The changing flow of energy through the climate system

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The main external influence on Earth is from radiation.
Incoming solar shortwave radiation is uneven owing to geometry and rotation of Earth.
Outgoing long-wave radiation is more uniform.
My new book, Submitted Nov 5 with the satellite imagery from Nov 5, 2020

Has
• 18 Chapters,
• 128 Figures
• 100K words

Topic of today’s talk is mostly Chapters 9 & 14.

Hurricane Eta
Nov 5, 2019
Energy on Earth

The climate is changing from increased GHGs that create an energy imbalance.
The planet warms until OLR increases to match the ASR. But there are many feedbacks and complexities.

The most fundamental measure that the climate is changing is Earth’s Energy Imbalance.

Major advantage: it is the net result of all complicated feedbacks.

GHG: Greenhouse Gases
OLR: Outgoing Longwave Radiation
ASR: Absorbed Solar Radiation
The EEI is the net effect after all of the complicated feedbacks (from clouds, aerosols, water vapor etc) have operated.
Earth’s Energy Imbalance
(net effect after all feedbacks included)

Varies over time but is now about:

0.9 W m\(^{-2}\).

Globally this is about 500 TeraWatts

= 500,000,000,000,000 Watts.

In 2018 global electricity generation was about 5.7 TeraWatts

*Factor of 90 less*

The direct effects of humans are small:
except locally in cities.
It is mainly through interference with natural flows of energy that matters

1 Christmas tree light is about 0.4 W.
Earth’s Energy Imbalance
(net effect after all feedbacks included)

$0.9 \text{ W m}^{-2}$

small compared to natural flow of energy:

$240 \text{ W m}^{-2}$.

So this is NOT how climate change is experienced.

Instead it has to **accumulate**, which it does under some circumstances, since it is always in the same direction.
Global warming means more heat:

Where does the heat go?

1. Warms land and atmosphere
2. Heat storage in the ocean (raises sea level)
3. Melts land ice (raises sea level)
4. Melts sea ice and warms melted water
5. Evaporates moisture ⇒ rain storms, cloud
   ⇒ possibly reflection to space

>90%
Controlling Heat

**Human body:** sweats

**Homes:** Evaporative coolers (swamp coolers)

**Planet Earth:** Evaporation (if moisture available)

* e.g., When sun comes out after showers, the first thing that happens is that the puddles dry up: before the temperature increases.
Global temperature and carbon dioxide: anomalies through 2020

Base period 1900-99; data from NOAA
Earth’s Energy Imbalance

TOA radiation

Mean
0.7 W m⁻²

Loss of Arctic sea ice and less low cloud. PDO +ve

OLR represents outgoing temperature

Monthly anomalies and 12-month running mean
0.36 W m⁻² => 184 TW
Earth’s Energy Imbalance

TOA radiation

EEI 1.2 W m$^{-2}$

Mean 0.7 W m$^{-2}$

Total solar irradiance contributions

Monthly anomalies and 12-month running mean
What about the atmosphere?

Warmer air holds more moisture

7% per °C = 4% per °F

Global warming:

More heat
More drying
More evaporation
More moisture

More rain
More drought
Take a parcel of air: when it rises (for whatever reason), it expands and cools, and any moisture in it condenses and forms a cloud, and then it rains the moisture out.
Most precipitation comes from moisture convergence by weather systems.

Low level winds bring in moisture from afar.

More moisture means heavier rains.
Adapted from Trenberth 1999
What about the atmosphere?

1 $\text{W m}^{-2}$ (globally) is 510 TW.

64 TW ($0.12 \text{ W m}^{-2}$) accounts for 35% of EEI variability s.d.
Effects accumulate in melted ice

Increased Glacier retreat since the early 1990s

Muir Glacier, Alaska

Arctic sea ice loss: over 40% in summer

This is extent, not volume
Greenland and Antarctica ice melt in terms of energy is about -2.6 and -1.1 TW \( \cong 0.007 \text{ W m}^{-2} \)

<table>
<thead>
<tr>
<th></th>
<th>( \frac{dM}{dt} ) (Gt a(^{-1}))</th>
<th>SLR potential (m)</th>
<th>Total SLE 2003–2019 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Floating</td>
<td>Grounded</td>
<td></td>
</tr>
<tr>
<td>Greenland</td>
<td>N/A</td>
<td>-200 ± 12</td>
<td>7.4</td>
</tr>
<tr>
<td>EAIS</td>
<td>106 ± 29</td>
<td>90 ± 21</td>
<td>51.1</td>
</tr>
<tr>
<td>WAIS</td>
<td>-76 ± 49</td>
<td>-169 ± 10</td>
<td>5.6</td>
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<tr>
<td>AP</td>
<td>-14 ± 28</td>
<td>-39 ± 5</td>
<td>0.5</td>
</tr>
<tr>
<td>Antarctica</td>
<td>15 ± 65</td>
<td>-118 ± 24</td>
<td>57.2</td>
</tr>
</tbody>
</table>

Smith et al. 2019 Science
Effects accumulate in melted ice

Greenland melting has increased

Global ice melt in terms of energy is about 11 TW ≈ 0.03 W m⁻²
What about land?

If land is wet: heat goes into evaporation. But in a drought, the heat accumulates.

- **Drying**
- **Heating**

1 W m$^{-2}$ over a month, if accumulated, is equivalent to 720 W m$^{-2}$ over 1 hour.

720 W is equivalent to full power in small microwave oven. 1 m$^2$ is 10 sq ft.

⇒ 1 microwave oven at full power every square foot for 6 minutes:

No wonder things catch on fire!
What about land?

Land use and land cover change from clearing for agriculture and pasture, and wood harvest is about 1/3 of human CO$_2$ emissions.

It also changes energy fluxes via albedo, hydrology, and vegetation; and via irrigation.

Forest increased 7% globally 1982 to 2016

loss in tropics vs increase in extratropics

Bare ground increased 3%.

Surface signal takes ~ 50 years to penetrate to 50 m depth. Varies spatially, especially where water plays a role.
What about land?

Borehole temperature changes: rate of land warming after 1950 is ~6 - 7 TW, increasing after 2000 to ~10 -12 TW.

Inland waters cover 2.6% of continental area. Artificial reservoirs have increased global lake volume by 3.2%: modestly since 2005. Since 2005, the mean trend in global lake, river and reservoir heat uptake is ~0.4 TW and energy in increased mass of waters in reservoirs is about 0.9 TW.

vanderkelen et al. 2020: GRL

A borehole may be constructed for: extraction of water, oil or natural gas; a geotechnical investigation to assess ground properties (e.g., for construction purposes); environmental site assessment; mineral exploration; as a pilot hole for installing piers or underground utilities; geothermal installations, or underground storage of unwanted substances.

Most boreholes are drilled for other purposes, and are therefore heavily biased as to where they are located.
What about the oceans?

OHC
Ocean Heat Content

New observations: Argo floats, since about 2005
Trend in ocean heat 1960 to 2019

Cheng et al 2020
Global ocean heat content change in the upper 2000 m

OHC anomaly (ZJ)

Annual mean

Monthly mean

Baseline 1981-2010

OHC heat content stripes

0-500m

500-1000m

1000-1500m

1500-2000m

Cheng et al. 2021
OHC and rates of change

0.8 W m$^{-2}$

El Niño
A consequence of glacier melt and ocean heating: Sea Level Rise

380 ZJ ocean warming since 1960 corresponds to ~47 mm global SLR (thermometric)
<table>
<thead>
<tr>
<th>Component</th>
<th>Value (TW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>3.4</td>
</tr>
<tr>
<td>Thawing permafrost:</td>
<td>2</td>
</tr>
<tr>
<td>Land warming</td>
<td>14</td>
</tr>
<tr>
<td>Arctic Sea ice</td>
<td>3.8</td>
</tr>
<tr>
<td>Greenland</td>
<td>2.6</td>
</tr>
<tr>
<td>Antarctica</td>
<td>1.2</td>
</tr>
<tr>
<td>Glaciers</td>
<td>3.4</td>
</tr>
<tr>
<td><strong>Ice Total</strong></td>
<td><strong>11</strong></td>
</tr>
<tr>
<td><strong>Non-ocean</strong></td>
<td><strong>30 TW (7% total)</strong></td>
</tr>
<tr>
<td>vs Ocean*</td>
<td><strong>430±70 TW</strong></td>
</tr>
</tbody>
</table>

**EEI:** \(0.9±0.15 \text{ W m}^{-2}\) since 2005

* Includes contribution from below 2000m depth.
Regional manifestations
Vertically integrated energy budgets

The divergence of the energy transport has to match the sources and sinks, and any change in storage.

\[ \nabla \cdot F_A = Q_1 - Q_2 = R_T + F_s \]

\[ \nabla \cdot F_O = -\frac{dOHC}{dt} - F_s \]
Balancing the energy budget locally:
Annual mean surface flux

Trenberth et al. 2019
Meridional Energy Transports

Ocean Mean annual cycle

Ensemble mean. Sea-ice formation/melt included
Meridional Heat Transports (MHT) variability adjusted to satisfy global constraints.

Ensemble mean
March 2000 to March 2018
12-mo running means.
Atlantic MHT

Top 2000m

12-mo running mean

Ensemble mean
North Atlantic meridional heat transport 26°N

RAPID/MOCHA is an ocean moored array across about 26°N

ORAS5 is operational and high resolution (2000m).

0.15 PW offset
12 month running means
Meridional Heat Transport
0-2000m
12-mo running mean

Pacific

Niño 3.4

Trenberth and Zhang 2019
Indonesian ThroughFlow (ITF)

- ITF component (from model with ITF open vs closed)
- Results from ORAS (Meyer et al. 2018) below

Trenberth and Zhang 2019
Unprecedented 2015/16 Tasman Sea marine heatwave

- Oliver et al (2017; N Comms): most intense heatwave ever in Tasman Sea in 2015/16
- 251 days reaching a maximum intensity of 2.9°C
- Anomalous convergence of heat linked to the southward flowing East Australian Current.

Ecosystem impacts:
- New disease outbreaks in farmed shellfish, mortality of wild molluscs and out-of-range species observations.
- Mass mortality of abalone, oysters, salmon, giant kelp. Surfers affected...
- Yellowtail kingfish, snapper, mahi mahi, moki, moonlighter, dusky morwong fish
Other regional marine consequences
Marine heat wave
“The Blob”
2014–2016

The whole food web was decimated:
- Phytoplankton
- Zooplankton
- Krill
- Swarms of small fish
- Birds—auklets, murres
- Cod 100 million
- Humpback whales hundreds
disappeared by 2017

Cornwall: 1 Feb Science 2019
SST and changes
83 dead
Displaced more than 1,000,000
Damages $150 to $180B

(Reuters)

Landfall Aug 25 cat 4
Peak 300,000 homes no power
185,000 homes damaged
1 in 6 had flood insurance
440,000 registered with FEMA
for aid as of Sep 1.

64.58” of rainfall at Nederland
TX: highest anywhere in US
60.54” at Lake Charles…
OHC changes: Harvey

OHC loss: $5.9 \times 10^{20} \text{ J}$
Rain LH: $6.0 \times 10^{20} \text{ J}$

Base period 1961-90
Other Consequences
Some recent **Floods, heatwaves, wildfires**

- **More Than 1,000 Died in South Asia Floods Summer 2017**
  - 41 million people affected
  - 330 mm rain in Mumbai 29 Aug

- **India flooding Sep 2019**

- **UK flooding Oct 2019**

- **Venice Nov 2019**

- **Flooding Japan: July 2-9 2018**
  - Heaviest rainfall in 35 years
  - Death toll >200;
  - >7000 homeless
  - Also Oct 2019

- **Heatwaves Japan 26 July, 18:**
  - >80 deaths; >22,600 with heat stroke in hospitals
  - Kumagaya: 41.1°C (106°F):
    - Highest ever in Japan.
  - Tokyo: temperatures 40°C.

- **California wildfires Nov 2018 Camp Fire: Deadliest, most destructive ever.**
  - 77 dead + 12,637 houses burned
  - 3,800 other structures
  - 152,000 acres
  - >8000 blazes, very poor air quality

- **Oct-Nov 2019: Kincade: blackouts; 180K evacuated**

- **Brazil (Amazon) wildfires Aug 2019**
Are recent typhoon/hurricane disasters natural?

(Hurricanes Harvey, Irma, Maria, Florence, Michael, Dorian, Cyclones Idai, Kenneth, Fani; Typhoons Mangkhut, Hagibis)

- Yes: hurricanes are natural
- No: they are supersized

These events would not have occurred without human-induced climate change.

And they have been further exacerbated by poor preparedness.

1. Wind related damage as the storm comes ashore
   Consequences: flying debris, falling trees, power outages

2. Coastal storm surge
   Much worse if landfall occurs at high tide
   Mainly coastal: worse if no wetlands or buffer
   Worsens as sea level rises

3. Heavy rains and flooding
   Can extend far inland

With climate change:
- More intense hurricanes
- Bigger hurricanes
- Longer-lasting hurricanes
- More flooding rains
Typhoons on tracks for Asia in 2020

TYPHOON PARADE:

Vamco 7th to hit Vietnam:

>100 died. 400,000 homes destroyed in Oct

Goni 31 Oct 20

Molave Oct. 28, 2020

Typhoon Goni on Oct 31, 2020

Typhoon Vamco on Oct 7, 2020

Typhoon Molave on Oct 28, 2020

Typhoons on tracks for Asia in 2020
Subtropical Storm Iota made headlines as the 30th named storm of the 2020 Atlantic Hurricane Season this week. (16 Nov 20)
Yasa Dec 17, 2020
Cat. 5 devastated Fiji
CATASTROPHIC FIRE DANGER
Greater Sydney
Greater Hunter
Illawarra/Shoalhaven
Tuesday 12 November 2019

Mean live fuel moisture content
Oct 24 - 31, 2019

Dry
Transitional
Wet
Recent wildfire (can’t model dryness)

Source: unpublished data, R. H. Nolan, M. M. Boer, R. A. Bradstock
California wildfires 2020

2020 exceeded 2018 as worst on record.

17 Sep:
More than 3.3 million acres have burned so far this season in California, double the record set in 2018. The blazes destroyed over 4,200 structures and killed 25 people.

Fires in California through mid-September burned enough forest to put about 91 million metric tons of CO₂ into the air: 3x more than total CO₂ emissions for providing power to the entire state.
Costs of Climate Change

- Climate change is happening
- It is caused by human activities
- For many events we can estimate that the difference from climate change is 5 to 20%
- But this means records are broken
- Thresholds are crossed
- Things break/food/burn; people die
- **EXTREME NON-LINEARITY**

- So instead of US$1B in damage, the damage is $100B
- The real cost of climate change is grossly underestimated by economists.

“The straw that breaks the camel’s back” syndrome
EEI has implications for the future

- We can now balance the energy budget locally
- We can link these variations to heat waves which have profound consequences in both hemispheres.
- These methods bring in new information
  - there is a lot of information in the coupled system not being utilized in many analyses.
- Constrains many datasets --- and models
Some Recommendations

- **EEI** varies esp. with clouds, and ENSO
- **It is not well known**
  - OHC can and must be done much better as a coupled problem, not an ocean one.
  - Land is largely unknown
  - Ice is poorly known: various syntheses do not overlap
  - Surface fluxes can be useful but only in a coupled context
- **Analyzing** land and ice in this framework would greatly improve knowledge about each component and set the stage for **initialized Earth system prediction**
- **Models** must improve, and using this framework provides a way.
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