Variety of observational tools developed for global satellite observations, and many observations that are to be sustained over the coming decade but...
• The NASA downscaling project - lessons learned
• Sat obs capabilities today & challenges looming
• Exemplifying a ‘decade’ of progress
• A couple of examples of new ways to using data
• Model obs synergy
• Looking forward
Assessing the Credibility of Dynamically-Downscaled Climate Projections: A NASA Pilot Study

Multi-Center NASA (JPL, GSFC, MSFC, AMES) Working Group

Downscaling Assessment Questions

• Under ideal forcing conditions (e.g., high-quality re-analyses), how good is the RCM at replicating important weather and climate processes/phenomena?
• Under what conditions does downscaling (RCMs driven by GCMs) give valid results?
• Do high-resolution RCMs (5 km or finer) offer anything that can’t be obtained via today’s “high” but coarser resolution GCMs (25-50 km or coarser)?
Downscaling Assessment
Narrow Scope – Focus only on 3 Impactful Phenomena

Northeast Wintertime Storms (NESs)
- Extreme precipitation/snowfall events
- Extreme wind events

Midcontinent Summertime MCSs
- Warm / Dry Climate Model Biases
- Extreme weather events

West Coast Wintertime Atmospheric Rivers (ARs)
- Crucial for water resources/availability
- Associated with most flooding events
• Based on the metrics developed, the study results do not show dramatic improvement of the downscaled fields compared to the reanalysis fields (which were at ~ 0.5 degree resolution)
• Performance metrics vary by season, region, variable, and phenomenon of interest.
• NU-WRF and M2R12K generally capture climatology (particularly winter). In numerous evaluations (though not all) they show some systematic improvement over MERRA-2. This is good!
• All simulations improved realism of the diurnal cycle relative to MERRA-2.
• Nudging usually improves performance metrics.
• Resolution seems to have marginal impact (a surprise!) but there are cases where higher resolution did systematically improve representation of precipitation.
• **Many evaluations were observation limited. When we get down to 4km even our “gold standard” observations don’t have the resolution and accuracy to support a robust evaluation of results.**
What the last two decades has revealed is the viability of active systems - just as ‘affordable’ and just as reliable

Pros: Delivers vertical profiles and information that is much less ambiguous

Cons: narrow swath, limited coverage

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sensor</th>
<th>Native (measurement) Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T(z), q(z)$</td>
<td>COSMIC</td>
<td>$\Delta x \sim 100s$ of km, ~daily, $\Delta z &lt; 1$km</td>
</tr>
<tr>
<td>Winds</td>
<td>AIRS, IASI*</td>
<td>$\Delta x \sim 10$km, twice daily, $\Delta z \sim 2$km</td>
</tr>
<tr>
<td>ocean surface only</td>
<td>Scatterometry</td>
<td>$\Delta x &gt; 10$km, daily</td>
</tr>
<tr>
<td>Precipitation (liquid)</td>
<td>MODIS, VIRS</td>
<td>$\Delta x &gt; 10$km, sub-daily (&gt;3hr)</td>
</tr>
<tr>
<td>Clouds</td>
<td>MODIS, VIRS CloudSat/CALIPSO</td>
<td>$\Delta x \sim 1$km, daily, $\Delta z \sim 500$m</td>
</tr>
</tbody>
</table>

* IASI to go on geostationary – sub-hourly

+ Data composited in space on 100s km, monthly
Thoughts

• We are at a point in time where the paradigm is shifting – model resolutions (e.g. CPMs) are now below the native resolutions of almost all satellite observations.

• It is unlikely that we will see fields of observed variables at resolutions now being produced by O(1km) models.

• Thus we are left to ponder do observations need to be at these same resolutions, if not then at what resolution and for what variables?

• How do we more effectively use the observations of today and of the future?
Selected Progress

• Clouds ain’t where we think the where this last 30+ years
• Dreary models – we know by how much and why and more or less how to fix them
• We know much more about the cloudy nature of convection & are beginning to understand what the broader Earth science implications
• We know we there is a SW southern ocean bias and how to fix it
• Frozen precipitation – we now have reasonable measures of it (at least in polar regions)
Some highlights of progress over the past decade

Hartmann et al (1992)

To be frank, passive climatologies of clouds mis-assign clouds in significant ways
The dreariness is not just a state of climate models but also of global CPMs??? So there is still ‘physics’ to be improved even as resolutions increase
The shape of tropical deep convection

- Smallest 25% (<12,000 km$^2$)
- Largest 25% (>40,000 km$^2$)

“Superclusters” – produces the majority of the high clouds

Yuan and Houze 2010
The shape and size of deep convection

Table J.10.3-1. Means of various length scales as a function of the number of cores (with 25th and 75th percentiles in parentheses), as derived from CloudSat analyses by Igel & van den Heever [59]. "3+" cores signifies that the values are for clouds with 3 or more convective cores.

<table>
<thead>
<tr>
<th>Cores</th>
<th>Pedestal Width (km)</th>
<th>Anvil Width (km)</th>
<th>Cutoff Height (km)</th>
<th>Anvil Depth (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11 (5, 13)</td>
<td>95 (33, 119)</td>
<td>7.2 (6.0, 8.3)</td>
<td>6.4 (5.3, 7.3)</td>
</tr>
<tr>
<td>2</td>
<td>20 (14, 25)</td>
<td>121 (50, 153)</td>
<td>7.3 (6.0, 8.4)</td>
<td>6.7 (5.7, 7.8)</td>
</tr>
<tr>
<td>3+</td>
<td>110 (42, 148)</td>
<td>335 (150, 440)</td>
<td>7.1 (6.0, 8.1)</td>
<td>7.7 (6.0, 8.8)</td>
</tr>
</tbody>
</table>

Inference from 2 dimensional (x,z) data

Anvil width

\[(\text{pedestal width})^{2/3}\]

Inference from 2 dimensional (x,y) data
The Southern Ocean SW radiation bias

Forbes et al. 2016
(ECMWF Newsletter 146)

Annual mean 10-20 Wm$^{-2}$ TOA SW bias (too little reflection) over Southern Ocean

ECMWF low resolution “climate” bias

ECMWF high resolution “analysis” bias

dx=125 km 1 year forecast – CERES

dx=16 km 24 hour forecast – CERES

(dx = horizontal resolution, TOA = top of atmosphere)
Supercooled liquid water now present at the tops of convective clouds in cold-air outbreaks

Forbes, pers comm
More liquid water path (closer to SSMI/S) and SW radiation bias dramatically reduced!

Forbes et al. 2016 ECMWF Newsletter 146
Also UKMO Bodas-Salcedo et al 2016
Genuine progress on frozen precipitation
New ways of using data – process oriented

Two examples

Deep convection

Warm rain
CRM ‘surrogate’ observations of tropical deep convection


Too anecdotal to suggest systemic problem with CRMs?
Cloud-top buoyancy

\[ B = g \frac{T_{\text{parcel}} - T_{\text{env}}}{T_{\text{env}}} \]

Entrainment: By estimating \( \theta_e \) of convective top and placing it in the context of the ambient \( \theta_e \) profile, we are able to calculate the entraining rate (using the entraining plume model).

Negative buoyancy

Positive buoyancy

Cloud-top buoyancy (K)

Luo et al. (2010); Wang et al. (2011)

Terminal congestus

Luo et al. (2014)
Observing the warm rain process globally

\[ r_e = \frac{n(r)r^3 \, dr}{n(r)r^2 \, dr} \]

\[ q_c = \frac{4}{3} \, \frac{n(r)r^3 \, dr}{d} \]

\[ \frac{dR}{dt} = \frac{E_c}{4} \frac{V_t(R)}{w} q_c \]

\[ dh = V_t(R) \, dt \]

\[ \frac{dZ_e}{Z_e} = \frac{dR}{R} = \frac{E_c}{4} \frac{q_c}{w} dh \]

\[ \frac{d \ln Z_e}{d} = \frac{E_c}{6} \]

\[ d = \frac{3}{2} \frac{q_c}{w} \]
Example: Warm-rain formation process using A-Train data, GCMs and process models.

Z vs Optical Depth for different $R_{\text{eff}}$ from CloudSat/MODIS and from the HadGEM2 model

Suzuki et al. 2015

Effect of different autoconversion parametrizations
<table>
<thead>
<tr>
<th>CRM</th>
<th>Suzuki et al. (JAS’11)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$R_e=4-10,\text{mm}$</strong></td>
<td><strong>$R_e=10-15,\text{mm}$</strong></td>
</tr>
<tr>
<td><strong>A-Train</strong></td>
<td><strong>NICAM (1-mom)</strong></td>
</tr>
<tr>
<td>(a) A-Train/$r_e=4-10,\mu\text{m}$</td>
<td>(e) NICAM/$r_e=4-10,\mu\text{m}$</td>
</tr>
</tbody>
</table>
Some key challenges:

- Capturing **orographic precipitation** remains a challenge for remote sensing of precipitation.

- A large fraction of the precipitation falls in winter and as snow over mountains. Yet, snow retrieval skill is limited from space.

- In practice we don’t determine precipitation phase from space. It is based on established relationship between temperature and precipitation phase observed in stations. Given that temperature data is often from reanalysis and at coarse spatial resolution it can be a large source of uncertainty.

- High resolution modeling remains as a viable alternative to help.
Surface radar data challenges in orography

Fig. 4. Relative statistics for 48 months of collocated Stage IV and CloudSat precipitation detections. (left) Data from all temperatures; (middle), (right) only data for which the 2-m near-surface air temperatures from ECMWF are >0°C and <0°C, respectively. Grid boxes are omitted if the corresponding CloudSat standard errors are found to be >25%, as computed by Eq. (1).

Smalley et al., 2015
Moving from 0.4x0.4 deg. Resolution that is typical resolution of reanalyses to 0.04 x0.04 deg. we can experience about 3°C or higher error in temperature in topographically complex regions. The impact appears critical for many applications including snow-rain separation.

Behrangi et al. 2016 (submitted to J. of water resources research)
At some point we will evolve to a more integrated system in which models and observations on various scales and of different types are more fully integrated.
Charting the course for the next decade of Earth observations

nas.edu/esas2017

The National Academies of
SCIENCE • ENGINEERING • MEDICINE
<table>
<thead>
<tr>
<th>Extreme Events</th>
<th>Weather: Minutes to</th>
<th>Climate Variability and Change</th>
<th>Marine &amp; Terrestrial</th>
<th>Global Hydrological Cycle</th>
<th>Earth Surface &amp; Interior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Cycle</td>
<td>Sub-seasonal</td>
<td>Eco-systems</td>
<td>&amp; Water Resources</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon Cycle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology &amp; Innovations Cross-Cut</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applications’ Science Cross-Cut</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ESAS 2017 Panels**

(WORKING GROUPS (Tentative))
• Provides more accurate measures of condensed mass because biases get removed
• Provides methods to estimate mass flux, previously unthinkable
Generally, **the more extreme a precipitation index is, the more sensitive it is to product and resolution choice.**

A **minimum resolution exists where observations exhibit agreement on extremes.** Product sensitivity is prominent at resolutions of 1°x1° and finer. Thus inter-product differences will be particularly problematic when evaluating precipitation extremes in high resolution global climate models. This provides an insight on the finest resolution models should be evaluated at.
INTENSE workshop

Sub-daily rainfall extremes: data, processes and modelling

The Core, Newcastle upon Tyne, 13-15th September 2016
Questions to ponder

Q1: What are the glaring observational gaps that obstruct progress in understanding and modeling the moist atmosphere?
   • Boundary layer?
   • Convective transport?
   • Entrainment/detrainment?
   • Other?

Q2: What level of complexity in observations is really needed to advance our understanding and ability to model moist atmospheric processes?
   • Is information on bulk microphysics enough?
   • Representativeness? Large volumes of coarse data (e.g. global) versus very small samples of higher resolved information?

Q3: Are we really making the most effective use of the observational capabilities we currently have?
   • Assimilation of cloud/precipitation information?
   • Use of simulators?
   • Surface data & field expt data?
   • Growing data records

(Model) data without validation is merely rumour
Vertical motion measurement from space

- **Diabatic Heating**: truth
- **Vertical air velocity**: truth
- **Total vertical velocity**: truth
- **Observed vertical velocity**: EarthCARE W-band
- **Observed vertical velocity**: ACE W-band
- **Observed vertical velocity**: ACE Ka-band

10 km averaging

1.8 km averaging

[Diagram image with various data visualizations and color scales]
COPERNICUS SENTINELS

SENTINEL-6 (Jason-CS)
- 2020
- Radar altimeter
- 10 days
- Measure precision sea-surface height for ocean and climate studies

SENTINEL-5
- 2021
- Ultraviolet/visible/near-infrared/short-wave infrared spectrometer on Metop-SG A satellite
- Daily
- Monitoring of air pollution, stratospheric ozone, solar radiation and climate

SENTINEL-5 precursor
- 2016
- Ultraviolet/visible/near-infrared/short-wave infrared spectrometer
- Daily
- Monitoring of air pollution, stratospheric ozone, solar radiation and climate

SENTINEL-1
- Launch Date: 1A: Launched; 1B: 2016
- Payload: All Weather Imaging Radar
- Revisit time: 1-6 Days
- Applications: Monitoring sea ice and the Arctic, Land Surface motion risks, disaster response

SENTINEL-2
- 2A: Launched; 2B: 2016
- Optical imaging sensor with 13 bands
- 2-5 days
- Monitoring land-use changes, agriculture and ecosystems, volcanoes and landslides

SENTINEL-3
- 3A: Launched; 3B: 2017
- Radar altimeter, Sea/land surface temperature radiometer, sea/land colour imager
- 1-2 days ( imagers); 27 days ( altimeter)
- Sea-surface and land-ice topography, sea and land surface temperature and colour

SENTINEL-4
- 2021
- Ultraviolet/visible/near-infrared spectrometer on MTG-S satellite
- Geostationary. Hourly coverage of Europe/North Africa
- Monitoring of air pollution, stratospheric ozone, solar radiation
Fig. 1. Stage IV precipitation accumulation coverage for the Northwest (NW), California–Nevada (CN), Colorado Basin (CB), Missouri Basin (MB), Arkansas–Red Basin (AB), West Gulf (WG), North Central (NC), Lower Mississippi (LM), Ohio (OH), Northeast (NE), Middle Atlantic (MA), and Southeast (SE) RFC basins. Study coverage is limited to the CONUS.
Fig. 4. Relative statistics for 48 months of collocated Stage IV and CloudSat precipitation detections. (left) Data from all temperatures; (middle), (right) only data for which the 2-m near-surface air temperatures from ECMWF are $>0^\circ C$ and $<0^\circ C$, respectively. Grid boxes are omitted if the corresponding CloudSat standard errors are found to be $>25\%$, as computed by Eq. (1).
• Occurrence frequency of hot towers with different reference levels (from ETH10dBZ greater than 10 to 15km).
• This maps illustrate how the occurrence frequency of HT will change over weaker HT (e.g., larger entrainment) to stronger HT (e.g., small entrainment).
• The assumption of 14km is closest to the statistics given by Rieh and Malkus (1979) whose coverage of HT over 30S-30N is 0.02%.
Cloud-top MSE
($T_b$ has been corrected for non-blackbody effect)

\[ C_p T + gz + L_v q \]

\[ B = g \frac{T_{\text{parcel}}}{T_{\text{env}}} \]

$T_{\text{parcel}} = 193$ K; $T_{\text{env}} = 198$ K

Negatively buoyant!

Luo et al. (2010)
Integrate this equation from PBL upward to the observed cloud top height. Iterate \( \lambda \) until the calculated MSE matches the observed MSE. Then that’s the inferred entrainment rate

\[
\frac{d}{dz} = \left( \cdots \right)
\]

Caveat: 1) Assuming the environment (50 km) MSE represents that of the cloud base, 2) using the bulk entraining plume model

Energy boost from ice nucleation is ignored for now, but could be included using CloudSat IWC product

Luo et al. (2010)
Histogram of $\lambda$ as a function of CTH

Luo et al. (2010)
Entrainment rate

Buoyancy

Deep convection: $B < 0 \& \lambda < 10\%$/km

“Terminal” cumulus congestus: $B < 0 \& \lambda$ up to $50\%$/km

“Transient” cumulus congestus: $B > 0 \& \lambda \sim 10\%$/km

$Luo\ et\ al.\ (2010)$

\[ \Delta T = T_{\text{parcel}} - T_{\text{env}} \ (K) \]
Questions to ponder

Q1: What are the glaring observational gaps that obstruct progress in understanding and modeling the moist atmosphere?
   • Boundary layer?
   • Convective transport?
   • Entrainment/detrainment?
   • Other?

Q2: What level of complexity in observations is really needed to advance our understanding and ability to model moist atmospheric processes?
   • Is information on bulk microphysics enough?
   • Representativeness? Large volumes of coarse data (e.g. global) versus very small samples of higher resolved information?

Q3: Are we really making the most effective use of the observational capabilities we currently have?
   • Assimilation of cloud/precipitation information?
   • Use of simulators?
   • Surface data & field expt data?
   • Growing data records

(Model) data without validation is merely rumour
• The boundary layer
• Warm clouds
• Mixed phased clouds
• Convection
• Aerosol and ‘degrees of freedom’
• Heating distributions (radiative and latent heating)
• Polar clouds and precipitation
• Prospects for the decade ahead
How do we define it and what do we want to observe?

So if we really want to study the primary physical drivers of aerosol science instead of the aftermath, we absolutely need good PBL measurements (Reid, 2016, CC 10 year anniversary).

BL height resolved variables: T,q,v, fluxes, cloud macro and microphysics....
Atmospheric Boundary Layer Height
Eastern Pacific Stratocumulus Region

Mean height

Height variability (std)


2) Observations of warm cloud processes

\[ \frac{dR}{dt} = \frac{E_c}{4_w} \frac{V_t(R)}{q_c} \]

\[ dh = V_t(R) dt \]

\[ \frac{dR}{dh} = \frac{E_c}{4_w q_c} \]

\[ \frac{dR}{R} = \frac{E_c}{4_w} \frac{q_c}{R} dh \]

\[ \frac{dZ_e}{Z_e} = \frac{dR}{R} \]

\[ d = \frac{3}{2} \frac{1}{w} \frac{q_c}{R} dh \]

\[ \frac{d\ln Z_e}{d} = \frac{E_c}{6} \]
A ‘drizzle’ gap
Spectral bin models captures this drizzle gap.
Understanding processes - improving parametrizations
Using observation synergy and modelling studies

Example: Warm-rain formation process using A-Train data, GCMs and process models.

Z vs Optical Depth for different $R_{\text{eff}}$ from CloudSat/MODIS and from the HadGEM2 model

Suzuki et al. 2015
Effect of different autoconversion parametrizations
Polar precipitation
Global Mean = 62 mm yr$^{-1}$
(By comparison it rains ~ 1000 mm yr$^{-1}$)

Mass trend (2004-2011) from GRACE
~0.32 mm/year sea level rise.

- 5 warm and moist storms account for unprecedented mass gain.

Boening et al., 2012; 2016
Role of Clouds in Ice Sheet Melt

- On average, more than 40% of the clouds over the Greenland Ice Sheet contain super-cooled liquid water (70% in summer, 25% in winter).
Clouds enhance the net surface radiation on the ice sheet by an average of nearly 30 ± 6 Wm⁻² relative to clear conditions.

Unfrozen liquid droplets account for HALF of this forcing.

This is enough energy to melt up to 90 Gt of ice each year.

Surface modeling suggests that this effect results in about 25 Gt of additional runoff each year after warming and sublimation are accounted for.

van Tricht et al., *Nature Comm.* (2016)
Low clouds and model biases in surface temperature

Greenland is too cold in CESM (Kay pers com).
4) Deep Convection
Aerosol and (a lack of) DOF
What's missing GCMs – insufficient DOF that buffer the system

The 'Twomey' effect - cloud responses are more complicated than that

\[ \frac{R_e}{R_e} + \frac{LWP}{LWP} \propto \]

1000's of ship track data accumulated globally

Moist stable

Albedo change

\[ \Delta A[A(1-A)] \]

Water path change

\[ \Delta (\ln LWP) \]

ERA Interim

Global cloud data

Moist/dry: RH above cloud top higher/lower than 40%.
Stable/Unstable: LTS (Θ_{200mb} - Θ_{SFC}) larger/lower than 17K.

Non-raining (82.6%)
Raining (17.4%)

Moist/stable
Moist/unstable
Dry/stable
Dry/unstable
New data sources - World wide weather radar coverage
> 800 systems listed by Heistermann et al., 2013

Europe, UK: Nimrod, OPERA, EUMETNET 17 countries,
Northern Germany: Precipitation and Attenuation Estimates from a High Resolution Weather Radar Network (PATTERN)
US: NEXRAD (Next-Generation Radar), network of 160 high-resolution S-band Doppler weather radars
Atmospheric Boundary Layer Thermodynamic Structure: Blending Infrared and Radar Observations

Results from a large-eddy simulation of a cumulus show the key characteristics of the measurements proposed: A differential absorption radar on LEO provides water vapor profiles within cloudy areas along a ‘curtain’ (grey in figure) with resolution on the order 1.0x1.0x0.5 km³. An IR sounder provides the 3D context of temperature and water vapor structure by sampling the adjacent clear sky regions with resolution of order 1x1 km².
• Provides more accurate measures of condensed mass because biases get removed
• Provides methods to estimate mass flux, previously unthinkable
Questions to ponder

Q1: What are the glaring observational gaps that obstruct progress in understanding and modeling the moist atmosphere?
   • Boundary layer?
   • Convective transport?
   • Entrainment/detrainment?
   • Other?

Q2: What level of complexity in observations is really needed to advance our understanding and ability to model moist atmospheric processes?
   • Is information on bulk microphysics enough?
   • Representativeness? Large volumes of coarse data (e.g. global) versus very small samples of higher resolved information?

Q3: Are we really making the most effective use of the observational capabilities we currently have?
   • Assimilation of cloud/precipitation information?
   • Use of simulators?
   • Surface data & field expt data?
   • Growing data records
Adding The Vertical Dimension
