CAMF—A Coldwater-fisheries Adaptive Management Framework

A Tough Reality:
Climate Change, Trout Habitat and the Upper Dolores Watershed

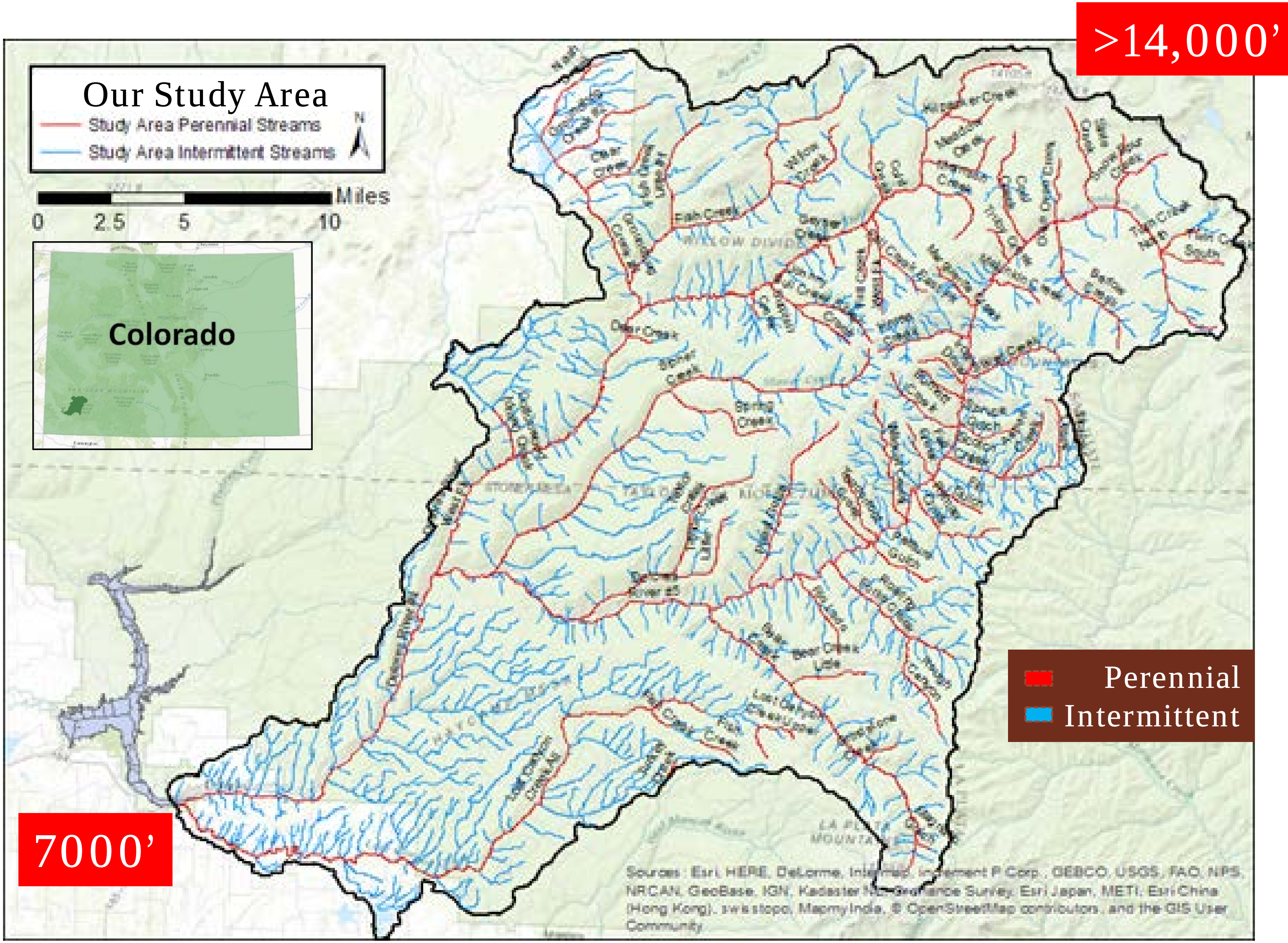
Study by Dolores River Anglers
Chapter 145, Trout Unlimited

Duncan Rose, DRA

Western Regional/CTU Rendezvous 2018

What Is the Purpose of CAMF?

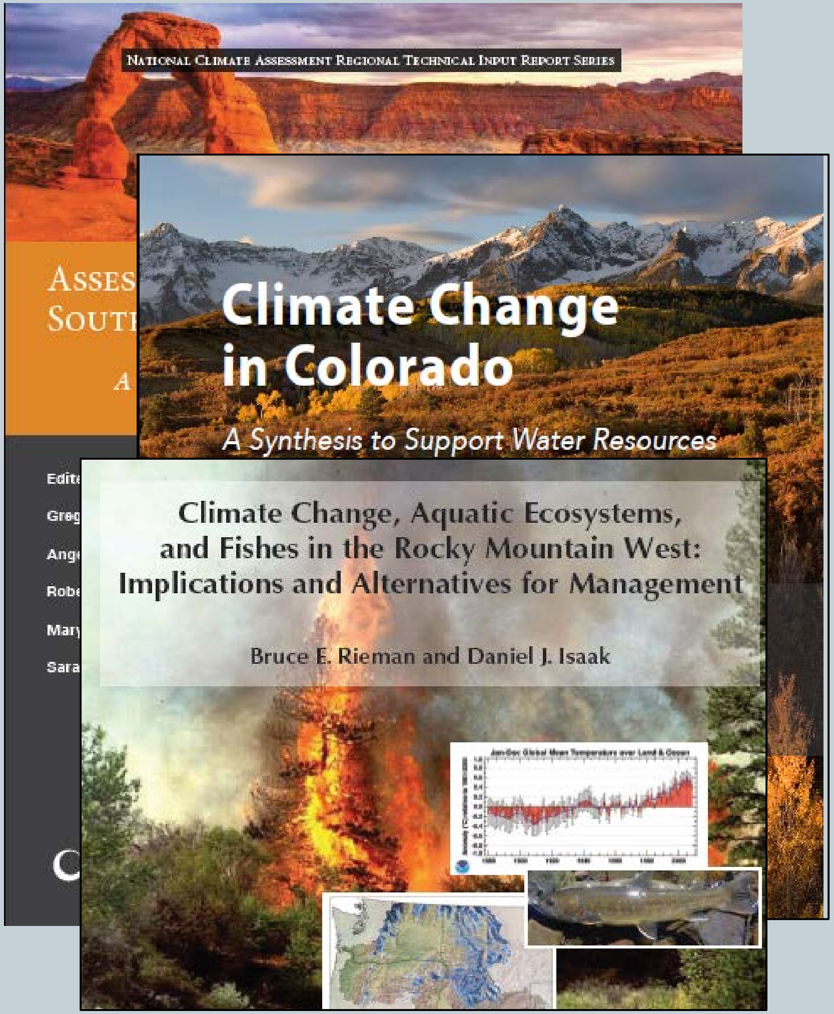
- CAMF is the result of a three-year effort to systematically identify and map *native and wild **trout strongholds** within the context of climate change.*
- *We wanted to build a long-term framework to inform DRA and agency management decisions.*
- This effort is specifically focused over a long timeframe (to 2100) on the upper Dolores watershed, situated in the Four Corners area of southwestern Colorado.
- We wanted our efforts to be transferable to interested chapters.
- We incorporated three core paradigms: 1) trout habitat limiting factors analysis, 2) vulnerability analysis, and 3) adaptive management/planning.



>14,000’
Our Study Area
Study Area Perennial Streams
Study Area Intermittent Streams
N
Miles
0 2.5 5 10
Colorado
Perennial
Intermittent
7000’
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Substantial changes are underway & ahead

- With very few exceptions, *current* coldwater-fisheries in the Study Area are healthy; populations are persistent.
- However, local data and highly credible science indicate that substantial systemic changes are already underway, thought to be due largely to greenhouse effects.
- Our review of on-point climate change research for the Southwest indicates that climate change will substantially and increasingly continue to affect our Study Area between now and 2100.
- The major impacts fall around two ecological attributes: *temperature and precipitation*.



CAMF- Searching for “Strongholds”!

- Core Question: Which stream reaches are likely to have persistent trout populations in the face of climate change ?

Four Stages of the Project

Trout habitat limiting factors “state of the science”

Climate change modeling, esp. for Southwest Colorado

Downscale to San Juans, UD vulnerability analysis in UD

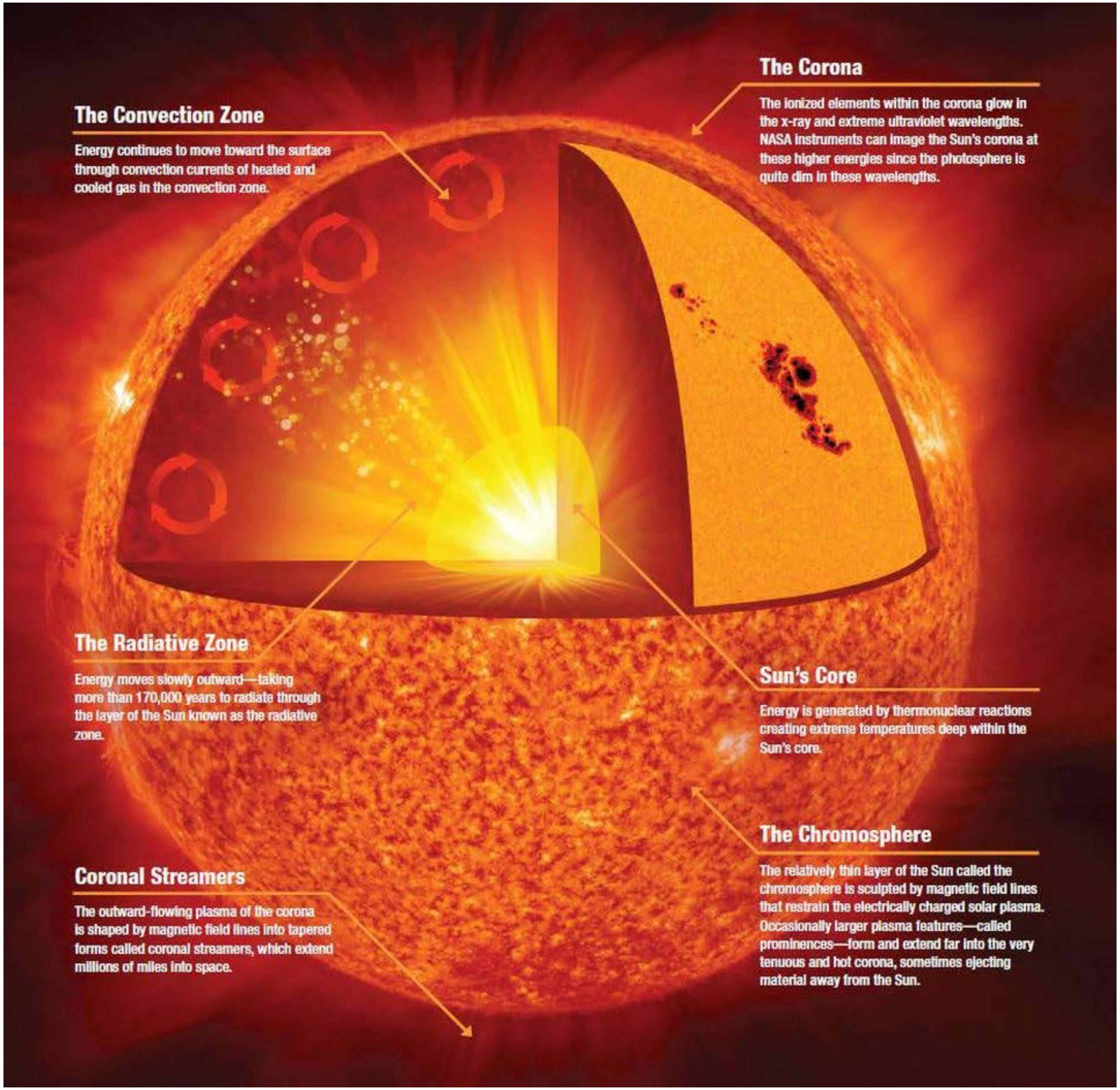
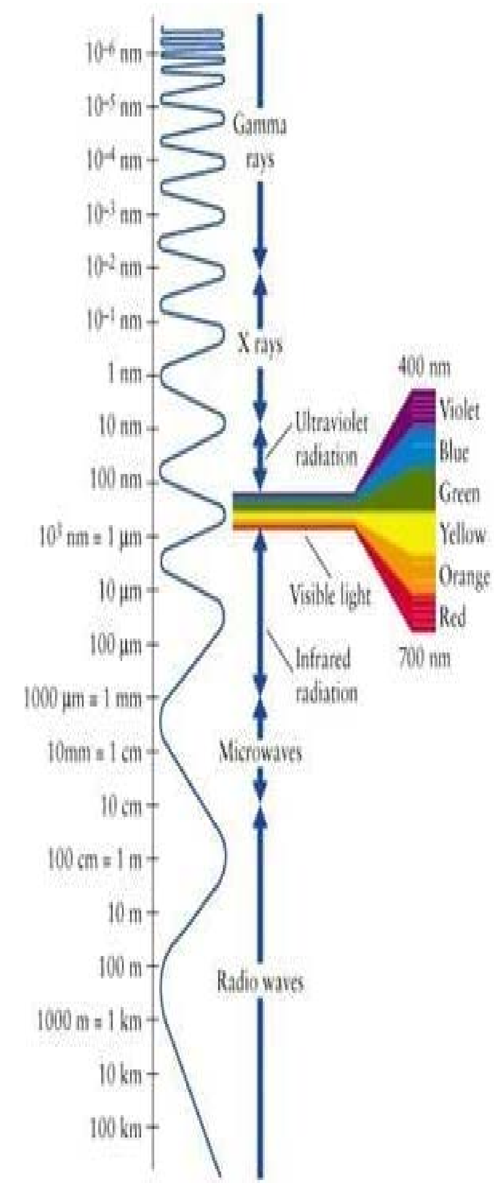
Adaptive management considerations in UD

Why and How Is Our Global Climate Changing?

Climate Change – a Brief Refresher

Climate change and the Greenhouse Effect

- *"…the Greenhouse Effect (GHE), due mostly to greenhouse gases, is largely caused by the fact that the atmosphere emits IR (infrared) energy downward, the so-called "back radiation*".
- This single component of the whole GHE process basically, then, determines all of the other features of the greenhouse effect and leads to net GHE warming of the Earth's surface."


The Corona
The ionized elements within the corona glow in the x-ray and extreme ultraviolet wavelengths. NASA instruments can image the Sun's corona at these higher energies since the photosphere is quite dim in these wavelengths.
The Convection Zone
Energy continues to move toward the surface through convection currents of heated and cooled gas in the convection zone.
The Radiative Zone
Energy moves slowly outward—taking more than 170,000 years to radiate through the layer of the Sun known as the radiative zone.
Sun's Core
Energy is generated by thermonuclear reactions creating extreme temperatures deep within the Sun's core.
The Chromosphere
The relatively thin layer of the Sun called the chromosphere is sculpted by magnetic field lines that restrain the electrically charged solar plasma. Occasionally larger plasma features—called prominences—form and extend far into the very tenuous and hot corona, sometimes ejecting material away from the Sun.
Coronal Streamers
The outward-flowing plasma of the corona is shaped by magnetic field lines into tapered forms called coronal streamers, which extend millions of miles into space.

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1000 µm = 1 mm
10mm = 1 cm
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100 cm = 1 m
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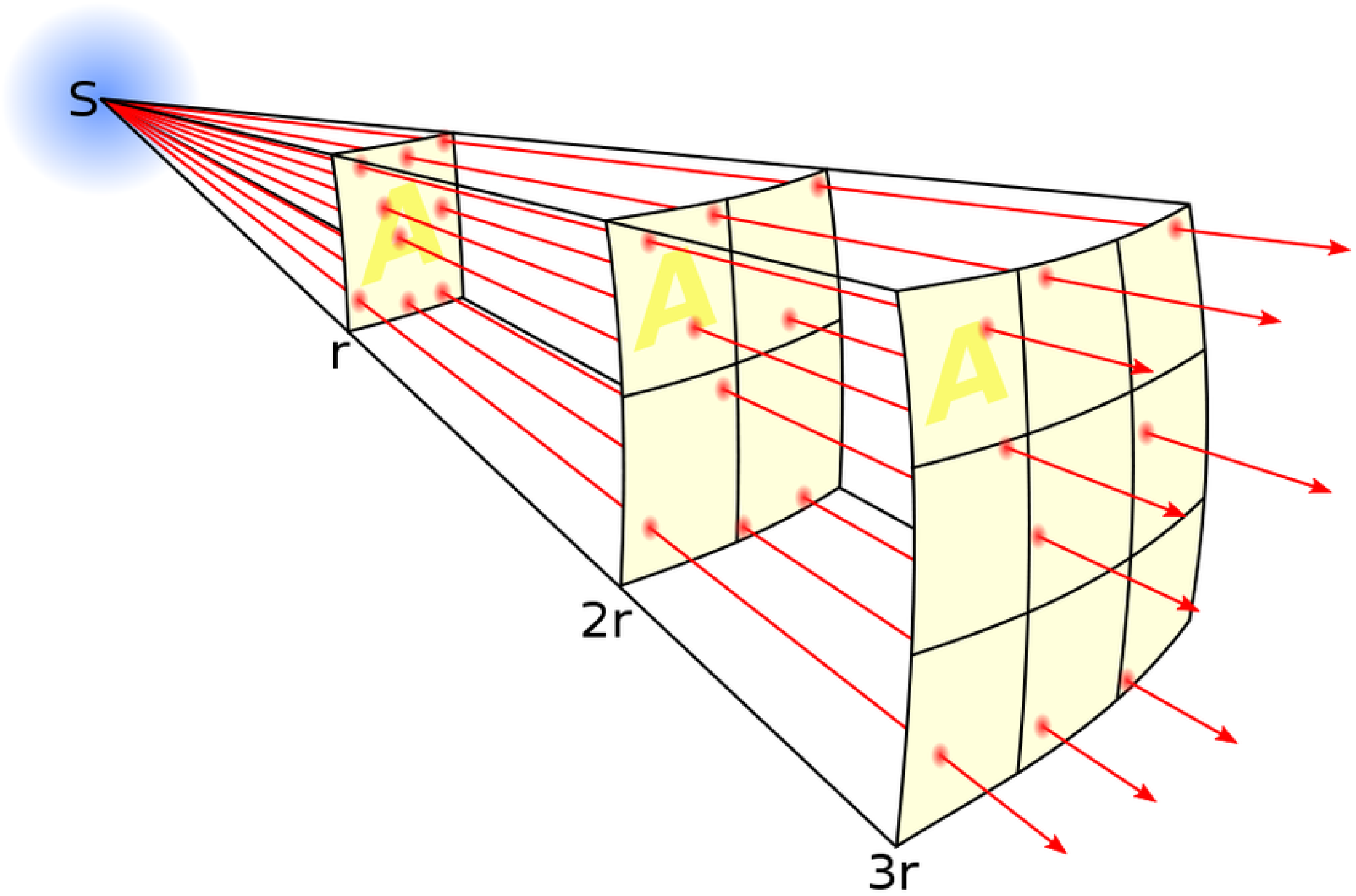
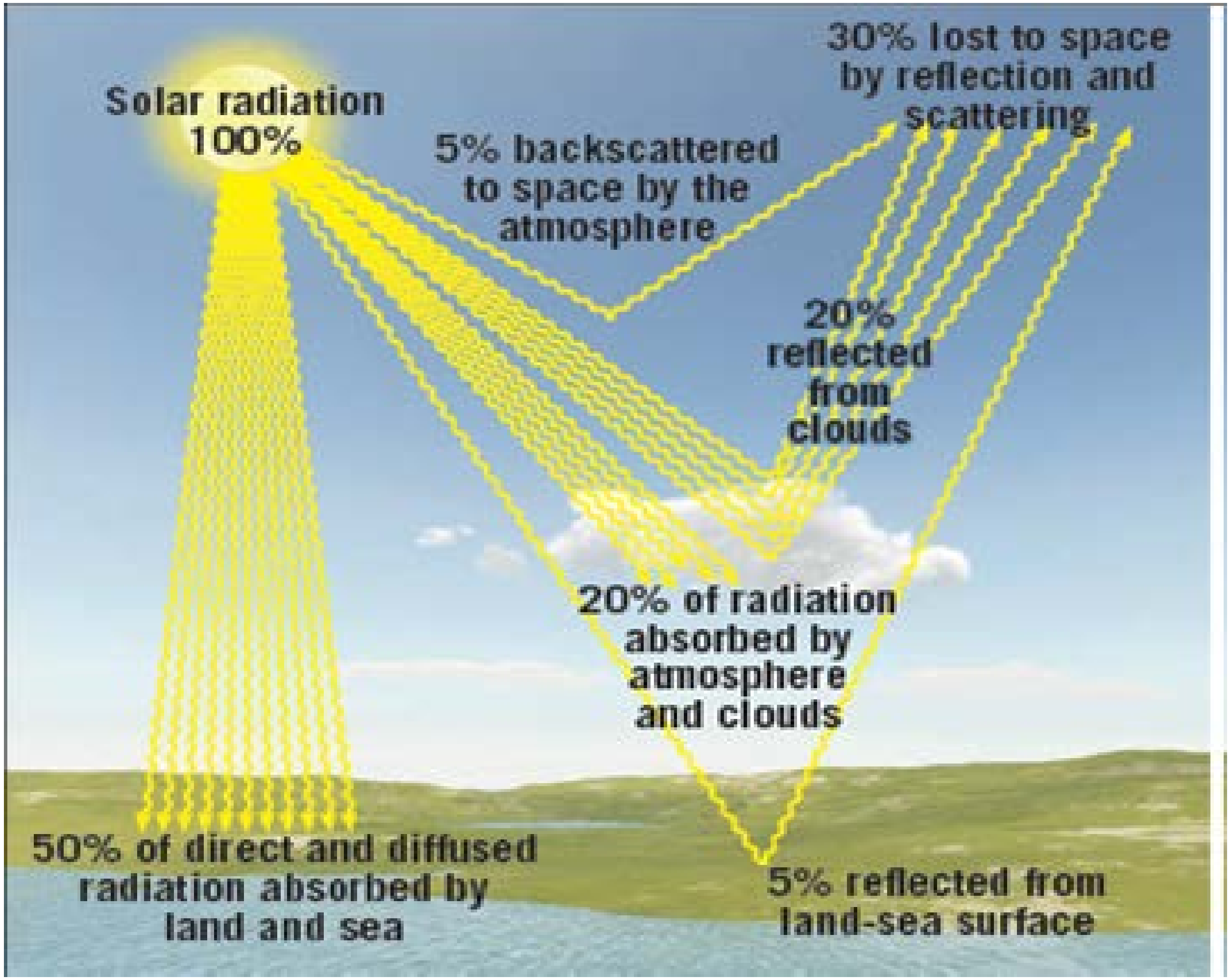
100 m
1000 m = 1 km
10 km
100 km
Gamma rays
X rays
Ultraviolet radiation
Visible light
Infrared radiation
Microwaves
Radio waves
400 nm
Violet
Blue
Green
Yellow
Orange
Red
700 nm

As Radiative Energy Spreads, Density Reduces With Square of Distance



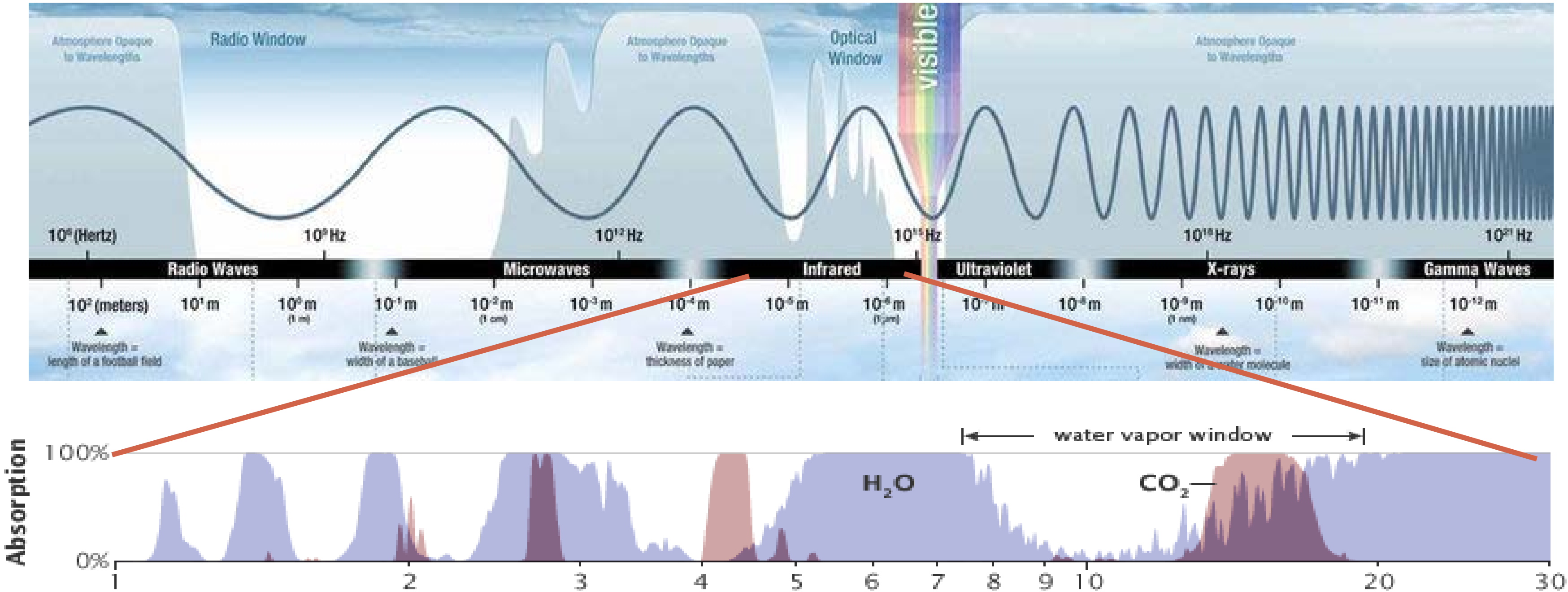
https://www.forbes.com/sites/startswithabang/2019/01/02/the-simplest-explanation-of-global-warming-ever/#22ea6b4232b1

Reflection & Absorption: Earth's "Energy Budget"



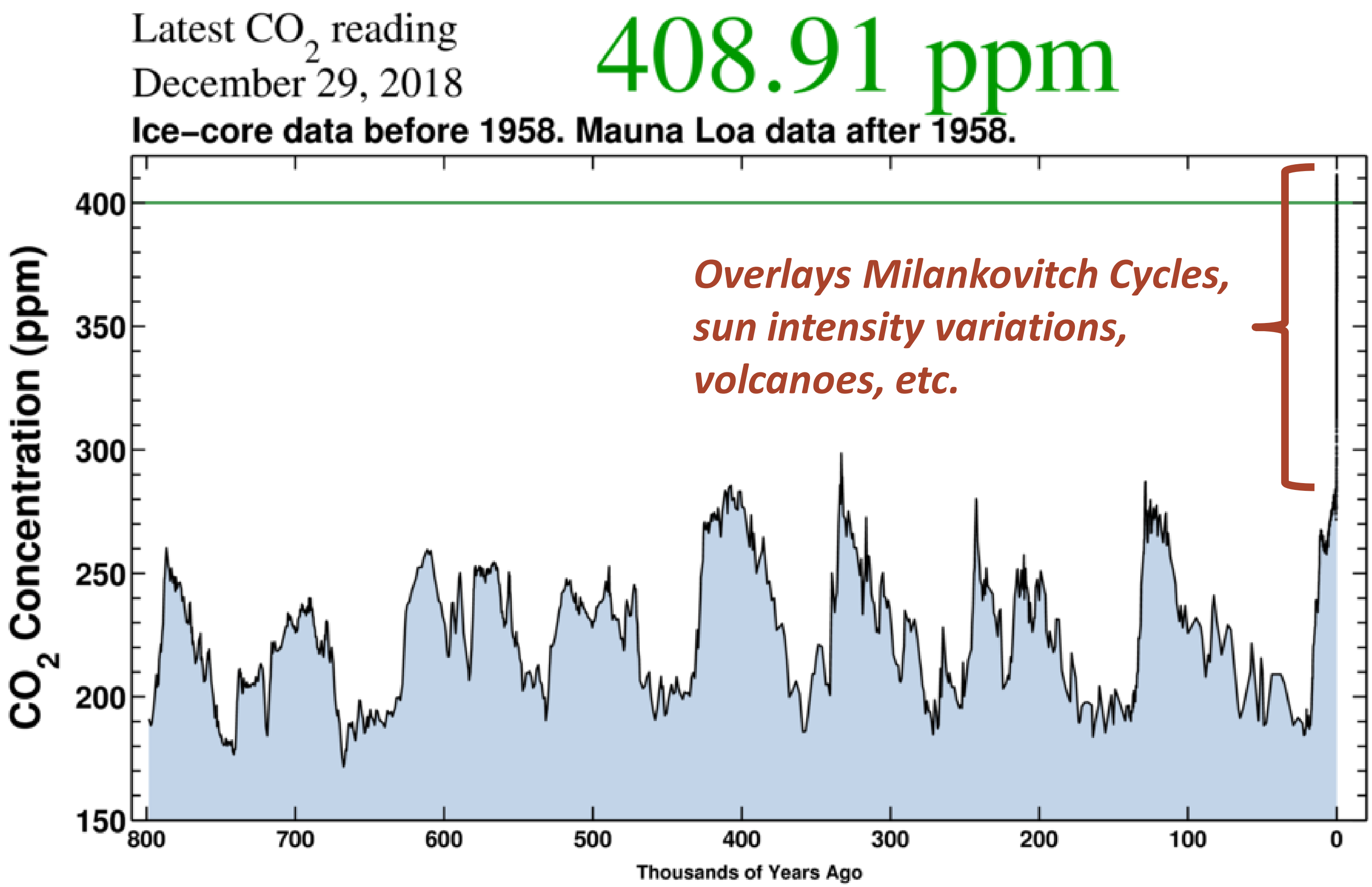
https://pmm.nasa.gov/education/lesson-plans/global-energy-budget

The Atmosphere's Radiation Windows



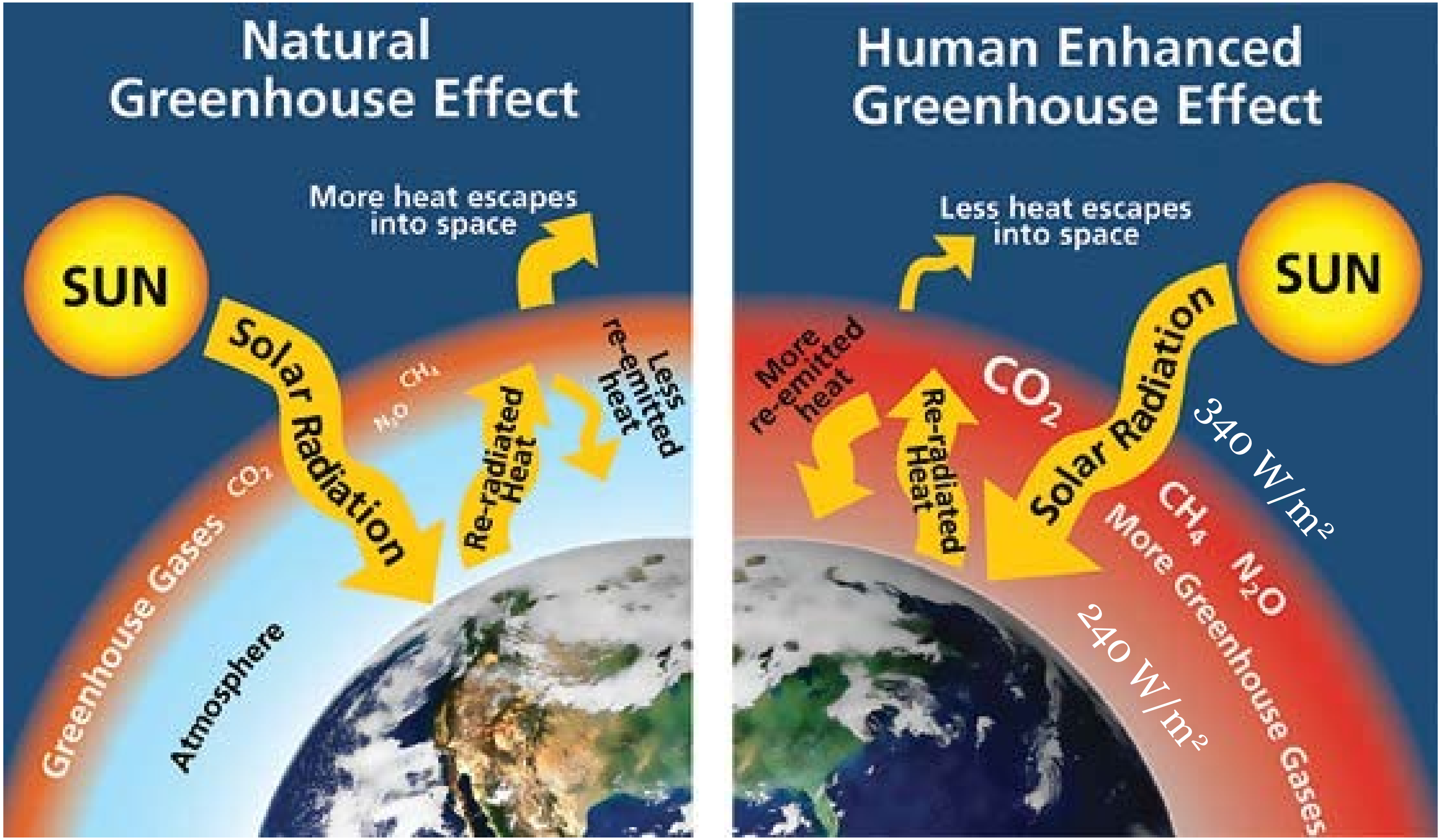
The major atmospheric gases (oxygen and nitrogen) are transparent to incoming sunlight; they are also transparent to outgoing thermal infrared. However, water vapor, carbon dioxide, methane, and other trace gases are opaque to many wavelengths of thermal infrared energy. Clouds, aerosols, water vapor, and ozone directly absorb 23 percent of incoming solar energy. Evaporation and convection transfer 25 and 5 percent of incoming solar energy from the surface to the atmosphere. These three processes transfer the equivalent of 53 percent of the incoming solar energy to the atmosphere.

Greenhouse Gases are Climbing Rapidly



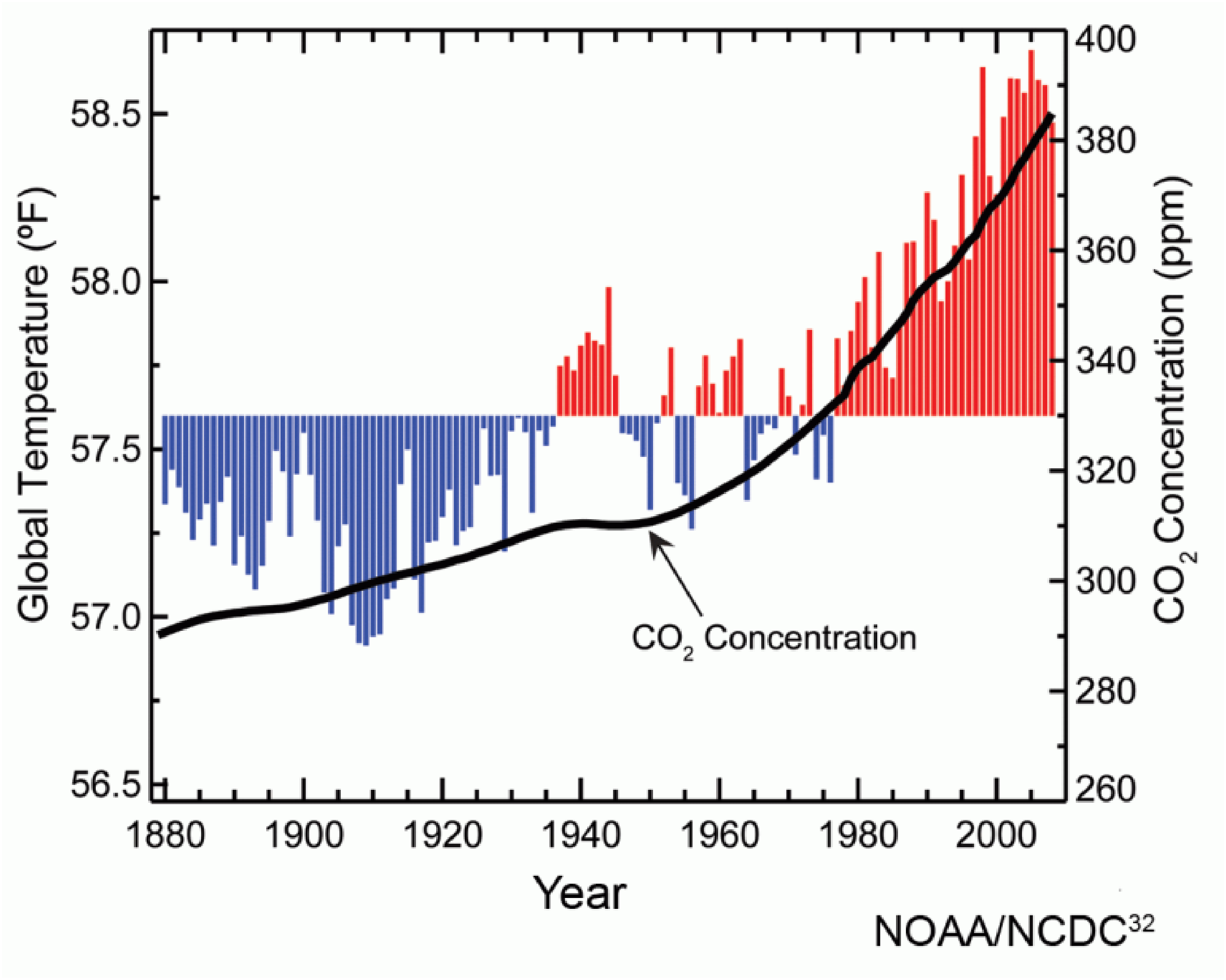
https://scripps.ucsd.edu/programs/keelingcurve/

Increasing Greenhouse Gases Trap More Heat

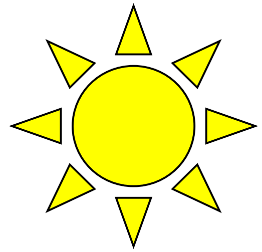


https://www.nps.gov/goga/learn/nature/climate-change-causes.htm

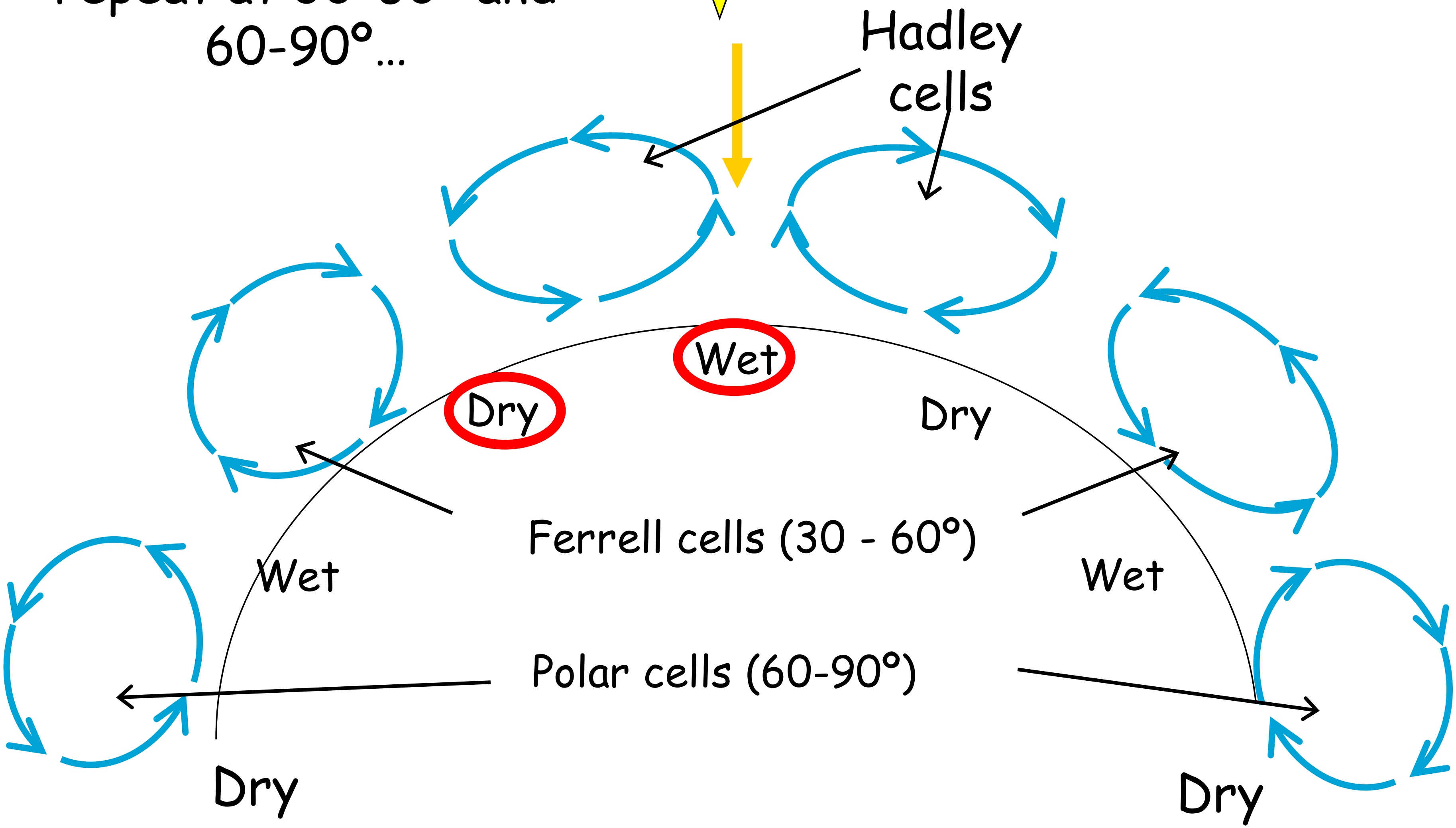
As CO2 Rise, So Do Temperatures



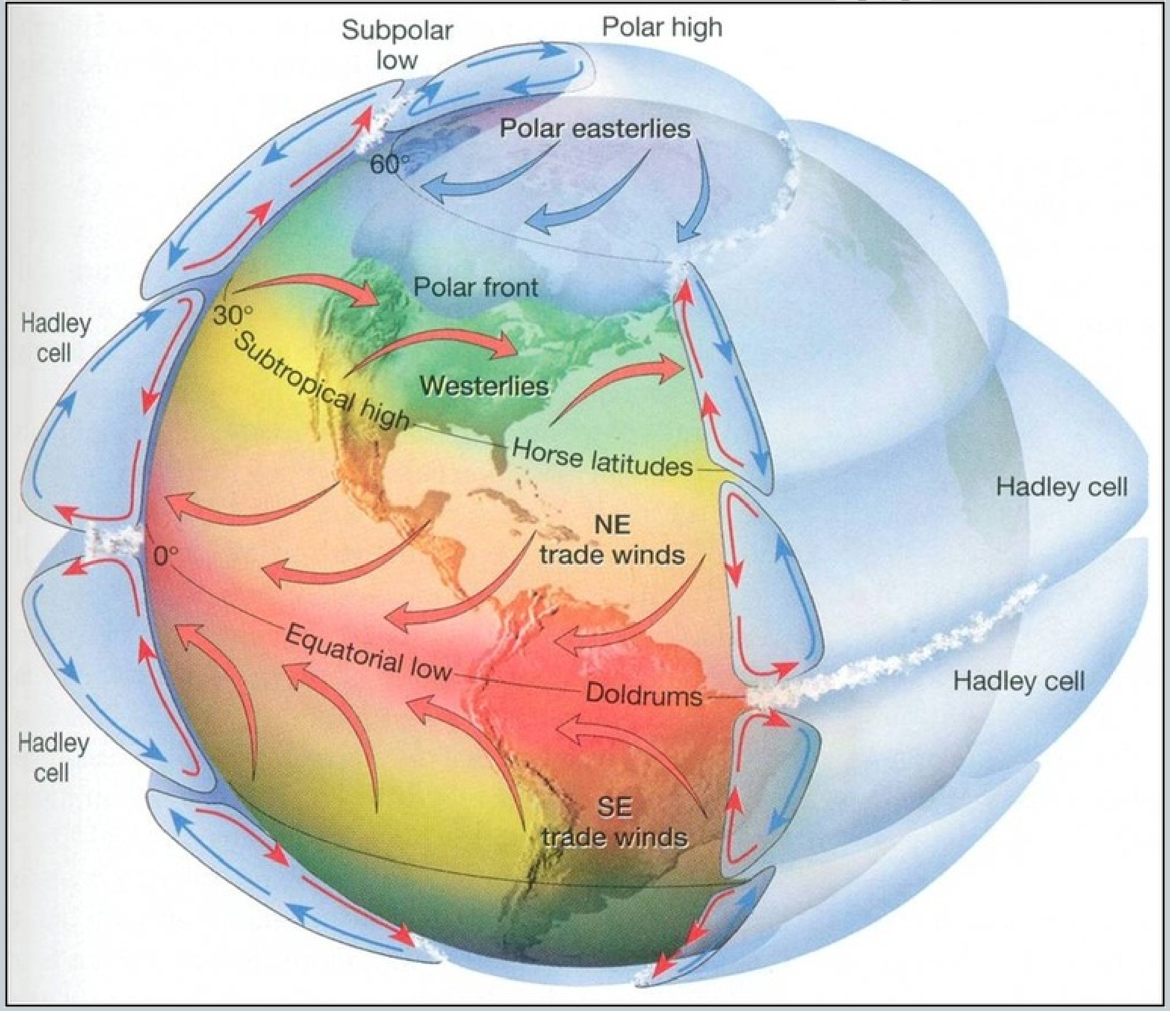
Circulation patterns repeat at 30-60° and 60-90°…



These are called circulation cells – the basic units of vertical atmospheric circulation



Ocean/Air interface - The Intertropical Convergence Zones (ITCZs) Conveyor Belt



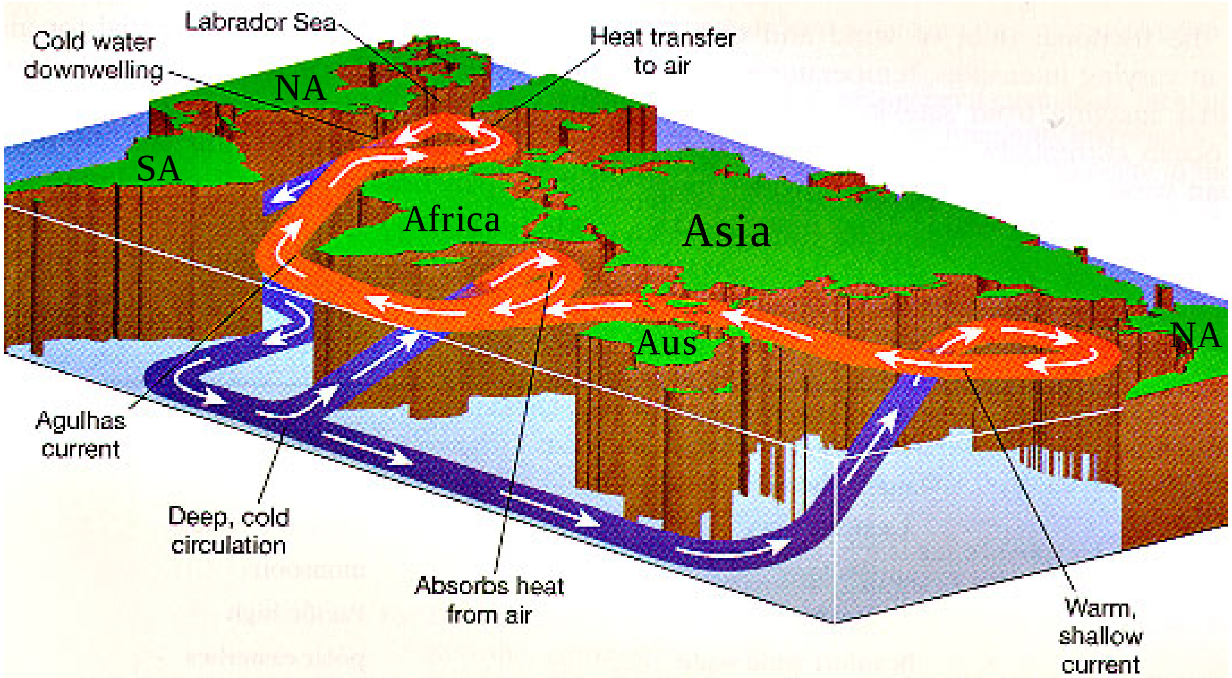
Ocean currents move 40% of "excess heat" from equator to poles (60% of heat transport is carried by atmosphere through storms that move along pressure gradients).

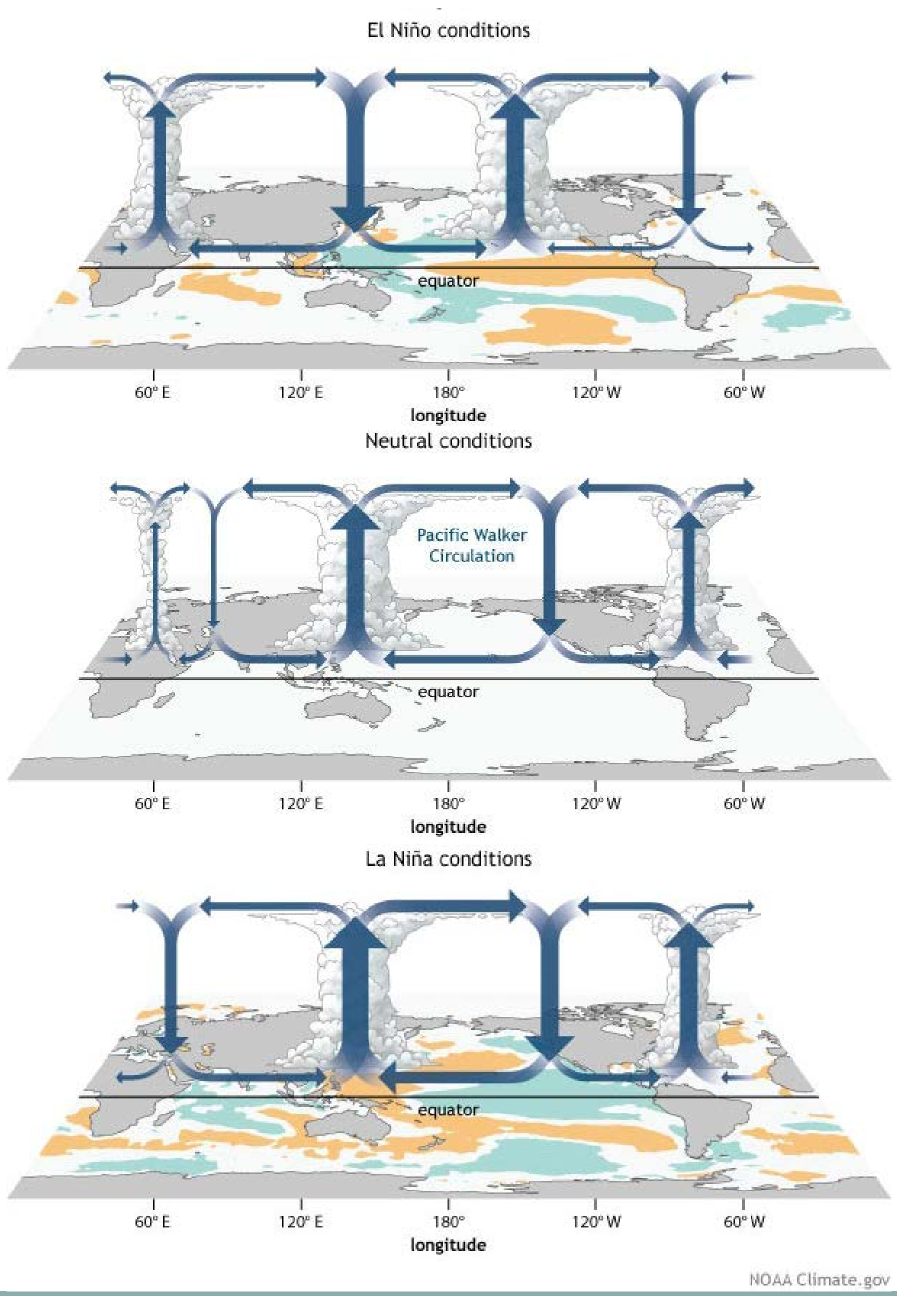
http://www.regents-earthscience.com/climate.html

Heat Transfer Into, Through Oceans Drives Currents

Deep ocean currents are driven by cooling, freezing of pole-bound water (thermohaline circulation).

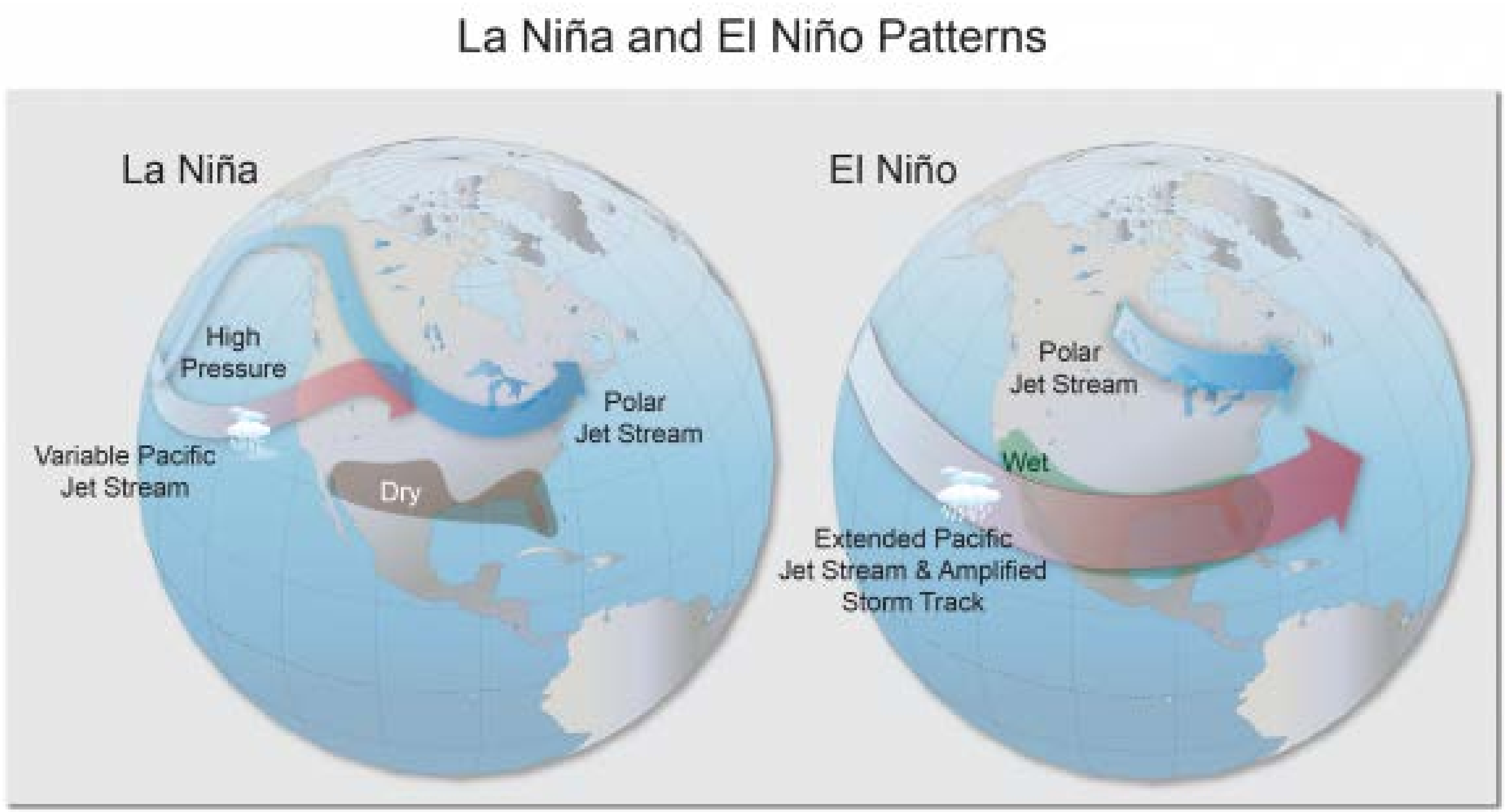
- Deepwater formation occurs at high latitudes (near Greenland and Antarctic)
- Upwelling at lower latitudes, western continental margins due to Coriolis effect.





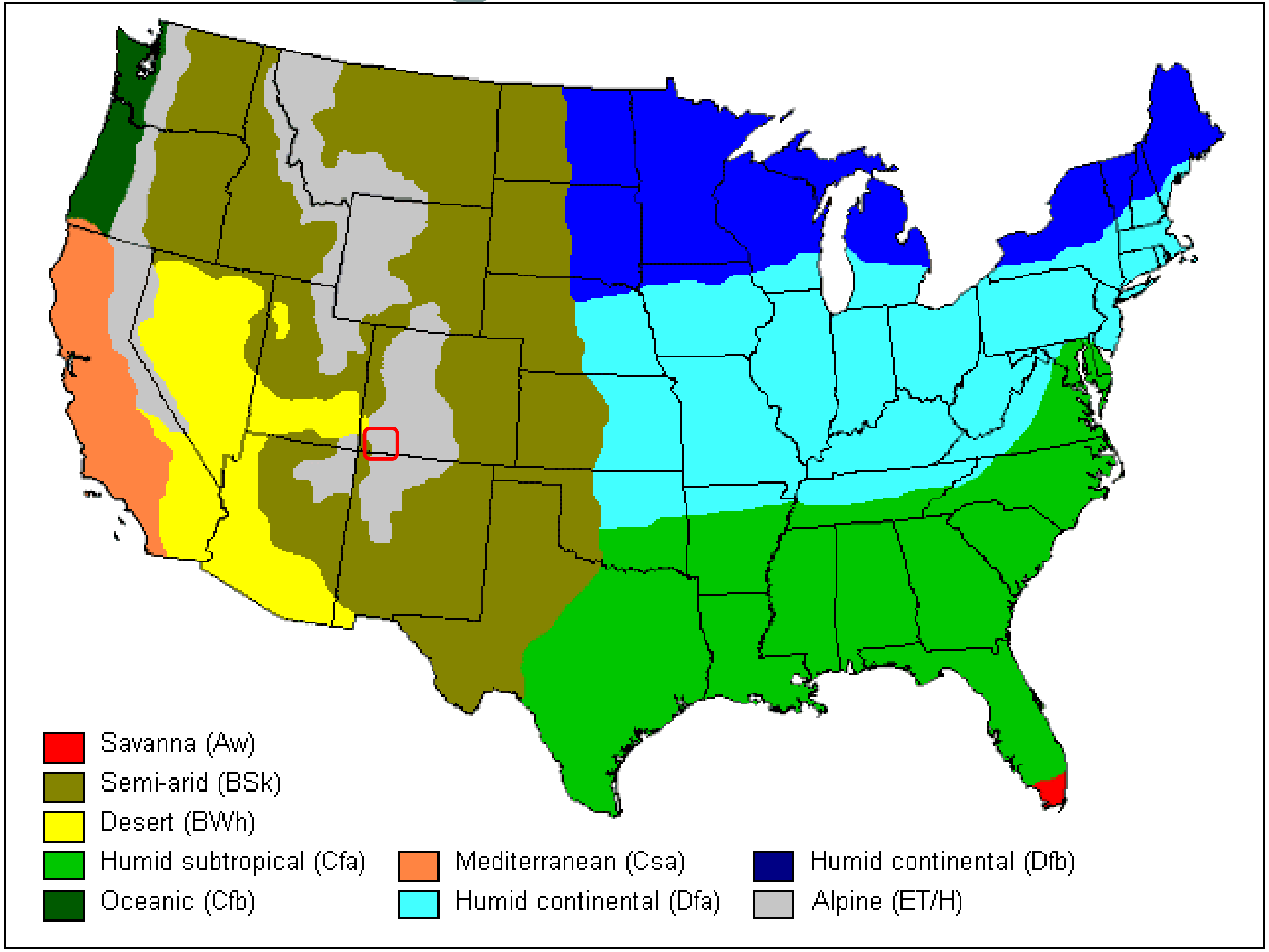
The Thermodynamics of the Air/Ocean Interface Drives Global Weather System…

…Which Drives Local Weather Systems…



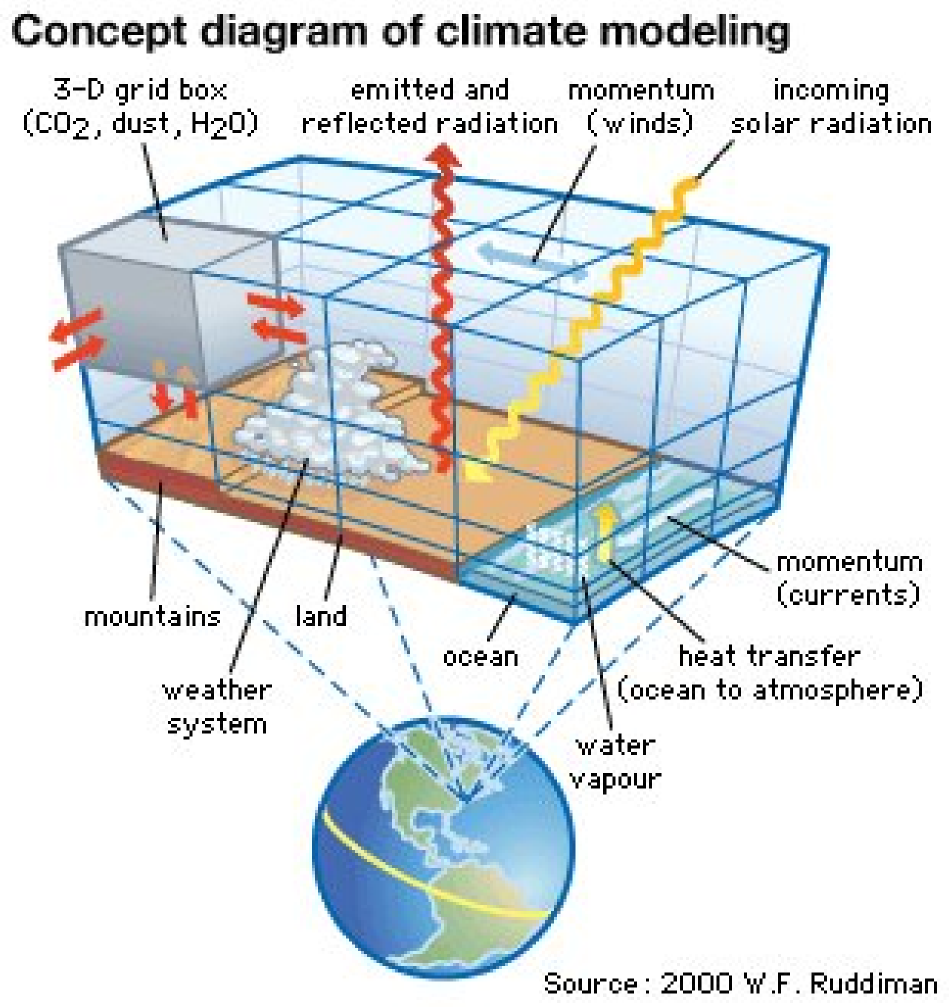
…Which, Over Time, Results In Definable Climate Zones

Climate of any region is predictable from topography, wind and ocean currents



http://www.ocs.orst.edu/pub/maps/Precipitation/Total/States/WA/wa.gif fire.biol.wwu.edu/hooper/416_02**climate**.ppt

CMIP5: Climate Modeling Meets "RCPs"



1. At the heart of climate change modeling are physical and probabilistic climate models.
2. Population growth, land use changes and other more qualitative aspects (human systems) are incorporated.
3. These are tied together with qualitative modeling for policy decision scenarios – "RCPs".

- Four substantially different scenarios that characterize the possible impact of climate change policy/action on GHG emissions levels have been developed by the Intergovernmental Panel on Climate Change (IPCC).
- These scenarios are used as standard baselines for discussion. The scenarios are termed “Representative Concentration Pathways”, or “RCPs”.
- Each RCP is associated with a number that represents the average net increase from solar gain ***in watts per square meter*** over the face of the earth under that scenario.

RCP 2.5

Assumes aggressive mitigation strategies are deployed that see CO@ levels decrease by mid 2020s and to reach zero levels by 2080. This scenario will stabilize global mean temperature increase below 2C relative to ~1870. CO_2 peaks at 490 PPM.

RCP 4.5

Assumes moderately high global action to control emissions. Emissions fall below 2015 levels by 2070 and CO_2 concentrations stabilize by 2100 at about twice 1870 levels. CO_2 peaks at 650 PPM.

RCP 6.0

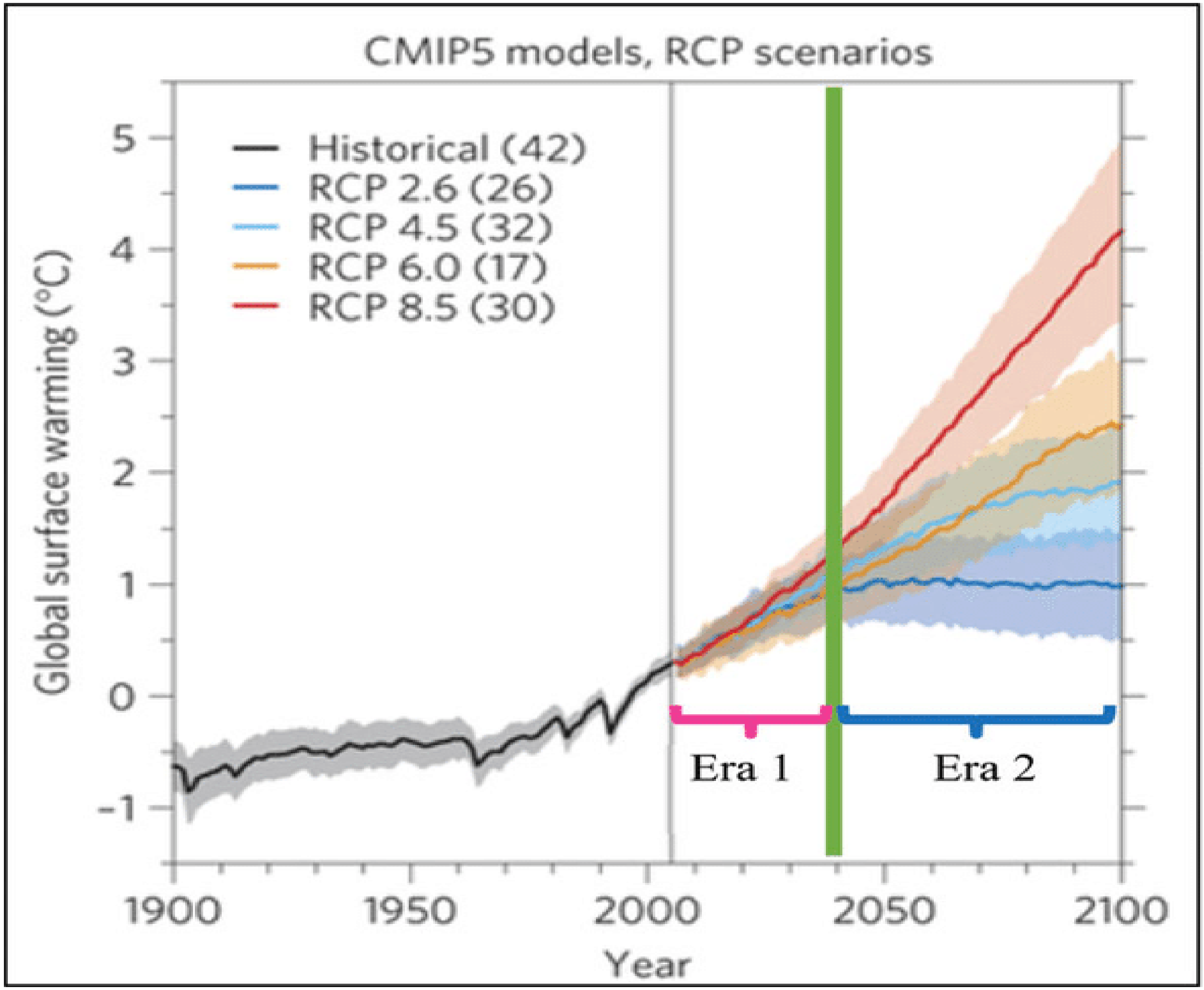
Assumes moderately low global action to control emissions. This is a stabilization scenario where emissions keep rising until about 2018, then level off. CO_2 concentrations take into 2100 to stabilize at about 850 ppm.

RCP 8.5

Assumes “business as usual”, no significant moderation of GHG. By 2100 atmospheric concentrations of CO_2 peak at 1370 ppm, 3 to 4 times higher than 1870 era.

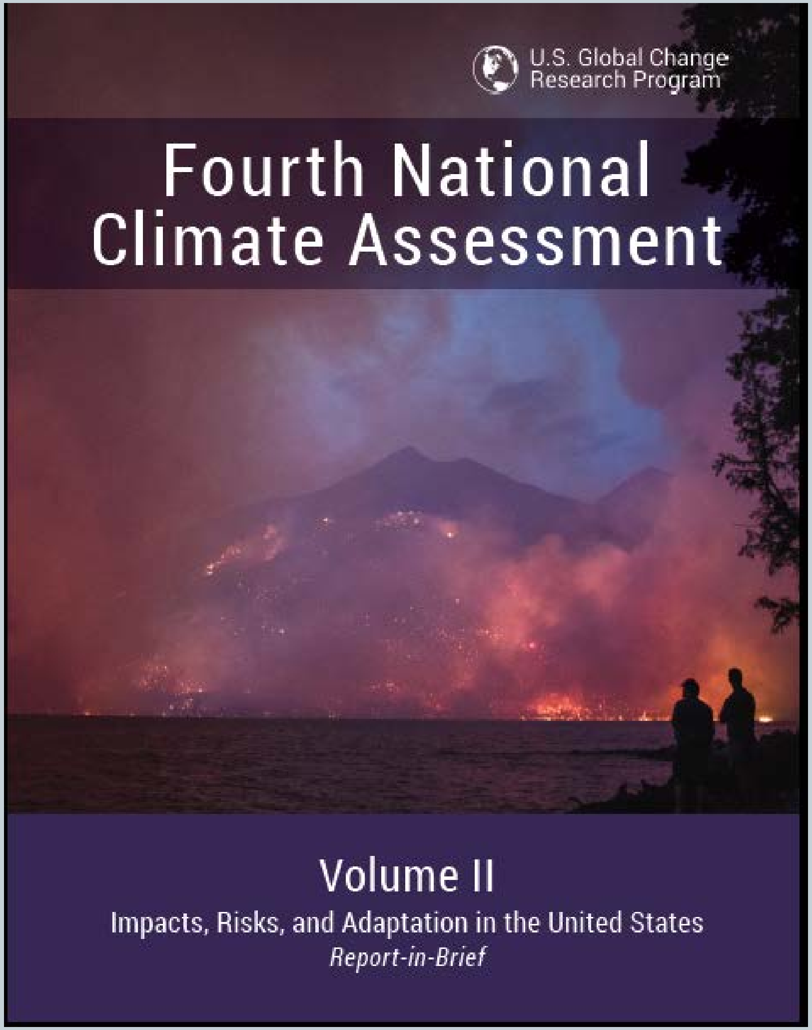
CMIP5: How the 4 RCPs Reflect Future GMT*

*Global Mean Temperatures



Downscaling to the Southwest, Upper Dolores

#1. Fourth National Climate Assessment (2018)



- "Earth's climate is now changing faster than at any point in the history of modern civilization, primarily as a result of human activities.
- Climate-related risks will continue to grow without additional action.
- Humans are adding carbon dioxide to the atmosphere at a rate far greater than it is removed by natural processes, creating a long-lived reservoir of the gas in the atmosphere and oceans that is driving the climate to a warmer and warmer state.
- Many places are subject to more than one climate-related impact, such as… drought coupled with extreme heat, wildfire, and flooding.
- The compounding effects of these impacts result in increased risks to people, infrastructure, and interconnected economic sectors."

https://nca2018.globalchange.gov/

#2: PNAS* - Drought Hydrology in Colorado River Basin

SPECIAL FEATURE

Future dryness in the southwest US and the hydrology of the early 21st century drought

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Edited by Glen M. MacDonald, University of California, Los Angeles, CA, and accepted by the Editorial Board March 18, 2010 (received for review October 26, 2009)

Recently the Southwest has experienced a spate of dryness, which presents a challenge to the sustainability of current water use by human and natural systems in the region. In the Colorado River Basin, the early 21st century drought has been the most extreme in over a century of Colorado River flows, and might occur in any given century with probability of only 60%. However, hydrological model runs from downscaled Intergovernmental Panel on Climate Change Fourth Assessment climate change simulations suggest that the region is likely to become drier and experience more severe droughts than this. In the latter half of the 21st century the models produced considerably greater drought activity, particularly in the Colorado River Basin, as judged from soil moisture anomalies and other hydrological measures. As in the historical record, most of the simulated extreme droughts build up and persist over many years. Durations of depleted soil moisture over the historical record ranged from 4 to 10 years, but in the 21st century simulations, some of the dry events persisted for 12 years or more. Summers during the observed early 21st century drought were remarkably warm, a feature also evident in many simulated droughts of the 21st century. These severe future droughts are aggravated by enhanced, globally warmed temperatures that reduce spring snowpack and late spring and summer soil moisture. As the climate continues to warm and soil moisture deficits accumulate beyond historical levels, the model simulations suggest that sustaining water supplies in parts of the Southwest will be a challenge.

climate change | regional modeling | sustainability | water resources

Persistent dry conditions have generally prevailed in the Southwest during the early years of the 21st century (1), after wetter than normal conditions in the preceding years. Such droughts have substantial impacts on the humans, animals, and plants inhabiting the Southwest, and call into question whether we can sustain the water resources that we have come to depend upon in the 20th century. This study uses high resolution ($1/8° \times 1/8°$) hydrological model simulations, driven by observed and downscaled global climate model meteorological fields, to investigate the region's droughts. Our goals are to place the 21st century drought into the context of the 20th century, and determine how Southwest drought is likely to change from its 20th century patterns in the future.

The Southwest's hydrology is marked by strong variability on seasonal to multiannual time scales, reflecting its sensitivity to fluctuations in large scale atmospheric circulation patterns. Preinstrumental paleoclimate records indicate that periods of extreme dryness have occurred sporadically during the last millennium (2, 3), so the 21st century drought is far from unprecedented. Some of the most prominent of these prehistoric droughts occurred in the midst of anomalously warm conditions, perhaps in similar fashion to the recent early 21st century drought. A protracted period of such dry conditions is likely to make currently scheduled water deliveries from the Colorado River unsustainable in the future, and have other significant impacts on the Southwest's inhabitants (4, 5).

Although the recent drought may have significant contributions from natural variability, it is notable that hydrological changes in the region over the last 50 years cannot be fully explained by natural variability, and instead show the signature of anthropogenic climate change (6–9). GCM projections show reduced precipitation over many lower midlatitude continental regions, including the Southwest, as the climate warms from greenhouse gases (10–13). The obvious question is whether the 21st century drought is the harbinger of things to come.

Besides having enormous economic and societal consequences, drought has considerable effects upon ecosystems. An epidemic of conifer tree die-offs in western US forests has been provoked by severe dryness and insect infestation, evidently exacerbated by warmer temperatures in both the growing and cool seasons (14–16). An increase in the number and areal extent of wildfire in middle elevation forests (17) has been attributed to an advance in spring snowmelt and warmer spring and summer temperatures. Likely warming and possible drying of the climate in future decades is projected to increase the occurrence and impact of wildfires over much of the Southwest (18). All these applications motivate a detailed examination of Southwest droughts.

Data and Models

We use observed temperature and precipitation to force the Variable Infiltration Capacity (VIC) hydrological model on a $1/8° \times 1/8°$ grid across the western US. This allows us to analyze VIC's estimates of key hydrological fields, such as soil moisture, that are poorly observed over the historical time period. VIC has been shown to produce realistic simulations of the hydroclimate's mean and variability in this region (8, 19, 20). We will refer to these estimates as VIC-OBS. *SI Text* (sections S1 and S2) contains details on the hydrological modeling process.

We use twelve global climate models (GCMs) used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (10, 11) to investigate effects of climate change on the Southwestern United States. The full list of models is given in *SI Text* (section S3). We further analyze the output of two of the twelve models, Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 and Centre National de Recherches Météorologiques (CNRM) CM3. These two models produce temperature and precipitation simulations falling within the larger ensemble of changes from the set of 12 GCMs, and were among the few models that provided the continuous daily output necessary to drive VIC. More information on the simulation quality of these models is given in *SI Text* (section S3). We statistically downscale the

Author contributions: D.R.C. and T.P.B. designed research; D.R.C., T.D., D.W.P., M.T., and A.G. performed research; T.D., D.W.P., M.T., and A.G. analyzed data; and D.R.C., T.D., and D.W.P. wrote the paper.

The authors declare no conflict of interest.

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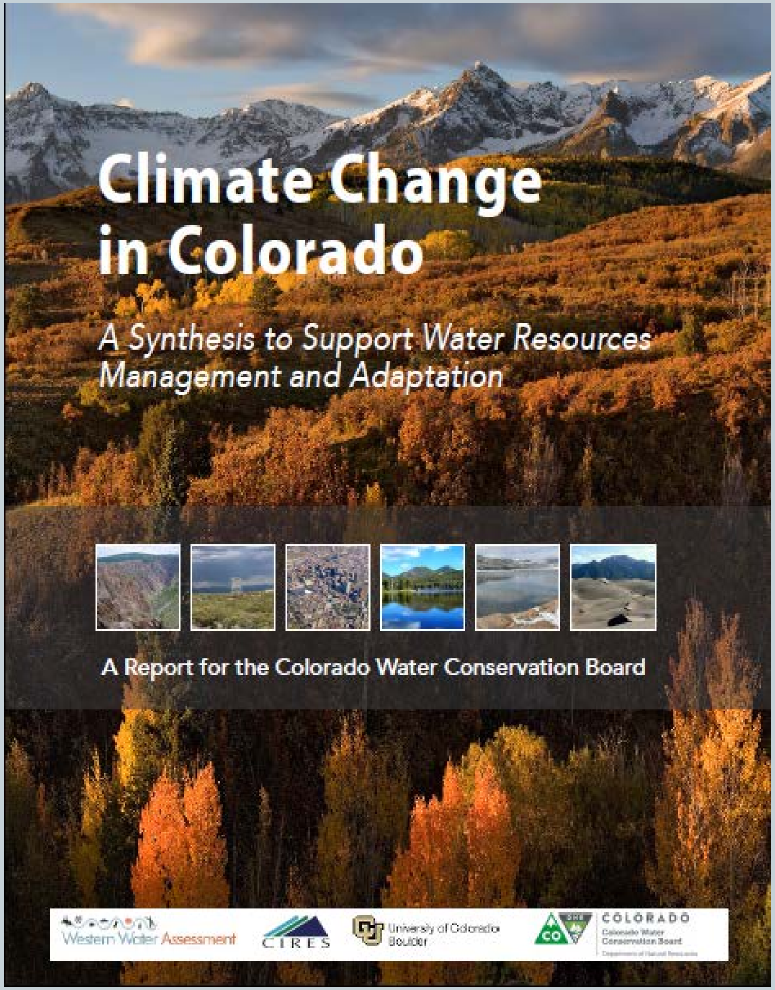
This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.0912391107/-/DCSupplemental.

- The Southwest becomes more arid over the 21st century in the CNRM and GFDL model simulations, as judged by changes in VIC-MOD's regional aggregate snow pack and soil moisture, … with associated deficit precipitation and reductions in runoff.
- Downscaled climate model projections show longer and more intense future droughts in the Colorado basin, and a high likelihood of worst-in-century droughts with multiyear flow deficits that exceed any in the observational record by 60–70%.
- As the climate continues to warm and soil moisture deficits accumulate beyond historical levels, the model simulations suggest that sustaining water supplies in parts of the Southwest will be a challenge.

*Proceedings of the National Academy of Sciences (US)

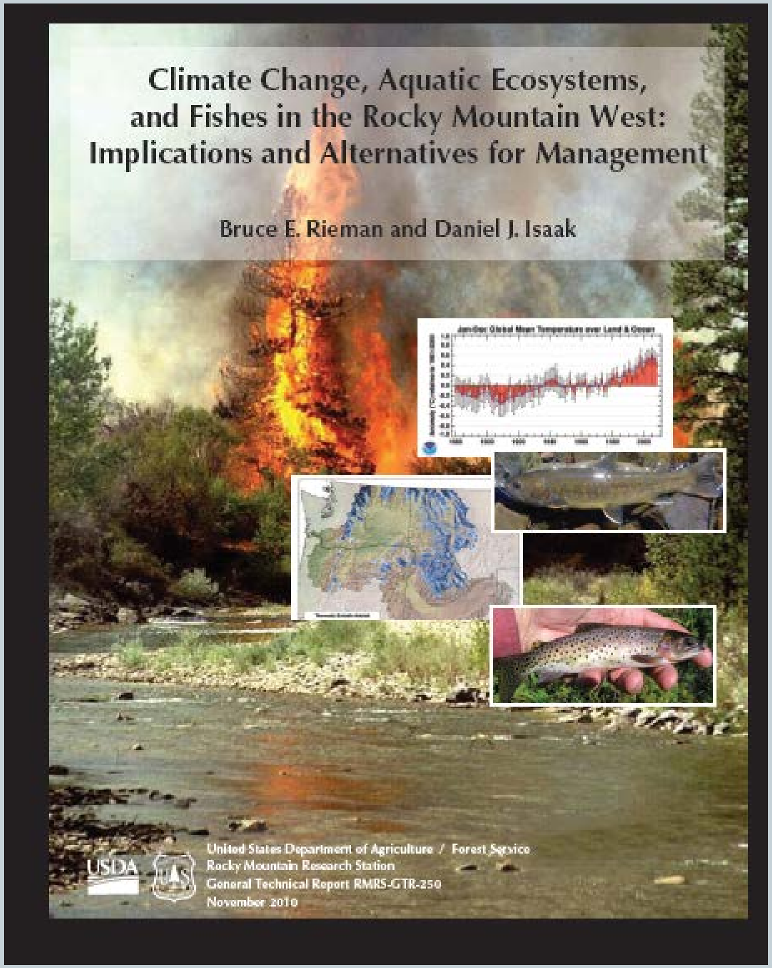
#3: "Climate Change in Colorado"



- Current climate models project that Colorado will warm by 2.5°F by 2025 and 4°F by 2050. Summers are likely to warm more than winters.
- Warmer temperatures will affect evaporation rates in our rivers, streams and reservoirs, perhaps making less water available for beneficial use.
- A projected seasonal shift in precipitation may result in more mid-winter precipitation throughout the state and, in some areas, a decrease in late spring and summer precipitation.
- Lower elevation snowpack (below 8200 ft.) is likely to decline, with modest declines projected for high elevation snowpack (above 8200 ft.).
- The timing of runoff is projected to shift earlier in the spring, which may reduce late summer stream flows. These changes will probably occur regardless of changes in precipitation.

http://wwa.colorado.edu/climate/co2014report/

#4: USDA Forrest Service & Rocky Mountain Research Station



- "As climate change progresses, however, long-term warming trends and increasing variability will result in more frequent events (e.g., droughts, intense precipitation, and periods of unusually warm weather) that were considered extreme during the twentieth century, and the magnitude of these events may also exceed recent historical levels.
- Changes in stream environments will parallel trends in the climate system, with streams becoming warmer, more variable in flow timing and amount, and subject to more frequent extreme events that could be synchronized across broader areas through regional flooding, droughts, and wildfires.
- Climate change is also likely to influence channel structure and forest and riparian communities through altered patterns and severity or intensity of wildfire, inputs of sediment and large wood, and disturbances such as debris flows."

http://www.regions.noaa.gov/western/wp-content/uploads/2011/08/2010_USFW_Climate_Change_Aquatic_Ecosystems_and_Fishes.pdf

Summary: Projected Mid-to-Late Century Drought in the Southwest

- All substantial climate change studies for the Southwest project substantially increasing severe drought across the Southwest, especially from mid century on.
- The studies indicate southwestern drought will increase in intensity with periodic drought of 2 to 5 year duration by 2035, to decadal drought by 2070, to perhaps multi-decadal drought by the end of the century.
- Such drought (multi-decadal) is beyond the experience of post Ancient Puebloan culture, and not seen since the late 13th century, if ever.
- "Our results point to a remarkably drier future that falls far outside the contemporary experience of natural and human systems in Western North America, conditions that may present a substantial challenge to adaptation." (Unprecedented 21st century drought risk in the American Southwest and Central Plains. Cook et al. *Science Advances* 12 Feb 2015: Vol. 1, no. 1, e1400082 DOI: 10.1126/sciadv.1400082)

Magnitude of the Challenge Ahead…

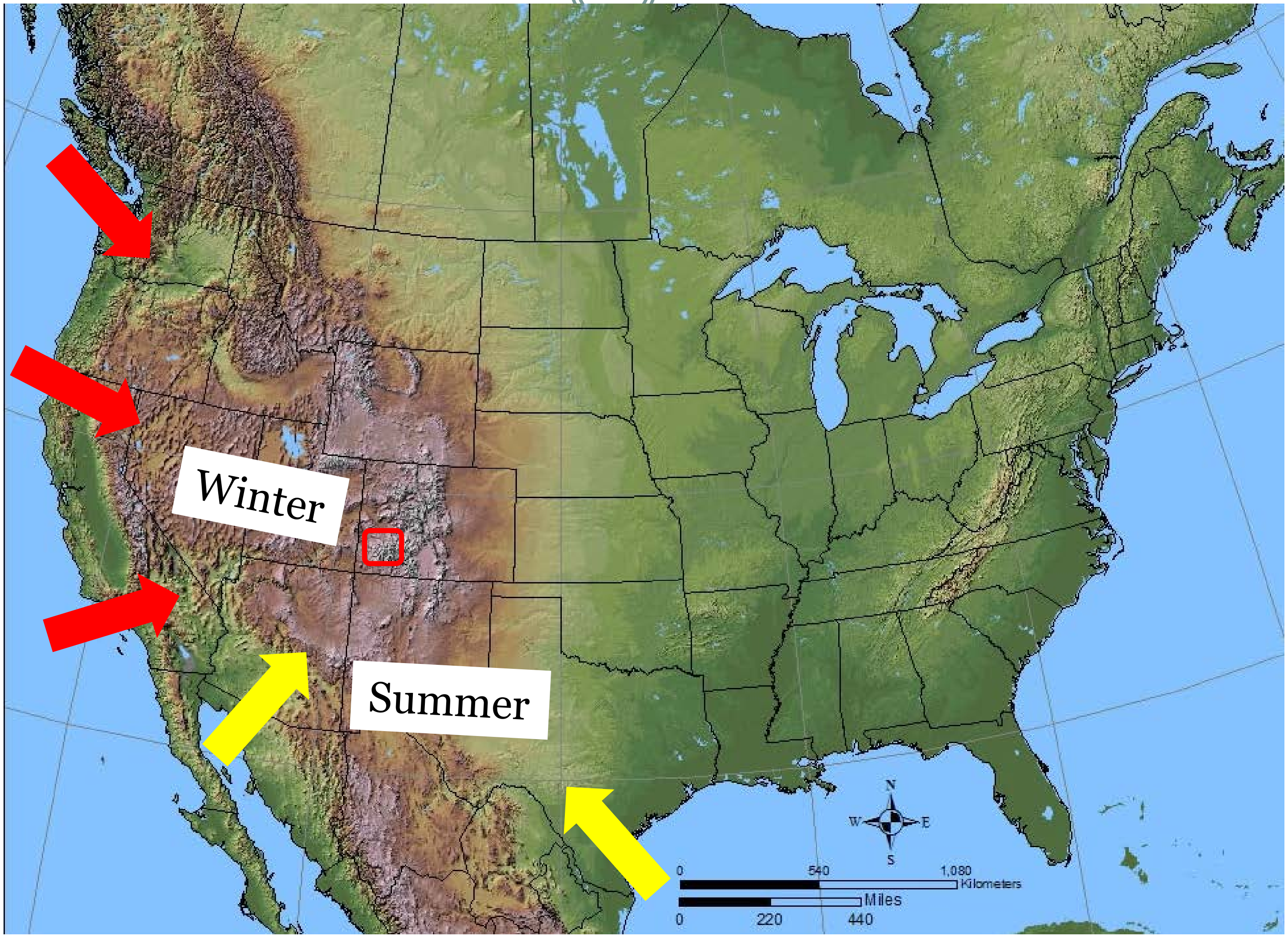
- "The observed increase in global carbon emissions over the past 15–20 years has been consistent with higher scenarios (e.g., RCP8.5) (*very high confidence*). In 2014 and 2015, emission growth rates slowed as economic growth became less carbon-intensive (*medium confidence*). Even if this slowing trend continues, however, it is not yet at a rate that would limit the increase in the global average temperature to well below 3.6°F (2°C) above preindustrial levels (*high confidence*). (National Climate Assessment 4 (2017), ES p31)"
- "According to the analysis from the Precourt Institute for Energy at Stanford,
  - to keep the planet under 2 degrees Celsius warmer compared to pre-industrial levels, *the global economy needs to triple its annual investment in low-emissions technology* — from $750 billion per year between 2010 and 2015 to $2.3 trillion per year going forward until 2040…
  - In the first half of the decade, private institutional investors — which include pension, mutual and sovereign wealth funds alongside billionaires — invested a total of $3.4 trillion in the world economy per year, the analysis found. ***That means at current investment levels, two out of every three dollars invested per year would need to go toward clean energy to halt catastrophic warming."***
- "…UN officials warned that overall, countries are not doing enough to limit greenhouse gas emissions. The 'Emissions Gap" report released Tuesday noted that pledges within the Paris deal are "only a third of what is needed to avoid worst impacts of climate change."

https://www.washingtonpost.com/news/powerpost/wp/category/the-energy-202/?utm_term=.148c778b1f7c&wpisrc=nl_energy202&wpmm=1

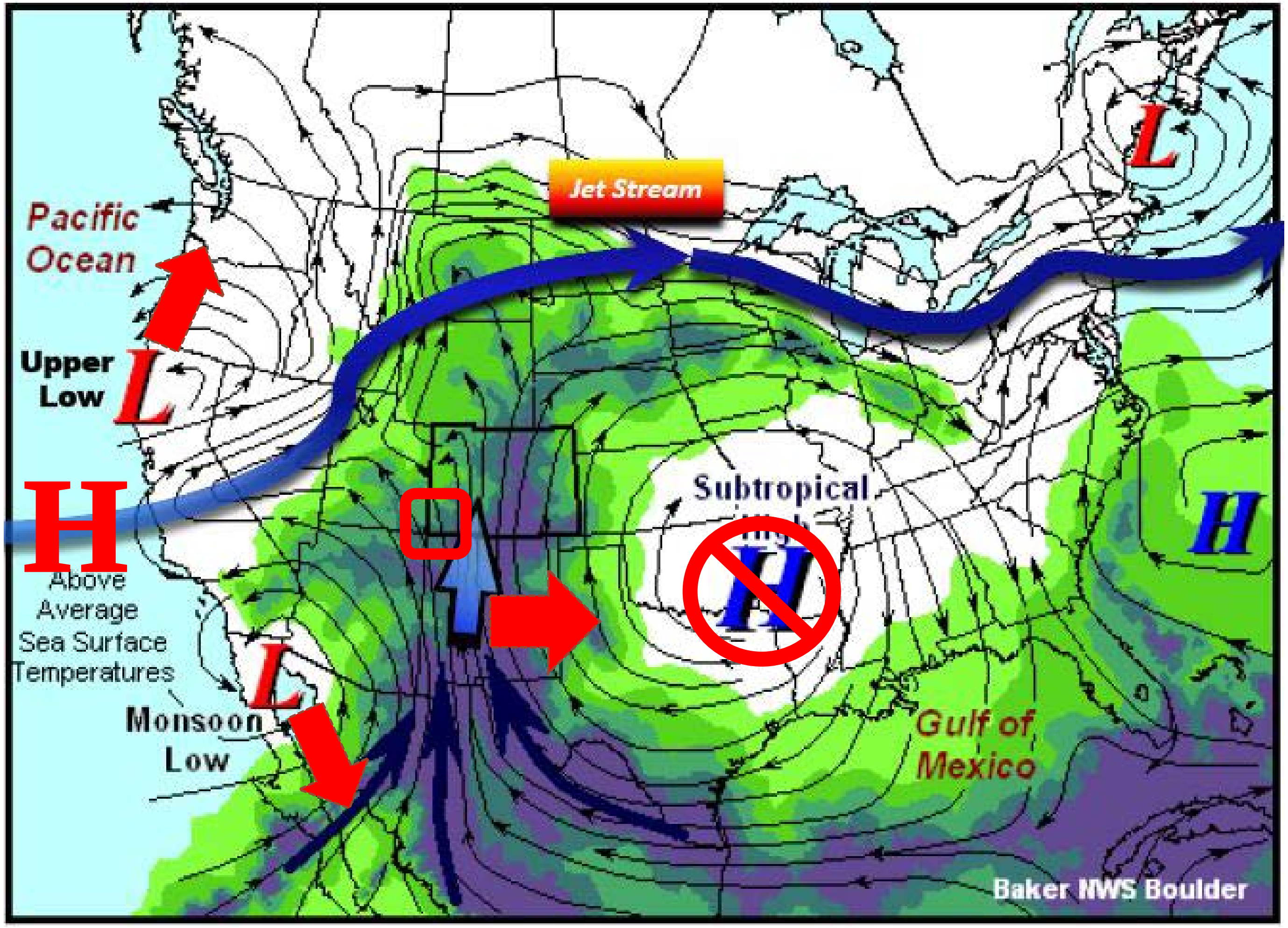
Major Engines of Our Local Climate

- Global climate models are "top down" models of world climate systems. Downscaling to a local area requires the interfacing of higher scale model findings with local characteristics and meteorology.
- Generally speaking, four major factors combine to shape our local 4 Corners' climate:
  - The Southern Oscillation (El Nino, La Nina, "Normal" cycles)
  - Summer monsoon rain
  - Geomorphology
  - Desert

Local Geomorphic Context: Prevailing Moisture Flow Patterns



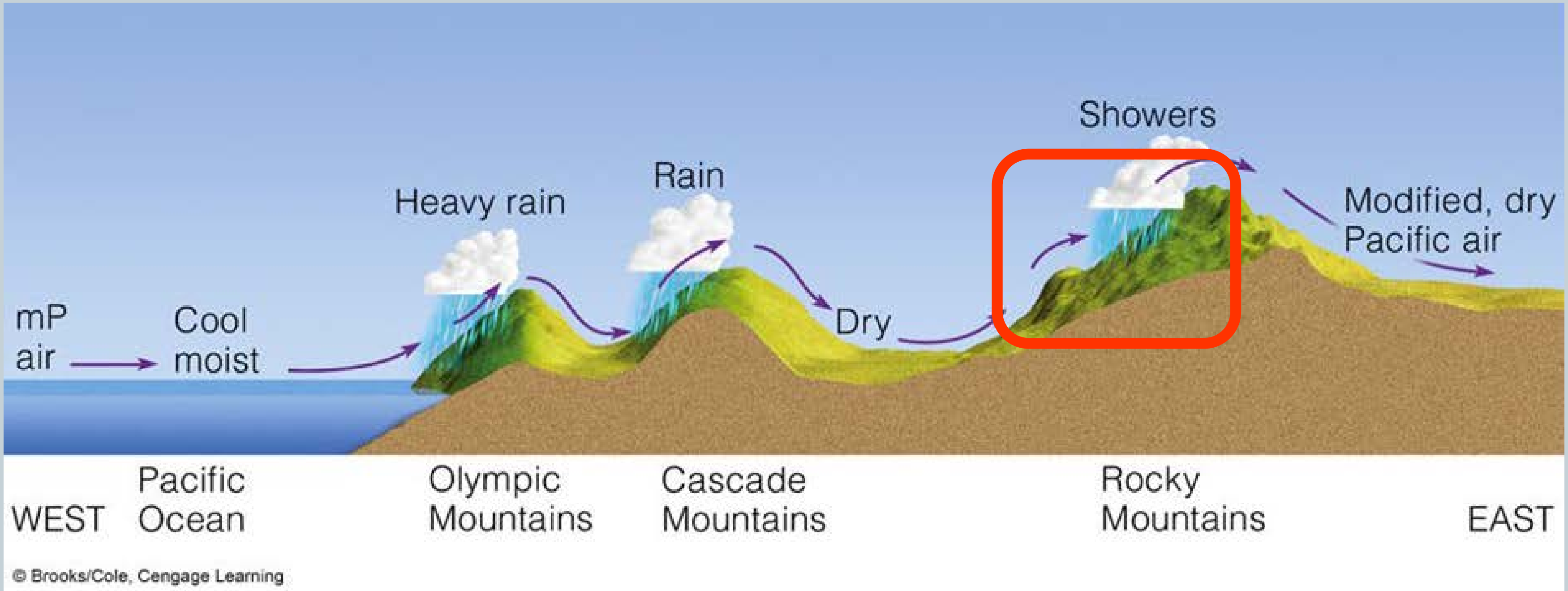
Southwestern Monsoon Pattern



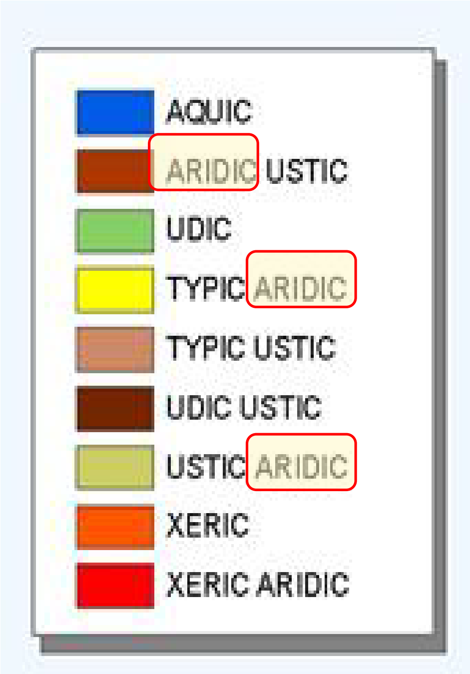
http://climate.colostate.edu/images/monsoon.jpg

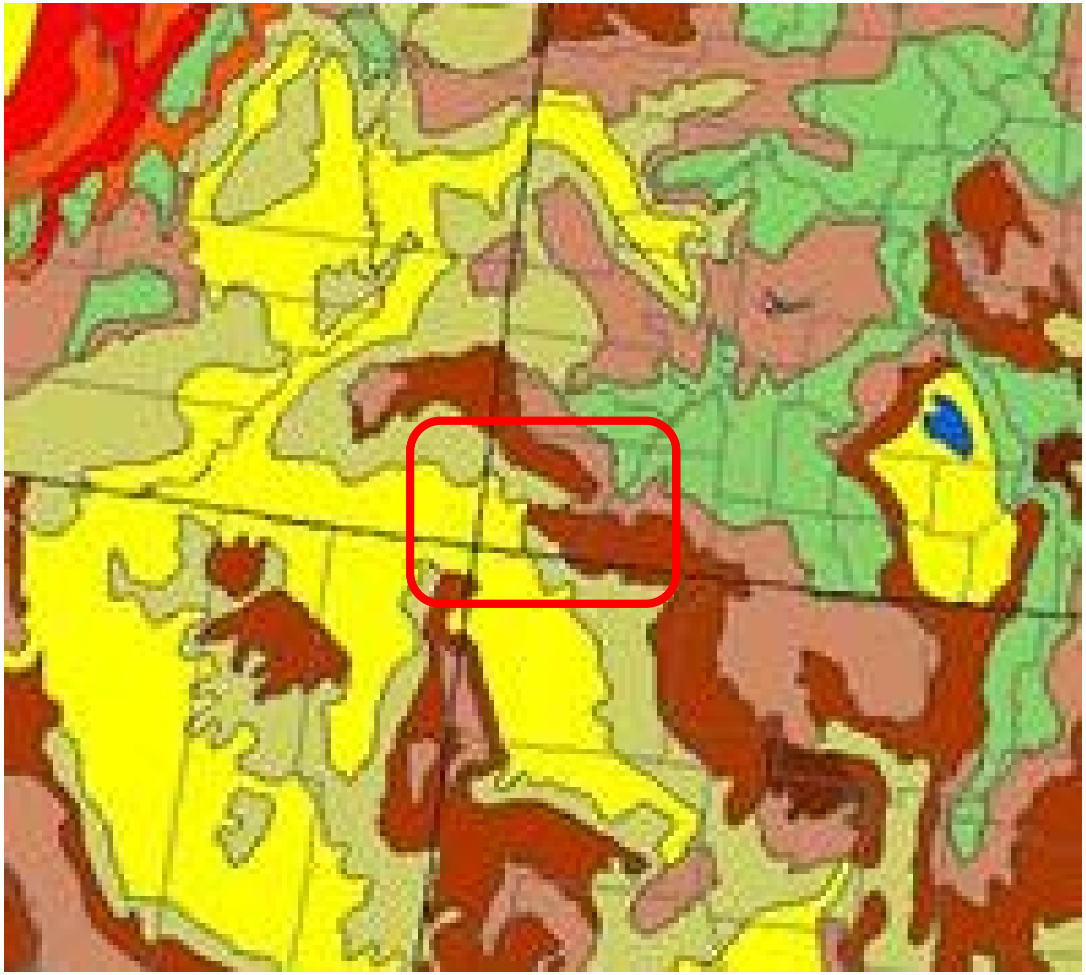
The "Orographic" Mountain Effect

- Air hits mountains, rises to clear mountains
- Rising air cools, condenses
- Falls as precip, allowing remaining (dryer) air to pass over
- The higher the mountain, the more moisture is released



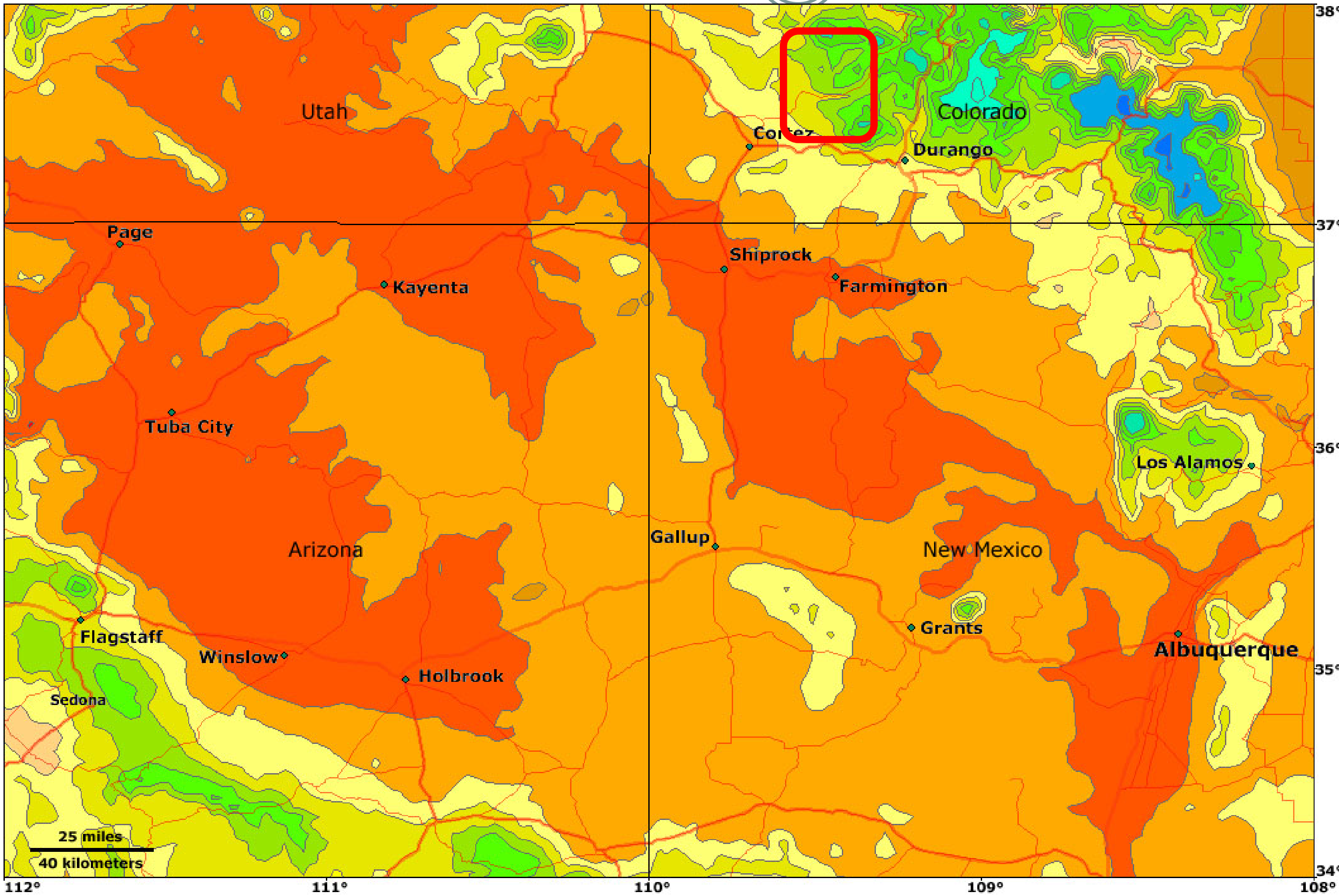
Resultant Soil Moisture Map Characterizes 4 Corners



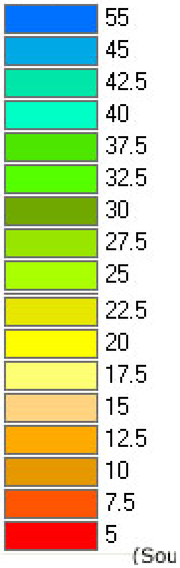


Historically arid in nature

The Hot Stove Effect: Pacific Moisture is Substantially Evaporated By Time It Hits San Juans



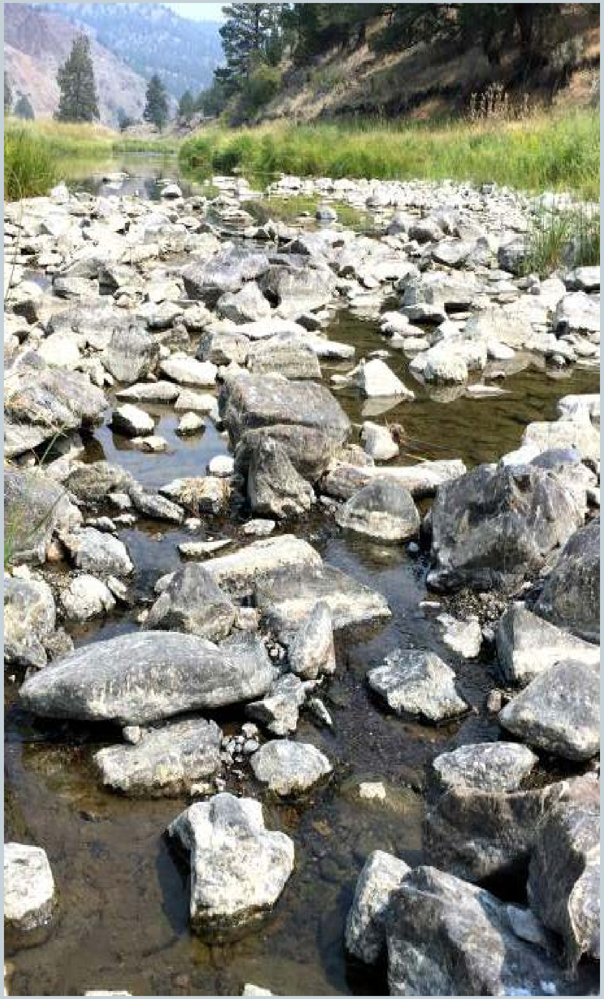
Average Annual Precipitation 1980 – 2010 Inches



http://geomaps.wr.usgs.gov/navajo/4corners/maps/precipitation.html

Increasing Temperatures, Thermodynamics and Stream-Flow

- The thermodynamics of increasing air and ground temperatures impacts stream-flow by increasing:
  - Evaporation from streams and soil
  - Transpiration from plants
  - Virga
- A 2016 CSU-led "energy budget" study concluded that the increase in evapotranspiration from a 4°C (7°F) increase in temperature (heat energy) will reduce mean stream-flow by about 23% on the Front Range and 29% on the Western Slope in Colorado.
- Additionally, increasing heat may drive orographic precipitation up in elevation (before condensation can occur) and more eastward into the mountain interior (due to prevailing westerlies) before it falls as rain or snow, thereby reducing precipitation in our Study Area.

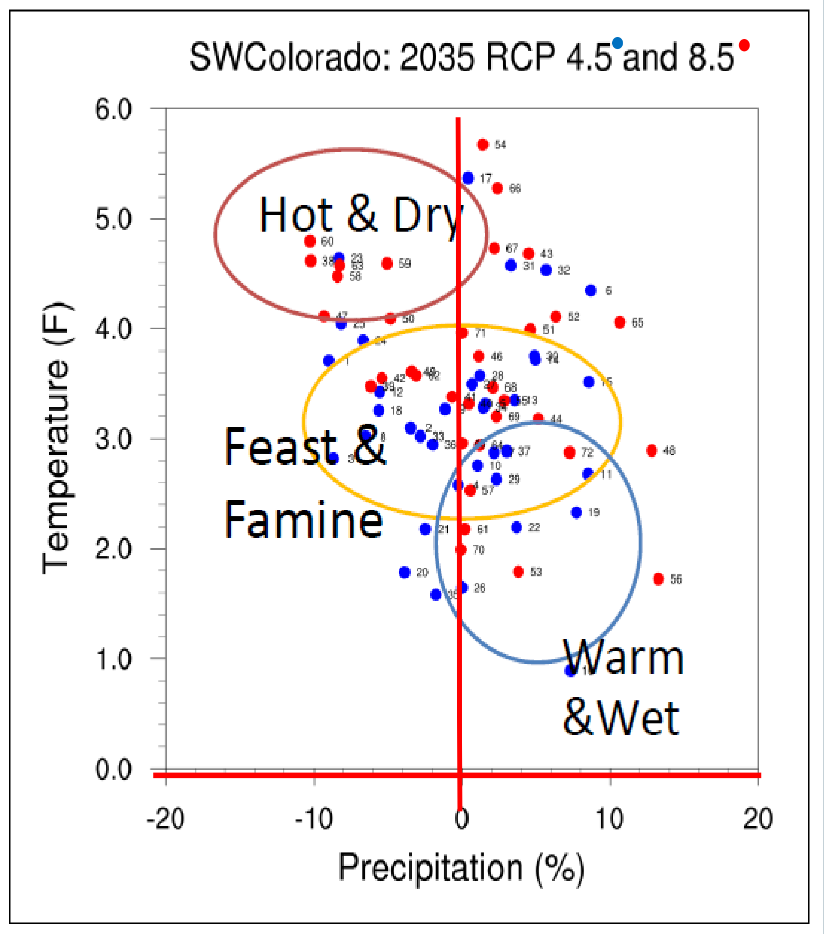


Take Away Points…

- The timing, intensity and duration of the Southern Pacific Oscillation is changing and will likely continue to change as long as greenhouse gas production increases.
- The variations of the Southern Pacific Oscillation are further impacted by our local geography:
  - Our Study Area is at the interface of extensive high desert and substantial mountains. Much of the surface area over which our air borne moisture travels is arid and will likely become more so.
  - The orographic effect of the San Juans/La Platas on Pacific/Gulf moisture is the primary reason we even have a fishery here (compare us with area around Kenyata and Tuba City; Abajo, La Sal's and Henry mountains; Uncompagres) – with some help from latitude; otherwise, our area would likely be desert.
  - Increasing surface heat will likely affect orographic patterns in the San Juans/La Platas. As ground surface temperatures rise, soil and air moisture is reduced, raising the elevation at which condensation occurs (and increasing radiant energy increases evaporation/sublimation in the air column), likely reducing the amount of precipitation falling in our part of the mountains.
- To the east, as the Central Plains dry out through increased ground temperatures, summer monsoonal storms may reduce in number and become more intense.
- As surface temperatures increase over an already hot, arid area, it seems likely that a combination of reduced soil moisture and increased surface heat energy will increase virga and move orographic effects to higher elevation and eastward, thereby reducing surface level precipitation.

MSI/Rangwalla Three Climate Scenario "Clusters"

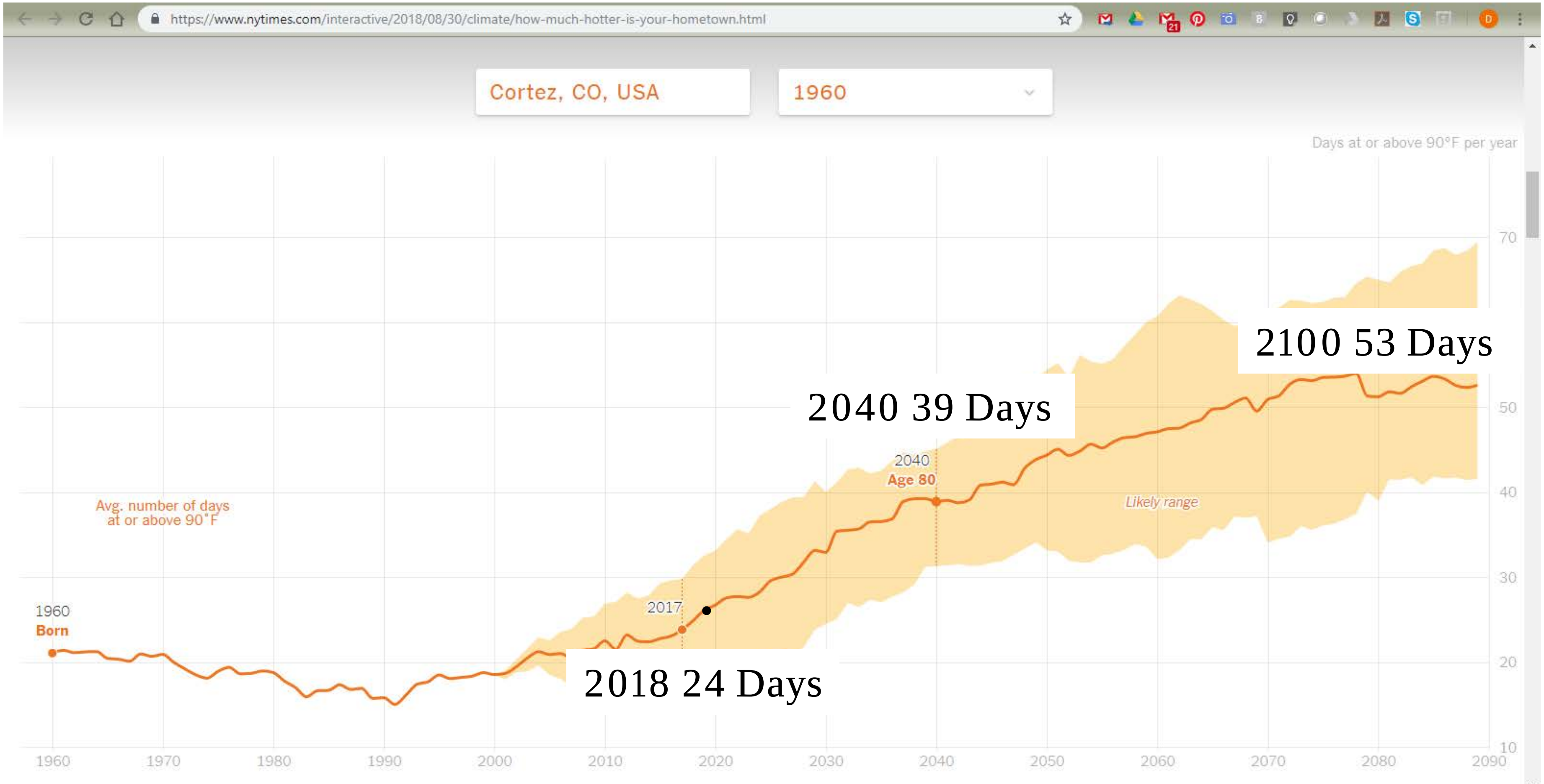
- Downscaled research that specifically models climate change in the San Juan mountains identifies three "clusters" found within 72 modeled scenarios that characterize the impact on the Study Area (Mountain Studies Institute):
  - Warm and Wet,
  - Hot and Dry and
  - Feast and Famine.
- Of the three, two (Hot and Dry and Feast and Famine) pose the most serious challenges to trout habitat. Drought is the underlying force for both. In these two clusters, simulations show drought to steadily increase in both intensity and duration through the study period.
- While reflecting a less intense impact on our area, Warm and Wet could still pose challenges through warmer water, increased flow velocity, changed flow timing and increased inter and intra aquatic-specie competition (fish and food).



Scenarios	Hot and Dry	Feast and Famine	Warm and Wet
Temperature	Annual temperature increases by 5F; At lower elevations: summer days with temperature above 77F (25C) increases by 1 month, and nights with temperature above 68F = 10	Annual temperature increases by 3F; At lower elevations: summer days with temperature above 77F (25C) increases by 2 weeks, and nights with temperature above 68F = 20	Annual temperature increases by 2F; At lower elevations: summer days with temperature above 77F (25C) increases by 1 week
Precipitation	Annual precipitation decreases by 10%; less frequent and more intense individual rain events; summer monsoon rains decrease by 20%	Annual precipitation does not change but much greater fluctuations year to year (leading to more frequent feast or famine conditions); El Nino of 1982/83 strength occurs every 7 years	Annual precipitation increases by 10%; more intense individual rain events; summer monsoon rains increase by 10%
Runoff	Runoff decreases by 20% and peak runoff occurs 3 weeks earlier	Runoff decreases by 10% and peak runoff occurs 2 weeks earlier	Runoff volume does not change but peak runoff earlier by 1 week
Heat Wave	Severe and long lasting; every summer is warmer compared to 2002 or 2012 (5F above normal)	Hot summers like 2002 and 2012 occur once every 3 years	Hot summers like 2002 and 2012 occur once every decade
Drought	More frequent drought years like 2002/2012 - every 5 years	Drought years like 2002/2012 occur once every decade	No change in frequency but moderate increases in intensity; fewer cases of multi-year drought
Snowline or Freezing Level	Snowline moves up by 1200ft	Snowline moves up by 900ft	Snowline moves up by 600ft
Wildfire	Fire season widens by 1 month; greater fire frequency (12x) and extent (16x) in high elevation forest	Fire risk during dry years is very high at all elevations b/c of large fuel build up from wet years; on average fire frequency increases 8x, and area burnt increases 11x	Increases in fire frequency (4x) and extent (6x)
Dust Storms	Extreme spring dust events like 2009 every other year; causing snowmelt and peak runoff to be six weeks earlier	Frequency of extreme dust events increases from current but tied to extreme dry years	Same as current
Flood Risk	Flood less frequent but risk increases for big summer rain events	Risk increases substantially during the wet years	Flood frequency increases substantially as well as the overall risk
Growing Season	Increases by 3 weeks	Increases by 2 weeks	Increases by 1 week

MSI: Three Climate Scenarios for the San Juan Basin Region by 2035

NYT: Average Number of Days Above 90^0+



Key Messages from the San Juan Models

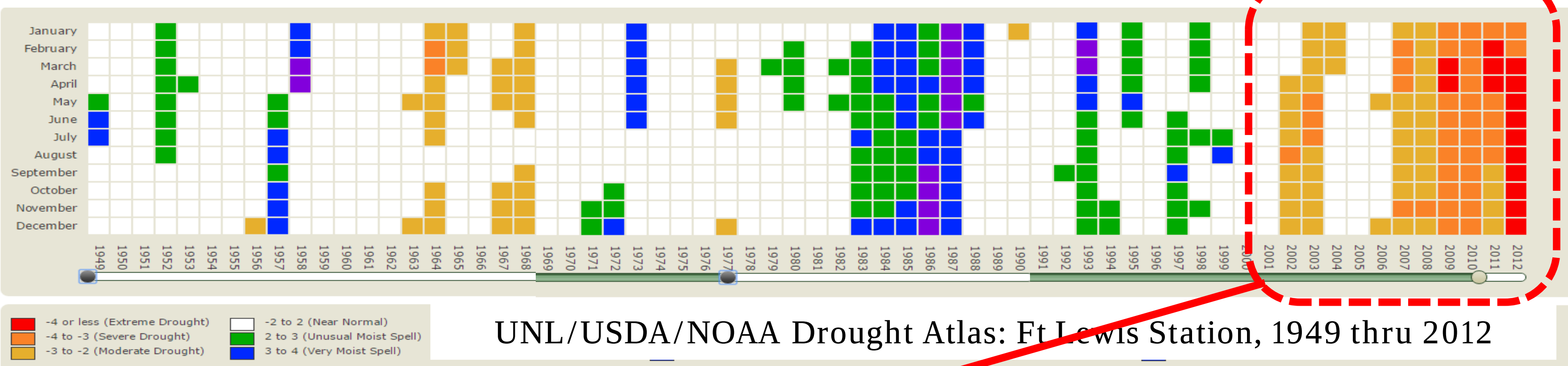
- In all 72 scenarios modeled for the San Juan Mountains by the Mountain Studies Institute, temperatures are likely to increase steadily over the analysis period (2017 – 2100).
- Precipitation may well stay close to current levels (models are inconclusive), but will change "phase proportions" (less snow, more rain) and timing (snow starting later and ending earlier). This will likely reduce available *effective* (trout habitat "beneficial") precipitation.
- Most models indicate *drought* will likely increase in both intensity and duration, with potentially very substantial drought becoming increasingly prevalent between 2050 and 2100.

Drought: Duration>52 Consecutive Weeks

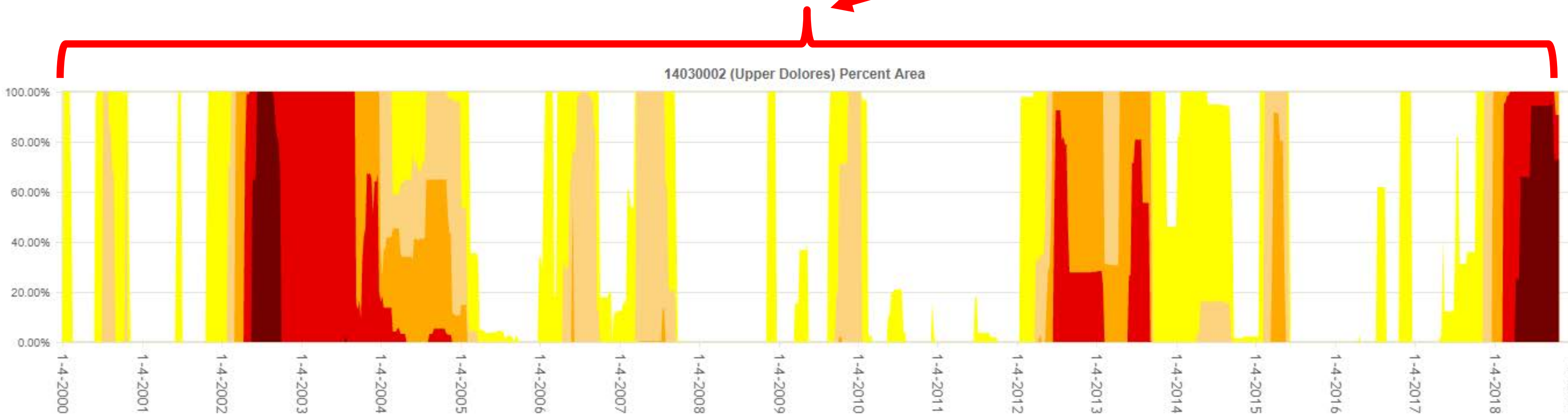
CO counties with drought >52 consecutive weeks							
FIPS	startDate	endDate	Consecutive Weeks	**Years**	state	county	http://droughtmonitor.unl.edu/MapsAndData/MapsandDataServices/StatisticalData/WeeksInDrought.aspx
8033	30-10-01	29-03-05	179	**3.4**	CO	Dolores County	
8033	03-01-06	25-09-07	91	**1.75**	CO	Dolores County	Expand all rows to see all other counties in state
8033	24-01-12	09-06-15	177	**3.4**	CO	Dolores County	
8083	30-10-01	10-05-05	185	**3.6**	CO	Montezuma County	
8083	03-01-06	25-09-07	91	**1.8**	CO	Montezuma County	
8083	24-01-12	29-12-15	206	**4.0**	CO	Montezuma County	

- Three periods of drought exceeded 52 consecutive weeks in 4 Corners since 1954. All three have occurred since 2001!
- We seem to be already in the Feast and Famine scenario.
- Will we move to Hot and Dry?

Drought, an increasingly persistent pattern…



UNL/USDA/NOAA Drought Atlas: Ft Lewis Station, 1949 thru 2012

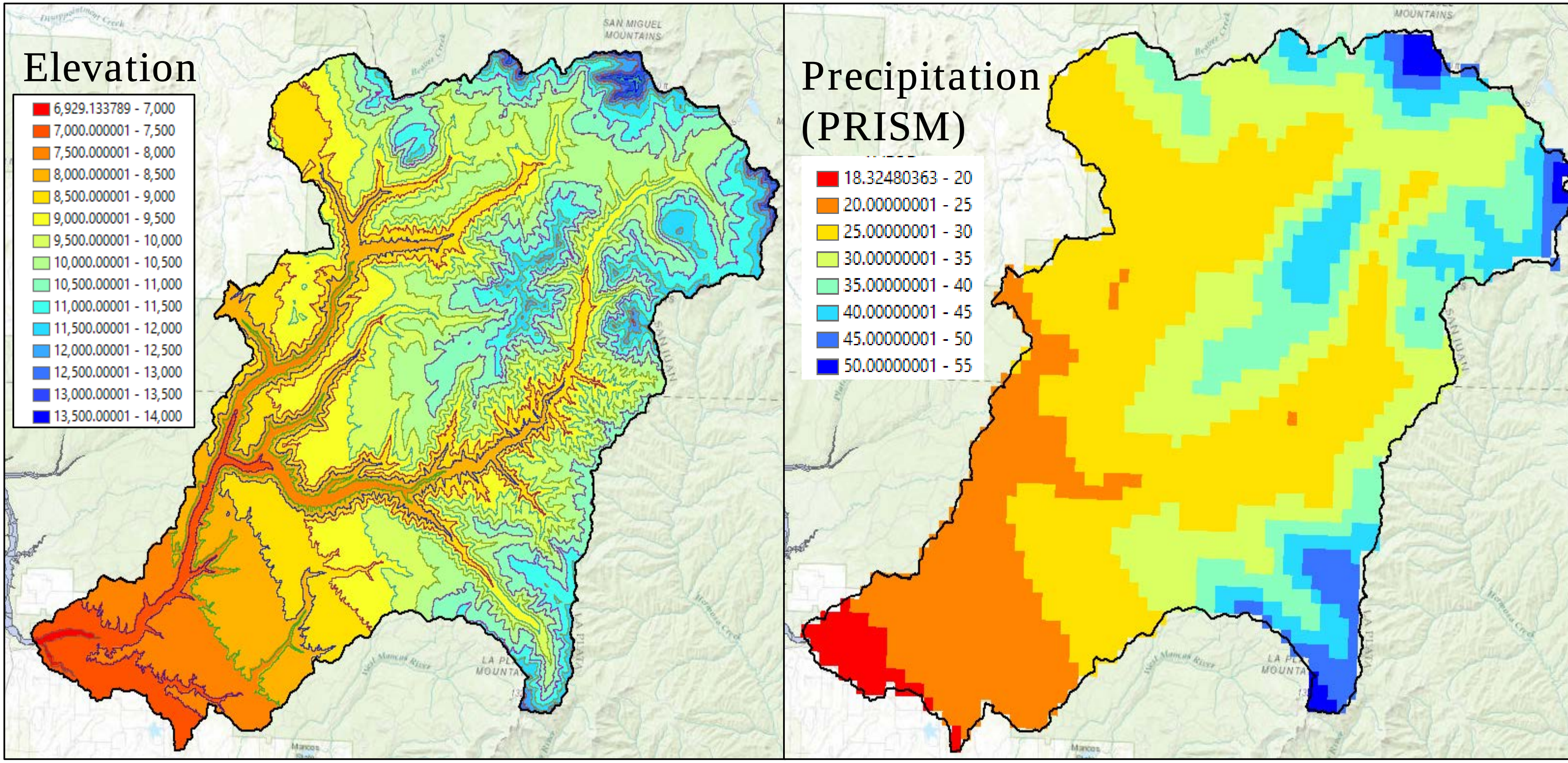


https://droughtmonitor.unl.edu/Data/Timeseries.aspx

Intensity: Impact of 2002 Drought on Flow

- Why use 2002 as a benchmark for drought flow?
  - On the list of "record low flow" for a given date (that is, a listing of the year in which the lowest flow occurred for each of the 365 days in a year), 2002 accounts for 100 of the 365 days.
  - Arguably, then, 2002 can be regarded as the most intense drought since records (1900).
- When the actual flow rate for each day of 2002 was then compared to the mean flow for that day for each of the 365 days, 2002 recorded an average of 45% less flow *per day* than the 62 year mean.

Orography: Elevation & Precipitation



Precipitation Is Closely Tied to Elevation!

Back to the Trout

CAMF- Searching for “Strongholds”!

- Core Question: Which stream reaches are likely to have persistent trout populations in the face of climate change ?

Trout habitat limiting factors
“state of the science”

Climate change modeling,
esp. for Southwest Colorado

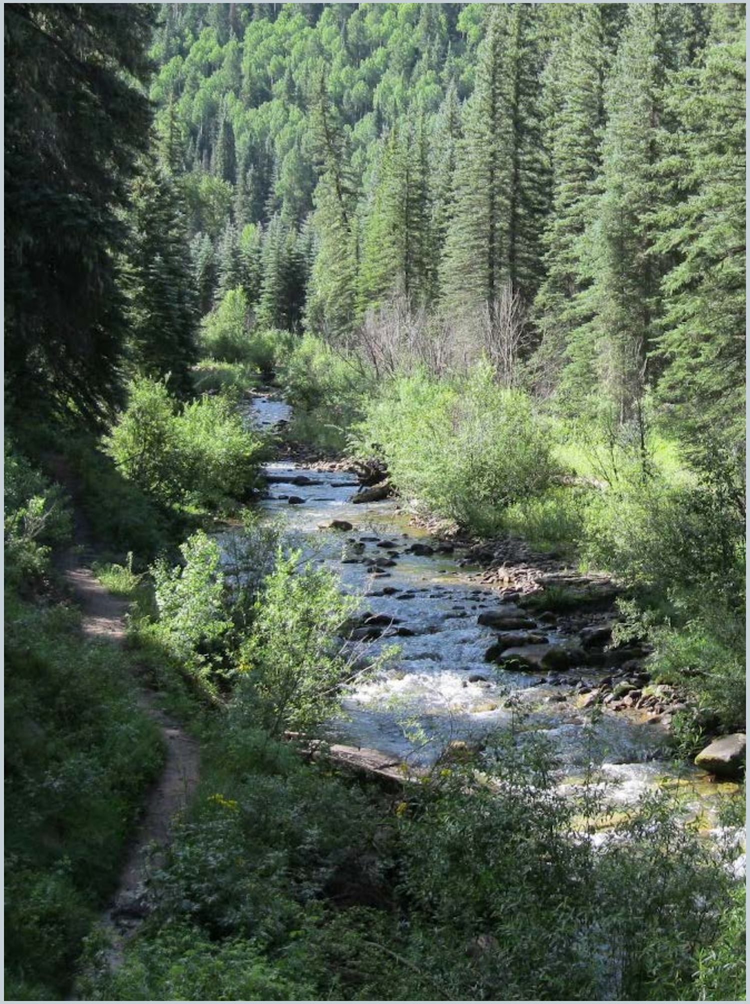
Downscale to San Juans, UD
vulnerability analysis in UD

Adaptive management
considerations in UD

Four Stages of
the Project

Where Will Trout Habitat Likely Persevere?

- Those streams that will be the most likely candidates for sustained habitat and populations to 2100:
  1. Are fed by large watersheds at high elevations,
  2. Have moderate gradient,
  3. Have many feeder streams and fens/wetlands at higher elevation, and
  4. Are shaded through riparian cover, north facing aspect and narrower valley "walls".
- Those streams without these characteristics will likely struggle to persist as habitats through extended drought due to 1) stream drying and 2) water temperatures reaching limiting thresholds.



Ranking Vulnerability to Climate Change

- Relative vulnerability is ranked by
  - Geophysical/hydrological features (stream-flow)
  - Temperature (elevation)
- Geophysical/hydrological features include:
  - Watershed size in square miles
  - M7D10Y Low Flow ("Mean 7-day, 10-year low-flow")
  - Mean annual precipitation
  - Mean basin elevation
  - Mean basin wall slope
  - % watershed above 7500 feet
  - Elevation of stream mouth
  - Headwaters elevation
  - Average gradient
- Primary data sources/tools:
  - StreamStats
  - PRISM
  - GIS (National Map, National Hydrographic Dataset)

Table 8.1: Ranking of Existing Trout Streams in Study Area by Long-Term Vulnerability to Climate Change (Low to High)

OBJECT ID	STREAM NAME	Quintile	Composite Score	Stream Length Miles	Watershed Size Sq Miles	M7D10Y Low Flow	Mean Annual Precip	Mean Basin Elevation	Mean Basin Wall Slope	% Area watershed above 7500ft	Elevation of Stream Mouth	Headwtrs elevation	Average Gradient	Miles by Category
	Quintile 1: Lowest Vulnerability													
142	East Fork Dolores River	1	11	6.35	1	1	1	1	2	1	1	1	2	
82	Barlow C[illegible]	[illegible]	15	5.53	2	1	1	1	3	1	2	2	[illegible]	
87	Coal Cre[illegible]	[illegible]	18	4.44	2	2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	[illegible]	
16	Slate Cre[illegible]	[illegible]	18	3.98	3	2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	[illegible]	
127	Snow Sp[illegible]	[illegible]	18	3.02	2	2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4	[illegible]	
125	Silver Cre[illegible]	[illegible]	19	3.78	2	2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4	[illegible]	
139	Twin Cre[illegible]	[illegible]	20	1.68	4	5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	[illegible]	
83	Bear Creek	1	21	13.71	1	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3	[illegible]	
101	Fish Creek @ SWA	1	21	12.95	1	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3	[illegible]	[illegible]
	Quintile 2: Lower Vulnerability													
93	Dolores River West Fk	2	22	34.84	1	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	[illegible]	
15	Lizard Head Creek	2	22	1.45	5	5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3	[illegible]	
116	Meadow Creek	2	22	3.45	3	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3	[illegible]	
130	Stoner Creek	2	22	17.99	1	1	5	5	2	1	5	1	[illegible]	
23	T[illegible]	[illegible]	[illegible]	2.37	5	5	1	1	3	1	1	1	[illegible]	
117	M[illegible]	[illegible]	[illegible]	3.56	4	5	2	2	1	1	2	3	[illegible]	
121	R[illegible]	[illegible]	[illegible]	5.74	1	1	3	4	3	1	4	4	[illegible]	
122	Rough Canyon	2	23	3.95	2	2	2	3	3	1	3	3	[illegible]	
98	Fall Creek East Fk	2	24	2.06	5	5	1	1	4	1	1	1	[illegible]	
108	Horse Creek	2	24	3.40	3	2	1	2	5	1	3	2	[illegible]	
113	Lost Canyon (above Dipping Vat Cree[illegible])	2	24	1.50	5	5	2	3	1	1	1	3	[illegible]	
92	Upper Dolores (#5)	2	24	35.20	1	1	3	4	3	1	5	5	[illegible]	[illegible]
	Quintile 3: Moderate Vulnerability													
88	Coke Oven Creek	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	1	2	3	[illegible]	
96	Fall Creek (Dunton)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3	1	[illegible]	5	[illegible]	
102	Fish Creek	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3	1	[illegible]	4	[illegible]	
111	Kilpacker C[illegible]	[illegible]	25	[illegible]	5	5	1	1	5	[illegible]	[illegible]	[illegible]	[illegible]	
1	Nash Cree[illegible]	[illegible]	25	4.72	2	3	4	5	1	[illegible]	[illegible]	[illegible]	[illegible]	
128	Spring Creek	3	25	4.58	3	3	4	4	1	[illegible]	[illegible]	3	[illegible]	
107	Upper Groundhog Creek (#2)	3	25	4.27	3	3	4	4	[illegible]	[illegible]	[illegible]	4	[illegible]	
141	Willow Creek	3	25	4.31	3	3	4	4	[illegible]	[illegible]	3	4	2	27.93
	Quintile 4: Higher Vulnerability													
124	Scotch Creek	4	26	4.46	2	2	4	[illegible]	[illegible]	[illegible]	4	1	[illegible]	
131	Straight Creek	4	26	2.58	5	5	[illegible]	[illegible]	[illegible]	1	1	1	[illegible]	
91	[illegible]	[illegible]	[illegible]	14.68	1	1	[illegible]	[illegible]	[illegible]	2	5	5	[illegible]	
134	[illegible]	[illegible]	[illegible]	8.71	1	2	[illegible]	[illegible]	2	1	5	4	[illegible]	
105	[illegible]	[illegible]	[illegible]	1.43	5	[illegible]	[illegible]	[illegible]	4	1	2	5	[illegible]	
119	Priest Gulch	4	28	6.97	2	[illegible]	[illegible]	4	4	1	5	2	[illegible]	
84	Bear Creek Little	4	29	2.69	[illegible]	[illegible]	[illegible]	3	2	1	3	4	[illegible]	
85	Burnett Creek	4	29	3.28	[illegible]	[illegible]	[illegible]	2	5	1	3	1	[illegible]	
17	Marguerite Creek	4	29	2.10	[illegible]	[illegible]	2	2	5	1	2	2	[illegible]	[illegible]
	Quintile 5: Highest Vulnerability													
112	Lost Canyon Creek (All)	5	30	[illegible]	[illegible]	4	5	5	1	5	5	3	[illegible]	
18	Silver Creek (Johnny Bull)	5	30	[illegible]	[illegible]	5	3	3	5	1	2	1	[illegible]	
140	Wildcat Cree[illegible]	[illegible]	30	[illegible]	[illegible]	3	4	4	5	1	4	1	[illegible]	
123	Ryman Creek	[illegible]	32	[illegible]	3	3	5	4	5	1	4	3	[illegible]	
86	Clear Creek	[illegible]	33	2.87	4	5	5	5	1	1	4	5	[illegible]	
135	Taylor Creek Little	5	33	3.46	4	5	5	4	2	1	4	4	[illegible]	
120	Rio Lado	5	37	3.29	4	5	5	5	4	1	5	4	4	
136	Tenderfoot Creek	5	37	2.95	4	5	5	5	4	1	4	4	5	50.28
	Total Miles			296.1										296.1

1: Lowest Vulnerability

2: Moderately Low

3: Moderate

4: Moderately High

5: Highest

Our 46 streams with Trout

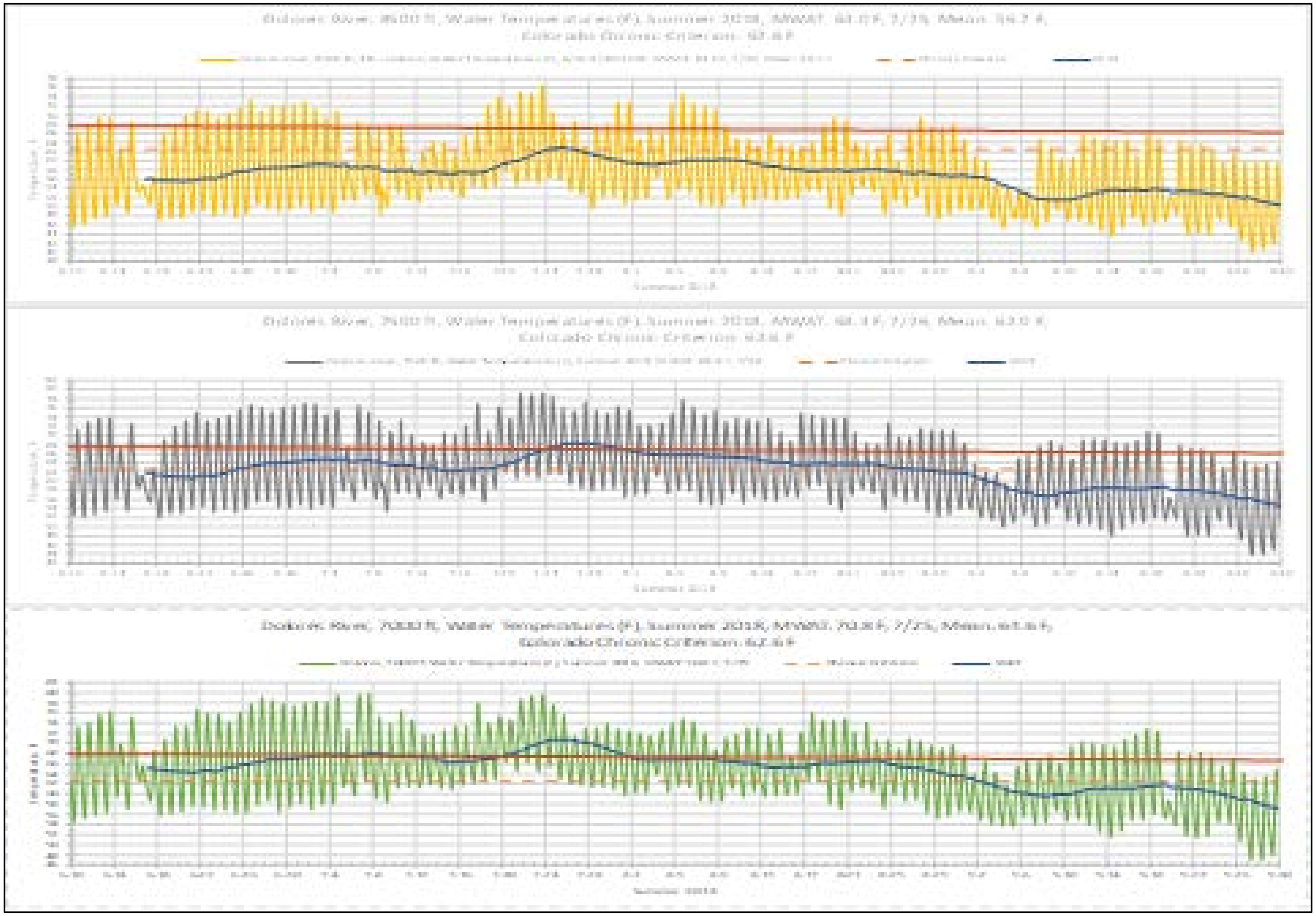
9 Hydrologic attributes for each stream from StreamStats/GIS

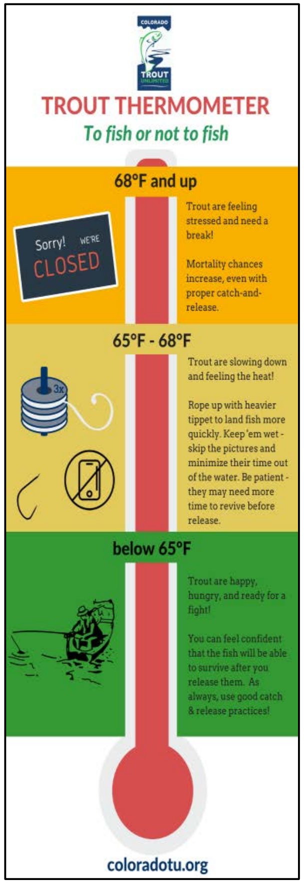
Relative Vulnerability!

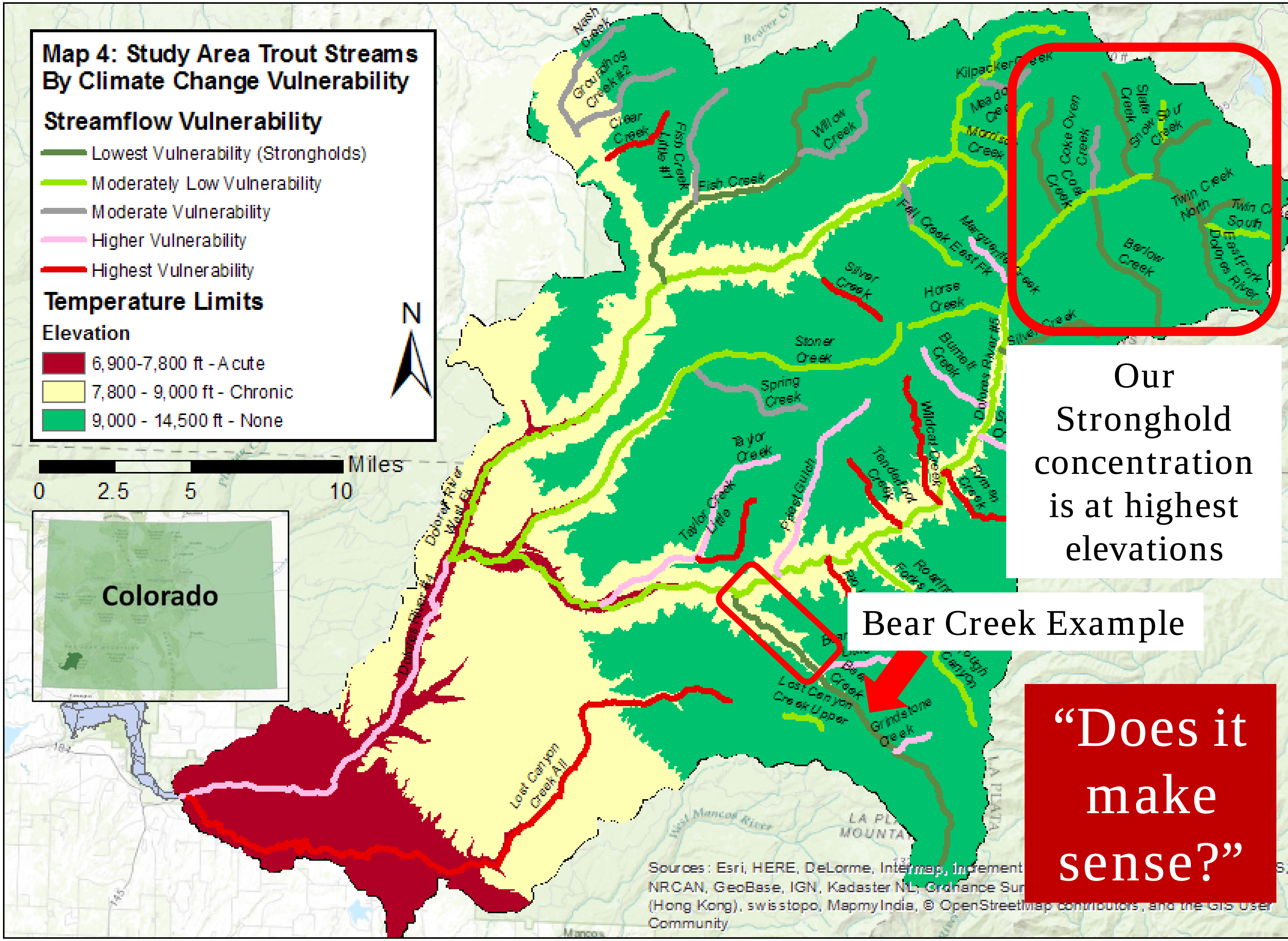
Composite Worksheet: Ranking 46 Trout Streams by Geophysical/ Hydrological Vulnerability (Streamflow) [Low (Green) to High (Red)]

"Does it make sense?" Map!

Impact of Projected Warming by Elevation

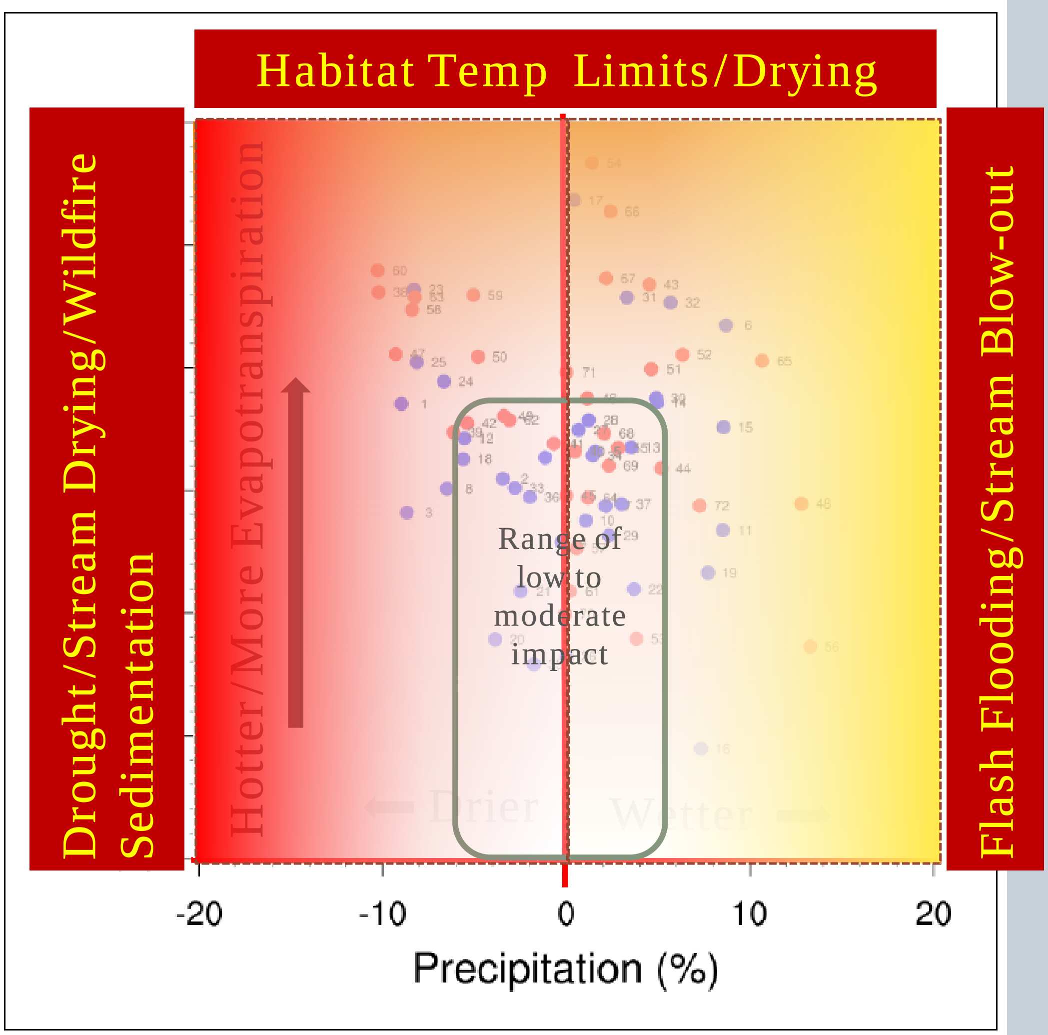





Map 4: Study Area Trout Streams By Climate Change Vulnerability
Streamflow Vulnerability
Lowest Vulnerability (Strongholds)
Moderately Low Vulnerability
Moderate Vulnerability
Higher Vulnerability
Highest Vulnerability
Temperature Limits
Elevation
6,900-7,800 ft - Acute
7,800 - 9,000 ft - Chronic
9,000 - 14,500 ft - None
N
Miles
0 2.5 5 10
Colorado
Our Stronghold concentration is at highest elevations
Bear Creek Example
“Does it make sense?”
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Vulnerability>Adaptability: Integrated Framework

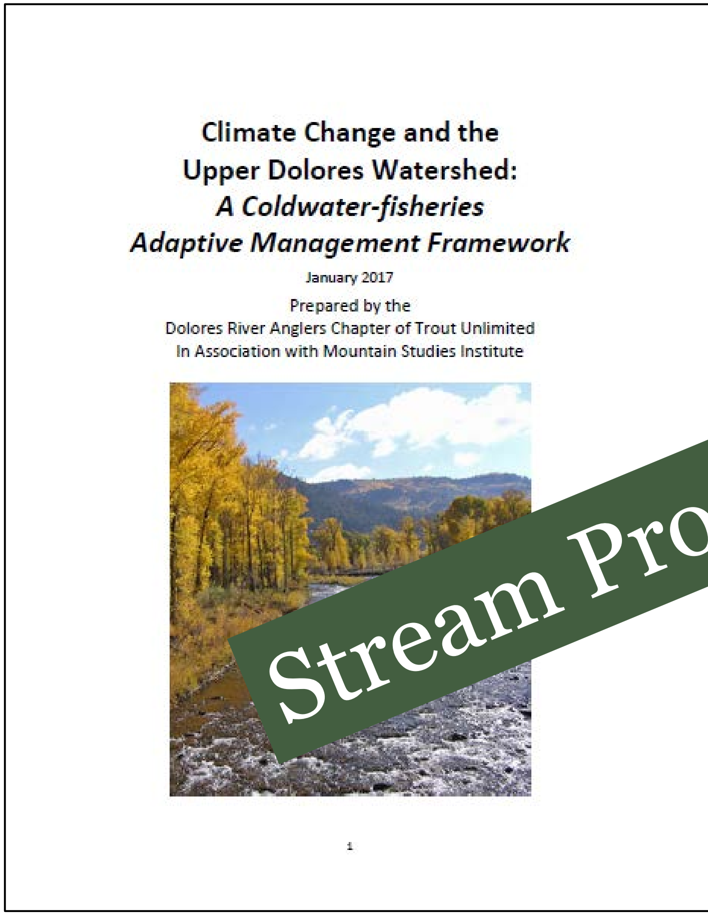
Key to managing ecological vulnerability is managing habitat *resistance* (capacity to withstand disturbances) and *resilience* (capacity to recover from disturbances).



Emergent Management Strategies

- Increased protection/regulation: As more fishermen become concentrated within a steadily reducing habitat range, more protection/regulation such as In-stream flow, NFS Land Management Area restrictions, strict catch and release, reach closure/rotation, barbless hooks, and even closure periods for specific reaches may have to be introduced. More wildlife officers will likely be required.
- In/near-stream construction: Consider carefully selected in-stream and near-stream habitat modifications where cost effective (directing larger investments at long-range strongholds). Protecting, enhancing and creating pools/pockets is essential as is sustaining and providing riparian cover.
- Integrated management: As the forests become dryer and ecosystems and habitats change, coordination between Colorado Parks & Wildlife, The National Forest Service and National Park management teams across disciplines (hydrology, fire management, road and trail maintenance, etc.) becomes vital.
- Coordination with water users: Coordination with local water districts, irrigation companies, etc., becomes critical as flow diminishes and irrigation increases.
- Low-impact philosophy: Public outreach to inculcate a value of low impact use of all lands, but especially public lands, becomes increasingly important.

CAMF – Forms Our (DRA) Conservation Work-Program Framework


Climate Change and the
Upper Dolores Watershed:
A Coldwater-fisheries
Adaptive Management Framework
January 2017
Prepared by the
Dolores River Anglers Chapter of Trout Unlimited
In Association with Mountain Studies Institute


Fin Sa


Temp
Monitoring


Stream Protection

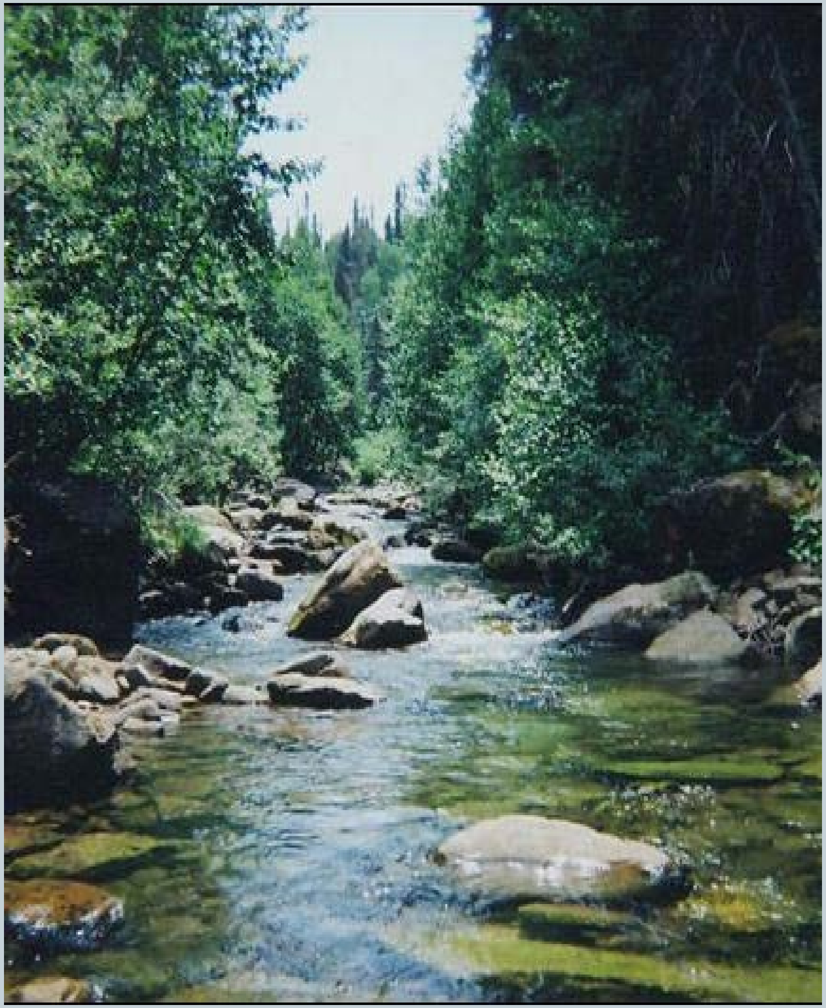

In/Near -
Stream Work

Stream Protection Working Group

CWCB

Ending Study Thoughts…

- The engines driving climate change are both massive and relentless. Many streams/reaches in our Study Area will face very serious challenges as they approach mid century, much less 2100.
- Some will respond well to carefully selected mitigation efforts.
- Many, though, may well be outside the range of cost-effective management over the long run and will either become warmer-water fisheries or will simply dissipate.
- To paraphrase Reinholt Neibuhr's famous Serenity Prayer, "may we have the wisdom to know the difference".



For More Information Contact:
Duncan Rose at tduncan.rose@gmail.com or 970.570.9905

Download the study and/or presentations:
http://coloradotu.org/camf/

Dolores River Anglers
Chapter 145, Trout Unlimited

Thanks…and tight lines!

Duncan Rose

“Parking Lot”

RCPs (1)

- **RCP2.6** represents the lower end of possible mitigation strategies, where emissions peak in the next decade or so, and then decline rapidly. This scenario is only possible if the world has gone carbon-negative by the 2070s, presumably by developing wide-scale carbon-capture and storage(CCS) technologies. This might be possible with an energy mix by 2070 of at least 35% renewables, 45% fossil fuels with full CCS (and 20% without), along with use of biomass, tree planting, and perhaps some other air-capture technologies. *[My interpretation: this is the most optimistic scenario, in which we manage to do everything short of geo-engineering, and we get started immediately].*

RCPs (2)

- **RCP4.5** represents a less aggressive emissions mitigation policy, where emissions peak before mid-century, and then fall, but not to zero. Under this scenario, concentrations stabilize by the end of the century, but won't start falling, so the extra radiative forcing at the year 2100 is still more than double what it is today, at $4.5 W/m^2$. *[My interpretation: this is the compromise future in which most countries work hard to reduce emissions, with a fair degree of success, but where CCS turns out not to be viable for massive deployment].*

RCPs (3)

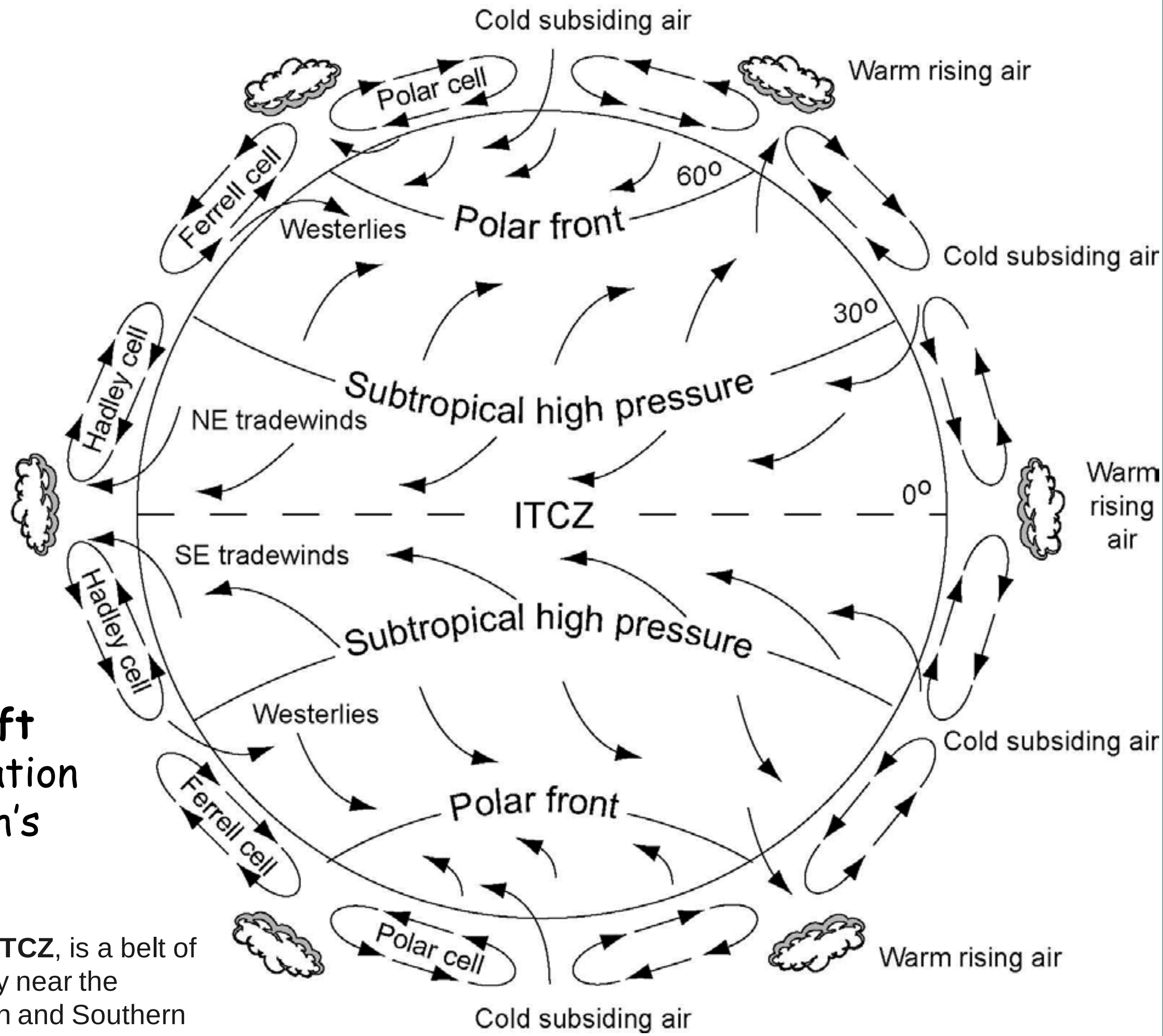
- **RCP6** represents the more optimistic of the non-mitigation futures. *[My interpretation: this scenario is a world without any coordinated climate policy, but where there is still significant uptake of renewable power, but not enough to offset fossil-fuel driven growth among developing nations].*
- **RCP8.5** represents the more pessimistic of the non-mitigation futures. For example, by 2070, we would still be getting about 80% of the world's energy needs from fossil fuels, without CCS, while the remaining 20% come from renewables and/or nuclear. *[My interpretation: this is the closest to the "drill, baby, drill" scenario beloved of certain right-wing American politicians]."*

Air rises and falls
in Hadley, Ferrel, and
Polar cells
(vertical circulation)

Circulation cells
explain global
distribution of
rainfall

Earth's rotation
determines
wind direction
(horizontal circulation,
Coriolis force)

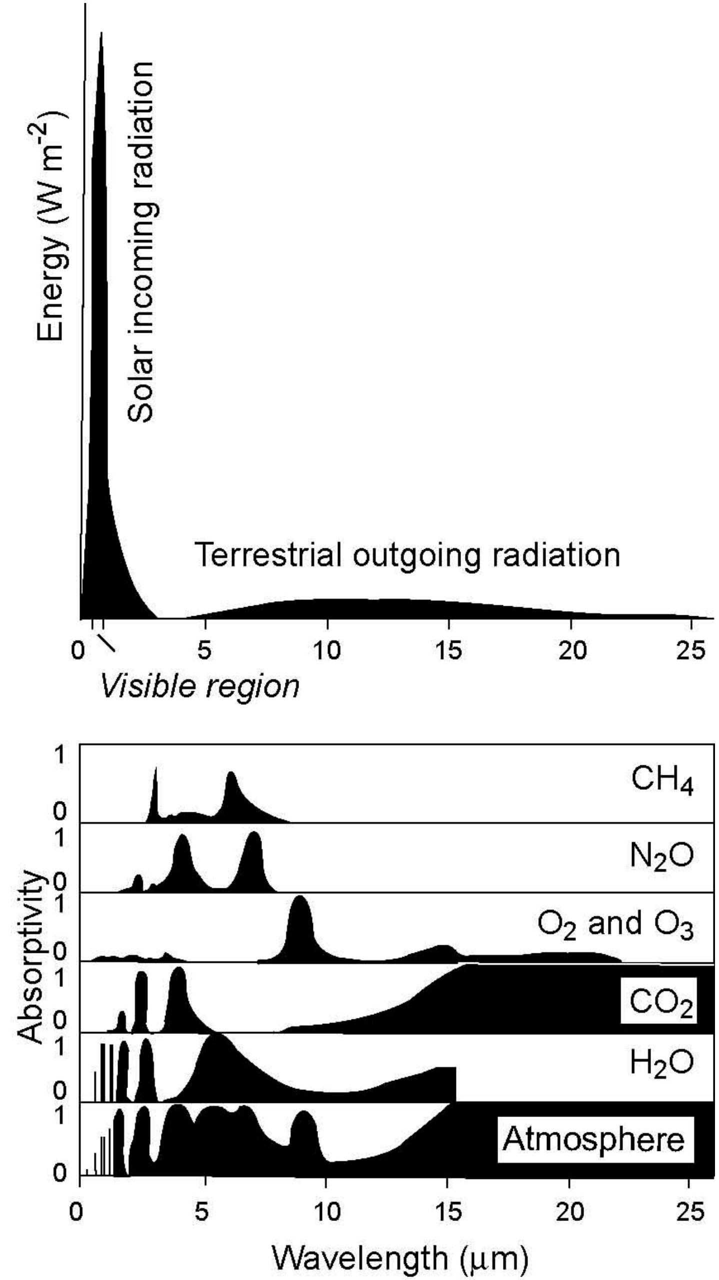
ITCZ* and cell locations **shift seasonally** depending on location of maximal heating of Earth's surface



*The **Inter Tropical Convergence Zone**, or **ITCZ**, is a belt of low pressure which circles the Earth generally near the equator where the trade winds of the Northern and Southern Hemispheres come together.

2.6

Atmosphere is more transparent to incoming short-wave radiation than to outgoing long-wave radiation

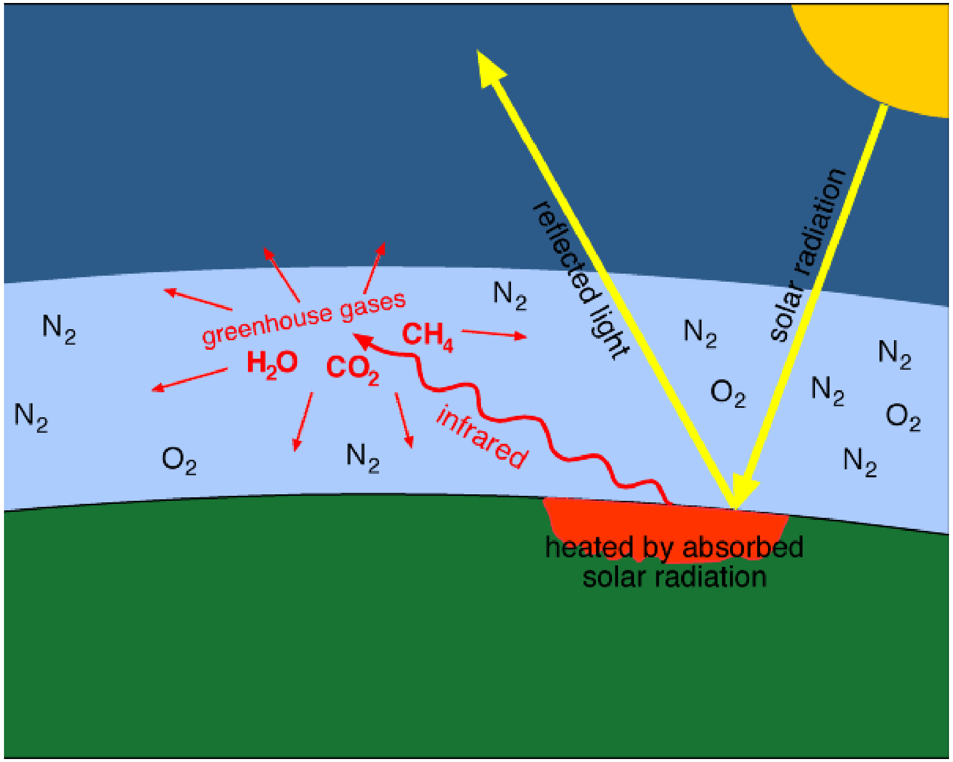


The temperature of a body determines wavelengths of energy emitted

Solar radiation has high energy (shortwave) that readily penetrates the atmosphere

Earth emits low-energy (longwave) radiation that is absorbed by different gases in the atmosphere

Reflected Infrared Energy Heats Atmosphere

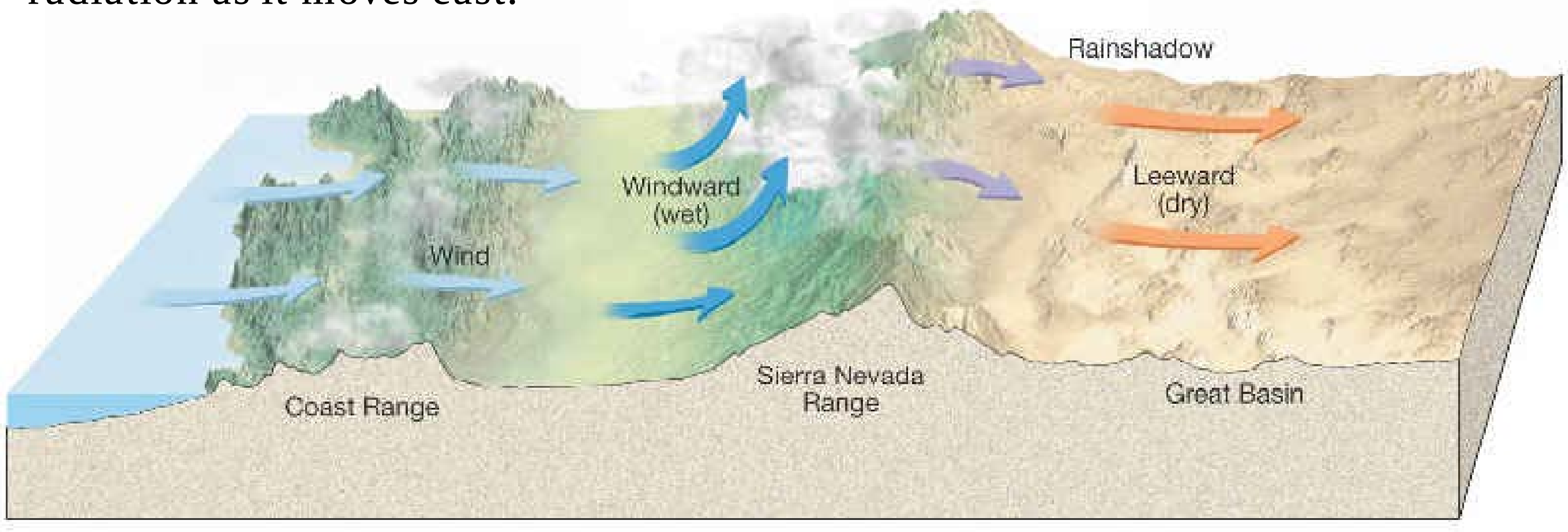


Due in part to the warming effects of the greenhouse gases, the global average temperature is about 15°C (59°F). Without the greenhouse gases the global average temperature would be much colder, about -18°C (0°F)

- Most of the sun's energy that falls on the Earth's surface is in the visible light portion of the electromagnetic spectrum. This is in large part because the Earth's atmosphere is transparent to these wavelengths (with a functioning ozone layer, the higher frequencies like ultraviolet are mostly screened out).
- Part of the sunlight is reflected back into space, depending on the reflectivity of the surface.
- Part of the sunlight is absorbed by the Earth and held as thermal energy. This heat is then re-radiated in the form of longer wavelength infrared radiation.
- While the dominant gases of the atmosphere (nitrogen and oxygen) are transparent to infrared, the so-called greenhouse gasses, primarily water vapor (H_2O), CO_2, and methane (CH_4), absorb some of the infrared radiation.
- They collect this heat energy and hold it in the atmosphere, delaying its passage back out of the atmosphere.

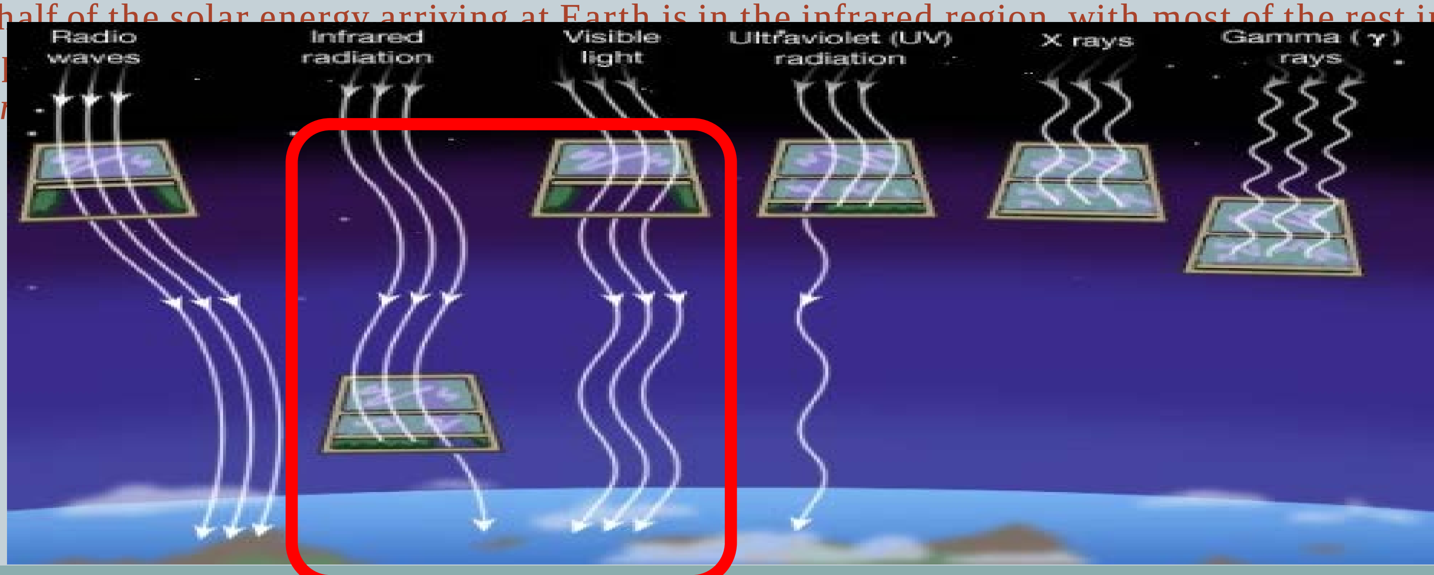
Moist Pacific Air Dries As It Moves Westward

Moist air is dried by 1) the orographic “rain shadow” effect and 2) desert radiation as it moves east.



Sun’s Radiation and the Atmosphere (2)

- However, the Earth's atmosphere protects us from exposure to a range of higher energy waves that can be harmful to life. This is because different materials can block different types of light. More specifically, the earth's *atmosphere* only allows certain wavelengths of light to penetrate to the surface.)
- Electromagnetic radiation is reflected or absorbed mainly by several gases in the Earth's atmosphere, among the most important being water vapor, carbon dioxide, ozone and methane.
- Some radiation, such as visible light, largely passes (is transmitted) through the atmosphere. Those regions of the spectrum with wavelengths that can pass through the atmosphere are referred to as "atmospheric windows.“
- About half of the solar energy arriving at Earth is in the infrared region, with most of the rest in the visible p *ut 48%* *is absor*



Text: https://science.nasa.gov/ems/01_intro

Graphic: https://www.e-education.psu.edu/astro801/content/l3_p4.html

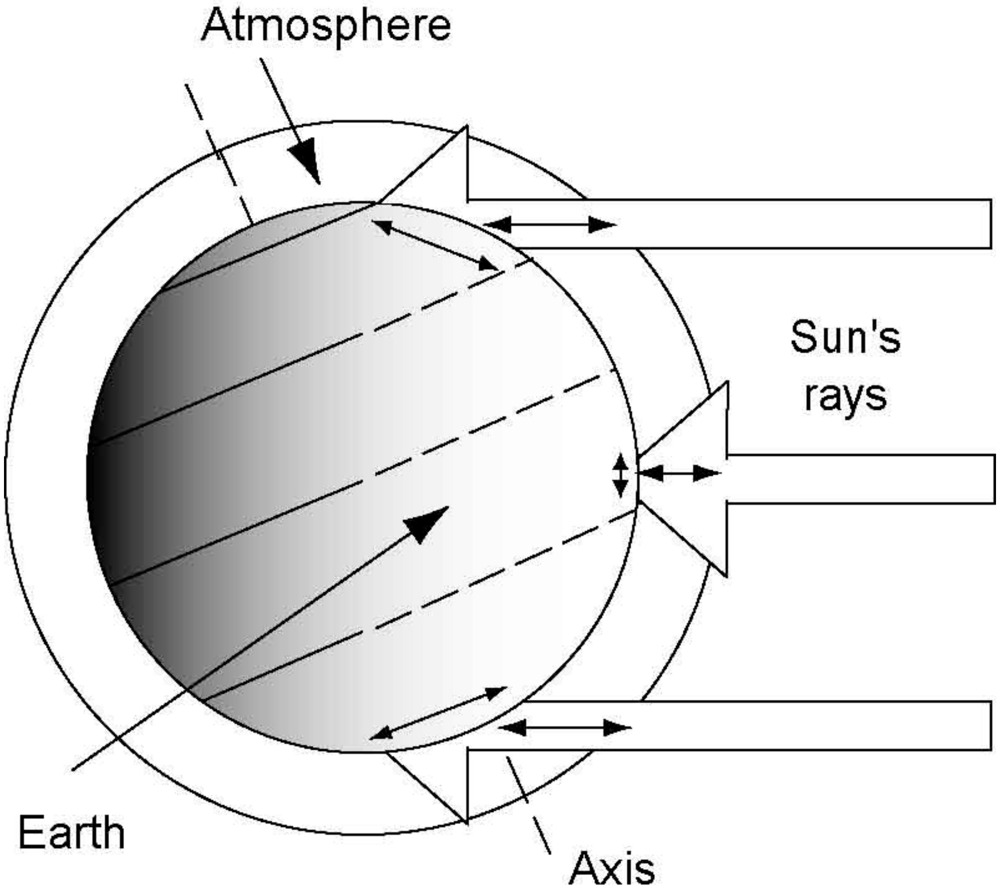
Atmospheric circulation - Uneven heating of Earth's surface causes atmospheric circulation

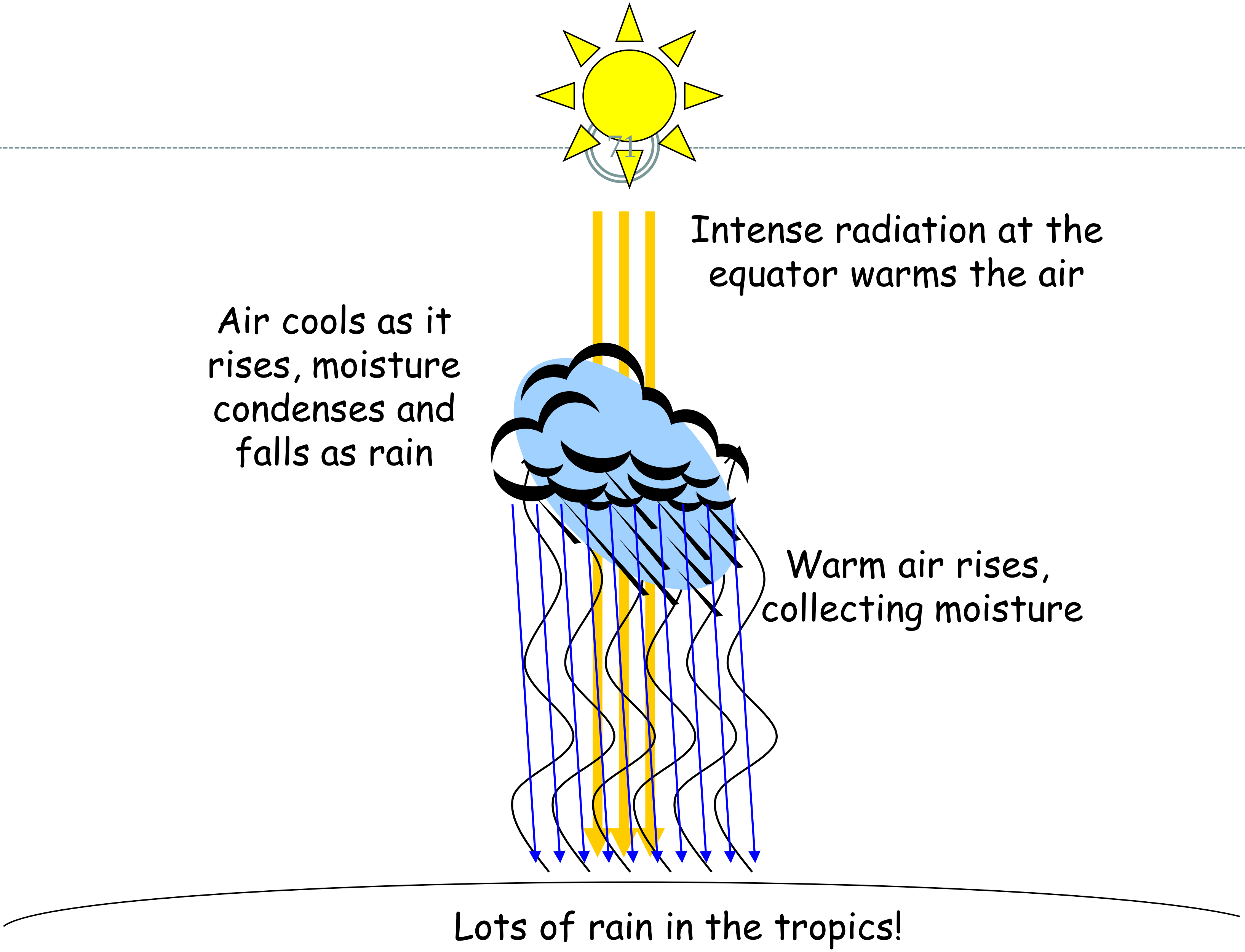
Greater heating at equator than poles

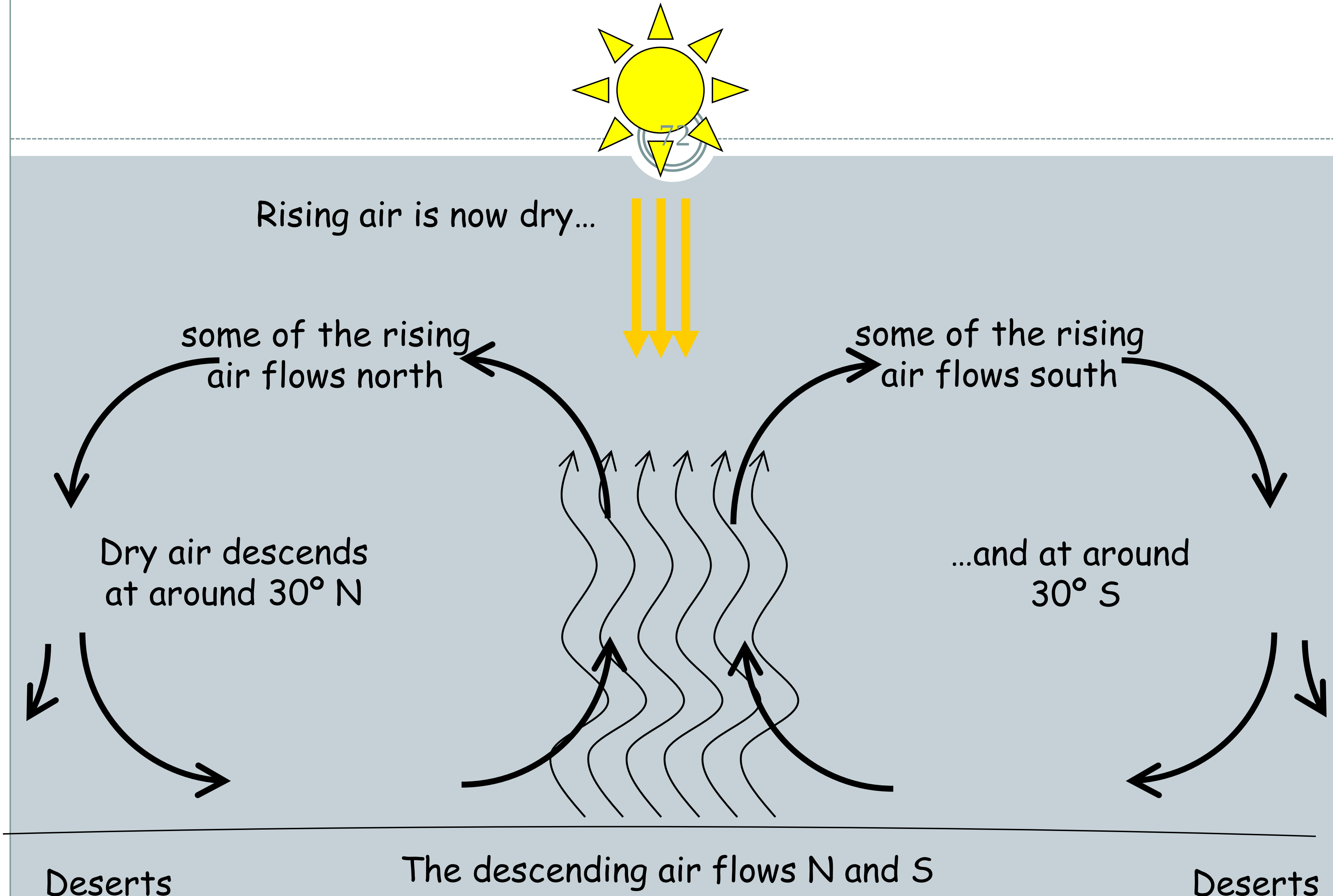
Therefore

1. Net transfer of energy from Equator to poles.
2. Transfer occurs through circulation of atmosphere and oceans.

Here's how it works…




Intense radiation at the equator warms the air
Air cools as it rises, moisture condenses and falls as rain
Warm air rises, collecting moisture
Lots of rain in the tropics!



fire.biol.wwu.edu/hooper/416_02**climate**.ppt

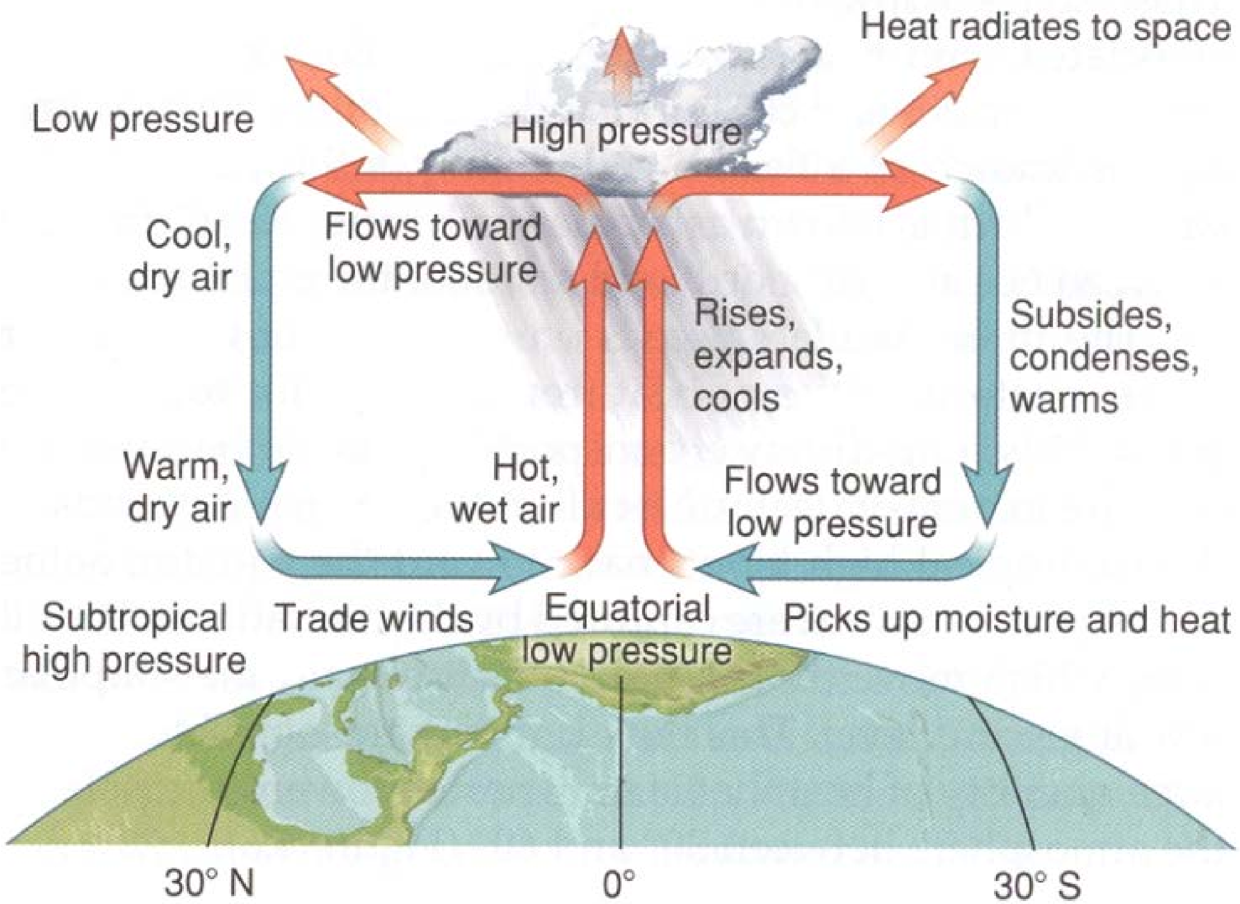
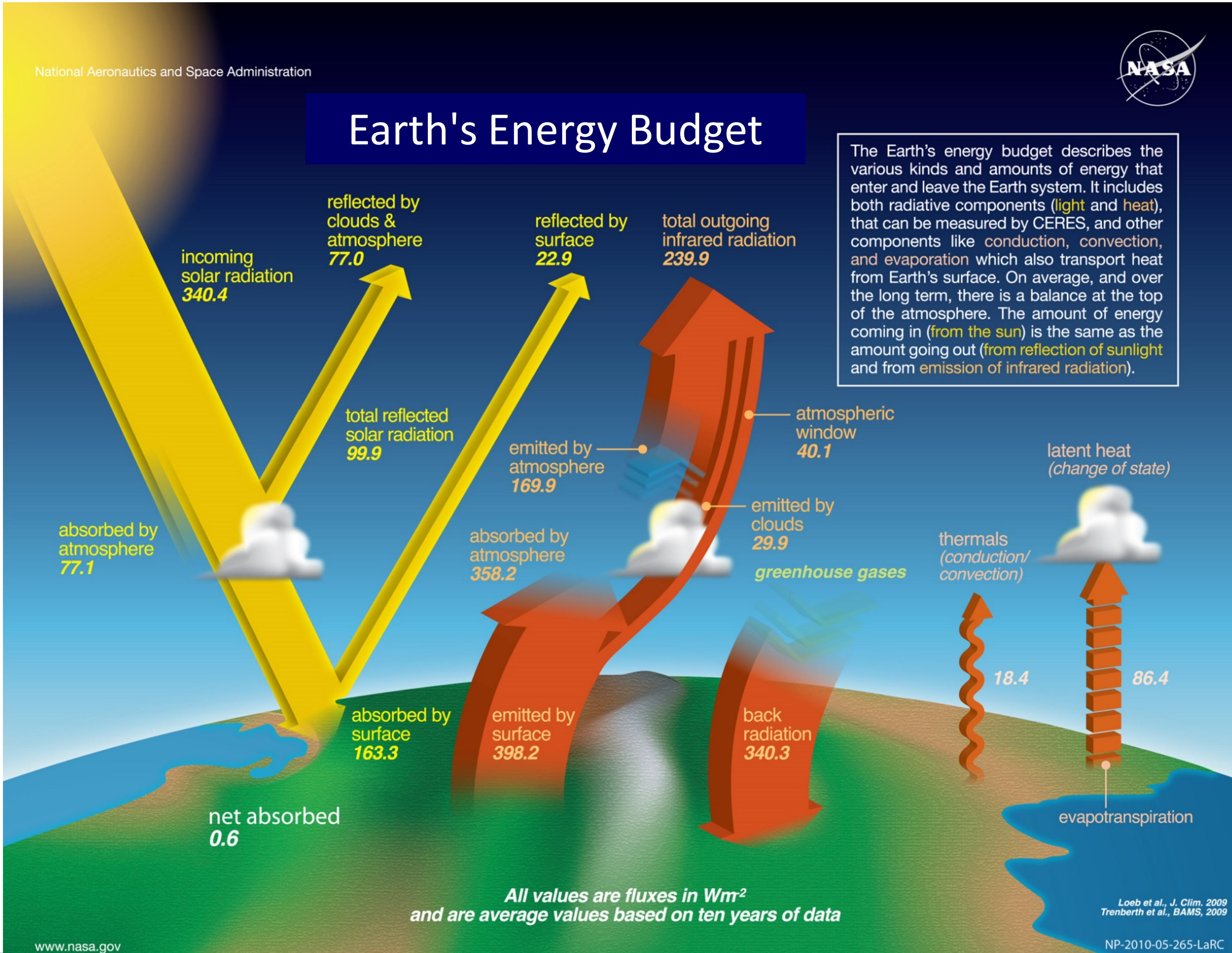
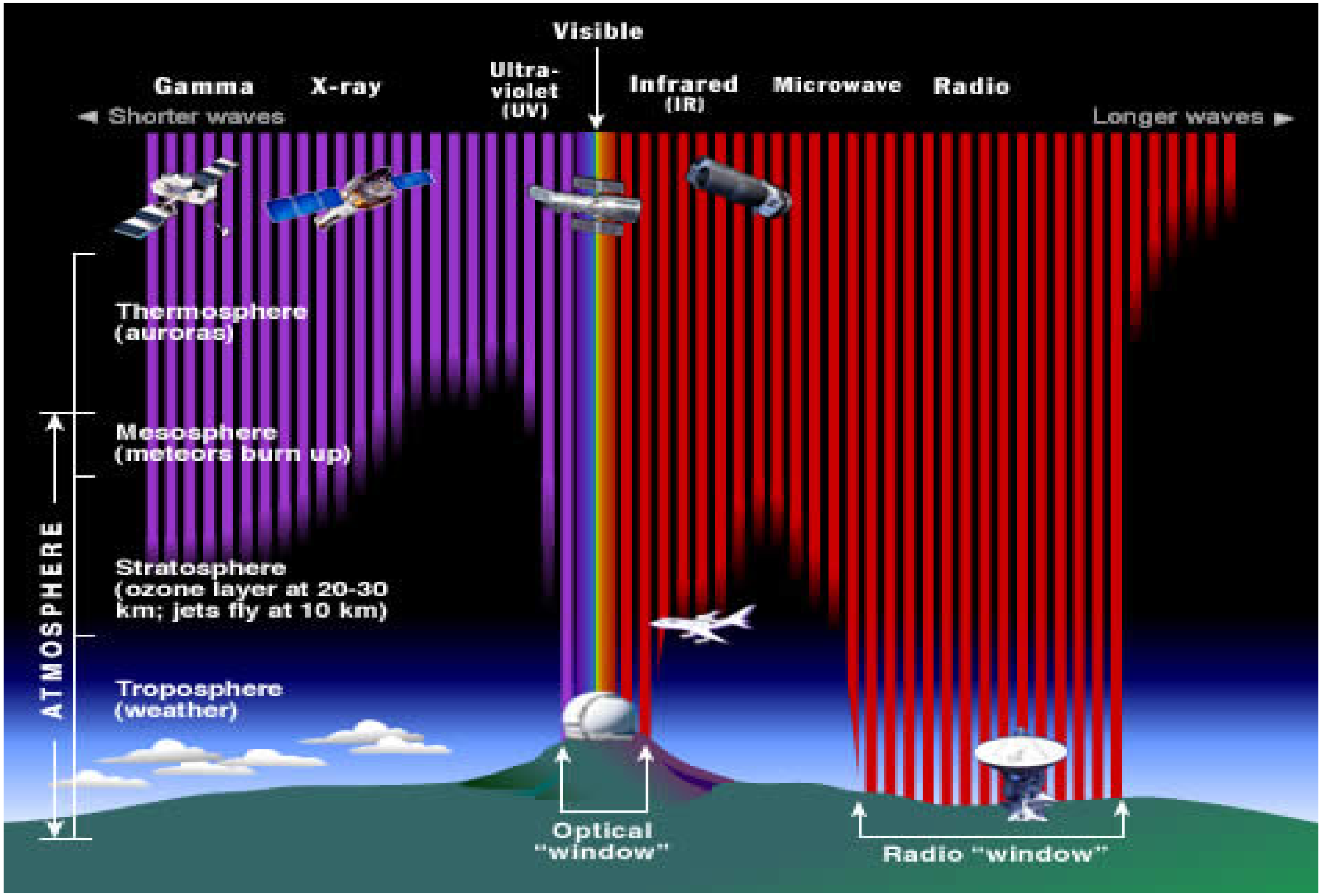


FIGURE 4.7 ***Atmospheric Convection Cell*** *Warm air rises at the equator. As it rises, it cools and generates large amounts of precipitation. Air cools as it moves away from the equator. At about 30° north or south the dense air falls toward Earth's surface. As it does, it warms and tends to reduce precipitation. Once this air reaches the surface, pressure differences cause air to move along the surface toward the equator.*

Convection Moves Hot, Moist Air High Into The Atmosphere Where Cooling and Pressure Gradient Dries and Drops the Air


National Aeronautics and Space Administration
NASA
Earth's Energy Budget
The Earth's energy budget describes the various kinds and amounts of energy that enter and leave the Earth system. It includes both radiative components (light and heat), that can be measured by CERES, and other components like conduction, convection, and evaporation which also transport heat from Earth's surface. On average, and over the long term, there is a balance at the top of the atmosphere. The amount of energy coming in (from the sun) is the same as the amount going out (from reflection of sunlight and from emission of infrared radiation).
incoming solar radiation 340.4
reflected by clouds & atmosphere 77.0
reflected by surface 22.9
total outgoing infrared radiation 239.9
total reflected solar radiation 99.9
atmospheric window 40.1
emitted by atmosphere 169.9
latent heat (change of state)
emitted by clouds 29.9
absorbed by atmosphere 77.1
absorbed by atmosphere 358.2
greenhouse gases
thermals (conduction/ convection)
18.4
86.4
absorbed by surface 163.3
emitted by surface 398.2
back radiation 340.3
net absorbed 0.6
evapotranspiration
All values are fluxes in Wm-2 and are average values based on ten years of data
Loeb et al., J. Clim. 2009
Trenberth et al., BAMS, 2009
www.nasa.gov
NP-2010-05-265-LaRC


Visible
Gamma
X-ray
Ultra-
violet
(UV)
Infrared
(IR)
Microwave
Radio
Shorter waves
Longer waves
Thermosphere
(auroras)
Mesosphere
(meteors burn up)
Stratosphere
(ozone layer at 20-30
km; jets fly at 10 km)
Troposphere
(weather)
ATMOSPHERE
Optical
"window"
Radio "window"