Part III: simulations, predictions, and climate change:

the challenges
Catch-up from last lecture: observations and reanalyses in the EBUS
Synoptic-scale frontal forcing can dominate short time scales
Init: Thu, 30 Nov 2017 12Z 500 hPa Geopot. (gpdm), T (C), Bodendruck (hPa)
IV. atmospheric observations and models in the EBUS
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Radiosonde profiles against reanalysis products in the Benguela
Radiosonde profiles against reanalysis products in the Benguela
The scarcity of in-situ data acquisition in operation product leads to systematic biases in the reanalyses which tend to reflect common model biases.
Acquired in-situ wind observations (Cape Diaz, Luedritz)

Courtesy: Jean-Paul Roux
A recent intercomparison of reanalysis and satellite products

Surface winds from atmospheric reanalysis lead to contrasting oceanic forcing and coastal upwelling patterns

Fernando G. Taboada*,a,b, Charles A. Stocka, Stephen M. Griffiesa, John Dunnea, Jasmin G. Johna, R. Justin Smallc, Hiroyuki Tsujinod

NCEP/NCAR
\[ \delta = 15.8 \ [6.6, 44.9] \]
However...
<table>
<thead>
<tr>
<th>Cloud-controlling factor</th>
<th>Physical explanation</th>
<th>Observational support</th>
<th>Modeling support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strengthened inversion stability</td>
<td>Reduced mixing across inversion keeps boundary layer shallower, more humid and more cloudy</td>
<td>Wood and Bretherton (2006)</td>
<td>Bretherton et al. (2013)</td>
</tr>
<tr>
<td>Reduced subsidence</td>
<td>Deeper boundary layer increases cloud</td>
<td>Myers and Norris (2013)</td>
<td>Blossey et al. (2013)</td>
</tr>
<tr>
<td>Increased horizontal cold advection</td>
<td>Greater destabilization of the surface–atmosphere interface increases upward buoyancy flux promoting more clouds</td>
<td>Norris and Iacobellis (2005)</td>
<td>N/A</td>
</tr>
<tr>
<td>Increased free-tropospheric humidity</td>
<td>Entrainment drying is reduced, thus moistening the boundary layer and increasing cloud</td>
<td>M16</td>
<td>van der Dussen et al. (2015)</td>
</tr>
<tr>
<td>Decreased downward longwave radiation</td>
<td>Reduced downward longwave radiation increases cloud-top radiative cooling, driving more turbulence supporting cloud</td>
<td>Christensen et al. (2013)</td>
<td>Bretherton et al. (2013)</td>
</tr>
<tr>
<td>Colder Sea-surface temperature (SST)</td>
<td>Colder temperature reduces the efficiency of entrainment necessitating more cloud to produce a given entrainment rate</td>
<td>Q15</td>
<td>Bretherton and Blossey (2014)</td>
</tr>
<tr>
<td>Increased surface wind speed</td>
<td>Increased surface driven shear mixing increases latent heat flux and cloud</td>
<td>Brueck et al. (2015)</td>
<td>Bretherton et al. (2013)</td>
</tr>
</tbody>
</table>
this approach [...] relies primarily on observations of the cloud response to controlling factors and does not depend on the simulation of clouds by climate models. (It does rely on model predictions of how the controlling factors change with climate, however).

[...] Our synthesis of the results from these studies is that the contribution of tropical low clouds to the global mean cloud feedback is $0.25 \pm 0.18 \text{ W m}^{-2} \text{ K}^{-1}$

[...] The range of local cloud feedbacks from large-eddy simulations is 0.3–2.3 W m$^{-2}$ K$^{-1}$
So, models...
Climate prediction today
Climate prediction today

“Model” (e.g. CESM2)
Climate prediction today

“Model” (e.g. CESM2)

“Scientist” (e.g. me)
The Pacific Sc inversion in forecast models
At least some models are also able to capture the dynamically forced Sc variability. This ability is not critically resolution-dependent.

Abel et al. 2010
High dynamical complexity

The California Current System

Fig. 1. Instantaneous SST at $t = 30$ days. The SST computed from ICC3 is superimposed onto the full USW12 field. The boundaries of the ICC domains are delineated by black lines.

Capet et al, JPO 2008a
High system complexity
The global circulation and moist convection
The annual march of the SSTs and of the ITCZ
NorESM CAM4 biases

- Hadley circulation too symmetric
- Double ITCZ
- ENSO active predominantly in ASO
- Excessive precip over SA & central Africa

SST biases

Precip biases
GALES model (deep convection case)

https://www.youtube.com/watch?v=Bb0HnaYNUx4
MPAS 4km simulation

https://www.youtube.com/watch?v=UmiB4Ynd9Al
The Hadley circulation of most CMIP5 models is severely biased.
Schematic of the proposed mechanism for the double-ITCZ bias.

Hwang Y, and Frierson D M W PNAS 2013;110:4935-4940
Impact of conserving angular momentum under (numerical) advection (Tonrizzo et al 2019, under revision in JAMES)
PyCLES model (DYCOMS II simulation)

Day 256

/home/thomas/literature/Schneider_etal_2019_ScLES.SImovie.mp4
The horizontal and vertical grid spacings are 50 m and 10 m, respectively, for a total of 2 million grid points. We conducted additional simulations at a coarser resolution (75 m × 15 m), with essentially unchanged results (Supplementary Fig. 4). Therefore, although our LES resolution is not sufficient to have reached numerical convergence, we are confident in the numerical robustness of the results.
..., we are confident in the numerical robustness of the results.
The 1:1 map of the world

“In the Deserts of the West, still today, there are tattered Ruins of that Map, inhabited by Animals and Beggars; in all the Land there is no other Relic of the Disciplines of Geography.”

Jorge Luis Borges: Del Rigor en la Ciencia. (Translation A. Hurley).
Analysis of CMIP5 simulations
Persistent model errors

Summer (JJA) Sea Surface temperature bias pattern in CMIP5 ensemble
White stipples indicate model biases that are consistent across all CMIPx models

Can we improve climate prediction in the Tropical Atlantic by improving model simulations?

Tonizacco and Woolnough, 2013
Model mean-state and seasonal-cycle biases related to the large-scale distribution of convective precipitation.

Richter et al. 2012
The CMIP5 set shows ubiquity of warm & wet error in south Atlantic

AR5 (25 models): SST - HadISST
Annual mean 1960–2004

AR5 (25 models): Precip - CMAP [mm/day]
Annual mean 1979–2004

[K] / [mm/day]
An analysis of error growth in initialised decadal forecasts

- We analyse the errors as a function of lead time in the initialised decadal hindcast integrations in CMIP5.

- This allows isolating areas of fast and slow error growth, potential mechanisms “before” and “after” coupling, and causal relationships linking atmospheric and oceanic errors.

- We focus primarily on the generation of SST errors in the marine coastal region of the South-East Atlantic.

- Restricted to models with a good ensemble of full-field initialised hindcasts and high-frequency diagnostics.

- Grand total of suitable CMIP5 hindcast sets at the time of analysis was 3.
Three models from CMIP5

CanCM4 (CCCma)

HadCM3 (UKMO)

CFSv2-2011 (NOAA-NCEP)
Proximate causes I: surface heat fluxes
Monthly-means hide the evolution: large & immediate warming by SHF in CFS
Proximate causes II: coastal windstress (a)
Proximate causes II: coastal windstress (b)
Associated biases I: subsurface OTs
Non-proximate causes I: ocean waves
Non-proximate causes II: equatorial thermocline
Non-proximate causes III: equatorial winds
Non-proximate causes IV: atmospheric circulation
Non-proximate causes V: feedbacks!
Three models from CMIP5

- CanCM4 (CCCma)
- HadCM3 (UKMO)
- CFSv2-2011 (NOAA-NCEP)
Combined Hovmueller diagrams (lat-time, left, along African coast, plus lon-time, right, along the Equatorial Atlantic) for the biases of the 16C isotherm depth (colours) and of the near-surface wind (contours; meridional component on left, zonal on right; black for positive values, white for negative values) for each of the three decadal hindcast systems analysed for initial error development from the CMIP5 ensemble in the tropical Atlantic. CFSv2 shows a centre of development mainly in the Gulf of Guinea, which however is triggered by excessive surface SW all along the eastern seaboard; before that couples, winds are mostly OK. CM4 has large initial zonal wind errors over the Equator, and thermc depth anomalies propagate into the Benguela area from there. CM3 has negative initial meridional wind errors in the Benguela which triggers a local warming; this later couples with the Equatorial winds generating additional thermocline errors that intensify the warming.
Part III: model climatologies and their biases

b. current work
De Silveira et al. 2019: impact of resolution on CCSM4 biases in Humboldt US

- Persistent problems with marine Sc
- At higher resolution south/south-easterlies too strong
De Silveira et al. 2019: impact of resolution on CCSM4 biases in Humboldt US

- Persistent problems with marine Sc
- Overall simulated atm. circulation probably too intense
De Silveira et al. 2019: impact of resolution on CCSM4 biases in Humboldt US

- Persistent problems with marine Sc
- Overall simulated atm. circulation probably too intense (error compensation with SSTs at low resolution)
Fast error development in seasonal hindcasts

February: zonal wind in tropical Pacific

May: ITCZ in tropical Atlantic

(Teferi Demissie, UniRes)
The systematic effect develops when a certain dynamical regime sets in, irrespective of initialisation date. PV constraint to cross-equatorial flow dependent on PBL stability the likely cause.

(Shonk, Demissie and Toniazzo 2019, under revision in ACP)
### III: Beyond diagnosis: sensitivity experiments in forecast mode

1. Correct biases surface heat and/or momentum fluxes e.g. over Equatorial region

2. Test effects on forecasts

Voldoire A. et al 2019
II: Development of “fast” biases in “TAMIP” integrations

Ma, H.-Y., et al., 2014: On the Correspondence between Mean Forecast Errors and Climate Errors in CMIP5 Models. J.Clim. 27, 1781-1798

Fig. 12. As in Fig. 5b, but for sea level pressure (hPa).
II: Development of “fast” biases in “TAMIP” integrations

- Biases of 5-day forecasts from ERA/I i.c.'s
- Diabatically coupled dynamical fields affected
- Large-scale (zonal-mean) wind drifts
- Bearing some resemblance with climatological biases

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Fig. 12. As in Fig. 5b, but for sea level pressure (hPa).
Fast growing, observationally unconstrained systematic biases affect reanalysis products.
What we *know*
Held and Soden 2006 and the role of subtropical warming

\[ H \sim OLR/Lq \quad H \sim OLR/N^2 \]

\[ N^2_{ITCZ} \quad N^2_{subt} \]
Held and Soden 2006 and the role of subtropical warming

\[ \delta(Mcq) \sim \deltaOLR \]

But

\[ \deltaOLR \sim 2 \%/K \text{ and } \deltaq \sim 7 \%/K \]

Therefore

\[ \deltaMc \sim -5 \%/K \]

Convective adjustment also implies

\[ \delta N^2_{ITCZ} \sim 2 \%/K \]

If \( H \sim Mc \), then for the subtropics

\[ \delta N^2_{subtr} \sim 7 \%/K. \]
Held and Soden 2006 and the role of subtropical warming

\[ \delta(Mcq) \sim \delta OLR \]

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Convective adjustment also implies

\[ \delta N^2_{ITCZ} \sim 2 \%/K \]

If \( H \sim M_c \), then for the subtropics

\[ \delta N^2_{subtr} \sim 7 \%/K. \]
Held and Soden 2006 and the role of subtropical warming

\[ \delta(Mc) \sim \delta \text{OLR} \]

But

\[ \delta \text{OLR} \sim 2 \%/K \text{ and } \delta q \sim 7 \%/K \]

Therefore

\[ \delta Mc \sim -5 \%/K \]

Convective adjustment also implies

\[ \delta N^2_{\text{ITCZ}} \sim 2 \%/K \]

**If** \( H \sim Mc \), then for the subtropics

\[ \delta N^2_{\text{subt}} \sim 7 \%/K. \]

Hence reduced thermal wind in subtropics. Since also \( \delta N^2_{\text{subpolar}} \) is small, there is increased thermal wind in mid-latitudes. But the HC subsequently responds to changing mid-latitude energy exports.
• Subtropical subsidence will weaken
• Stratification will strengthen

Hadley circulation *may* expand, but this is uncertain because...
Mid-latitude eddy fluxes represent a feedback on the tropical energy budget, circulation and ITCZ.
the large-scale subsidence in the troposphere weakens under warming\textsuperscript{32}, which lifts the cloud tops and counteracts the instability\textsuperscript{15,19,24}. Indeed, when we weaken the parameterized large-scale subsidence by 1 or 3\% per Kelvin of tropical SST increase (within the range of GCM responses to warming\textsuperscript{33}), the stratocumulus instability occurs at higher CO\textsubscript{2} levels: around 1,400 ppm with 1\% K\textsubscript{-1} subsidence weakening, and around 2,200 ppm with 3\% K\textsubscript{-1}
A few important points

1. Observational constraints are still too weak or uncertain

2. Modelling certain aspects of the climate (e.g. EBUS upwelling) requires understanding the physical mechanisms that govern them

3. In the case of the coastal jet, and important controlling factor is subsidence, via its implied thermal advection

4. Model are capable of simulating the related dynamics, but the climate feedbacks are uncertain

5. They fall short particularly in the background, large-scale circulation

6. This can and is probably often due to global imbalances

7. One way to analyse model errors is by imposing observed initial conditions and let them evolve freely

8. Another is to design idealised set-ups where the relevant mechanism (e.g. conservation of angular momentum) is tested in isolation

9. GCM at present do not reliably simulate feedbacks between forcing and circulation