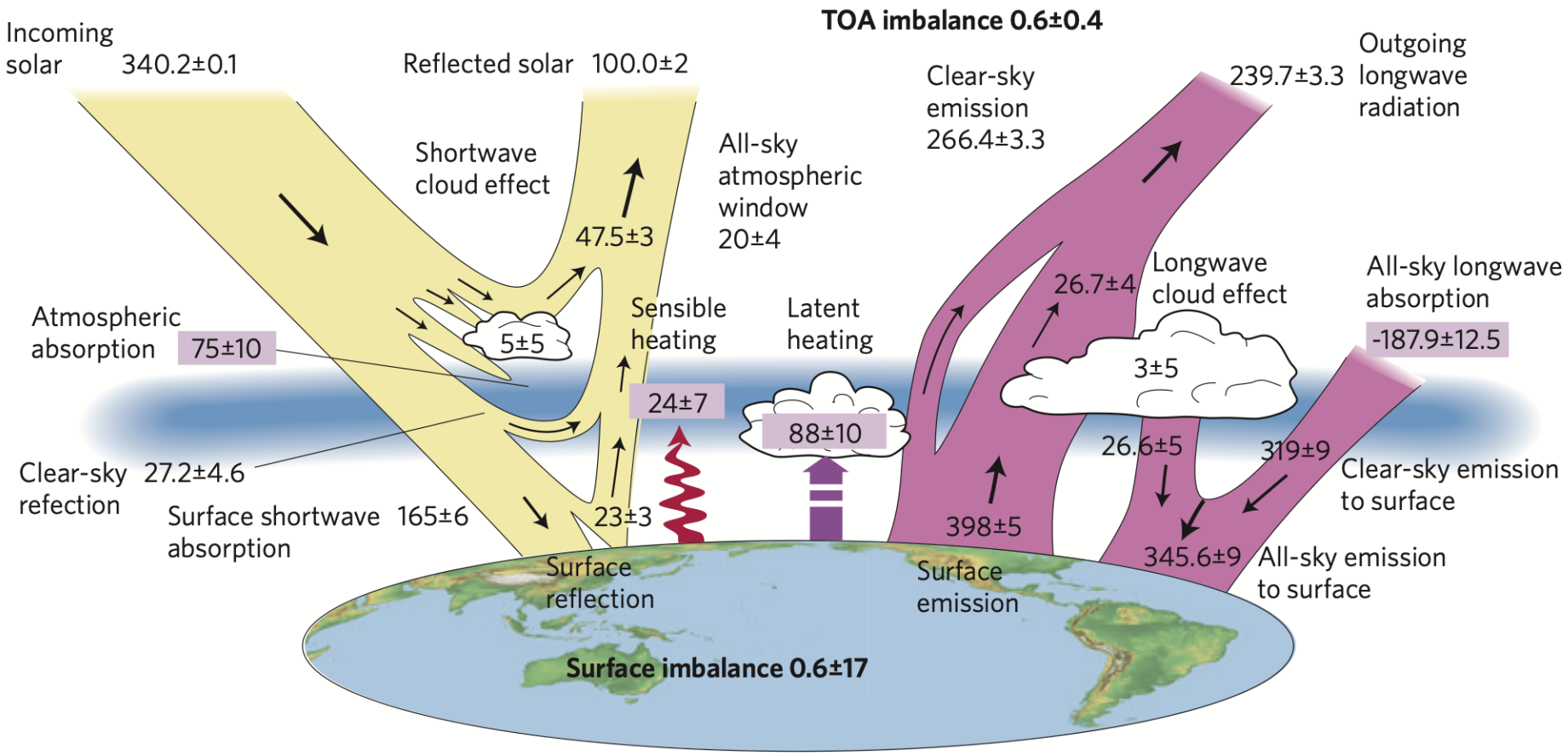
A clearer view of cloudy skies

Understanding systematic cloud and radiation errors in the ECMWF global model

1. Systematic radiation errors in global climate and NWP
2. Diagnosing systematic errors in cloud and radiation
3. Concluding Remarks

1. Systematic radiation errors in global climate and NWP

The Earth's Energy Balance



The global annual mean energy budget of Earth for the approximate period 2000–2010. All fluxes are in Wm^{-2}.

Stephens et al. (2012)

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Forster et al. (2021) IPCC 6th Assessment Report

± few Wm^{-2}

"Earth System Models typically show good agreement with global mean TOA fluxes from CERES-EBAF [but] show significant discrepancies on regional scales, often related to their representation of clouds"

± 10's of Wm^{-2}

(Trenberth and Fasullo, 2010; Donohoe and Battisti, 2012; Hwang and Frierson, 2013; J.-L.F. Li et al., 2013; Dolinar et al., 2015; Wild et al., 2015)

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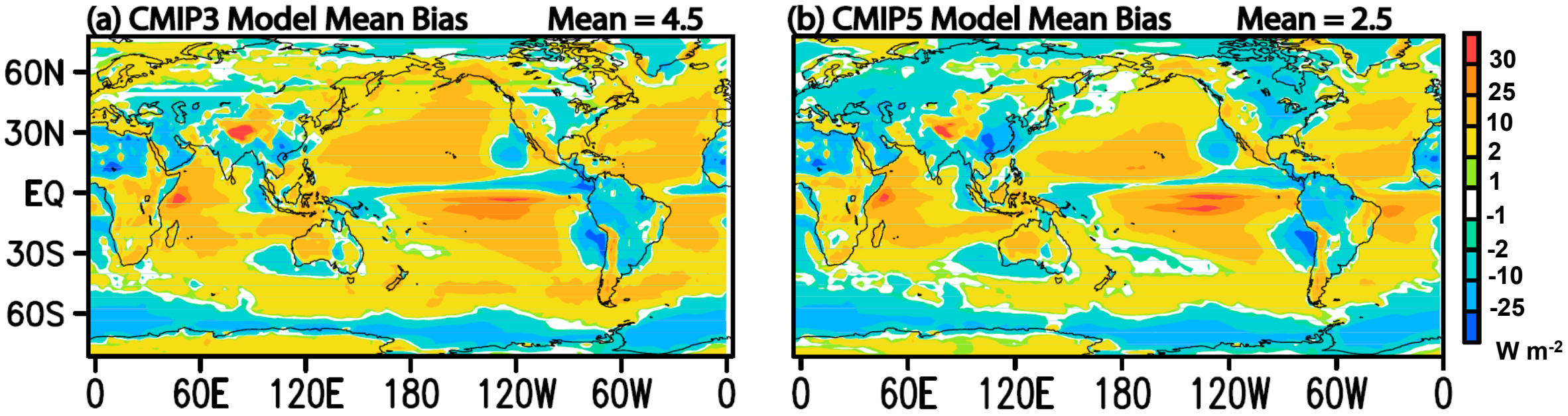
Global climate models – annual mean TOA net SW bias vs CERES

Multi-year annual mean top-of-atmosphere SW error versus CERES



Li et al. 2013

(orange = too reflective)
(blue = not reflective enough)

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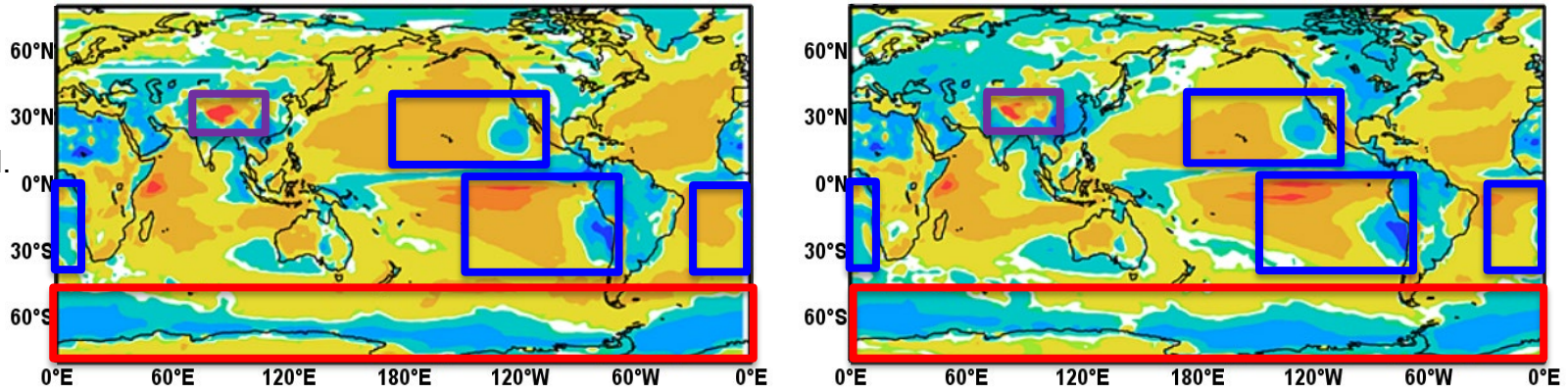
Comparing systematic radiation errors across models, resolutions and lead-times

Annual mean top-of-atmosphere SW radiation difference from CERES-EBAF

Climate - **CMIP3**

Climate - **CMIP5**

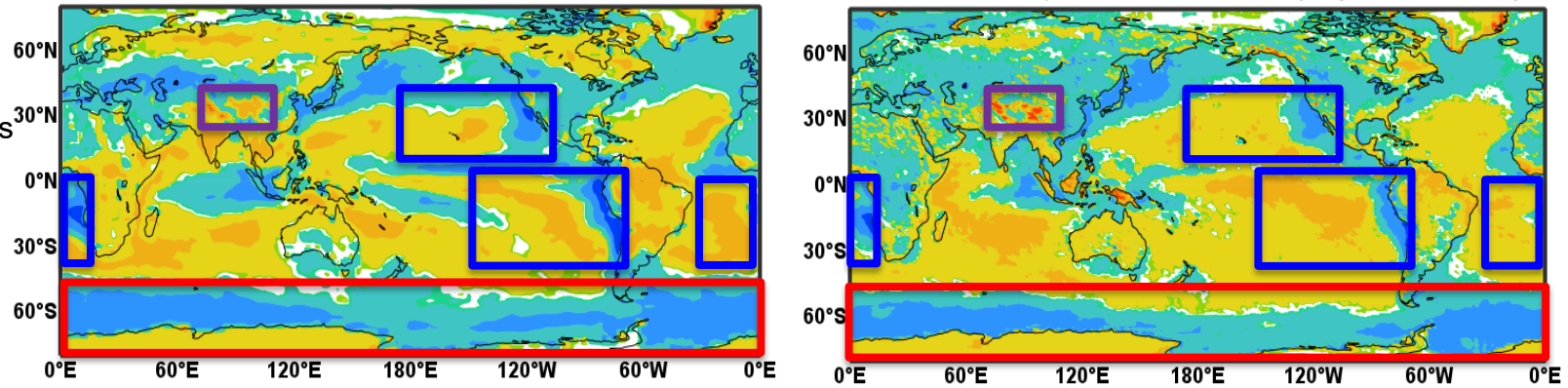
Li et al. 2013



ECMWF "climate" (low resolution, 80km)

ECMWF day-1 operational (highres, 9km)

Forbes et al. 2016



Albedo too low

Albedo too high

- Models tuned to give top-of-atmosphere radiative balance
- But significant geographical biases in both SW and LW
- Comparing models:
  climate and NWP,
  low and higher resolution,
  short- and long-ranges
- …many differences, which is telling us something…
- …and some similarities, which is also telling us something…
- Can use short-range forecasts (close to obs) to diagnose the sources of some of the biases

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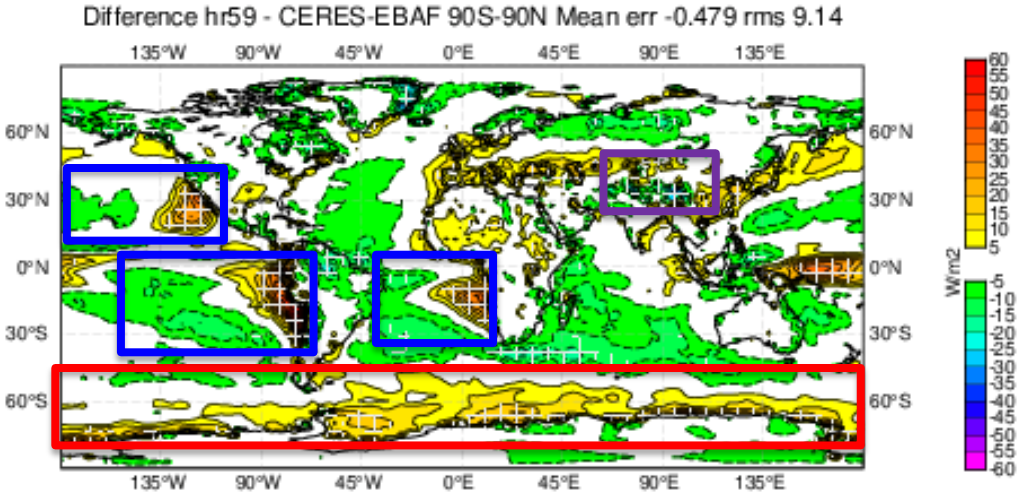
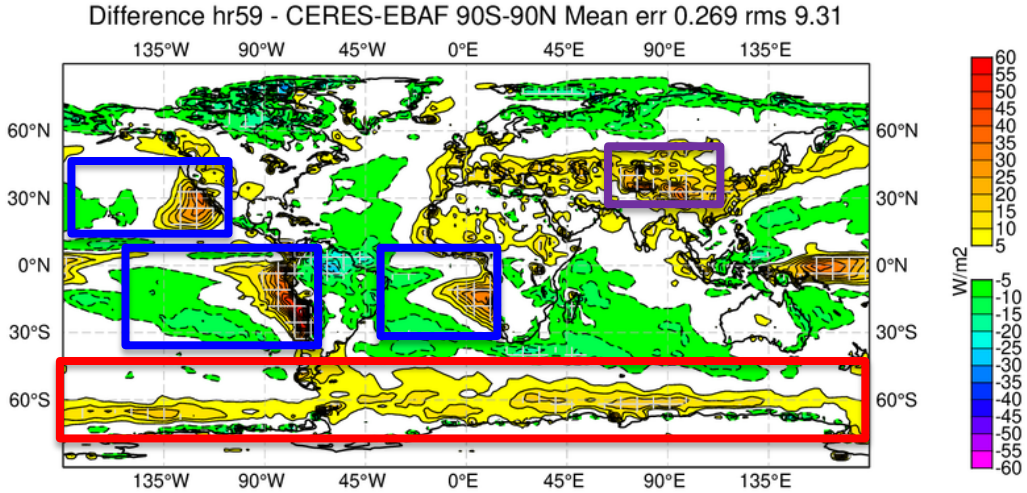
Most of the TOA SW bias is due to cloud errors

Multi-year annual mean top-of-atmosphere SW error versus CERES
from IFS 1-year free-running coupled TCo199 47r3 simulations

Net TOA SW bias



Net TOA SW cloud radiative effect (CRE) bias



- Southern-Ocean cloud not reflective enough
- Marine trade cumulus too reflective
- Marine stratocumulus not reflective enough
- Himalayas (albedo due to snow, too little cloud gives opposite bias)

Net = down minus up, so a positive bias means too little SW reflection

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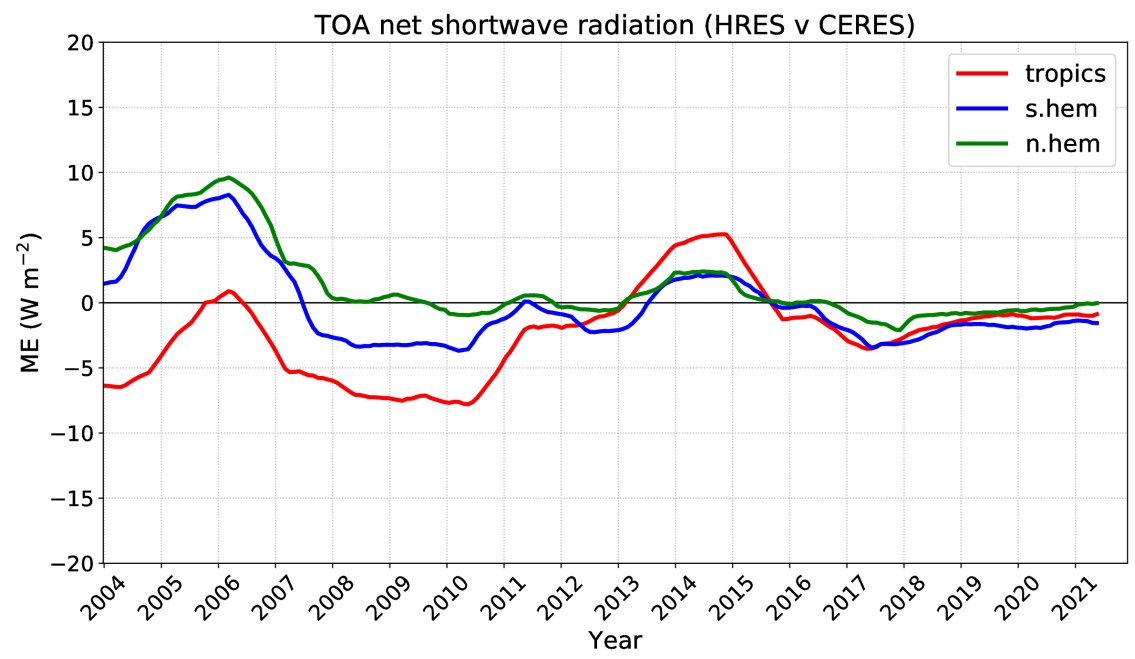
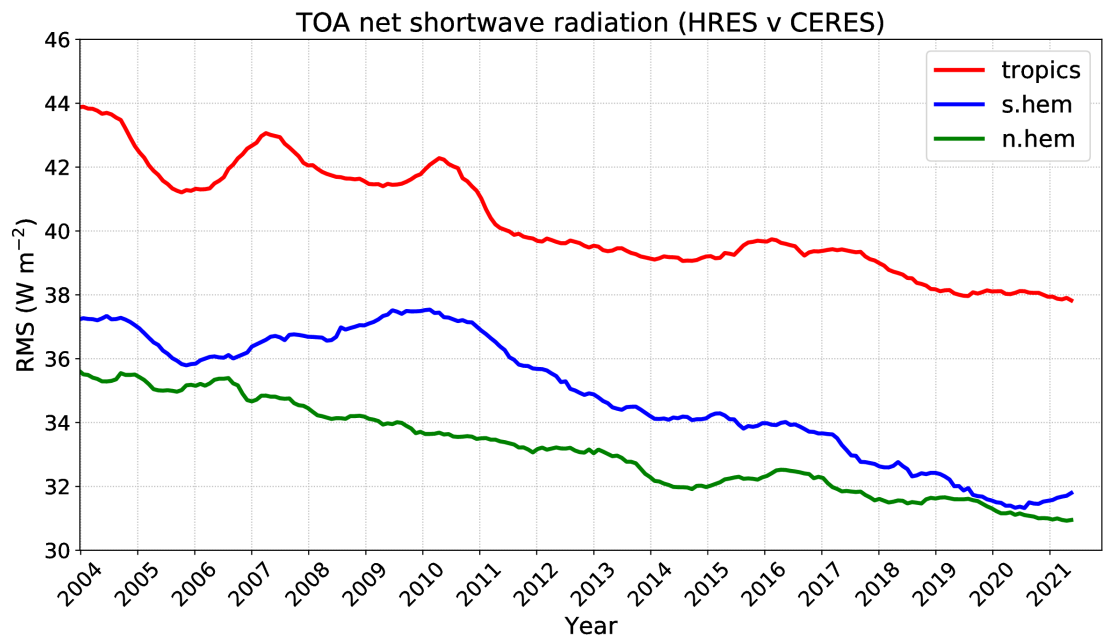
Reduction of TOA SW bias in operational IFS over the last 2 decades

Evolution of IFS operational day-5 TOA SW **bias** 2004-2021



Evolution of IFS operational day-5 TOA SW **RMSE** 2004-2021



Run: 00 UTC
Step: 120 h

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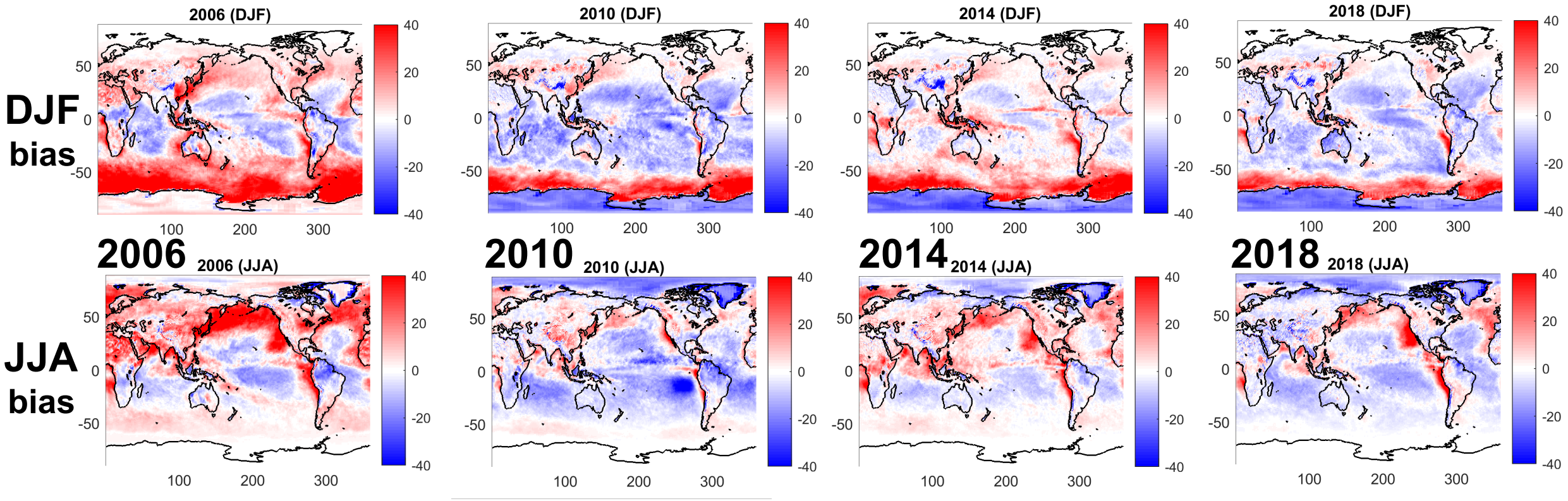
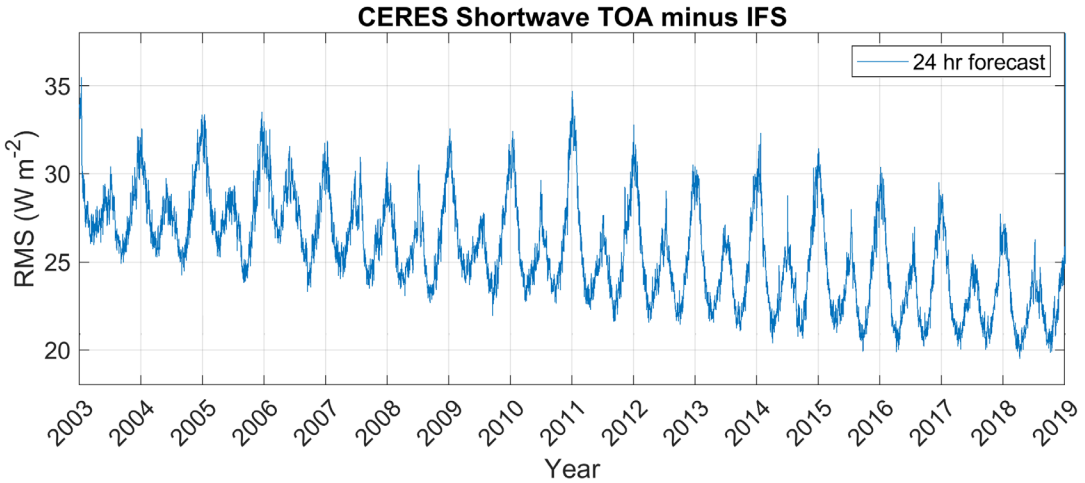
Thomas Haiden

Evaluation of net TOA SW radiation in IFS *operational* 24-h forecasts, 2003-2019



- Reduction in RMS error over time
- Improvement in Southern-Ocean low albedo DJF
- More balanced bias between marine stratocu and cu
- Antarctica too reflective after 2006



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Mark Fielding

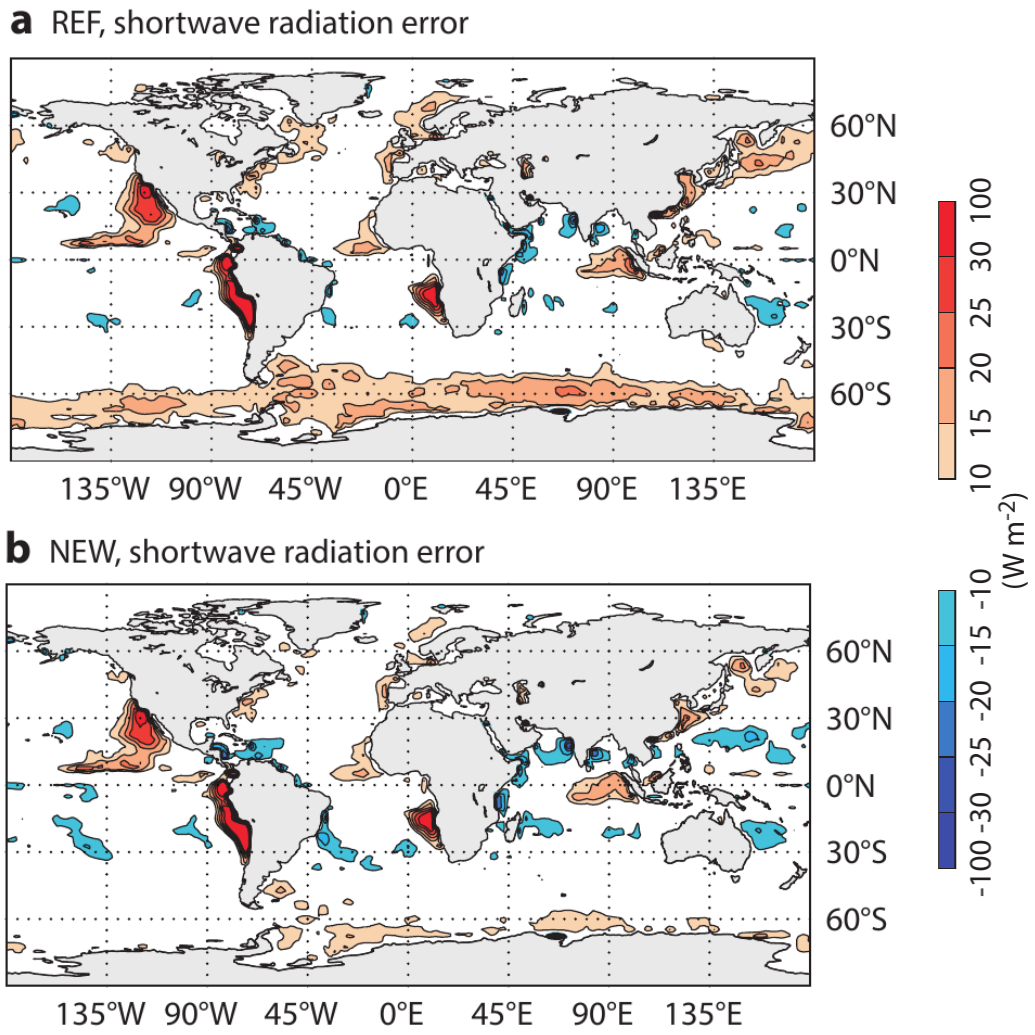
2. Diagnosing and reducing systematic errors in cloud and radiation

IFS Southern Ocean SW bias too low reflectance

- primarily due to lack of supercooled liquid water in convective cold air outbreaks

- Diagnosed from combination of SSMI/S increments in the assimilation (LWP), CERES (SWrad), CALIPSO (supercooled cloud tops)
- Increased supercooled liquid water from parametrized convective cloud detrainment
- Reduced SW error over SHem **and** NHem storm tracks (but change could only be partially implemented so far operationally)
- IFS coupled with ocean - SHem ocean warm SST bias also reduces

Annual mean TOA net SW radiation bias (vs CERES)
IFS 1-year free-running forecast



Forbes et al. 2016
(ECMWF Newsletter)

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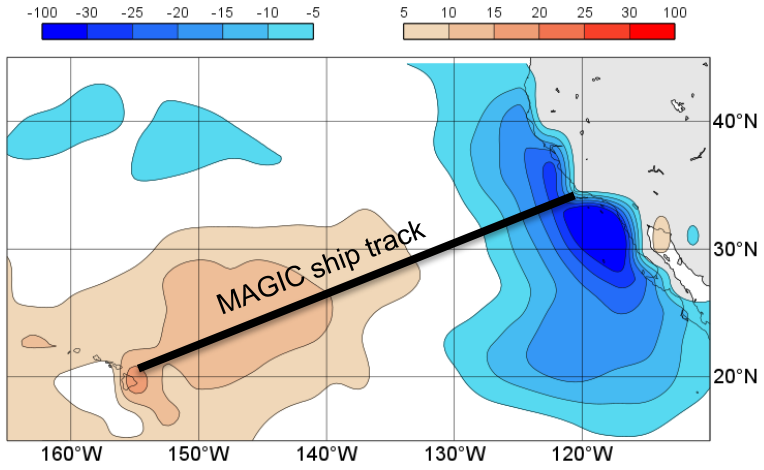
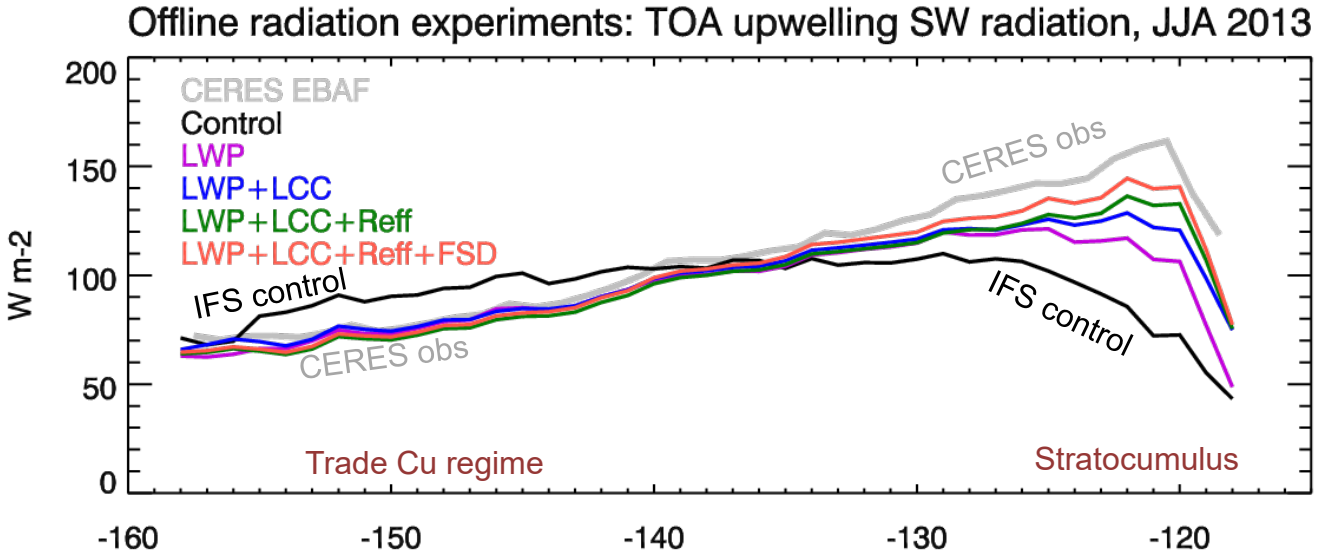
IFS subtropical marine stratocumulus too low reflectance
– multiple reasons related to cloud LWP and cover, R_{eff}, heterogeneity

TOA net SW bias (IFS – CERES) off the California coast with MAGIC obs ship track overlayed , JJA 2013



Quantifying the impact on SW radiation of changing aspects of the cloud to agree with obs



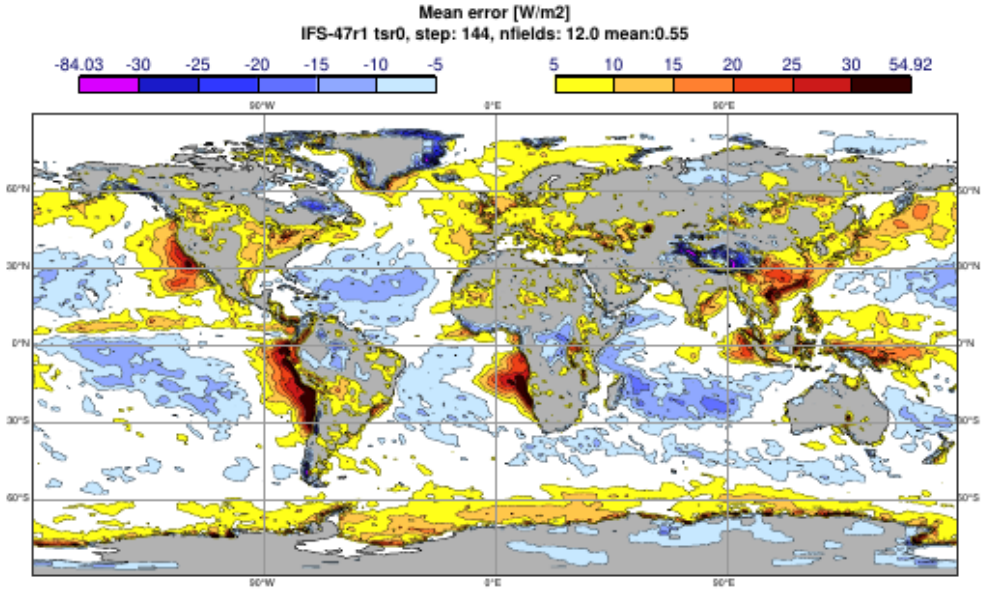
- In the trade cumulus regime, reducing the LWP corrects the SW bias
- In the stratocumulus regime, deficiencies identified in LWP, cloud cover (LCC), effective radius (Reff) and cloud heterogeneity (FSD)
- Still requires work on multiple aspects to solve the SW bias in marine stratocu!

Ahlgrimm et al. (2018, JAMES)

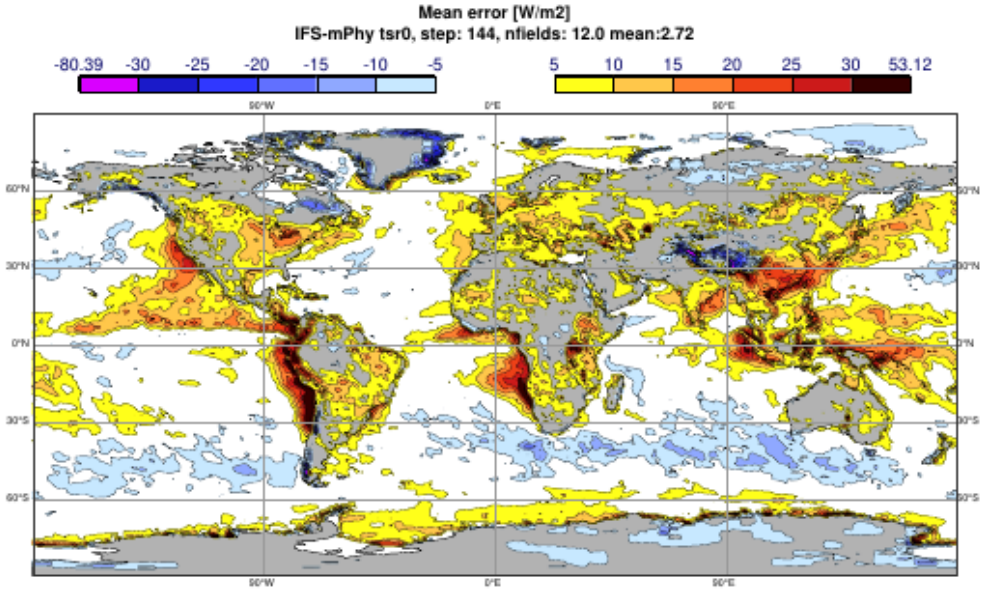
IFS trade cumulus too high reflectance – revised moist physics package in 47r3

- Major revision of moist physics in IFS 47r3 (oper Oct 2021) (Bechtold et al. 2021, Forbes et al. 2021, EC NL)
- Small improvement in cloud cover/LWP/SWrad in **marine stratocumulus regions**
- Significant improvement in SWrad in **marine trade cumulus regions**, but global bias then slightly worse
- Is the improvement for the right reasons?

Annual mean top-of-atmosphere shortwave radiation Day 5 forecast - CERES-EBAF



(a) IFS 47r1



(b) IFS 47r3 (revised moist physics)

From the DIMOSIC project (Magnusson et al. 2022)

Linus Magnusson

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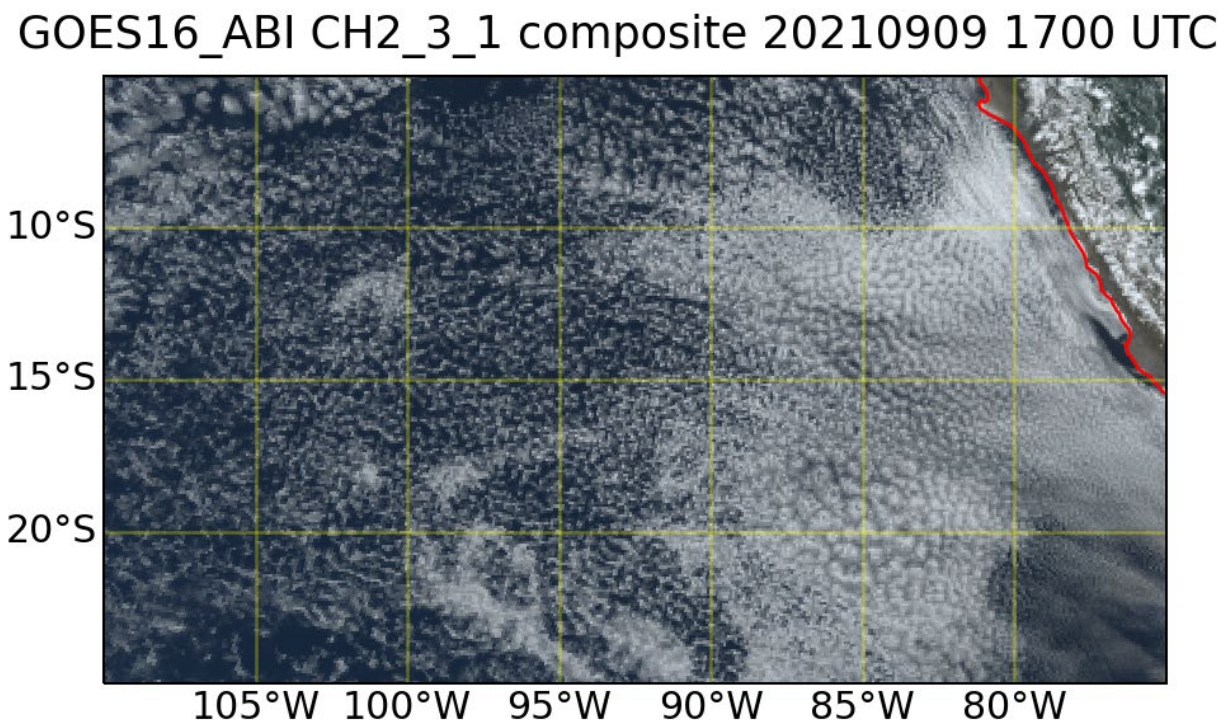
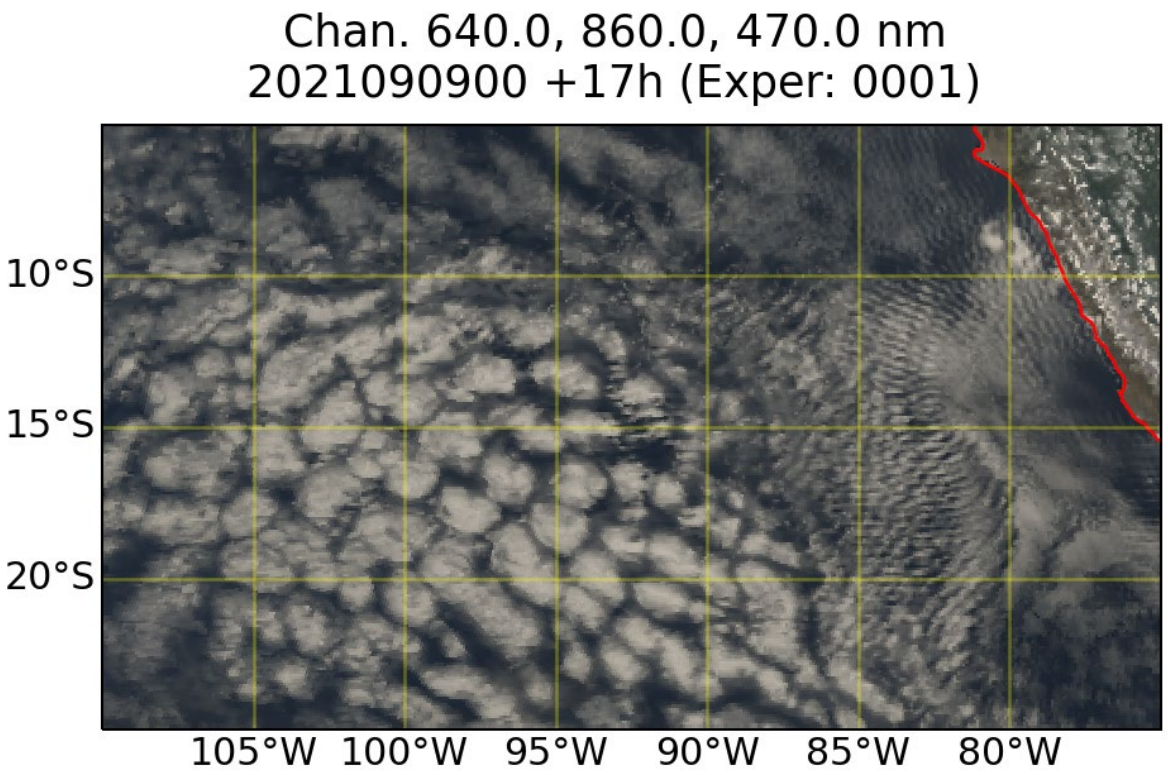
IRM versus GOES-16 ABI: South Tropical Pacific trade-wind clouds (CY47R1)

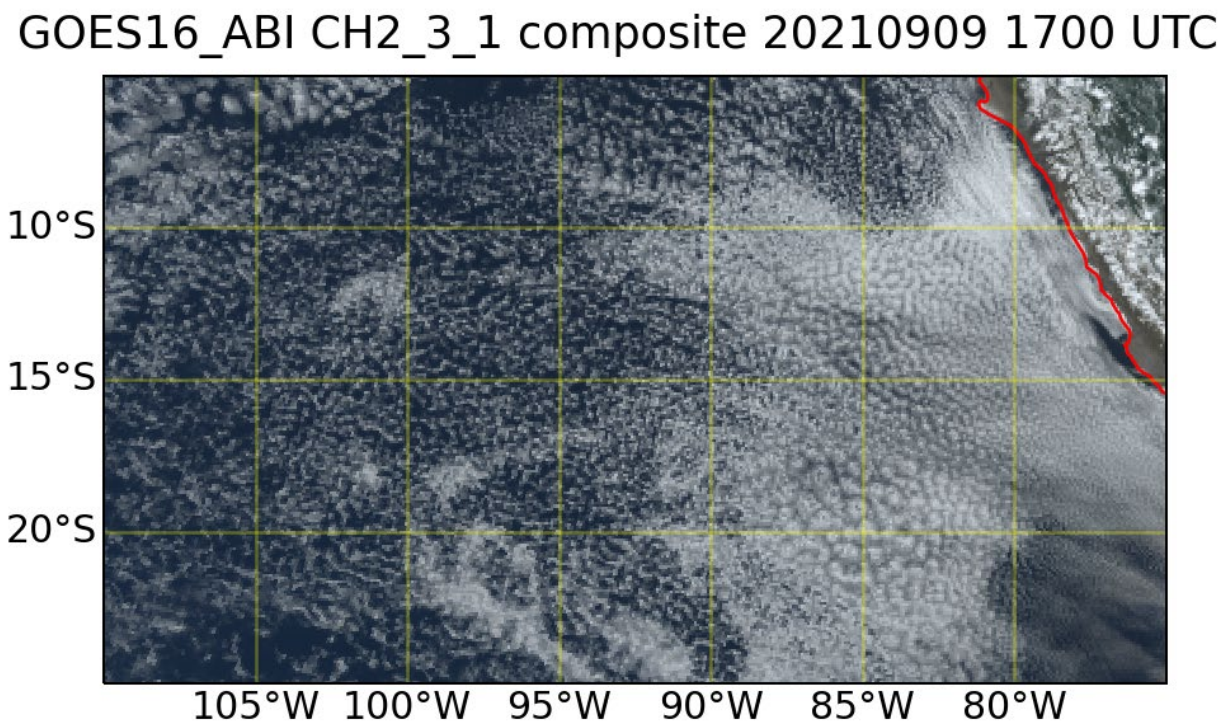


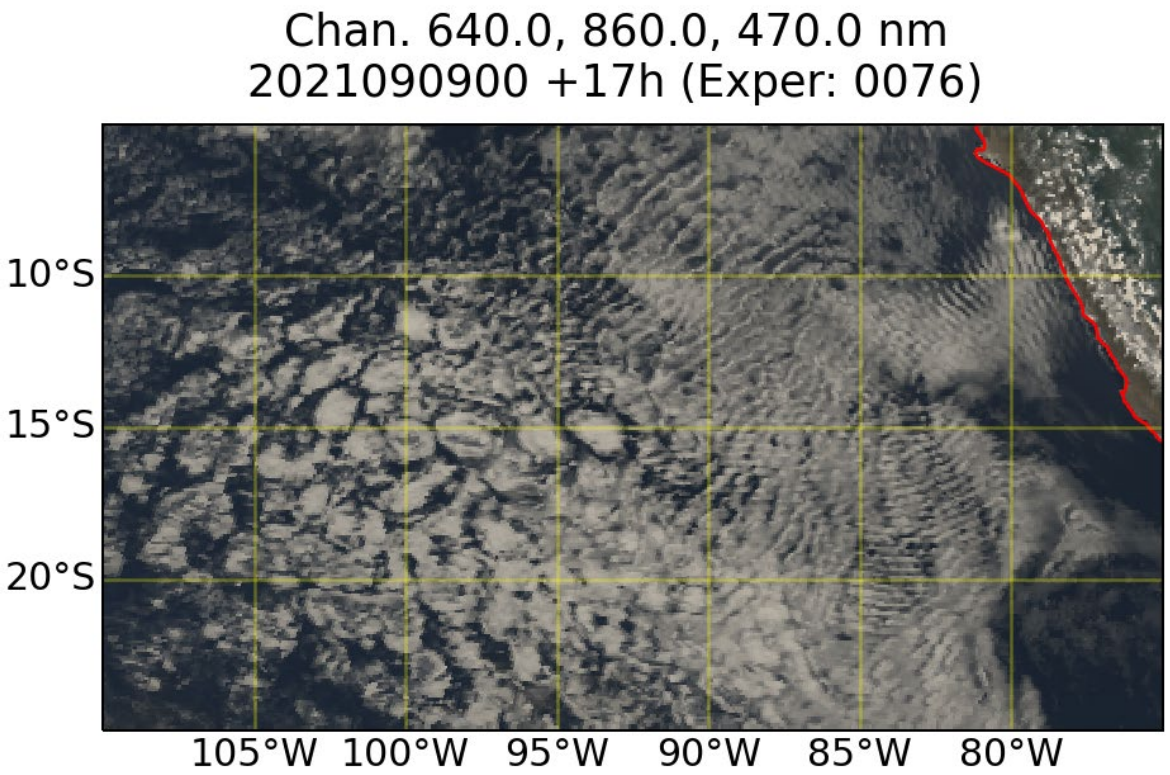


- IFS 47r1 produces far too large low-level trade-wind cloud clusters compared to observations
- Closed-cell convection in the IFS, but open-cell in observations

Philippe Lopez

IRM versus GOES-16 ABI: South Tropical Pacific trade-wind clouds (CY47R3)





- With CY47R3, trade-wind low-level cloud clusters tend to be smaller (i.e., closer to obs), but still remain too large.
- However, overall reduction in reflectance in the trade cumulus regime and increased reflectance in stratocumulus regime, except close to the coast.

Philippe Lopez

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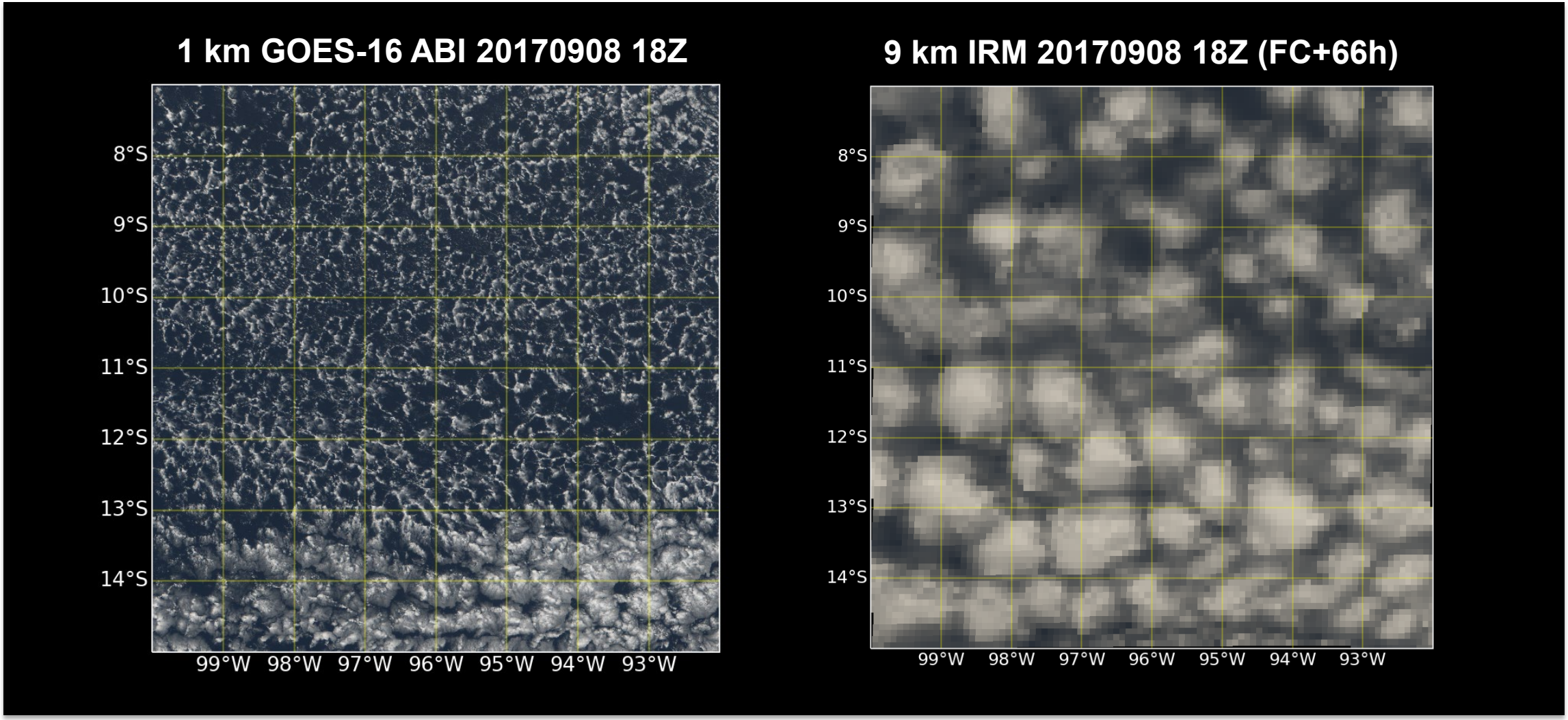
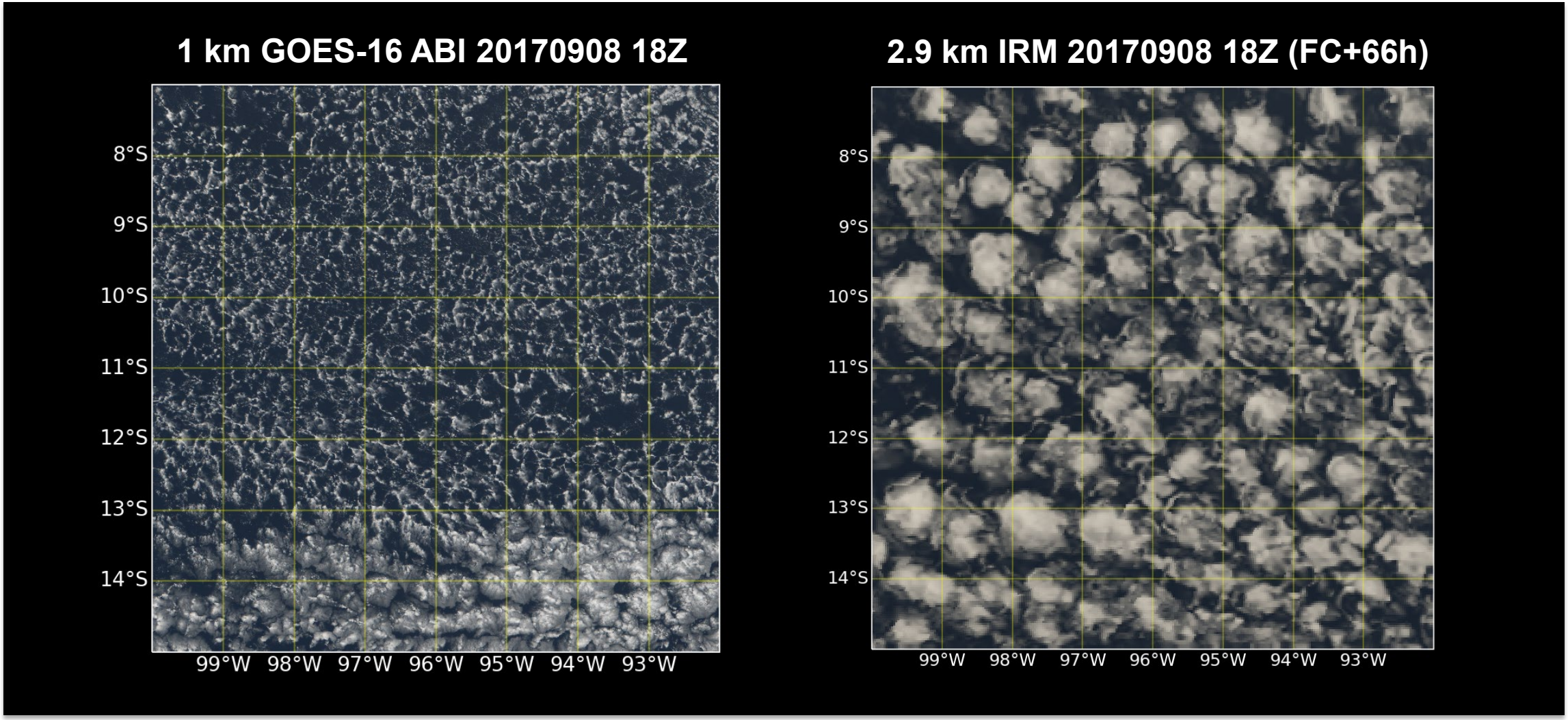
IRM versus GOES-16 ABI: South Tropical Pacific trade-wind clouds.

- **Could high resolution help with oversized cloud clusters in forecast?**



IRM versus GOES-16 ABI: South Tropical Pacific trade-wind clouds.

- **2.9-km resolution (expl. CONV) does not really help with oversized cloud clusters in forecast.**



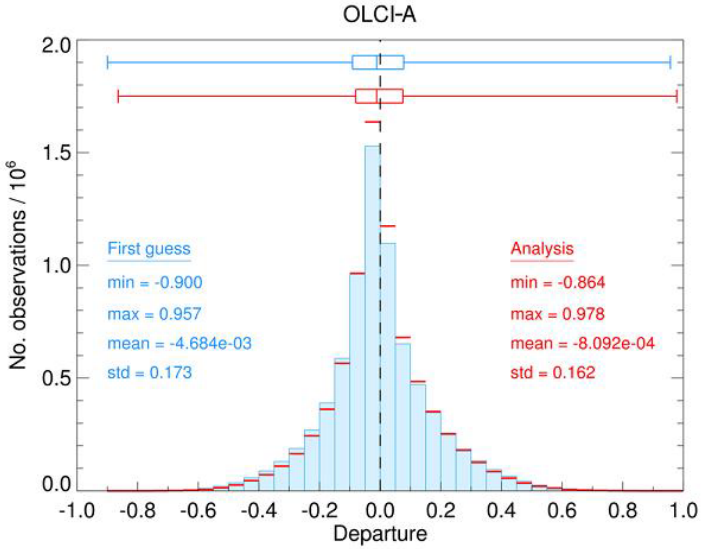
3. Concluding remarks

Towards operational assimilation of visible cloudy radiances

- Assimilation of visible reflectances – significant source of information on cloud!
- Fast radiative transfer for visible wavelengths available (e.g. Method for Fast Satellite Image Synthesis, MFASIS)
- Is the IFS visible reflectance good enough for operational assimilation of observations?
- Yes, but need to reduce key systematic errors in cloud and reflectance (also applies to other frequencies, e.g. microwave)

Obs - OLCI

Model – IFS (MFASIS)



First guess departures of monitored OCLI observations in IFS assimilation system

Liam Steele

ECMWF

Concluding Remarks

- Regional radiation errors are still too large in NWP and climate models!
- Of fundamental importance for the atmospheric/oceanic circulation,
  but reduced biases also needed for NWP assimilation of radiances to improve analyses
- Many of the errors are related to cloud
- Some errors are common across NWP models (days) and climate models (decades)
- Detailed studies are identifying and reducing the errors….
  – utilise synergy of observations, assimilation system diagnostics
  – process studies
  – “seamless” models – NWP to climate, days to decades, 100km to 1km

→ “a clearer view of cloudy skies”!

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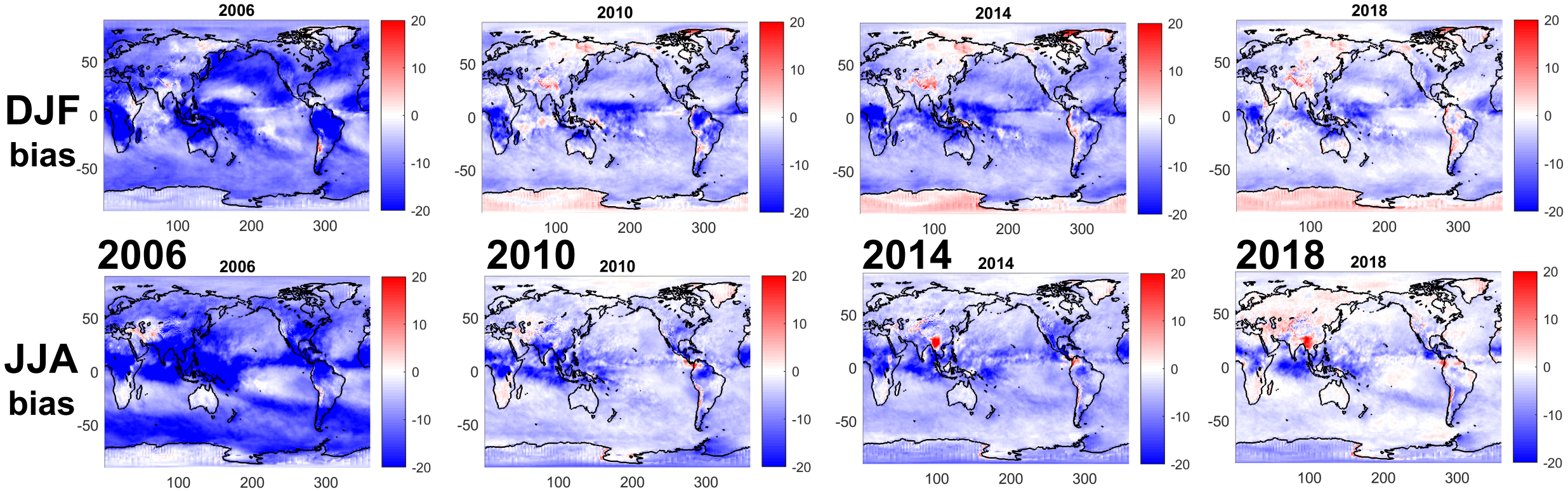
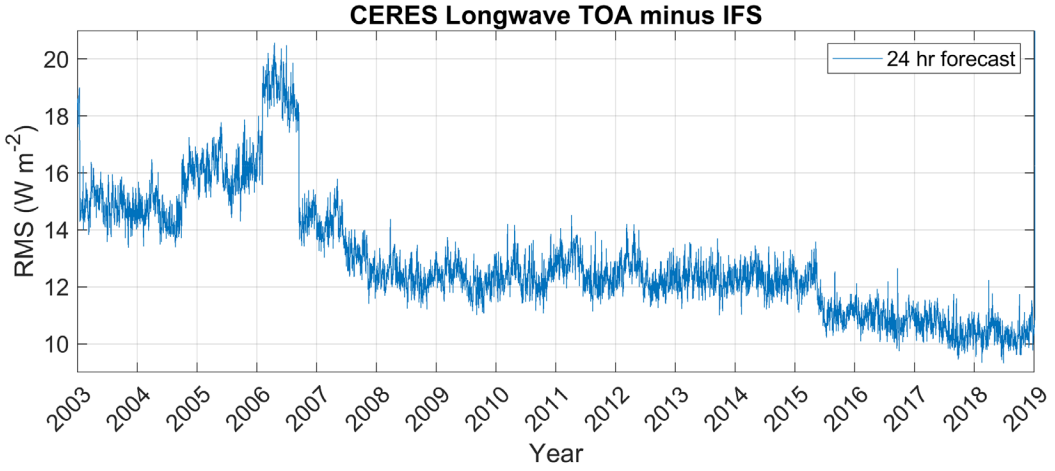
Questions?

Evaluation of TOA OLR radiation in IFS *operational* 24-h forecasts, 2003-2019



- Intermittent reduction in RMS error
- OLR still generally too high (-ve) , particularly over maritime continent, Indian Ocean, Africa
- Convective anvils not cold/deep enough?



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